Black Sea Journal of Agriculture
doi: 10.47115/bsagriculture.1518799

Open Access Journal
e-ISSN: 2618 – 6578

Review
Volume 7 - Issue (ICABGEH-23): 464-476/ August 2024

NUTRITIONAL ASPECTS FOR MODULATION OF POULTRY IMMUNE STIMULATION

Merve GÜNDÜZ[1]*, Arda SÖZCÜ[1], Üzeyir ÇAĞIRICI[2]

[1]*Bursa Uludağ University, Faculty of Agriculture, Department of Animal Science, 16059, Bursa, Türkiye*
[2]*Kaman Türk Telekom Osman Kulaksız Vocational and Technical Anatolian High School, 40300, Kırşehir, Türkiye*

Abstract: The immune system's defense mechanism has been affected by the management and nutrition conditions in poultry production. In biological aspects, Bursa Fabricius and Thymus are primary lymphoid organs that defend the body against diseases. The spleen, cecal tonsils, immunoglobulins, and various forms of mucosal immunity, BALT (bronchus-associated lymphoid tissue), MALT (mucosa-associated lymphoid tissue), CALT (conjunctiva-associated lymphoid tissue), and GALT (gut-associated lymphoid tissue), are also vital to their overall health. The management program (environmental conditions, heating, lighting practices) and feed (feed ingredients, composition, and feed additives) significantly affect birds' immunity and performance. Dietary supplementation enhances immune system activation by improving the lymphoid tissues and beneficial immune modulators and responses. During the past fifteen years, alternative feed additives (amino acids, minerals, vitamins, probiotics, prebiotics, synbiotics, and organic acids) have impacted animal production performance and immunity. Besides, feed additives, such as probiotics, prebiotics, vitamins, minerals, and organic acids, are essential for sustaining hormonal, physiological, and immunological processes. These additives, probiotics, vitamins (A, C, D, E), mineral (selenium) supplementations, and organic acids boost the immune system's activity against microbial pathogens and physiological stress mechanisms. Finally, this paper aims to review the current improvement in the relationship between nutrition and immunity in poultry.

Keywords: Immune system, B and T cells, Vitamins, Minerals, Organic acids

***Corresponding author:** Bursa Uludağ University, Faculty of Agriculture, Department of Animal Science, 16059, Bursa, Türkiye
E mail: mervegunduz@uludag.edu.tr (M. GÜNDÜZ)
Merve GÜNDÜZ https://orcid.org/0000-0002-5449-9893
Arda SÖZCÜ https://orcid.org/0000-0002-0955-4371
Üzeyir ÇAĞIRICI https://orcid.org/0009-0001-2445-0933

Received: July 19, 2024
Accepted: August 04, 2024
Published: August 15, 2024
Cite as: Gündüz M, Sözcü A, Çağirici Ü. 2024 Nutritional aspects for modulation of poultry immune stimulation. BSJ Agri, 7(Special Issue; ICABGEH-23): 464-476.

1. Introduction

The immune system is characterized by the innate (maternal) and adaptive immunological developmental processes against with inadequate defence mechanism and health issues, predisposing individuals to microbial infections (Wynn and Levy, 2010; Alkie et al., 2019). To prevent the spread of viral, bacterial, fungal, and parasitic diseases in the body, the immune system plays a major role with its activity. The body produces defense molecules called antibodies, which recognize and deactivate pathogens (Sarıca et al., 2009). Besides, different pathogens potentiate the cellular and humoral response by altering the immune system's reaction (Shaji et al., 2023).

The immune system consists of various organs and tissues, including the Bursa Fabricius, thymus, bone marrow, spleen, the harderian gland, lymph nodes, circulating lymphocytes, and lymphoid tissue in the alimentary tract in poultry (Panda et al., 2015). Lymphoid tissue may be specialized into two types: primary and secondary. The thymus and Bursa Fabricius are considered primary organs, whereas the spleen is a secondary type of lymphoid tissue. The Bursa Fabricius belongs to birds and is absent from mammals due to evolution. In both hens and mammals, primary lymphoid tissue reduces after puberty, with the effects of sex hormones (Junior et al., 2018).

Animals have a precise immune system mechanism that resists pathogens and adverse environmental conditions (Korver, 2023). Among the immunosuppressive components are management, feeding programs, and nutrition deficiencies, which cause health and welfare issues (Wlazlak et al., 2023). Also, immunosuppression decreases body weight gain and production performance and increases mortality and morbidity rates mainly due to secondary viral and bacterial infections (Fussell, 1998; Rehman et al., 2016). Immune system activation on metabolism has a significant impact on maintaining broiler health to optimize performance and cost-efficient production. Thus, acute activation of the immune system leads to inflammatory pathways with reduced feed intake. The hypothalamic-pituitary-adrenal axis is activated when the immune system detects a foreign substance and releases chemical messengers known as cytokines. These cytokines are responsible for initiating the production of acute phase proteins (APP) in the liver, transmitting feedback to the brain, resulting in common illness symptoms such as fever and decreased appetite

(Silverman et al., 2005; Rochell et al., 2016).

It has been stated that immunity and production performance in poultry are positively correlated. Antibody production and immunity regulation depend on non-genetic factors, which include nutritional concentrations in the diet. At the same time, it has been proven that imbalance between nutrients or toxicity, disorders in the bird's physiology may occur due to immunosuppression. The immune system's reaction to harmful microorganisms penetrating the animal's body is related to its nutritional condition. Immune system suppression may result in inadequate body weight gain and feed conversion ratio, high mortality rate, uniformity issues, secondary bacterial infections, and lymphoid organ atrophy (Aviagen, 2009; Abo-Al-Ela et al., 2021). Currently, modern broilers have a rapid growth rate, high body weight, and efficient feed conversion, which makes them vulnerable to high disease rates and necessitates strong immune function. Because the nutrients in the feed are utilized for muscle growth, fast-growing modern broilers tend to have low disease resistance and are susceptible to diseases (Song et al., 2021).

Numerous factors, including diseases, environmental conditions, management practices, vaccination programs, physical type of feed material, and nutrition-related stress, weaken the immune system, potentially increasing susceptibility to infections (Abo-Al-Ela et al., 2021; Wlazlak et al., 2023). Nutritional deficiencies in the feed supplementation may result in deterioration in the growth and development mechanism of the immune system. Additionally, insufficient vitamin levels may compromise the immune system, enhancing susceptibility to infection and inflammation. During metabolic processes, vitamins of A, D, E, and C have been shown to significantly impact immune system function (Khan et al., 2023). For this reason, the review focused on the relationship between nutrition and immune system modulation of poultry.

2. Primary Immune Organs

The formation of the immune system organs begins in the embryonic stage and entirely functions with advancing age. The immune system organs generate functional lymphocytes and release them into the peripheral immune system to actively participate in immune responses (Naukkarinen and Hippelãinen, 1989; Gordon and Manley, 2011). In the avian immune system, there are two primary organs. The first one is Bursa Fabricius, associated with B-cells, and the second is the Thymus, associated with T-cells. Both organs produce B and T cells to improve poultry immunity. The thymus is located in the neck's ventral region and under the thyroid gland in front of the chest cavity. This gland is surrounded by a thin capsule composed of connective tissue. The compartments of the thymus gland contain reticular cells and lymphocytes. The thymus gland's primary function is to protect the body from infection by activating lymphocytes before and immediately after birth. Autoreactive T cells are responsible for eliminating killing cells and synthesizing thymic hormones during the maturation of T lymphocytes in poultry (Sarıca et al., 2009). T and B cells progress to the secondary lymphoid tissue to provide a defense, which includes the spleen and mucosa-associated lymphoid tissue (MALT). The primary lymphoid tissue is crucial in selecting lymphocytes (including T-cells and B-cells) for a robust immune response while preventing autoimmunity (Yasuda et al., 2003).

The lymphoid stem cells in the bone marrow generate the T and B cell precursors (Ratcliffe and Jacobsen, 1994; Ratcliffe, 2006; Garcia et al., 2021). Bursa Fabricius is placed in the dorsal of the cloaca and is responsible for the maturation of B lymphocytes, the killing of autoreactive B cells, and the synthesis of hormones. The Bursa Fabricius produces B-cells, which are responsible for synthesizing antibodies. Moreover, bone marrow-derived stem cells that resemble lymphoid cells mature in the thymus and Bursa Fabricius before proceeding via the bloodstream and lymphatic circulation to peripheral immune organs (Gordon and Manley, 2011; Davison, 2022). During the exposure to foreign antigens, the immune cells exhibit proliferation and differentiation. Additionally, in peripheral blood lymphocytes, the proliferative activity indicates a strengthening functional activity of T and B cells, reflecting an elevated cellular immune function (Dekruyff et al., 1980; Naukkarinen and Hippelãinen, 1989).

3. Secondary Lymphoid Organs

It has been stated that spleen, bone marrow, harderian gland (in orbit), pineal gland (in the brain), mucosa-associated lymphoid tissues (MALT), bronchus-associated lymphoid tissue (BALT), gut-associated lymphoid tissue (GALT), conjunctiva-associated lymphoid tissue (CALT) are secondary lymphoid organs in birds. MALT, BALT, GALT, and CALT lymphoid tissues comprise approximately 50% of the cells in the spleen. These lymphoid tissues accumulate on the skin or mucosal surface, where foreign antigens enter the body (Gurjar, 2013). The spleen is the largest of the secondary lymphoid organs and is surrounded by a capsule composed of connective tissue. It has several functions for the aging erythrocytes, erythrocytes production in fetal life, and granulocytes in postnatal life, to contribute to the formation of antibodies through B lymphocytes, phagocytosis through macrophage, and for accumulation of red blood cells (Júnior et al., 2018). On the other hand, spleen size increases through hyperplasia tissue, known as splenomegaly, after exposure to pathogens. Lymphocyte hyperplasia has also been observed in MALT. The germinal center is where avian antibodies are effectively produced (Junior et al., 2018; Lewis et al., 2019). Additionally, chickens have three classes of immunoglobulins similar to mammals: IgA, IgM, and IgY (equivalent to IgG). Although it has been suggested that chickens also have antibodies similar to mammalian IgE and IgD, this has not been proven. Chicken IgY and mammalian IgG characterize immunological similarities, and the DNA sequence of chicken IgY is similar to human IgE (Shimizu et al., 1992; Aizenshtein et al., 2016; Pereira et al., 2019).

4. Nutrition and Immunity

Birds' immune systems benefit considerably from a well-balanced nutrition program. The function of the immune system is to struggle with the negative impacts of stress and protect against pathogenic diseases. The regulation of the immune system in poultry involves the progress of anatomy in lymphoid tissues, mucus production, immunologically active substances synthesis, cellular proliferation, activation, movement, intracellular killing of pathogens, and modulation and regulation of the immune process. The nutritional intake may influence chickens' immune reactions, substantially benefiting their well-being and health. Therefore, a balanced diet could enhance chickens' overall health by preventing stress-related immune suppression (Butcher and Miles, 2002). The stimulation of immune system reactions in poultry nutrition has been revealed (Montout et al., 2021; Selim et al., 2021; Yu et al., 2021).

Poultry production has been focused on improving feed efficiency, decreasing disease risk, and increasing performance (Korver, 2023). Feed additives in poultry nutrition have been used as an alternative to antibiotics due to their potential positive effects on the growth rate, feed conversion, and resistance against pathogenic diseases (Fonseca et al., 2010; Ganan et al., 2012). It is widely known that antibiotics have extensively impacted poultry production in terms of maintaining gut microorganism balance and promotion (Selaledi et al., 2020). Due to food safety concerns and the public demand for antibiotic-free farm animal products, many countries have banned of antibiotics in poultry nutrition as a routine of growth promotion (Neveling and Dicks, 2021). So that, alternatives to antibiotics are needed to sustain poultry productivity and promote their performance and immunologic response (Wickramasuriya et al., 2024).

Nutraceuticals, including essential minerals and vitamins, are fundamental to animal nutrition. Nutritional components significantly benefit by preventing diseases, exhibiting immunomodulatory properties, promoting overall health, and enhancing productivity, regulating gut microbiota (Alagawany et al., 2021; Shehata et al., 2022). Feed additives essentially comprise amino acids, minerals, vitamins, fatty acids, enzymes, prebiotics, probiotics, synbiotics, pigments, medicinal herbs, herbal extracts, antioxidants, organic acids, and flavoring agents (Alagawany et al., 2018; Mohammed et al., 2019; Elgeddawy et al., 2020; Adhikari et al., 2020; Rehman et al., 2020; Shehata et al., 2022). Synthetic supplements include essential amino acids (such as lysine, methionine, threonine, and tryptophan), vitamins, and minerals. Besides, nutraceutical dietary elements may enhance digestion, absorption, utilization, metabolism, and positive health status (Ravindran, 2010; Haq at al., 2016; Alagawany et al., 2021) (Table 1).

The nutrients have been known to potentially affect embryonic development and hatchability with the prevention of musculoskeletal, immunological, and circulatory issues (Uni et al., 2012). During embryogenesis, nutrients are mainly acquired from yolk, which mainly contains lipids and low levels of carbohydrates (Santos et al., 2010). Supplementing with bioactive substances such as amino acids, polyphenols, and prebiotics will enhance the immune system, reduce osteoporosis, and lower the risk of heart diseases (Chalamaiah et al., 2018). The application of in-ovo injection for various biological agents has been recognized for its efficacy in poultry production. The application of in-ovo entails using nutritional supplements such as carbohydrates, proteins, amino acids, vitamins, and minerals (Ohta et al., 1999; Bhanja et al., 2005; Zhai et al., 2011; Bakyaraj et al., 2012). L-Arginine (100 μg/μL/egg) in-ovo injection on the 14th day of the embryonic stage enhanced survival rates, body weight, and immune response (IgM) in Subramaniyan et al. (2019) research.

After hatching, the early feeding program has gained immense importance for the developmental process of immunity in birds. Firstly, innate immunity is considered the defense mechanism, and adaptive immunity is for the protection against specific pathogens by the functions of lymphoid cells and antibodies. It has been stated that innate immunity is essential to secure all living organisms' cellular integrity, homeostasis, and livability (Buchmann, 2014; Romo et al., 2016).

The formation of birds' defense mechanisms begins in embryogenesis and continues to function for several days after hatching (Yasuda et al., 2003). Maternal antibodies in the yolk protect embryos and chicks (approximately one month) against microbial infection during egg incubation and after hatching. The secondary lymphoid tissues complete their development one week after hatching, facilitating an effective immune response and specific antibody production in chick vaccination (Yasuda et al., 2003; Hamal et al., 2006). Additionally, the post-hatching period is significant due to a lack of maternal immunity (approximately one week) (O'Neal and Ketterson, 2012).

Table 1. Dietary supplementation in poultry immune stimulation

Dietary Supplementation	Species	Effects	Reference	Access Web
Probiotics *Bacillus coagulans, Lactobacillus plantarum*	Broilers	The higher level of serum IgY, IgA, IgM concentration	Yu et al., 2022	https://pubmed.ncbi.nlm.nih.gov/35265699/
Probiotics *Lactobacillus fermentum, Saccharomyces cerevisiae*	Broilers	The higher proportions of CD3+, CD4+, and CD8+ T-lymphocytes	Bai et al., 2013	https://pubmed.ncbi.nlm.nih.gov/23436517/
Probiotics *DFM supplementation*	Broilers	Regulation of gut microbiota by increasing the log concentrations of beneficial bacteria (*Bacillus, Bifidobacterium, C. butyricum,* and *Lactobacillus*)	Heak et al., 2018	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6212764/
Probiotics *Bacillus subtilis, Lactic acid bacteria, Saccharomyces*	Laying hens	Decreased the expression level of proinflammatory cytokines such as *IL-1*, *IL-6* and *TNF-α* in ovary	Xu et al., 2023	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC9902371/
Prebiotics *Mannan-oligosaccharides, Beta-d-glucan*	Broilers	Improved the chicken gut microbiome and alleviated the negative effects of heat stress	Sayed et al., 2023	https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10460421/
Amino acids *Glutamine, arginine, threonine*	Broilers	Improve the immune response against an *Eimeria and E. coli* challenge	Gottardo et al., 2017	https://www.scielo.cl/scielo.php?script=sci_arttext&pid=S0719-81322017000300175
Aminoacids *l-threonine*	Laying hens	Linearly increasing levels of IgG and total Ig	Azzam et al., 2011	https://www.sciencedirect.com/science/article/pii/S1056617119312589
Minerals *Organic and inorganic Zinc, selenium, chromium*	Broilers	Increased humoral immune response and upregulation of chTLR4 gene expression in bursa and spleen indicates a beneficial effect of OTM in augmentation of the immune system	Jain et al., 2021	https://pubmed.ncbi.nlm.nih.gov/34220108/
Minerals *Chelated form Manganese, selenium, copper, iron, zinc*	Broiler Breeder	Significant increase in the antibody titre against Newcastle disease	Mohammadi et al., 2023	https://www.tandfonline.com/doi/full/10.1080/1828051X.2023.2215248
Minerals *Zinc, copper, manganese chelated with the hydroxy analogue of methionine*	Laying hens	Trace minerals in the chelated form improved bird immune response to antigenic challenge at wk 63	Manangi et al., 2015	https://www.sciencedirect.com/science/article/pii/S1056617119303046
Vitamins *Vitamin A and K3*	Laying hens	Improved the intestine antioxidant capacity	Li et al., 2022	https://www.scielo.br/j/rbca/a/FDydzRcrPkdG93B6mwKfSYq/?lang=en
Vitamins *Vitamin E*	Broilers	There was no increase in antibody titer against the IB virus with 300mg Vitamin E /kg feed additive	Sadiq et al., 2023	https://dx.doi.org/10.36380/jwpr.2023.13
Organic Acids *SAS- Formic acid, propionic acid, soft acid SAP- Propionic acid, citric acid, soft acid*	Laying hens	Significant increase in small intestinal villi with the addition of SAS and SAP	Gül et al., 2014	DOI: 10.1399/eps.2013.5
Organic acids and essential oil *Sorbic acid, fumaric acid, thymol*	Broilers	Higher villus height of the duodenum and jejunum and muscular layers of the duodenum and ileum (0.30 g/kg EOA during the grower period)	Yang et al., 2018	https://pubmed.ncbi.nlm.nih.gov/30564758/

5. Nutritional Aspects in Poultry Immunity

5.1. Amino Acids

Dietary supplementation has been essential in optimizing poultry production due to obtaining better performance and health status with lower feed efficiency. The immune system consistently functions with sufficient levels of protein, energy, and micronutrients, vitamins, and minerals in nutrition (Butcher and Miles, 2002; Alagawany et al., 2021). Amino acids are the fundamental components of protein, the primary substances contributing to the growth of chickens and the production of eggs (Baker, 2009). The mechanism of lymphocyte activation, natural killer cells, and macrophages regulating intracellular redox balance, gene expression, and cytokine production related to amino acid supplementation. Therefore, appropriate dietary amino acids are critical for inhibiting infectious disorders, particularly viral infections (Chandra ve Kumari, 1994; Calder, 2013; Montout et al., 2021).

Several amino acids, such as methionine, threonine, and arginine, were studied to determine their contribution to a beneficial host immunological response (Montout et al., 2021). It has been indicated that different methionine supplementation levels of 0.60% and 0.90% in turkeys and broilers respectively resulted in increased methionine levels in the peripheral blood (Mirzaaghatabar et al., 2011; Kubinska et al., 2014). Also, in broilers, the dietary supplementation of %0.65 methionine and %0.13 choline may result in higher antibody levels (Swain and Johri, 2000).

Arginine has been characterized as a regulator of both innate and adaptive immunity (Lindez and Reith, 2021). Dietary arginine supplementation in metabolic processes may affect birds' immunological responses to physiological hemostasis under stressful conditions. A group of enzymes known as nitric oxide synthases are responsible for converting arginine into citrulline and nitric oxide as the sole route of nitric oxide synthesis (Förstermann et al., 1991; Fernandes et al., 2009). Nitric oxide exhibits cytotoxic effects on immuno-activated cells and regulates the immune system (Hibbs et al., 1988). Furthermore, arginine enhances interleukin production and T lymphocyte proliferation in broiler chickens (Rodriguez et al., 2017; Montout et al., 2021). Increasing dietary arginine over 0.45% may affect macrophage phagocytosis by stimulating the production of key cytokines, particularly IL-1, IL-2, INF, and TNF-a in broiler chickens (Emadi et al., 2010; Xu et al., 2018).

Supplementing lysine and methionine enhanced antibody production in broiler chickens against Newcastle and Gumboro infections (Bouyeh, 2012). A deficiency in dietary lysine inhibits protein synthesis, including cytokines, and lymphocyte proliferation, impairing immune responses in chickens and leading to morbidity and mortality in response to infection (Kidd, 2004). Insufficient dietary lysine levels may result in hen antibody responses and cell-mediated immunity (Chen et al., 2003).

Several essential amino acids (leucine, isoleucine, and valine) have been used in poultry nutrition. These amino acids contribute to protein synthesis, immune response modulation, intestinal tract health, and villi development (Kim et al., 2022; Liu et al., 2023). Leucine, isoleucine, and valine amino acids provide the amino groups for the synthesis of glutamine and recreate a crucial role in maintaining the gut barrier functions for epithelial cells. Furthermore, the immune system considerably depends on protein synthesis to produce cytokines, immunoglobulins, immune cells, and other essential immune molecules (Morgan, 2021; Montout et al., 2021). According to Liu et al. (2023), there were no significant differences between the effects of reduced-protein diets supplemented with arginine or branched-chain amino acids on the short-chain fatty acid profile in the cecal content of broiler chickens challenged with Eimeria spp on day 21.

L-carnitine is present in high lymphocyte concentrations for biological functions. Two essential amino acids (lysine and methionine), three vitamins (ascorbate, niacin in the form of nicotin amide adenine dinucleotide and vitamin B6), and reduced iron ($Fe2+$) are required as cofactors for the enzymes involved in the metabolic pathway of L-carnitine synthesis (Borum, 1983; Rebouche, 1992; Leibetseder, 1995; Adabi et al., 2011). These amino acids inhibit the apoptosis of immune cells and enhance their proliferative response to mitogens (Adabi et al., 2019). It has been reported that supplementing the diet of broiler chickens with 100 mg/kg of L-carnitine enhances the innate immune response by boosting acute phase protein production, and L-carnitine reveals glucocorticoid effects (Buyse et al., 2007). The supplementation of L-carnitine considerably enhanced total IgG and IgA responses but not IgM in broilers (Mast et al., 2000). In a study, the addition of 100 mg/kg L-carnitine supplementation indicated significantly effect on higher antibody response and Newcastle disease virus in broiler. Besides, 100 mg/kg L-carnitine supplementation group showed the highest Bursa Fabricius, spleen and thymus weight compared to 0, 25 and 75 mg/kg L-carnitine group (Golzar et al., 2007).

5.2. Probiotics, Prebiotics and Synbiotics

Bacterial population in the intestinal tract is necessary for appropriate immune function and obtaining better feed efficiency with probiotics in poultry. Primary, probiotics consist of live beneficial microorganisms for the host animal's health and welfare due to stimulating effects for intestinal microbial balance (Moreno et al., 2006). Probiotic species consist of Lactobacillus bulgaricus, Lactobacillus plantarum, Streptococcus thermophils, Bifidobacterim bifidum, Aspergillus oryzae (Khaksefidi and Rahimi, 2005; Ashayerizadeh et al., 2009; Kabir, 2009). Bacteria have a mutually beneficial relationship with the intestinal cells and microorganisms in the gastrointestinal tract. Probiotics significantly contribute to changes in the intestinal structure and digestive processes by stimulating the immune system. They also inhibit the growth of pathogenic bacteria, leading to an improvement in overall performance (Awad et al., 2009; El-Shenway and Soltan, 2015). Probiotics have importance for the immune system with including boosting the activity of macrophages, lymphocytes, and NK cells. They also enhance the oxidative burst of heterophils, resulting in increased production of immunoglobulins (IgG, IgM, and IgA). Also, probiotics have the potential effects to regulate the gastrointestinal tract and maintain an optimal balance between anti-inflammatory and pro-inflammatory cytokines. Besides, the population of lamina propria lymphocytes (LPL) and intestinal epithelial lymphocytes (IEL) has increased with the probiotics activity in the small intestine while restricting the proliferation of detrimental microorganisms (Yeşilyurt et al., 2021).

Bacillus subtilis-based probiotic supplement has been approved to improve immune and oxidative responses in shackled broiler chickens under pre-slaughter stress challenge. The levels of IgG, IgA, and IgM of the shackled broiler chickens exposed to preslaughter stress were investigated. In the result of this study, IgG and IgA levels (mg/dL) in serum concentration were found similar between control, 0.25 g/kg feed, and 0.5 g/kg feed supplementation groups. In contrast, the level of IgM (mg/dL) in serum concentration was higher in the control group compared to 0.25 g/kg and 0.5 g/kg treatment groups (Mohammed et al., 2024).

Prebiotics are non-digestible feed ingredients that benefit by promoting the growth or activity of some bacterial species in the colon to improve host health (Ganguly, 2013). Prebiotics are small carbohydrate fragments, possibly commercially used as galactose, fructose, and mannose oligosaccharides. There are some prebiotics, such as fructooligosaccharide (FOS), transgalactooligosaccharide (TOS), inulin, glucooligosaccharide, xylooligosaccharide, isomaltooligosaccharide, soybean oligosaccharide, polydextrose, and lactosucrose (Vulevic et al., 2004; Propulla, 2008; Ganguly, 2013). Furthermore, mannan oligosaccharide (MOS) may be derived from the outer cell wall of Saccharomyces spp. yeast promotes gut health with pathogenic bacteria in type-I fimbriae or agglutinating various bacterial strains and increasing villi length, uniformity, and integrity (Spring et al., 2000; Loddi et al., 2004). Oligosaccharides are prebiotics that boost chickens' intestinal morphology and stimulate the activation of the immune system (Sayed et al., 2023). Oligosaccharides may be more active on macrophages to regulate the production of inflammatory cytokines and cytokines by T-helper cells (Th) during the immunological processes (Csernus et al., 2020).

Sittiya and Nii (2024) investigated the effects of oligosaccharides on the immune reactions in laying hens challenged with dextran sodium sulfate. Consequently, BOS (oligosaccharide extract from bamboo shoots) also increased *IFN-γ* in the liver and Th-17 cytokines in the intestine in laying hens. In contrast, there are no significant differences in intestinal or liver morphology. On the other hand, BOS (oligosaccharide extract from bamboo shoots) suppressed an increase in leukocyte accumulation in the liver under DSS (dextran sodium sulfate treatment). These results approved that BOS (oligosaccharide extract from bamboo shoots) may enhance egg quality and Th-1 and Th-17 immune function without causing tissue damage under normal conditions, and it may suppress the excessive inflammatory responses during inflammation.

Synbiotics are a combination of probiotics and prebiotics that act as effective substitutes for antibiotics in feed (Dong et al., 2016; Mohammed et al., 2018; Ren et al., 2019). The beneficial effect of the synbiotics has impacted the gastrointestinal tract and health status in animals. Moreover, different synbiotics comprise probiotic strains, Lactobacillus plantarum, Lactobacillus reuteri, Lactobacillus pentosus, and Saccharomyces cerevisiae (Śliżewska et al., 2020). Due to the regulation of physiological balance and modifying both innate and adaptive immune responses against stress, synbiotics have gained immense importance in poultry nutrition (Seifert et al., 2011). It has been demonstrated that different levels of the synbiotic supplementation significantly changed plasma levels of the antioxidant enzyme GPx in heat-stressed broiler chickens (Mohammed et al., 2019).

5.3. Minerals

Minerals are essential micronutrients for activating optimal physiological processes and health status. The inclusion of microelements in poultry diets is common in commercial practice due to their importance in reproduction and immune function (Saripinar-Aksu et al., 2012). An adequate mineral supply in the diet is crucial for optimal poultry production. The lack of minerals in the diet may lead to various health issues in chicks (Pal, 2017). In poultry nutrition, optimizing animal health may be associated with adding zinc, selenium, chromium and zeolite to the diet program for rearing broilers and laying hens (Park et al., 2004; Tayeb and Qader, 2012; Jain et al., 2021; Elsherbeni et al., 2024).

Dietary zinc decreases feed intake and stimulates avian antibody production with plasma corticosterone levels (Onbasilar and Erol, 2007). It has been shown that dietary zinc supplementation of up to 80 ppm level enhances humoral and cell-mediated immune responses in broilers by Sunder et al. (2008). On the other hand, dietary zinc (up to 110 ppm) and higher doses (up to 10,000 mg/kg) in the diet result in inhibiting the colonization of Salmonella enteritidis (SE) in laying hens (Kubena et al., 2001).

Selenium is essential for optimal immune response and involves innate and acquired immune systems. This essential trace element is a component of selenoproteins, which are involved in various animal physiological processes. Although plants and fungi do not need selenium, they can convert mineral forms of selenium present in the soil into various organic forms, such as selenomethionine and methyl selenocysteine, as a strategy of adaptation. Selenoproteins influence immunity through multiple mechanisms, and nutrition could modulate the immune system to resist pathogens. Selenium regulates oxidative stress, redox, and other cellular processes in all tissues and cell types, including immune responses. Selenium interacts with vitamin E in tissues to protect biological membranes from oxidative damage (Allmang et al., 2009). On the otherside, in Jain et al. (2021) study, the plasma IgG concentrations (μg/mL) showed significant differences between groups at 21, 28, 35 day age of broilers with feed different concentrations of organic and inorganic trace minerals (zinc, selenium, and chromium) supplementation.

Zeolite is a silicate mineral that is considered highly effective and non-toxic. Dietary supplementation of zeolite has been used as a feed additive. Additionally, the use of zeolite directly impacts on production performance and meat quality (Zhou et al., 2014; Abd El-Hady, 2020; Dashtestani et al., 2021). Zeolite has been used in biological processes to reduce ammonia and smell emissions from poultry production by absorbing nitrogenous metabolites such as ammonium (NH_4^+) and ammonia (NH_3) (Schneider et al., 2017). Elsherbeni et al. (2024) investigated the effects of using zeolite on lymphoid organs (%) in 42-day-old broiler chickens. In this study, thymus and Bursa Fabricus weights (%) were found to be higher in the 10g/kg zeolite diet supplementation group. In another study by Abdelrahman et al. (2023), it was shown that dietary zeolite supplementation at levels of 0.5%, 1.0%, 1.5%, and 2.0% resulted in a statistically significant reduction in spleen weight of broiler chicks compared to the untreated group. However, the different zeolite treatments did not significantly affect the thymus and Bursa Fabricus weights.

5.4. Vitamins

The use of vitamins in nutrition is essential for maintaining a healthy immune system in poultry. It has been stated that vitamin level insufficiency has led to compromised immune function, increased susceptibility to infections, and inflammation. In poultry nutrition, vitamins (A, D, E, and C) significantly impact the immunologic process with various activation mechanisms. Firstly, vitamin A enhances mucosal immunity, reduces free radicals, and maintains epithelial cell integrity. Vitamin A comprises several brightly colored and fat-soluble molecules involving retinol, retinal, retinoic acid (RA), and pro-vitamin A carotenoids. Carotenoids have multiple functions: immune regulation and stimulation, antioxidant, antimutagenic, and anticarcinogenic properties. Avian and mammalian species may not synthesize carotenoids, unlike plants and microorganisms. Therefore, chickens must obtain carotenoids from their diet as the yolk initially provides vitamin A during embryonic development. However, after hatching, they require dietary sources of vitamin A (Khan et al., 2023). Post-hatch immune system function improved with the addition of vitamin A to the diet (Shojadoost et al., 2021).

Vitamin D is a type of fat-soluble vitamin that is obtained through sunlight exposure or supplements. Vitamin D is absorbed by the small intestine and then taken up by the liver, where it is converted into 25-hydroxyvitamin D3 (25(OH)D3), the stored form of vitamin D in the body. Vitamin D3 (1,25(OH)2D3), the physiologically active form of the vitamin, is produced in the kidneys by the enzyme 1a-hydroxylase. This form is responsible for the biological actions of vitamin D, regulating bone and mineral metabolism and modulating immune responses (Fakhoury et al., 2020; Wei et al., 2024). It has been demonstrated that 25(OH)D3 increases the synthesis of nitric oxide, promotes the activity of innate immune cells, modifies adaptive immunity, and produces antimicrobial proteins and inflammatory cytokines in chickens (Shanmugasundaram et al., 2019; Fakhoury et al., 2020; Sharma et al., 2024).

Vitamin C, commonly known as L-ascorbic acid, is a water-soluble vitamin that the body converts from glucose. In the body, vitamin C does not accumulate, and excess levels are promptly excreted by the kidneys, resulting in decreased absorption (Johnston et al., 2006; Shojadoost et al., 2021; Hieu et al., 2022). Vitamin C is an antioxidant that protects cells from damage caused by free radicals generated by infection or toxins. Birds may produce vitamin C due to an enzyme called L-gulonolactone oxidase in their renal tissue, which converts l-gulono-g-lactone into ascorbic acid. However, vitamin C requirements increase when chickens experience stressful conditions such as beak trimming, vaccination, transportation, thermal stress, or infection. Therefore, supplementing vitamin C alleviates the adverse effects of these stressful conditions (Abidin and Khatoon, 2013).

Vitamin E is a fat-soluble antioxidant with four distinct functional forms. Among these forms, a-tocopherol is the most biologically active and naturally abundant. This vitamin is well-known for its potential to counteract the adverse effects of free radicals on cell integrity that can occur during normal cell metabolism and inflammation. In poultry, it is crucial to supplement the diet with vitamin E to maintain fertility and hatchability in parent stocks and to prevent nutritional encephalopathy and myopathies in chickens and turkeys. Vitamin E supplementation (or other antioxidants) becomes even more critical when oxidizable fats are included in the feed. The supplementation of vitamin E may prevent the oxidation of unsaturated fats. However, the level of active vitamin E and unsaturated fat used in poultry nutrition may be adequate in intestinal absorption, potentially decreasing the antioxidant status by increasing lipid peroxidation (Pompeua et al., 2018). Vitamin E boosts immune system activity by inhibiting the synthesis of prostaglandins, which may cause inflammation and hinder the immune response. Vitamin E also prevents oxidation, which is responsible for the production of prostaglandins. Vitamin E is primarily known for its antioxidant properties, effectively reducing the damage caused by free radicals during metabolic stress and immunological disorders. Vitamin E regulates the production of free radicals and gene expression caused by free radical signaling gene expression (Packer and Suzuki, 1993). Deficiency of vitamin E and selenium may impair the immune response in poultry, as indicated in the research conducted by Lewis et al. (2019).

5.5. Organic Acids

Organic acids are a type of feed additives that may promote good health and stimulate immunity in poultry. These acids are categorized as organic chemical compounds that contain the carboxyl group COOH in their structure. It is also known that formic, acetic, propionic, malic, fumaric, and citric acids are commonly utilized in poultry nutrition (Hajati, 2018; Khan et al., 2022). Besides, organic acids upregulate harmful microorganisms' inhibition mechanism by reducing the environment's pH level. By penetrating the biological membranes of microorganisms and disrupting their cell function through electrolytic dissociation, organic acids may also restrict bacterial growth (Feye et al., 2021; Pope et al., 2022). It has been stated that formic acid supplementation has beneficially affected broiler chicken performance (body weight gain, feed intake, and feed conversion ratio). It may also enhance the growth of intestinal villi and increase the number of lymphocytes in the spleen and antibody levels for the prevention of disease (Tawfeeq and Al-Mashhdani, 2020).

Organic acids have been significantly effective in body growth rate, feed efficiency, nutrient digestibility, meat quality, immune response, and suppressing pathogenic bacteria (Yang et al., 2018; Adhikari et al., 2020). The enhancements may be completed by lowering the pH in the gastrointestinal tract, optimizing nutrient utilization in diets, inhibiting pathogen growth, and improving immune response in poultry (Alagawany et al., 2021). Recently, Liao et al. (2020) found a strong correlation between gut microbial communities and organic acids, contributing to the gut health status of broilers. The function of gut microbiota is known as an endocrine organ regulating the immune system through synthesizing interferon/cytokines and immunoglobulins (IgG, IgM, and IgA), activating white blood cells like lymphocytes and natural killer cells, and boosting the activity of macrophages and heterophils (Clarke et al., 2014; Abd El-Hack et al., 2020).

Moreover, acetic acid (0.30 g/kg of) may be responsible to prevent gastric apoptosis and stimulate mucin synthesis (Liu et al., 2017). Also, butyric acid plays a crucial role in promoting intestinal development and maintaining the integrity of intestinal epithelial cells (Sun and O'riordan, 2013). Numerous studies have shown that dietary organic acids can inhibit the growth and spread of harmful opportunistic pathogens such as Salmonella, E. Coli, and Clostridium while also promoting the growth of beneficial microorganisms such as Lactobacillus, Bacillus, and Bifidobacterium in the intestine (Lee et al., 2015; Nguyen et al., 2018; Gao et al., 2019). Additionally, in organic acids treatment group, the relative weights of lymphoid organs, such as Bursa Fabricius, thymus, and spleen, were found to be higher compared to the control treatment group, which is strongly related to immunological responses in chickens (Ghazala et al., 2011; Yang et al., 2018). These organic acids stimulate specific and non-specific immune responses in broiler chickens by activating macrophages, increasing cytokine production, and IgA, IgG, and IgM levels. Besides, organic acids inhibit bacterial infection growth, proliferation, and intestinal mucosa inflammation (Abd El-Hack et al., 2022).

5. Conclusion

A balanced diet with essential feed supplements (amino acids, probiotics, prebiotics, synbiotics, minerals, vitamins, and organic acids) stimulates the immune system. Dietary deficiencies may cause several health issues and economic losses in profitability for production. Besides, nutrition has been associated with immunologic processes in commercial production systems under various management conditions. Because of that, understanding the patterns of these feed additives is necessary for optimizing strong immunity.

Author Contributions

The percentage of the author(s) contributions is presented below. All authors reviewed and approved the final version of the manuscript.

	M.G	A.S	Ü.Ç
C	60	30	10
D	60	30	10
S	60	40	-
L	70	20	10
W	70	20	10
CR	70	20	10
SR	60	30	10

C=Concept, D= design, S= supervision, L= literature search, W= writing, CR= critical review, SR= submission and revision.

Conflict of Interest

The authors declared that there is no conflict of interest.

Acknowledgments

This article was presented as an oral presentation at the VII. International Congress on Domestic Animal Breeding, Genetics and Husbandry - 2023 (ICABGEH-23) Krakow, POLAND, September 18 - 20, 2023.

References

Abd El-Hack ME, El-Saadony MT, Salem HM, El-Tahan AM, Soliman MM, Youssef GBA, Taha AE, Soliman SM, Ahmed AE, El-kott AF, Al Syaad KM, Swelum AA. 2022. Alternatives to antibiotics for organic poultry production: types, modes of action and impacts on bird's health and production. Poult Sci, 101(4): 101696.

Abd El-Hack ME, El-Saadony MT, Shafi ME, Qattan SYA, Batiha Ge, Khafaga AF, Abdel-Moneim AE, Alagawany M. 2020. Probiotics in poultry feed: A comprehensive review. J Anim Physiol Anim Nutr, 104(6): 1835-1850.

Abd El-Hady AM. 2020. Effect of incorporating natural zeolite with or without phytase enzyme into broilers diets on blood constituents and carcass traits. Egypt Poult Sci J, 40: 225-242.

Abdelrahman MM, Al-Baadani HH, Qaid MM, Al-Garadi MA, Suliman GM, Alobre MM, Al-Mufarrej SI. 2023. Using natural zeolite as a feed additive in broilers’ diets for enhancing growth performance, carcass characteristics, and meat quality traits. Life, 13: 1548.

Abidin Z, Khatoon A. 2013. Heat stress in poultry and the beneficial effects of ascorbic acid (vitamin C) supplementation during periods of heat stress. World’s Poult Sci J, 69: 135-152.

Abo-Al-Ela HG, El-Kassas S, El-Naggar K, E. Abdo S, Jahejo AR, Wakeel RA. 2021. Stress and immunity in poultry: light management and nanotechnology as effective immune enhancers to fight stress. Cell Stress and Chaperones, 26: 457-472.

Adabi SG, Ceylan N, Çiftci İ, Ceylan, A. 2019. Response of growing chicks to supplementation of low protein diets with leucine, valine and glycine-glutamic acid. S Afr J Anim, 49: 1047-1062.

Adabi SHG, Cooper RG, Ceylan N, Corduk M. 2011. L-carnitine and its functional effects in poultry nutrition. J World’s Poult Sci, 67(2): 277-296.

Adhikari P, Yadav S, Cosby DE, Cox NA, Jendza JA, Kimy WK. 2020. Research Note: Effect of organic acid mixture on growth performance and Salmonella Typhimurium colonization in broiler chickens. Poult Sci, 99(5): 2145862.

Aizenshtein R, Yosipovicha M, Kvint R, Shadmon S, Krispel E, Shuster E, Eliyahu D, Finger A, Banet-Noach C, Shahar E, Pitcovski J. 2016. Practical aspects in the use of passive immunization as an alternative to attenuated viral vaccines. Vaccine, 34(22): 2513-2518.

Alagawany M, Abd El-Hack ME, Farag MR, Sachan S, Karthik K, Dhama K. 2018. The use of probiotics as eco-friendly alternatives for antibiotics in poultry nutrition. Environ Sci Pollut Res Int, 25(11): 10611-10618.

Alagawany M, Elnesr SS, Farag MR, Tiwari R, Yatoo MI, Karthik K, Michalak I, Dhama K. 2021. Nutritional significance of amino acids, vitamins and minerals as nutraceuticals in poultry production and health - a comprehensive review. Vet Quart, 41(1): 1-29.

Alkie TN, Yitbarek A, Hodgins DC, Kulkarni RR, Taha-Abdelaziz K, Sharif S. 2019. Development of innate immunity in chicken embryos and newly hatched chicks: a disease control perspective. Avian Pathol, 48(4): 288-310.

Allmang C, Wurth L, Krol A. 2009. The selenium to selenoprotein pathway in eukaryotes: More molecular partners than anticipated. Biochim Biophys Acta, 1790(11): 1415-1423.

Ashayerizadeh A, Dabiri N, Ashayerizadeh O, Mirzadeh KH, Roshanfekr H, Mamooee M. 2009. Effect of dietary antibiotic, probiotic and prebiotic as growth promoters, on growth performance, carcass characteristics and hematological indices of broiler chickens. Pak J Biol Sci, 12: 52-57.

Aviagen. 2009. Immunosuppression in broilers. Aviagen publishers, New York, USA, 0809-AVN-021, pp:254.

Awad WA, Chareeb K, Abdel-Raheem S, Bohm J. 2009. Effects of dietary inclusion of probiotic and symbiotic on broiler chickens' growth performance, organ weight, and intestinal histomorphology. Poult Sci, 88: 49-56.

Azzam MMM, Dong XY, Xie P, Wang C, Zou XT. 2011. The effect of supplemental l-threonine on laying performance, serum free amino acids, and immune function of laying hens under high-temperature and high-humidity environmental climates. J Appl Poult Res, 20: 361-370.

Bai SP, Wu AM, Ding XM, Lei Y, Bai J, Zhang KY, Chio JS. 2013. Effects of probiotic-supplemented diets on growth performance and intestinal immune characteristics of broiler chickens. Poult Sci, 92: 663-670.

Baker DH. 2009. Advances in protein-amino acid nutrition of poultry. Amino Acids, 37: 29-41.

Bakyaraj S, Bhanja SK, Majumdar S, Dash B. 2012. Modulation of post-hatch growth and immunity through in ovo supplementated nutrients in broiler chickens. J Sci Food Agric, 92: 313-20.

Bhanja SK, Mandal AB. 2005. Effect of in ovo injection of critical amino acids on pre- and post-hatch growth, immunocompetence, and development of digestive organs in broiler chickens. Asian Australas J Anim Sci, 18: 524-31.

Borum PR. 1983. Carnitine. Annu Rev Nutr, 3: 233-259.

Bouyeh, M. 2012. Effect of excess lysine and methionine on immune system and performance of broilers. Ann Biol Res, 3: 3218-3224.

Buchmann K. 2014. Evolution of innate immunity: clues from invertebrates via fish to mammals. Front Immunol, 5: 459.

Butcher GD, Miles D. 2002. Interrelationship between nutrition and immunity. UF/IFAS Extension. University of Florida.

Buyse J, Swennen Q, Niewold TA, Klasing KC, Janssens GPJ, Baumgartner M, Goddeeris BM. 2007. Dietary L-carnitine supplementation enhances the lipopolysaccharide-induced acute phase protein response in broiler chickens. Vet Immunol Immunopathol, 118(1-2): 154-119.

Calder PC. 2013. Feeding the immune system. Proc Nutr Soc, 72: 299-309.

Chalamaiah M, Yu W, Wu J. 2018. Immunomodulatory and anticancer protein hydrolysates (peptides) from food proteins: A review. Food Chem, 245: 205-222.

Chandra RK, Kumari S. 1994. Nutrition and immunity: An overview. J Nutr, 124: 1433-1435.

Chen C, Sander J, Dale NM. 2003. The effect of dietary lysine deficiency on the immune response to Newcastle disease vaccination in chickens. Avian Diseases, 47(4): 1346-1351.

Clarke G, Stilling RM, Kennedy PJ, Stanton C, Cryan JF, Dinan TG. 2014. Minireview: gut microbiota: the neglected endocrine organ. Mol Endocrinol, 28: 1221-1238.

Csernus B, Biró S, Babinszky L, Komlósi I, Jávor A, Stündl L, Remenyik J, Bai P, Oláh J, Pesti-Asbóth G, Czeglédi L. 2020. Effect of carotenoids, oligosaccharides and anthocyanins on growth performance, immunological parameters and intestinal morphology in broiler chickens challenged with escherichia coli lipopolysaccharide. Animals (Basel), 10(2): 347.

Dashtestani F, Ma’mani L, Jokar F, Maleki M, Fard EM, Salekdeh HG. 2021. Zeolite-based nanocomposite as a smart pH-sensitive nanovehicle for release of xylanase as poultry feed supplement. Sci Rep, 11: 21386.

Dashtestani SA, Kang DR, Park JR, Siddiqui SH, Ravichandiran P, Yoo DJ, Na CS, Shim KS. 2019. Effect of in ovo injection of l-arginine in different chicken embryonic development stages on post-hatchability, immune response, and myo-d and myogenin proteins. Animals, 9: 357.

Davison F. 2022. The importance of the avian immune system and its unique features. Elsevier, London, UK, pp: 1-9.

Dekruyff R, Kim YT, Siskind GW, Weksler ME. 1980. Age related changes in the in vitro immune response: increased suppressor cell activity in immature and aged mice. J Immunol, 125: 142.

Dong ZL, Wang YW, Song D, Hou YJ, Wang WW, Qi WT, Yun TT, Li AK. 2016. The effects of dietary supplementation of microencapsulated enterococcus fecalis and the extract of camellia oleifera seed on growth performance, intestinal morphology, and intestinal mucosal immune functions in broiler chickens. Anim Feed Sci Technol, 212: 42-51.

Elgeddawy SA, Shaheen HM, El-Sayed YS, Abd Elaziz M, Darwish A, Samak D, Alagawany M. 2020. Effects of the dietary inclusion of a probiotic or prebiotic on florfenicol pharmacokinetic profile in broiler chicken. J Anim Physiol Anim Nutr, 104: 549-557.

El-Shenway MA, Soltan AM. 2015. Effect of dietary probiotic and/or prebiotic supplementation on growth performance, carcass traits and some serum biochemical alterations in broiler chicken. J Anim Sci Adv, 5: 1480-1492.

Elsherbeni A, Youssef I, Kamal M, Youssif MAM. 2024. Impact of adding zeolite to broilers' diet and litter on growth, blood parameters, immunity, and ammonia emission. Poult Sci, 103(7): 103981.

Emadi M, Jahanshiri F, Azizi JF, Kaveh K, Bejo MH, Ideris A, Assumaidaee AA, Alimon RA. 2010. Immunostimulatory effects of arginine in broiler chickens challenged with vaccine strain of infectious Bursal Disease virus. J Anim Vet Adv, 9: 594-600.

Fakhoury HMA, Kvietys PR, AlKattan W, Anouti FA, Elahi MA, Karras SN, Grant WB. 2020. Vitamin D and intestinal homeostasis: Barrier, microbiota, and immune modulation. J Steroid Biochem Mol Biol, 200: 105663.

Fernandes JI, Murakami AE, Martins EN, Sakamoto MI, Garcia ER. 2009. Effect of arginine on the development of the pectoralis muscle and the diameter and the protein: deoxyribonucleic acid rate of its skeletal myofibers in broilers. Poultr Sci, 88: 1399-406.

Feye KM, Dittoe DK, Jendza JA, Caldas-Cueva yJP, Mallmann zBA, Booher zB, Tellez-Isaias G, Owens zCM, Kidd, zMT, Rickex SC. 2021. A comparison of formic acid or monoglycerides to formaldehyde on production efficiency, nutrient absorption, and meat yield and quality of Cobb 700 broilers. Poult Sci, 100: 101476.

Fonseca BB, Beletti ME, Da Silva MS, Da Silva PL, Duarte IN, Rossi DA. 2010. Microbiota of the cecum, ileum morphology, pH of the crop and performance of broiler chickens supplemented with probiotics. Rev Bras Zootec, 39: 1756-1760.

Förstermann U, Pollock JS, Schmidt HH, Heller M, Murad F. 1991. Calmodulin-dependent endothelium-derived relaxing factor/nitric oxide synthase activity is present in the particulate and cytosolic fractions of bovine aortic endothelial cells. Proc Natl Acad Sci, 88: 1788-1792.

Fussell LW. 1998. Poultry industry strategies for control of immunosuppressive diseases. Poult Sci, 77: 1193-1196.

Ganan M, Silván JM, Carrascosa AV, Martínez-Rodríguez AJ. 2012. Alternative strategies to use antibiotics or chemical products for controlling Campylobacter in the food chain. Food Contr, 24: 6-14.

Ganguly S. 2013. Supplementation of prebiotics, probiotics and acids on immunity in poultry feed: a brief review. World's Poult Sci J, 69(3): 639-648.

Gao YY, Zhang X, Xu L, Peng H, Wang C, Bi Y. 2019. Encapsulated blends of essential oils and organic acids improved performance, intestinal morphology, cecal microflora, and jejunal enzyme activity of broilers. Czech J Anim Sci, 64(5): 189-198.

Garcia P, Wang Y, Viallet J, Jilkova ZM. 2021. The chicken embryo model: a novel and relevant model for immune-based studies. Front Immunol, 12: 791081.

Ghazala AA, Atta AM, Elkloub K, Mustafa MEL, Shata RFH. 2011. Effect of dietary supplementation of organic acids on performance, nutrients digestibility and health of broiler chicks. Int J Poultry Sci, 10(3): 176-184.

Golzar SHA, Rahimi SH, Kamali MA, Torshizi KMA. 2007. The effects of two dietary levels of L-carnitine and vegetable fat powder on quality of cockerels sperm, and fertility and hatchability in broiler breeders. J Vet Res, 62: 107-114.

Gordon J, Manley NR. 2011. Mechanisms of thymus organogenesis and morphogenesis. Development, 138: 3865-78.

Gottardo ET, Junior AMB, Lemke BV, Silva AM, Pasa CLB, Fernandes JIM. 2017. Immune response in Eimeria sp. and E. coli challenged broilers supplemented with amino acids. Austral J Vet Sci, 49: 175-184.

Gurjar RS. 2013. Cell-mediated immunity after ocular Arktype infectious bronchitis virus vaccination. MSC thesis, Auburn University.

Gül M, Tunç MA, Cengiz S, Yildiz A. 2014. Effect of organic acids in diet on laying hens' performance, egg quality indices, intestinal microflora, and small intestinal villi height. Europ Poult Sci, 78: 1612-9199.

Hajati H. 2018. Application of organic acids in poultry nutrition. Int J Avian & Wildlife Biol, 3(4): 324-329.

Hamal KR, Burgess SC, Pevzner IY, Erf GF. 2006. Maternal antibody transfer from dams to their egg yolks, egg whites, and chicks in meat lines of chickens. Poult Sci, 85(8): 1364-72.

Haq Z, Jain RK, Khan N, Dar MY, Ali S, Gupta M, Varun TK. 2016. Recent advances in role of chromium and its antioxidant combinations in poultry nutrition: a review. Vet World, 9(12): 1392-1399.

Heak C, Sukon P, Sornplang P. 2018. Effect of direct-fed microbials on culturable gut microbiotas in broiler chickens: A meta-analysis of controlled trials. Asian Australas J Anim Sci, 31: 1781-1794.

Hibbs JR, Taintor RR, Vavrin Z, Rachlin EM. 1988. Nitric oxide: A cytotoxic activated macrophage effector molecule. Biochem Biophys Res Commun, 157: 87-94.

Hieu TV, Guntoro B, Qui NH, Quyen NTK, Hafiz FAA. 2022. The application of ascorbic acid as a therapeutic feed additive to boost immunity and antioxidant activity of poultry in heat stress environment. Vet World, 15(3): 685-693.

Jain AK, Mishra A, Singh AP, Patel P, Sheikh AA, Chandraker TR, Vandre R. 2021. Effects of different concentration of organic and inorganic trace minerals (zinc, selenium, and chromium) supplementation on expression of chTLR4 gene and humoral immune response in broilers. Vet World, 14(5): 1093-1101.

Johnson CS, Corte C, Swan PD. 2006. Marginal vitamin C status is associated with reduced fat oxidation during submaximal exercise in young adults. Nutr Metab, 3: 35.

Junior AF, dos Santos JP, Sousa IdO, Martin I, Alves EGL, Rosado IR. 2018. Gallus gallus domesticus: immune system and its potential for generation of immunobiologics. Ciênc Rural, 48(08): e20180250.

Kabir SML. 2009. The role of probiotics in the poultry industry. Int J Mol Sci, 10: 3531-3546.

Karachaliou CE, Vassilakopoulou V, Livaniou E. 2021. IgY technology: Methods for developing and evaluating avian immunoglobulins for the in vitro detection of biomolecules. World J Methodol, 11(5): 243-262.

Khaksefidi A, Rahimi SH. 2005. Effect of probiotic inclusion in the diet of broiler chickens on performance, feed efficiency and carcass quality. Asian-Aust J Anim Sci, 18: 1153-1156.

Khan RU, Khan A, Naz S, Ullah Q, Puvaˇca N, Laudadio V, Mazzei D, Seidavi A, Ayasan T, Tufarelli V. 2023. Pros and cons of dietary Vitamin A and its precursors in poultry health and production: A comprehensive review antioxidants. Antioxidants, 12: 1131.

Khan RU, Naz S, Raziq F, Qudratullah Q, Khan NA, Laudadio V, Tufarelli V, Ragni M. 2022. Prospects of organic acids as safe alternative to antibiotics in broiler chickens diet. Environ Sci Pollut R, 29: 32594-32604.

Kidd MT. 2004. Nutritional modulation of immune function in broilers. Poult Sci, 83: 650-657.

Kim WK, Singh AK, Wang J, Applegate T. 2022. Functional role of branched chain aminoacids in poultry: a review. Poult Sci, 101: 101715.

Korver DR. 2023. Review: Current challenges in poultry nutrition, health, and welfare. Anim, 17: 100755.

Kubena LF, Kwon YM, Byrd JA, Woodward CL, Moore RW, Ziprin RL, Anderson RC, Nisbet DJ, Ricke SC. 2001. Drinking water treatment and dietary treatment effects on Salmonella enteritidis in leghorn hens during forced molt. Poult Sci, 80: 88.

Kubinska M, Tykałowski B, Jankowski J, Koncicki A. 2014. Immunological and biochemical indicators in turkeys fed diets with a different Methionine content. Pol J Vet Sci, 17: 687-695.

Lee SI, Kim HS, Kim I. 2015. Microencapsulated organic acid blend with MCFAs can be used as an alternative to antibiotics for laying hens. Turk J of Vet Anim Sci, 39: 520-527.

Leibetseder J. 1995. Studies on the effects of L-carnitine in poultry. Arch Anim Nutr, 48: 97-108.

Lewis ED, Meydani SN, Wu D. 2019. Regulatory role of vitamin E in the immune system and inflammation. HHS Public Access, 71(4): 487-494.

Li L, Liu Z, Fang B, Xu J, Dong X, Yang L, Zhang Z, Guo S, Ding B. 2022. Effects of Vitamin A and K3 on immune function and intestinal antioxidant capacity of aged laying hens. Braz J Poult Sci, 24(4): 1-10.

Liao X, Shao Y, Sun G, Yang Y, Zhang L, Guo Y, Luo X, Lu L. 2020. The relationship among gut microbiota, short-chain fatty acids, and intestinal morphology of growing and healthy broilers. Poult Sci, 99(11): 5883-5895.

Líndez AMI, Reith W. 2021. Arginine-dependent immune responses. Cell Mol Life Sci, 78(13): 5303-5324.

Liu G, Ajao AM, Shanmugasundaram R, Taylor J, Ball E, Applegate TJ, Selvaraj R, Kyriazakis I, Olukosi OA, Kim WK. 2023. The effects of arginine and branched-chain amino acid supplementation to reduced-protein diet on intestinal health, cecal short-chain fatty acid profiles, and immune response in broiler chickens challenged with Eimeria spp: Poult Sci, 102(7): 102773.

Liu Y, Yang X, Xin H, Chen S, Yang C, Duan Y, Yang X. 2017. Effects of a protected inclusion of organic acids and essential oils as antibiotic growth promoter alternative on growth performance, intestinal morphology and gut microflora in broilers. Anim Sci J, 88: 1414-1424.

Loddi MM, Sato RN, Ariki J, Pedroso AA, Moraes VM, Kishibe R. 2004. Ação isolada ou combinada de antibiótico ou probiótico como promotores de crescimento em rações iniciais de frangos de corte. In: Reunião Anual da Sociedade Brasileira de Zootecnia, pp: 254.

Manangi MK, Vazques-A˜non M, Richards JD, Carter S, Knight CD. 2015. The impact of feeding supplemental chelated trace minerals on shell quality, tibia breaking strength, and immune response in laying hens. J Appl Poult Res, 24: 316-326.

Mast J., Buyse J, Goddeeris B.M. 2000. Dietary L-carnitine supplementation increases antigen specific Ig G production in broiler chickens. B J Nutr, 83: 161-166.

Mirzaaghatabar F, Saki AA, Zamani P, Aliarabi H, Matin HRH. 2011. Effect of different levels of diet methionine and metabolisable energy on broiler performance and immune system. Food Agric Immunol, 22: 93-103.

Mohammadi FF, Seidavi A, Bouyeh M. 2023. The effect of the chelated form of trace elements in diet on weight gain, production traits, egg specific gravity, immune system, blood parameters, liver enzymes, and progesterone hormone in Ross 308 broiler breeder chickens. Ital J Anim Sci, 22(1): 524-536.

Mohammed AA, Jacobs JA, Murugesan GR, Cheng HW. 2018. Effect of dietary synbiotic supplement on behavioral patterns and growth performance of broiler chickens reared under heat stress. Poult Sci, 97: 1101-1108.

Mohammed AA, Jiang S, Jacobs JA, Cheng HW. 2019. Effect of a synbiotic supplement on cecal microbial ecology, antioxidant status, and immune response of broiler chickens reared under heat stress. Poult Sci, 98: 4408-4415.

Mohammed AA, Mahmoud MA, Zaki RS, Cheng HW. 2024. Effect of a probiotic supplement (Bacillus subtilis) on struggling behavior, immune response, and meat quality of shackled broiler chickens exposed to pre-slaughter stress. Poult Sci, 2024: 104051.

Montout L, Poullet N, Bambou J. 2021. Systematic review of the interaction between nutrition and immunity in livestock: effect of dietary supplementation with synthetic amino acids. Animals, 11: 2813.

Moreno FMR, Sarantinopoulos P, Tsakalidou R, Vuyst LD. 2006. The role and application of enterococci in food and health. Int J Food Microbiol, 106: 1-24.

Morgan PM. 2021. Immune response in mammals and chickens. IgY-technology: production and application of egg yolk antibodies. Springer, Heidelberg, Germany, pp: 31-47.

Naukkarinen A, Hippelãinen M. 1989. Development of the peripheral immune function in the chicken: A study on the bursa of Fabricius isolated from the rest of the gut-associated lymphoid tissue (GALT). Apmis Acta Pathol Microbiol Immunol Scand, 97: 787-92.

Neveling DP, Dicks LMT. 2021. Probiotics: An Antibiotic replacement strategy for healthy broilers and productive rearing. Probiotics Antimicrob Proteins, 13: 1-11.

Nguyen DH, Lee KY, Mohammadigheisar M, Kim IH. 2018. Evaluation of the blend of organic acids and medium-chain fatty acids in matrix coating as antibiotic growth promoter alternative on growth performance, nutrient digestibility, blood profiles, excreta microflora, and carcass quality in broilers. Poult Sci, 97(12): 4351-4358.

O'Neal DM, Ketterson ED. 2012. Life-history evolution, hormones, and avian immune function. In: Demas GE, Nelson RJ (eds) Ecoimmunology. Oxford University Press, Inc., New York, NY, USA, pp: 142.

Ohta Y, Tsushima N, Koide K, Kidd MT, Ishibashi T. 1999. Effect of amino acid injection in broiler breeder eggs on embryonic growth and hatchability of chicks. Poult Sci, 78: 1493-1498.

Onbaşılar EE, Erol H. 2007. Effects of different forced molting methods on postmolt production, corticosterone level, and immune response to sheep red blood cells in laying hens. J Appl Poult Res, 16(4): 529-536.

Packer L, Suzuki Y. 1993. Vitamin E and alpha-lipoate: Role in antioxidant recycling and activation of the NK-B transcription factor. Mol Asp Med, 14: 229-239.

Pal M. 2017. The role of minerals and vitamins in poultry production. Agri World, 2017: 68-71.

Panda AK, Bhanja SK, Sunder GS. 2015. Early post-hatch nutrition on immune system development and function in broiler chickens. World's Poult Sci J, 71(2): 285-296.

Park SY, Birkhold SG, Kubena LF, Nisbet DJ, Ricke SC. 2004. Review on the role of dietary zinc in poultry nutrition, immunity, and reproduction. Biol Trace Elem Res, 101: 147-163.

Pereira EPV, Tilburg MFV, Florean EOPT, Guedes MIF. 2019. Egg yolk antibodies (IgY) and their applications in human and veterinary health: A review. Int Immunopharmacol, 73: 293-303.

Pompeua MA, Cavalcantib LFL, Torala FLB. 2018. Effect of vitamin E supplementation on growth performance, meat quality, and immune response of male broiler chickens: A meta-analysis. Livest Sci, 208: 5-13.

Pope JT, Walker GK, Rubio AA, Brake J, Jendza, yJA, Fahrenholzy AC. 2022. Effects of corn particle size distributions and formic acid on productive and processing performance of broilers. J Appl Poult Res, 31: 100288.

Propulla SG. 2008. Prebiotic: an emerging functional food. pp: 47-53. In: harnessing microbial diversity for use in animal nutrition. Natl Inst Anim Nutr Physiol, Adugodi, Bangalore, India, pp: 412.

Ratcliffe MJH, Jacobsen KA. 1994. Rearrangement of immunoglobulin genes in chicken B cell development. Semin Immunol, 6: 175-84.

Ratcliffe MJH. 2006. Antibodies, immunoglobulin genes and the bursa of Fabricius in chicken B cell development. Dev Comp Immunol, 30(1-2): 101-118.

Ravindran V. 2010. Poultry feed availability and nutrition in developing countries. Poultry Development Review. Food and Agriculture Organization of the United Nations.

Rebouche CJ. 1992. Carnitine function and requirements during the life cycle. Faseb J, 6: 3379-3386.

Rehman A, Arif M, Sajjad N, Al-Ghadi MQ, Alagawany M, Abd El-Hack ME, Alhimaidi AR, Elnesr SS, Almutairi BO, Amran RA, Hussein EOS, Swelum AA. 2020. Dietary effect of probiotics and prebiotics on broiler performance, carcass, and immunity. Poult Sci, 99: 6946-6953.

Rehman ZU, Meng C, Umar S, Munir M, Ding C. 2016. Interaction of infectious bursal disease virus with the immune system of poultry. World Poult Sci J, 72: 805-820.

Ren H, Vahjen W, Dadi T, Saliu EM, Zentek J. 2019. Synergistic effects of probiotics and phytobiotics on the intestinal microbiota in young broiler chicken. Microorganisms, 7: 684.

Rochell SA, Parsons HC, Dilger R. 2016. Influence of dietary amino acids reductions and Eimeria acervulina infection on growth performance and intestinal cytokine response of broilers fed low crude protein diets. Poult Sci, 95: 2602-2614.

Rodriguez PC, Ochoa AC, Al-Khami AA. 2017. Arginine metabolism in myeloid cells shapes innate and adaptive immunity. Front Immunol, 8: 93.

Romo MR, Perez-Martinez D, Ferrer CC. 2016. Innate immunity in vertebrates: an overview. Immunol, 148(2): 125-39.

Sadiq RK, Abrahimkhil MA, Rahimi N, Banuree SZ, Banuree SAH. 2023. Effects of dietary supplementation of Vitamin E on growth performance and immune system of broiler chickens. J World Poult Res, 13(1): 120-126.

Sahin K, Sahin N, Kucuk O. 2003. Effects of chromium and ascorbic acid supplementation on growth, carcass traits, serum metabolites, and antioxidant status of broiler chickens reared at a high ambient temperature (32°C). Nutr Res, 23(2): 225-238.

Santos DTT, Corzo A, Kidd MT, McDaniel CD, Torres FRA, Araujo LF. 2010. Influence of in ovo inoculation with various nutrients and egg size on broiler performance. J Appl Poult Res, 19: 1-12.

Sarıca Ş, Karataş Ü, Gözalan R. 2009. Kanatlılarda bağışıklık sistemi ve bağışıklık sistemini etkileyen besinsel faktörler. GOÜ Ziraat Fakültesi Dergisi, 26(2): 81-86.

Saripinar-Aksu D, Aksu T, Onel SE. 2012. Does inclusion at low levels of organically complexed minerals versus inorganic forms create a weakness in performance or antioxidant defense system in broiler diets? Int J Poult Sci, 11(10): 666-672.

Sayed Y, Hassan M, Salem HB, Al-Amry K, E. Eid G. 2023. Prophylactic influences of prebiotics on gut microbiome and immune response of heat-stressed broiler chickens. Nature Scientific Reports, 13: 13991.

Schneider AF, Zimmermann OF, Gewehr CE. 2017. Zeolites in poultry and swine production. Ciencia Rural, 47: 1-8.

Seifert C, Fritz C, Carlini N, Barth SW, Franz CMAP, Watzl B. 2011. Modulation of innate and adaptive immunity by the probiotic Bifidobacterium longum PCB133 in turkeys. Poult Sci, 90: 2275-2280.

Selaledi LA, Hassan ZM, Manyelo TG, Mabelebele M. 2020. The current status of the alternative use to antibiotics in poultry production: an african perspective. Antibiotics, 9: 594.

Selim S, Abdel-Megeid NS, Abou-Elnaga MK, Mahmoud SF. 2021. Early nutrition with different diets composition versus fasting on immunity-related gene expression and histomorphology of digestive and lymphoid organs of layer-type chicks. Animals, 11: 1568.

Shaji S, Selvaraj RK, Shanmugasundaram R. 2023. Salmonella infection in poultry: a review on the pathogen and control strategies. Microorganisms, 11: 2814.

Shanmugasundaram, R., Morris, A., Selvaraj, R., 2019. Effect of 25-hydroxycholecalciferol supplementation on turkey performance and immune cell parameters in a coccidial infection model. Poult Sci, 98: 1127-1133.

Sharma MK, Lee J, Shi H, Ko H, Goo D, Paneru D, Holladay SD, Gogal RM, Kim WK. 2024. Effect of dietary inclusion of 25-hydroxyvitamin D and vitamin E on performance, gut health, oxidative status, and immune response in laying hens infected with coccidiosis. Poult Sci, 103: 104033.

Shehata AA, Yalçın S, Latorre JD, Basiouni S, Attia YA, El-Wahab AA, Visscher C, El-Seedi HR, Huber C, Hafez HM, Eisenreich W, Tellez-Isaias G. 2022. Probiotics, prebiotics, and phytogenic substances for optimizing gut health in poultry. Microorganisms, 10: 395.

Shimizu M, Nagashima H, Sano K, Hashimoto K, Ozeki M, Tsuda K, Hatta H. 1992. Molecular stability of chicken and rabbit immunoglobulin G. Biosci Biotech Biochem, 56(2): 270-274.

Shojadoost B, Yitbarek A, Alizadeh M, Kulkarni RR, Astill J, Boodhoo N, Sharif S. 2021. Centennial review: effects of vitamins A, D, E, and C on the chicken immune system. Poult Sci, 100(4): 100930.

Silverman MN, Pearce BD, Biron CA, Miller AH. 2005. Immune modulation of the hypothalamic-pituitary-adrenal (hpa) axis during viral infection. Viral Immunol, 18(1): 41-78.

Sittiya J, Nii T. 2024. Effects of oligosaccharides on performance, intestinal morphology, microbiota and immune reactions in laying hens challenged with dextran sodium sulfate. Poult Sci, 2024: 104062.

Śliżewska K, Markowiak-Kopeć P, Żbikowski A, Szeleszczuk P. 2020. The effect of synbiotic preparations on the intestinal microbiota and her metabolism in broiler chickens. Sci Rep, 10: 4281.

Song B, Tang D, Yan S, Fan H, Li G, Shahid MS, Mahmood T and Guo Y. 2021. Effects of age on immune function in broiler chickens. J Anim Sci Biotechnol, 12: 42.

Spring P, Wenk C, Dawson KA, Newman KE. 2000. The effects of dietary mannan-oligosaccharides on cecal parameters and the concentrations of enteric bacteria in the ceca of Salmonella challenged broiler chicks. Poult Sci, 79: 205-211.

Subramaniyan SA, Kang DA, Park JR, Siddiqui SH, Ravichandiran P, Jing D, Sam Na C, Shim KS. 2019. Effect of in ovo injection of l-arginine in different chicken embryonic development stages on post-hatchability, immune response, and myo-d and myogenin proteins. Animals, 9(6): 357.

Sun Y, O'Riordan MX. 2013. Regulation of bacterial pathogenesis by intestinal short-chain fatty acids. Adv Appl Microbiol, 85: 93-118.

Sunder GS, Panda AK, Gopinath NCS, Rao SVR, Raju MVLN, Reddy MR, Kumar CV. 2008. Effects of higher levels of zinc supplementation on performance, mineral availability, and immune competence in broiler chickens. J Appl Poult Res, 17: 79-86.

Swain BK, Johri TS. 2000. Effect of supplemental methionine, choline and their combinations on the performance and immune response of broilers. Br Poult Sci, 41: 83-88.

Tawfeeq WS, Al-Mashhdani HE. 2020. Effect of adding propionic acid, formic acid, and antibiotics to broiler diet on the production performance, some histological traits, and microbial characteristics. Plant Arch, 20: 468-472.

Tayeb IH, Qader GK. 2012. Effect of feed supplementation of selenium and Vitamin E on production performance and some hematological parameters of broiler. KSU Doğa Bil Derg, 15(3): 46-56.

Uni Z, Yadgary L, Yair R. 2012. Nutritional limitations during poultry embryonic development. J Appl Poult Res, 21: 175-184.

Vulevic J, Rastall RA, Gibson GR. 2004. Developing a quantitative approach for determining the in vitro prebiotic potential of dietary oligosaccharides. FEMS Microbiol Lett, 236: 153-159.

Wei J, Li L, Peng Y, Luo J, Chen T, Xi Q, Zhang Y, Sun J. 2024. The effects of optimal dietary vitamin D3 on growth and carcass performance, tibia traits, meat quality, and ıntestinal morphology of chinese yellow-feathered broiler chickens. Animals, 14: 920.

Wickramasuriya SS, Ault J, Ritchie S, Gay CG, Lillehoj HS. 2024. Alternatives to antibiotic growth promoters for poultry: a bibliometric analysis of the research journals. Poult Sci, 103(9): 103987.

Wlazlak S, Pietrzak E, Biesek J, Dunislawska A. 2023. Modulation of the immune system of chickens a key factor in maintaining poultry production - a review. Poult Sci, 102: 102785.

Wynn JL, Levy O. 2010. Role of Innate Host Defenses in Susceptibility to Early Onset Neonatal Sepsis. Clin Perinatol, 37(2): 307-337.

Xu H, Lu Y, Li D, Yan C, Jiang Y, Hu Z, Zhang Z, Du R, Zhao X, Zhang Y, Tian Y, Zhu Q, Liu Y, Wang Y. 2023. Probiotic mediated intestinal microbiota and improved performance, egg quality and ovarian immune function of laying hens at different laying stage. Front Microbiol, 14: 1041072.

Xu YQ, Guo YW, Shi BL, Yan SM, Guo XY. 2018. Dietary arginine supplementation enhances the growth performance and immune status of broiler chickens. Livest Sci, 209: 8-13.

Yang X, Xin H, Yang C, Yang X. 2018. Impact of essential oils and organic acids on the growth performance, digestive functions and immunity of broiler chickens. Anim Nutr, 4: 388-393.

Yasuda M, Kajiwara E, Ekino S, Taura Y, Hirota Y, Horiuchi H, Matsuda H, Furusawa S. 2003. Immunobiology of chicken germinal center: I. Changes in surface Ig class expression in the chicken splenic germinal center after antigenic stimulation. Dev Comp Immunol, 27(2): 159-166.

Yeşilyurt N, Yılmaz B, Ağagündüz D, Capasso R. 2021. Involvement of probiotics and postbiotics in the immune system modulation. Biologics, 1: 89-110.

Yu J, Dong B, Zhao M, Liu L, Geng T, Gong D, Wang J. 2021. Dietary clostridium butyricum and bacillus subtilis promote goose growth by improving intestinal structure and function, antioxidative capacity and microbial composition. Animals, 11: 3174.

Yu Y, Li Q, Zeng X, Xu Y, Jin K, Liu J, Cao G. 2022. Effects of probiotics on the growth performance, antioxidant functions, immune responses, and caecal microbiota of broilers challenged by Lipopolysaccharide. Front Vet Sci, 9: 846649.

Zhai W, Gerard PD, Pulikanti R, Peebles ED. 2011. Effects of in ovo injection of carbohydrates on embryonic metabolism, hatchability, and subsequent somatic characteristics of broiler hatchlings. Poult Sci, 90: 2134-43.

Zhou P, Tan YQ, Zhang L, Zhou YM, Gao F, Zhou GH. 2014. Effects of dietary supplementation with the combination of zeolite and attapulgite on growth performance, nutrient digestibility, secretion of digestive enzymes and intestinal health in broiler chickens. Asian-Australas J Anim Sci, 27: 1311.