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JWPS
Journal of World's Poultry Science. 2022; 1(1): 1-11.
DOI: 10.58803/jwps.v1i1.1
http://jwps.rovedar.com/

Review Article

Methionine in Poultry Nutrition: A Review

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ARTICLE INFO

Article History:
Received: 05/05/2022
Accepted: 18/06/2022

Keywords:
Crude protein
Diet
Methionine
Poultry
Requirement

ABSTRACT

Methionine is an essential amino acid which is commonly used as a supplement in poultry diets. Multiple systems are involved in the absorption and transportation of liquid and powder Methionine in the segment of the jejunum. Methionine supplementation in a low-protein diet alleviates the negative effects of heat stress and improves the performance of chickens. The supplementation of the synthetic Methionine improves the amino acid balance and consequently promotes growth performance by enhancing the quantity and quality of egg production, feed efficiency, and protein synthesis, as well as decreasing fat synthesis in poultry breeds (Broiler Chicken, Laying hen, Turkey, Duck, Guinea fowl, Quail breeder, and Gees). Methionine supplementation also improves the immune response through the direct effects on protein synthesis and breakdown and indirect effects on the derivatives of Methionine. The variables, such as growing period, type of production, sex, and breed, influence the Methionine requirement. Moreover, the Methionine requirement expressed as a percentage of diet declines during the starter and grower phases.

1. Introduction

The best strategy to optimize production and reproduction in poultry species while mitigating the harmful effects of environmental conditions is proper nutrition[1,2,3]. One of the pillars of nutrition is the use of amino acids in poultry diets, among which Methionine (Met) represents the first limiting amino acid in broilers. As Bunchasak[4] reported, Met can act as an amino acid in the synthesis of protein and polyamine, a sulfur donor, a precursor of main intermediates in metabolic pathways (for instance, Carnitine or Cystine), and a methyl donor group for the normal formation of co-enzyme S-adenosyl Met in and normal cellular metabolism. According to Elnesr et al.[5], Met mainly functions as an antioxidant and the improvement in the antioxidant system activity is one of the solutions available to increase productivity in the poultry industry. Synthetic sources of Met, such as DL-Methionine (DL-Met), are included in poultry feed to optimize the dietary level of Met in animal hosts. Methionine plays an essential role in energy production and boosts the livability, performance, and feed efficiency utilization in poultry[2,6]. As Kidd et al.[7] asserted, healthy poultry respond positively to the inclusion of amino acids as feed additives, leading to a positive impact on performance. The addition of Met improves the reproduction performance, egg quality, and egg production of broiler breeders[8,9]. Methionine supplementation can also alter the immune response and is beneficial in reducing immunologic stress[10].

As a sulfur-containing amino acid, the availability of Met is crucial for several metabolic pathways, that is, the synthesis of proteins, transsulfuration, and methylation of DNA[4,11]. Methionine has a positive effect on the expression of stress-related genes and thus helps to protect cells against oxidative stress[12-15]. Methionine is supplemented during the fattening of broiler chickens, resulting in better performance and increased growth of breast and leg muscles[16-18]. It is evidenced that feeding broiler chickens with an increase in the Met concentrations leads to a decrease in abdominal fat as well as an increase in growth rate, breast muscle yield, and leg muscle yield [18-20]. Although the nutritional values, such as the protein and fat content, may influence the growth rate[21], these effects were not specifically related to the supplementation of Met[22]. As reported by Albrecht et al.[23], supplementation of Met leads

► *Cite this paper as*: Babazadeh D, Ahmadi Simab P. Methionine in Poultry Nutrition: A Review. Journal of World's Poultry Science. 2022; 1(1): 1-11. DOI: 10.58803/jwps.v1i1.1

to heavier fillets, a higher pH value, and longer sensory shelf life. The addition of Met to the poultry diet is correlated with the tendency to have less total body fat to improve growth performance and reduce odor-related compounds in excreta[24,25]. Furthermore, feeding excess dietary Met has been reported to impair body weight (BW) gain[26]. Similarly, Han and Baker[27] indicated that 0.5% excesses of Met are not harmful to young broiler chickens fed corn-soybean meal diets.

2. Molecular structure of Methionine

According to the specification, the product contains 98.5% L-Met, 0.5% water (loss on drying), and 0.1% ash. The analysis of five batches of the additive showed an average of 99.2% L- Met (range 98.5–99.9%) and of 0.41% (range 0.38–0.44%) for the sum of other amino acids (phenylalanine, leucine, tyrosine, isoleucine, and valine). Other constituents consisted of water (0.04–0.11%) and minerals (about 0.05%), including Ammonia which did not exceed 0.01%. The highest amount for unidentified impurities was calculated as 0.23% on a dry matter basis (Table 1).

3. Source of Methionine

Methionine sources are used in two forms (powder and liquid). Unlike many amino acids derived from fermentation processes, DL-Met (DLM) is produced from a complex chemical synthetic process, and the starting material for its production is acrolein (carbon aldehyde) derived from propylene (a petroleum derivative)[28]. There is no difference between L- Met, and DLM regarding the effectiveness [29]. Industrially, the powder and liquid forms of Met sources are mainly used, known as DL- Met (DLM: powder form) and DL-2, hydroxy-4-[methyl] butanoic acid (LMA: liquid form). Both powder and liquid forms consist of an L-isomer and a D-isomer at a ratio of 1:1. In the metabolic pathway of poultry, 70-100% of the D-isomer of DLM or LMA is converted to L-isomer[30,31,32,33]. Some research has indicated that meat chickens in the grower and finisher phases can obtain sufficient Met while foraging pastures [34]. Upadhyaya et al.[35] introduced Big Head fish as a rich source of Met.

4. Absorption and transportation

Amino acids, including Met, are mainly absorbed through the small intestine. As Soriano-Garcia et al.[36] indicated, the absorption of dipolar amino acids, such as L-Met by the small intestine (brush border membrane vesicles) in chickens, is mediated by multiple pathways. They reported that L-Met is transported by systems specific to neutral amino acids and systems that also transport cationic amino acids. Regarding age, Noy et al.[37] reported an increase in Met uptake capacity in both the duodenum and jejunum between hatching and 7 days of age, and a steady amount between 7 and 14 days of age. Therefore, they postulated that from 7 days of age, feed intake may be the major factor controlling nutrient uptake in chickens. Excess Met supplementation seems to reduce the potential of the uptake of Met itself and other nutrients. Soriano-Garcia et al.[36] reported that excess Met supplementation downregulates specific transport mechanisms of the small intestine involved in the apical L-Met transport. By focusing on differences between Met sources, different multiple transport systems appear to be involved in transporting both DLM and LMA. Knight et al.[38] reported that L-Met absorption may be accomplished by both concentration and energy-dependent processes, while the absorption of LMA is concentration-dependent. The mechanisms of Met absorption involve Na-dependent transport, Na-independent transport and/or diffusion, while the mechanisms suggested for LMA absorption include Na-independent but H-dependent transport and/or diffusion[38-41]. Methionine can increase the digestibility of other essential amino acids and also change the dynamics of amino acid transporters to reflect their availability[42]. Therefore, differences in the mechanism of transportation between the two Met sources may lead to different amounts of their transportation. Thus, the absorption and transportation of Met are complicated processes.

5. Interrelationship between Methionine and other nutrients

Among essential amino acids, Met seems to have many interrelationships with other nutrients (Cystine, Choline, Betain, Vitamin B6, Vitamin B12, and Folate) due to many metabolic pathways involving Met[4,32,43,44]. Methionine synthase is a Vitamin B_{12}-dependent enzyme. Vitamin B_{12} is essential for the synthesis of myelin in nerve tissue, a function probably related to Met production from the Met synthase reaction and the subsequent formation of S-adenosyl-methionine[43,44]. The molar efficacies of Met, 1/2 Cystine, and Cystine are the same[43]. Poultry requires both Met and Cystine for protein synthesis, so the total sulfur amino acids (TSAA) requirement should be taken into account. In avian species, it is generally accepted that around 45-50% of TSAA can be supplied by Cystine.

Table1. Molecular structure and characteristics of Methionine

Common Name	Chemical Name	CAS Number	Trade Names	Other Codes	Type of products
Methionine	$C_5H_{11}NO_2S$ 2-amino-4-(methylthio)butanoic acid	63-68-3 (L-); 59-51-8 (DL-)	Mepron® Alimet® Pedameth® Cotameth® Herbomethione®	EINECS: 200-432- 1	Tablet Capsule Syrup Injection

However, Cystine supplementation has a negative impact on voluntary feed intake when the diet is markedly deficient in TSAA (more than 50% of TSAA intake is provided by Cystine)[29]. Moreover, when the TSAA requirement is expressed as a percentage of the diet, the need for a Met plus Cystine combination is less than that for Met alone[45].

Since TSAA act as sulfur donors, sulfur supplementation influences the sparing effect between Met and Cystine. It seems that when sulfur sources are added to the diet, the sparing effect between Cystine and Met or the TSAA requirement is reduced. Sasse and Baker[46] found that when TSAA were at or near adequacy, the optimal percentage from Cystine was 48.4% in the presence of dietary K_2SO_4 and 52.6% in its absence. However, optimal performance occurred when TSAA were set at a deficient level. Using practical broiler finisher diets, three trials were carried out to determine the extent to which synthetic Met can be replaced by sodium sulphate. The results revealed that weight gain and the feed conversion ratio both increased with incremental increases in sodium sulphate in diets containing sub-optimal concentrations of TSAA[47]. Cystine can spare with Met in increasing the absorption of essential minerals, such as zinc[48]. Lysine and Met, as two essential precursors of L-carnitine, can play important roles in lipid and energy metabolism in poultry. L-carnitine is a natural, Vitamin-like substance that acts in the cells as a receptor molecule for activated fatty acid. Its major metabolic role appears to be the transport of long-chain fatty acids into the mitochondria for B-oxidation. A shortage of this substance results mainly in impaired energy metabolism and membrane function. In this regard, some studies have indicated that dietary supplementation of carnitine diets can be used to augment carnitine supply for use in metabolism, thereby facilitating fatty acid oxidation and reducing the amount of long-chain fatty acids available for storage in adipose tissue.

6. Protein level in the diet

Addition of synthetic amino acids like lysine and Met at high levels to the poultry diet can stimulate insulin secretion from the pancreas by being aggregated in plasma which in turn releases amino acids and fatty acids from the bodily saved sources leading to protein synthesis. The optimal level of Met in the diet seems to depend on the protein concentration in the diet. Vieira et al.[49] indicated that the optimum dietary TSAA level depends on the dietary protein level. The TSAA requirement does not change with age when it is expressed in terms of dietary protein[50]. In addition, a broiler chicken's requirement for TSAA increases with increasing dietary protein concentrations ranging from 19.7 to 25.9%[51,52]. Therefore, several investigators have suggested that the Met concentration in chicken diets should be around 2.5 to 4% of the protein concentration[51,53,54]. Although an increase in the dietary Met requirement is often found with elevated protein concentrations, the capacity to use Met for protein gain is also reduced[55]. Sterling et al.[56] intensively reviewed the ratio of protein, including amino acids, and found that the amino acid requirements expressed as a percentage of diet tended to decline as protein content increased. In laying hens, when the ratio of protein to Met was kept constant, Met supplementation to a high protein level (18% crude protein [CP]) decreased egg production, while supplementation to lower protein levels (14 and 16% CP) improved the production performance[57]. Jankowsk et al.[58] reported that higher dietary Met levels (45 vs. 30% of Lys content) increased the final BW of turkeys and cause a beneficial increase in plasma albumin concentration. In addition, Elsharkawy et al.[59] reported that supplementation of 0.1% Met to rooster diets can improve carcass characteristics and meat quality of progeny. Similarly, Liu et al.[60] indicated that supplementation of maternal diet with 0.1% coated Met had a positive effect on growth performance and carcass traits of offspring. According to Rehman et al.[61], in case DL-Met and L-Met are included in feed at a standard level, they are equally effective as a source of Met for the broiler chickens. These results may suggest that increasing the Cystine content by increasing dietary protein concentration reduces the Met requirement.

7. Methionine and heat stress

High environmental temperature decreases the feed intake to maintain homeothermy[62] and degrades subsequent live weight gain, digestibility, egg production, egg quality, and feed efficiency[63,64]. Diets with an amino acid imbalance or Met deficiency normally increase heat production[65] and induce a more negative effect of heat stress when the environmental temperature is high[64]. As balancing the amino acid composition in the diet with Met supplementation improves production performance through pathways of polyamine metabolism[62], glutathione (derived from Met) may reduce damage from oxidative stress. So, the TSAA requirement would be higher under hyper-thermoneutral conditions, compared to thermoneutral conditions. As Silva et al.[15] reported, raising broiler chickens at a high temperature requires higher TSAA consumption to achieve optimal growth performance. It is well established that dietary protein produces a high heat increment [63,66,67]. Therefore, a reduction in dietary protein content with suitable supplementation by essential amino acids alleviates the negative effects of heat stress. However, the reduction of limiting amino acid or protein content in the diet negatively affects production performance. On the other hand, Met supplementation in low-protein diets improves production performance [68-72]. Therefore, reducing the dietary protein concentration by Met supplementation diminishes the negative effects of heat stress. Gonzalez-Esquerra and Leeson[62] reported that Arg: Lys, Met source and duration of exposure to heat stress affected protein utilization in hyperthermic birds. Bunchasak and Silapasorn[64] found that Met intake of 439.93 mg/hen/day (14% CP, 0.44% Met) improved hen-day egg production and egg weight to the level of a control group (16% CP, 0.38% Met) leading to a Met intake of 372.94 mg/hen/day. Moreover, adding Met to a low-protein diet reduced the mortality rate of hens under heat stress, compared to a positive control group (16% CP; 0.038% Met) or negative control (14% CP; 0.26% Met). Mahmoodi et al.[73] revealed that up to 20% of the dietary Met requirements of broiler chickens exposed to heat stress can be fulfilled by Cholin (280 Chol and 560 Chol) and Betaine (320 Bet and 140 Chol + 160 Bet), without adversely affecting production performance. However, Amaefule et al.[74] used old Bovan Nera layers that had been in lay for 4 weeks to evaluate the effect of Met, lysine, and/or Vitamin C supplementation on egg production as well as external and internal egg quality characteristics of layers in a humid tropical zone. The findings indicated that none of these supplements had any benefit to the layer hens. Thus, age and production conditions may be factors to consider when adding Met in order to reduce the negative effect of heat stress.

8. Effect of Methionine on the immune system

Numerous human and animal model studies have indicated that Met is involved in the control of many functions in the body, including participation in protein synthesis in cells of the immune system[12,75-77]. Therefore, a similar effect of Met on the immune system of poultry could be expected.

There are some reports that high Met supplementation promotes good health for poultry. For example, the supplementation improved leukocyte migration inhibition, cellular immune response, and humoral immune response[78,79]. Moreover, it can increase blood serum total protein, albumin, globulin, and antibody response to Newcastle disease virus, and decrease serum aspartate aminotransferase and alanine aminotransferase[79]. Furthermore, Met supplementation can lead to an increase in total antibody, IgG, and response to the mitogen phytohemagglutinin (PHA), which might be related to T-cell help[80]. According to Bunchasak[4], an increased Met content, above the level required for optimal growth, improves the immune response through direct effects (protein synthesis and breakdown) and indirect effects involving Met derivatives. Since leukocytes are important targets for the action of amino acids, of particular interest is the response of the adaptive (acquired) immune system consisting of T cells, B cells, and humoral factors[81]. Particular attention is paid to the thymus, which is the site of T cell differentiation and development. Wu et al.[82] demonstrated that Met deficiency in the diet can impair cellular immune function in broiler chickens by ultrastructural pathological changes in the thymus, decreased T cell populations, reduction in the serum concentrations of interleukine-2, and T cell proliferation through an increase in the percentage of apoptotic cells. Wu et al.[82] Indicated that dietary Met deficiency reduces the population of IgA^+ B cells and the contents of sIgA, IgA, IgG, and IgM in the duodenum and jejunum, implying that the impairment of humoral immune function in the intestinal mucosal immunity in broiler chickens. Yaqoob et al.[83] reported that Met supplementation and threonine could effectively enhance growth performance and the immune system in broiler chickens.

According to the classification in Table 2, the F-AA group includes dietary Met+ Cystine. Sufficient dietary intake of both sulfur-containing amino acids is important for protein synthesis in cells of the immune system[75]. Cystine, however, should not be included in the diet at very high concentrations[13]. Takahashi et al.[84] demonstrated that both sulfur-containing amino acids (Met and Cystine) have a beneficial influence on immune and inflammatory responses.

According to Swain and Johri[78], Met plays a vital role in the humoral and cellular immune responses of poultry. It is known that amino acids are needed for the clonal proliferation of lymphocytes, the establishment of germinative centers in the bursa of Fabricius to refine immunoglobulin affinity, recruitment of new bone marrow monocytes and heterocysts, and synthesis of effector molecules (immunoglobulins, nitric oxide, lysozyme, complement), and communication molecules (such as cytokines and eicosanoids).

9. Methionine deficiency

Deficiency in Met consumption negatively affects animals by growth inhibition, the induction of metabolic disorder, and the reduction of disease defensive potential[65]. A Methionine deficiency typically leads to poor feed conversion, retarded growth in meat birds, and reduced egg production in layers and breeder[85]. Methionine is a major component of feathers. Methionine and Cystine (another sulfur-containing amino acid that is not essential for the diet) are critical to feather formation. A deficiency of Met results in poor feather growth and

Table 2. Classification of amino acids in poultry nutrition

Amino acid					
EAA	**F-EAA**	**CEAA**	**F-CEAA**	**NEAA**	**F-NEAA**
His	Arg	Gln	Glu	Ala	Asp
Ile	Cys		Tau	Asn	
Lys	Gly			Ser	
Phe	Leu				
Thr	**Met**				
Val	Pro				
	Trp				
	Tyr				

EAA: Essential amino acid, F-EAA: Functional-essential amino acid, CEAA: Conditionally essential amino acid, F-CEAA: Functional conditionally essential amino acid, NEAA: Nutritionally nonessential amino acid, F-NEAA: Functional-nutritionally nonessential amino acid increased feather pecking. A Met-deficient bird tends to eat feathers in an attempt to obtain enough Met, which can quickly turn into cannibalistic behavior in a flock[4].

Dietary deficiency in Met particularly affects arginine metabolism as evidenced by increased expression in the arginine transporter which putatively shifts arginine metabolism from nitric oxide to polyamine synthesis[42]. L-Arginine (L-Arg) supplementation in poultry diets improves egg production, egg weight, modulates lipid metabolism toward reducing total body fat accumulation to improve meat quality, and increases antioxidant defense under normal conditions. Methionine is necessary for the synthesis of choline as a factor forming lecithin and other phospholipids in poultry. Diets with low protein levels and insufficient choline may cause the accumulation of fat in the liver[86].

10. Reducing poultry nitrogen emissions

One of the environmental challenges that the poultry industry has been faced with is manure utilization or disposal. Poultry manure and its nitrogenous compounds can be a potential pollutant, causing eutrophication, nitrate or nitrite contamination of water, ammonia volatilization, and acid deposition in the air[87]. Therefore, reducing nitrogen excretion and emissions in poultry manure is important to maintain a clean environment. Proper nutrition is an important first step to optimize performance and growth in animals as well as reducing the negative impacts of nitrogen on the environment[76]. Amino acids, including Met, are components of protein nutrition that greatly influence growth[4]. Excess Met supplementation into diets increases nitrogen excretion and emissions to the environment. One way to reduce nitrogen excretion and emissions is to reduce CP levels and supplementing analogues of amino acids to meet the amino acid requirements[88]. Several analogue forms of Met are commercially available as economic alternatives for the animals. Supplementation of hydroxy analogues into low protein diets can minimize excess amino nitrogen in the diets and reduce nitrogen excretion[76]. Therefore, the effective use of such dietary strategies, a well-balanced feed formulation, and a precise way of rapidly quantitating the bioavailable Sulphur amino acid in feeds are required to be developed.

11. Organic standards

The National Organic Program rules initially stated that synthetic Met was a prohibited material for animal diets. An exemption was given to allow the industry to find alternatives[89]. As research continued in this area, the National Organic Standards Board recommended that the use of synthetic Met should be restricted originally to 4 pounds per ton for laying hens, 5 pounds per ton for broiler chickens, and 6 pounds per ton for turkeys and all other poultry. After October 1, 2012, the allowed levels were decreased to 2 pounds per ton for laying and broiler chickens, and 3 pounds per ton for turkeys and other poultry species.

12. Safety for the target species

The FEEDAP Panel considers that safety concerns for target species are highly unlikely to arise from the L-Met under the application. The safety of L-Met for the target animals has been assessed by the FEEDAP Panel[90]. The Panel based its assessment on the previously established safety of D-L Met and the specific metabolism of L-Met and concluded that no safety concerns were expected. The absorption, distribution, metabolism, and excretion of Met have been extensively described in a previous opinion of the FEEDAP Panel[91]. Therefore, the FEEDAP Panel concludes that L-Met produced by *Corynebacterium glutamic* KCCM 80184 and *Escherichia coli* KCCM 80096 is safe for the target species, consumers, and the environment.

13. Target species of poultry

13.1. Broiler chickens

Feed consumption is mainly controlled by dietary energy. Summers et al.[69] reported that the level and balance of essential amino acids (EAA) significantly affected feed intake, and consequently weight gain and carcass composition. Broiler chickens appear to react to amino acid deficiencies within a short period (hours) by adjusting their feed intake and/or selection and these responses are influenced by age and prior experience. It is reported that Met deficiencies decrease the feed intake of broiler chickens due to amino acid imbalances[4,85,92]. It can be assumed that, under amino acid imbalances, chickens lose the potential to adjust feed intake to satisfy their amino acid requirements; the main positive effect of Met supplementation may come from its improvement of feed intake via the amino acid balance. Genetic diversity also influences the Met utilization of chickens. Geraert et al.[93] observed that the genetically fat-type chickens had lower plasma concentrations of most glucogenic amino acids and higher levels of branched-chain and sulfur-containing amino acids than lean-type chickens. Many factors, such as genetic diversity, environmental conditions, nutrients, and stress, involve body fat deposition. Summers et al.[69] reported that the level and balance of EAA have a significant effect on feed intake, thereby influencing weight gain and carcass composition. Generally, larger chickens have more breast meat and a heavier abdominal fat pad. Increasing dietary Met increases the mass of breast meat but reduces the size of the abdominal fat pad due to a good balance of amino acids[4,19]. Additionally, Zhan et al.[94] reported that Met supplementation significantly increased breast muscle yield and decreased abdominal fat content. They found that supplementation with Met significantly increased the contents of creatine and free carnitine in the liver, the activity of hormone-sensitive lipase in abdominal fat, and the concentration of free fatty acid in serum, whereas the uric acid concentration in serum was significantly decreased. Therefore, the decrease in abdominal fat may be due to increased carnitine synthesis in the liver and hormone-sensitive lipase activity in abdominal fat[94].

13.2. Laying hen

Unlike broiler chickens, the Met requirement of laying hens should be expressed as mg/day. For white egg-laying hens, a requirement of approximately 775-800 mg TSAA/hen/days of which about 390 to 440 mg was Met, was found for a maximum of 80-83 eggs/100 hen/days[95]. The NRC[96] reported that the white-egg hens require 300 and 580 mg of Met and TSAA per hen daily, respectively, while the Met and TSAA requirements for the brown egg type of laying hens are 330 and 645/mg/hen/day, respectively. However, several researchers reported a higher requirement of Met for maximal egg production. It is reported the Met and TSAA requirements were around 424-440 and 740-811 mg per hen daily, respectively [64,97-99]. Thus, white egg-laying hens require lower TSAA than brown-egg laying hens, and commercial laying hens require higher TSAA than the NRC recommendation.

Consumption above 413 mg/day Met resulted in significantly increased albumen total solids and protein, and yolk protein significantly increased at 507 and 556 mg/day Met, compared to 413 mg/day Met[100]. The Methionine and TSAA requirements were greater for the middle and final quarters of production than for the initial quarter, and also the peak daily requirements for Met were 384.380 and 402 mg/day for egg production, egg weight, and egg mass, respectively[101]. These data indicate that the requirement for maximum egg production is less than that for maximum feed utilization[95-98] and the requirement for egg quality is higher than that for egg production and feed utilization.

These uncertain results may be due to a number of factors, such as environmental conditions, the management system, and dietary protein or energy levels. Therefore, Waldroup and Hellwig[101] suggested that adjustments should be made in dietary amino acid levels to compensate for changes in daily feed intake as influenced by environmental changes, feather covering, or other factors in order to maintain a constant amino acid intake, although adjustment based on age or stage of production is not justified. However, based on a review of the literature, it seems that Met intake should be higher than 420 mg/day to maximize the quantity and quality of egg production.

13.3 Duck

Methionine is usually the first limiting amino acid for ducks[102,103], which plays vital roles in protein synthesis, methylation process, and cellular antioxidant capacity [104,105]. Thus, extensive studies on Met requirement and its role in the growth of ducks have been conducted over the past decades [103,106,107]. The crystalline DL-Met is usually supplemented to balance the duck Met requirement of ducks. Theoretically, chemically synthesized DL-Met supplemented in the diet is a racemic mixture of equivalent D-Met and L-Met. The L-Met could be incorporated directly into the body with approximately 100% bioavailability, but D-Met must be converted to L-Met before the incorporation into protein[108]. Currently, L-Met, a new Met source, has been commercially available for duck diet formulation. The bio-efficacy of L-Met was approximately 1.4 times relative to DL-Met for the growth performance of starter ducks[109] as well as gut oxidative status and development of chickens [110]. However, to date, few studies have evaluated the Met requirement of starter ducks by dietary L-Met supplementation. Metabolizable energy (ME) is an index to evaluate energy levels in duck diets. High ME levels in the broiler diet result in a reduction of feed intake[111], which might influence the intake and utilization of other nutrients. Therefore, other nutrient requirements might be altered by dietary ME level. Previous studies showed that a higher dietary ME level required a greater lysine requirement for the starter phase of Pekin ducks[112] and also a greater Met requirement level should be supplemented in the growing phase of Pekin ducks[113].

The National Research Council[96] reported the requirement of Met for ducks from hatch to 14 days of age is 0.40%. Chen et al.[114] showed that the Met requirement of ducks from hatch to 3 weeks of age is almost 34% and 42%, respectively.

13.4. Quail breeder

The best strategy to optimize production and reproduction in poultry species while also mitigating the harmful results of environmental conditions is proper nutrition[59,115,116]. Methionine is the first limiting amino acid in maize/soybean-based quail diets, its supplementation provides scope for improvement of protein quality and reduction of dietary protein concentration. Abou-Kassem[117] found that the performance was significantly improved for quails fed a diet containing a Met level higher than the recommended level. Quails fed with Met diets showed higher hatchability and fertility than those fed the basal diet[117]. Kalvandi et al.[118] clarified that the supplementation of Met in quail diets increased eggshell thickness and Haugh unit score, but did not affect the yolk and albumen percentages. The improvement of egg quality in groups fed different levels of Met may be due to the fact that Met enhances the antioxidant performance within the body[119,120]. Therefore, the addition of Met boosted the reproduction performance, egg quality, and egg production of quail breeders[8].

13.5. Turkey

A fast growth rate in chickens and turkeys depends on high dietary concentrations of essential amino acids, including Met[32]. Atkinson et al.[121] indicated that Met addition to the basal diet produced highly significant increases in the egg production rate, varying from 7.73% to 9.73% over the basal-fed turkey hens. Body weight loss was significantly greater when the ration was supplemented with Met or a combination of lysine and

Met[56]. Egg size increased when the basal ration was supplemented with Met or the combination of lysine and Met[32].

Moran et al.[122] indicated that low Met increased fat proportions at week 6 and also reported the fat deposition helped to minimize repercussions of the inadequate Met intake, most likely due to the dietary protein catabolism and subsequent fat deposition, as well as the increased uric-acid forming enzymes.

Park et al.[123] reported that sufficient Met is important to keep reduced oxidative stress status in the gut and liver of turkey poultry and the use of L-Met as a source of Met replacing DL-Met seems to be beneficial to turkey poultry during 28 rearing days.

13.6. Guinea fowl

Guinea fowls are an important domestic fowl worldwide for leaner animal protein sources. The meat is lean and rich in essential fatty acids. Guinea fowl broilers have less abdominal fat, a leaner carcass, and lower cholesterol than chicken broilers when fed a comparative diet of 23% CP[124]. The requirement of Met and Cystine in the diet of French guinea fowl broilers was 0.45% and 0.35%, respectively, which is less than the requirement of chickens (In total 0.8% versus 0.9 % in a diet with 23% CP)[125]. In another study, the diet containing 0.45% Met and 0.35% Cystine at 0-3 weeks of age and the diet containing 0.50% Met and 0.40% Cystine at 4-8 weeks of age is recommended as efficient in French guinea fowl broilers[126]. Methionine was incorporated in at least 2.16% of the CP content of the respective diets in a study on Pearl Grey Guinea fowl[122].

13.7. Gees

The geese are considered to have one of the fastest growth rates of old domesticated birds reared for the production of meat. The source of dietary protein of high quality with an adequate balance of amino acids is one of the most important factors in feeding Egyptian geese, in particular throughout the rearing phase[8,127].

The supply of nutrients with adequate levels of CP and TSAA in geese diets through the rearing stage exerts a substantial impact on subsequent reproduction performance. The dietary level of CP and amino acids should meet the maintenance requirements and production needs of various poultry kinds, in particular toward the middle and end of the fattening period. Abou Kassem et al.[128] indicated that dietary levels of CP had significant impacts on feed intake and feed efficiency of growing Egyptian geese. The optimal dietary supplementation of Met could increase growth performance and Met and Cystine utilization in growing goslings[129]. Yuan et al.[130] reported that better productive performance can be obtained with an adequate level of indispensable amino acids, especially Met. In another relevant study, Ashour et al.[131] revealed that the consumption of diets with high levels of Met and Cystine can improve the productive performance, carcass, and meat quality of Egyptian geese during the rearing period. In the other investigation by Yang et al.[132], it was found that optimal Met dietary supplementation could increase growth performance and serum total protein, albumin, as well as globulin, and hepatic protein synthesis in growing goslings.

14. Conclusion

The level of Met supplementation should be carefully considered due to breed, sex, and growing period. The amount of Met required to support the immune system seems to be high and depends on the animal species because it has to be used not only for protein synthesis but also for the production of some antioxidants. The differences between DLM and LMA in absorption and utilization abilities under heat stress are still unclear because the absorption system is very complicated in poultry. However, LMA is usually used as a source of Met in most farms since the liquid form lets the farmers add it easily to the water.

Declarations

Competing interests

The authors declare that they have no competing interests.

Authors' contribution

Pouria Ahmadi Simab wrote the draft of the manuscript. Daryoush Babazadeh revised the draft of the manuscript and check the final version of the article.

Availability of data and materials

All collected data and related studies are done for publishing in the present journal.

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