Research Progress on the Application of Zinc in Egg Poultry Production

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Abstract

To promote the healthy and sustainable development of the egg-laying poultry industry, the regulation of poultry health and product quality has emerged as a key research focus. Zinc, as an essential trace element in egg-laying poultry, serves as a vital component and activator for numerous enzymes and active proteins, extensively participates in metabolic processes, and exerts important biological functions, thereby playing a crucial role in modulating the physiological status and product quality of egg-laying poultry. This article provides a concise overview of the biological functions of zinc in egg-laying poultry, reviews the research progress regarding its application in poultry production, discusses existing challenges, and outlines future perspectives, aiming to offer theoretical guidance for the rational utilization of zinc in egg-laying poultry production.

Full Text

Research Progress on Zinc Application in Laying Bird Production

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Abstract: To promote the healthy and sustainable development of the laying bird industry, regulating the health status and product quality of laying birds has become a research priority. As one of the essential trace elements in laying birds, zinc serves as a necessary component and activator of numerous enzymes and active proteins, participates extensively in metabolism, and exerts vital biological functions. It plays an important role in regulating the physiological status and product quality of laying birds. This paper summarizes the biological functions of zinc in laying birds, reviews research progress on its application in production, identifies existing problems, and outlines future prospects, aiming to provide theoretical references for the rational application of zinc in laying bird production.

Keywords: zinc; performance; egg quality; antioxidant and immune status; laying birds

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1. Biological Functions of Zinc in Laying Birds

Zinc, as a crucial trace element in animals, participates extensively in metabolism and performs multiple biological functions. In the body, zinc not only provides catalytic activity for enzymes but also plays an important structural role [2]. Zinc-containing metalloenzymes exist in all six enzyme classes: oxidoreductases (e.g., superoxide dismutase), transferases (e.g., RNA polymerase), hydrolases (e.g., alkaline phosphatase), lyases (e.g., carbonic anhydrase), isomerases (e.g., phosphomannomutase), and synthetases (e.g., tRNA synthetase) [3]. Consequently, zinc participates in biochemical processes including nucleic acid and protein synthesis, energy metabolism, and redox reactions, thereby influencing nutrient metabolism and animal growth.

The immune and antioxidant status are critical for maintaining homeostasis in laying birds. Zinc can reduce oxidative stress and enhance immune function [2]. It maintains the normal structure and function of biological membranes by scavenging excess free radicals through copper-zinc superoxide dismutase (Cu,Zn-SOD) and protecting membrane protein conformation while inhibiting peroxide production via metallothionein (MT), thus maintaining redox balance. Additionally, zinc promotes the growth and development of immune organs, enhances humoral and cellular immunity, and maintains normal lymphocyte function, thereby improving immune capacity [3]. Therefore, zinc plays a vital role in the health status of laying birds.

Zinc serves as an essential cofactor for carbonic anhydrase (CA), playing a crucial role in eggshell formation. CA promotes the hydration of carbon dioxide (CO) to form bicarbonate ions, facilitating calcium carbonate deposition in the shell gland. In vitro studies have shown that zinc promotes crystal growth during calcite formation [4]. Moreover, as a component of alkaline phosphatase (ALP), research indicates a significant negative correlation between ALP activity and calcium ion concentration in the uterus and isthmus [5], suggesting a relationship between ALP activity in the shell gland and calcium carbonate deposition. ALP also exhibits dephosphorylation activity, potentially regulating phosphorylated proteins in the eggshell matrix (such as osteopontin and Ovocleidin-116) and thereby influencing calcite crystal formation [6]. Thus, zinc can regulate eggshell quality in laying birds.

Furthermore, zinc is involved in animal reproduction [3], bone and feather development [7], and the metabolism of other trace elements and vitamins [8]. In summary, zinc is essential for maintaining the health and production requirements of laying birds.

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2. Research on Zinc Application in Laying Bird Production

As an essential component and activator of various enzymes, zinc plays important roles in laying birds and is closely related to production performance, product quality, and immune and antioxidant functions.

2.1 Effects of Zinc on Production Performance

Studies have shown that dietary supplementation with vitamin E (40 or 80 IU) or zinc (100 or 200 mg/kg as organic zinc) did not significantly affect feed intake or egg weight but significantly improved laying rate and feed efficiency in laying ducks (22–30 weeks of age), with similar effects between zinc and vitamin E, though no significant differences were observed among doses [9]. Supplementing the diet (containing 37 mg/kg zinc) with zinc (15–90 mg/kg as zinc sulfate) significantly affected laying rate and feed utilization in laying ducks (27–39 weeks of age), showing a quadratic response with increasing dose, with optimal performance observed at 30 and 45 mg/kg supplementation [10]. However, adding zinc sulfate (35-140 mg/kg) to laying hen diets (containing ~27 mg/kg zinc) did not significantly affect production performance (54–63 weeks of age) [11-12], though organic zinc linearly decreased average egg weight in older hens (63-68 weeks) [12-13]. Compared with 75 and 100 mg/kg supplementation, adding 50 mg/kg zinc (as zinc sulfate, zinc oxide, or zinc glycinate) to diets (33.40 mg/kg zinc) optimized production performance in laying hens (36–45 weeks), while higher doses reduced average egg weight and feed efficiency [14]. Additionally, high doses of chelated zinc (137–655 mg/kg) tended to decrease egg weight (57–60 weeks) and significantly reduced laying rate (48–56 weeks) [15]. Dietary supplementation with 300 or 600 mg/kg zinc (as zinc sulfate or amino acid zinc) to diets containing 60 mg/kg zinc did not significantly improve production performance in post-peak laying hens (42–54 weeks) [16].

These inconsistent results regarding zinc’ s effects on production performance may be attributed to differences in bird breeds, basal dietary zinc levels, supplementation doses, feeding periods, and rearing environments. Overall, high-dose zinc supplementation (>50 mg/kg) does not significantly improve laying hen performance and may even reduce average egg weight, particularly with organic zinc. Based on production performance, the zinc present in basal diets (~30 mg/kg) appears sufficient for laying hens, requiring no additional supplementation, which aligns with NRC (1994) recommendations (~35 mg/kg). Zinc can improve laying rate and feed efficiency in laying ducks, with peak-production ducks requiring an additional 30-45 mg/kg zinc beyond basal dietary levels (~30 mg/kg). This improvement may be related to enhanced antioxidant status, as the 30 and 45 mg/kg supplementation groups showed higher antioxidant capacity [10]. Zinc may also regulate performance by affecting nutrient digestibility, as 30-60 mg/kg zinc can improve dry matter, organic matter, crude protein, and crude fat digestibility [17], while zinc deficiency reduces appetite and feed efficiency, impairing growth [7]. However, these mechanisms require further verification.

2.2 Effects of Zinc on Product Quality

Eggshell breakage has become a major constraint to the healthy development of the laying bird industry. Reduced eggshell quality not only affects egg production and economic returns but also decreases egg quality and reduces hatchability and embryonic survival [18]. Therefore, improving eggshell quality is an urgent priority. Carbonic anhydrase is a zinc-containing enzyme that promotes calcium carbonate deposition in the shell gland [19]. Inhibition of CA activity and gene expression in the shell gland reduces eggshell quality [20-21], while increased CA activity improves eggshell quality [22].

Research shows that supplementing diets (24.10 mg/kg zinc) with zinc (70-104 mg/kg as zinc sulfate) in late-lay hens (59-63 weeks) improves eggshell ultrastructure and thickness by increasing plasma and shell gland CA activity [11]. As supplementation increased (35-140 mg/kg as zinc sulfate or amino acid zinc), shell gland CA activity and eggshell thickness showed linear and quadratic responses in hens (63-68 weeks), with amino acid zinc being more effective than zinc sulfate [13], though eggshell strength was unaffected [11-13]. Under heat stress, adding 1,000 mg/kg zinc (as zinc sulfate, zinc methionine, or EDTA-chelated zinc) increased eggshell weight and reduced breakage in hens (60-66 weeks) by increasing calcium-binding protein content and CA activity [23-24]. Supplementing manganese/zinc (30/50 mg/kg, 62-70 weeks) or manganese/zinc/copper (30/30/5 or 60/60/10 mg/kg, 69-78 weeks) improved eggshell quality in older hens without affecting younger birds [25-26], and zinc, manganese, and copper improved eggshell ultrastructure in hens (47-62 weeks) [27]. Thus, zinc can increase eggshell thickness by enhancing CA activity and improving ultrastructure, with greater effects in older hens, though eggshell strength remains unaffected. Based on eggshell quality, laying hens require an additional 70-100 mg/kg zinc beyond basal dietary levels (~30 mg/kg).

Fewer studies have examined zinc's effects on duck eggshell quality. Supplementing diets (37 mg/kg zinc) with zinc sulfate (15-90 mg/kg) did not significantly affect eggshell quality in laying ducks (27-39 weeks) [10], while zinc methionine (20-40 mg/kg) significantly improved eggshell strength in young ducks without affecting thickness [28]. Eggshell ultrastructure is crucial for quality and has become an important evaluation indicator, but research in ducks is scarce, and systematic studies on dietary zinc' s effects are lacking. The impacts of zinc source and dosage on duck eggshell quality require further investigation.

Eggs are ideal vehicles for nutrient fortification. Due to zinc's multiple biological functions, dietary supplementation can enrich eggs with zinc, providing a dietary source for human supplementation. Zinc content in chicken eggs is typically 10–11 g/g, with 99% deposited in the yolk [29-30]. Numerous studies show that dietary zinc supplementation (as zinc sulfate or organic zinc) increases zinc enrichment in eggs [31-33]. Adding 300 or 600 mg/kg zinc (inorganic or organic) to diets containing 60 mg/kg zinc increased yolk zinc by ~5.8% and 10.6%, respectively, without affecting albumen zinc [16]. Stahl et al. [31] reported that high zinc doses (1,762 or 1,861 mg/kg) increased egg zinc by 57-90% compared to control diets (26–28 mg/kg), while 218 or 257 mg/kg increased zinc by 25%. Thus, yolk zinc increases with dietary zinc, though the magnitude varies due to differences in basal zinc levels and sources. However, few studies have examined zinc deposition in duck eggs. High zinc doses (1,000–3,000 mg/kg) increased duck yolk zinc by 17.01–102.56% [34]. As 99% of zinc is deposited in the yolk for embryonic development [35], research on zinc' s effects on offspring is limited. Zinc does not significantly affect fresh egg quality [10-12], but 200 mg/kg organic zinc in duck diets showed better antioxidant effects than 40 or 80 IU vitamin E [9]. Whether zinc affects egg quality during storage through antioxidant effects and the role of dosage require further study.

2.3 Effects of Zinc on Bird Health

Cellular metabolism generates large amounts of reactive oxygen species, and the vigorous lipid metabolism in laying birds necessitates a robust antioxidant system. The body contains numerous antioxidants, including enzymes (GSH-Px, SOD, CAT) and non-enzymatic antioxidants (GSH, vitamins, MT), which inhibit oxidation and scavenge oxidative products to maintain redox balance [36]. Zinc maintains MT content, serves as an essential component of Cu,Zn-SOD, and protects thiols and other chemical groups, protecting biological structures from free radical damage [3].

Studies show that 100 mg/kg zinc (as amino acid zinc) increases SOD activity, total antioxidant capacity (T-AOC), and GSH content while reducing malondialdehyde (MDA) in liver and spleen of laying hens (45–65 weeks) [37]. Supplementing diets (27.95 mg/kg zinc) with zinc (30–120 mg/kg as zinc sulfate) linearly increased liver Cu,Zn-SOD activity in Brown laying hens (20–40 weeks), with no further increase beyond 60 mg/kg [38]. Adding zinc (35, 70, or 140 mg/kg as zinc sulfate or zinc methionine) to diets (29.04 mg/kg zinc) significantly increased plasma and liver Cu,Zn-SOD activity, T-AOC, and anti-superoxide anion capacity while reducing MDA in hens (58–64 weeks), with 70 mg/kg zinc sulfate showing optimal antioxidant performance [12]. Additionally, zinc supplementation (15–90 mg/kg as zinc sulfate) to diets (37 mg/kg zinc) significantly affected antioxidant status in laying ducks (27–39 weeks), increasing plasma GSH-Px and total SOD activities with a quadratic response, with optimal effects at 30 and 45 mg/kg [10]. In growing ducks (4–12 weeks), 30–60 mg/kg zinc (as zinc sulfate) increased serum T-AOC, though not significantly, while higher doses (200 or 1,000 mg/kg) decreased T-AOC [39]. Thus, appropriate zinc levels improve antioxidant status, with recommended additional zinc of 60–70 mg/kg for laying hens and 30–45 mg/kg for laying ducks when basal dietary zinc is ~30 mg/kg.

Few studies have examined zinc' s effects on antioxidant function in breeding birds, though extensive research demonstrates zinc' s close relationship with the immune system [40-42]. Zinc maintains normal immune organ function, promotes immune cell proliferation and differentiation, regulates cytokine secretion and activity, and modulates immune cell apoptosis [43]. Since laying birds 基本完成 immune system development before laying, zinc' s regulatory effects are more pronounced during rearing. Zinc deficiency (22.9 vs. 100.0 mg/kg) severely inhibited immune organ development and peripheral blood T lymphocyte activation, reduced serum IgG and red blood cell immune function, and caused pathological damage in ducklings (1–49 days) [44]. Adding zinc sulfate to basal diets (33.3 mg/kg zinc) improved immune organ development and increased serum immunoglobulin and interleukin-2 (IL-2) concentrations in ducklings (0–4 weeks), with optimal effects at 48.2–57.9 mg/kg additional zinc [45]. In growing ducks (4–10 weeks), low (0 mg/kg) or high (1,000 mg/kg) zinc inhibited immune performance, while 30 mg/kg met requirements for normal immune organ development [39]. Zinc also promoted immune organ development and enhanced cellular immunity in laying hens [37], with 40–70 mg/kg zinc (as zinc methionine) significantly increasing T lymphocyte transformation index and serum IgG in hens (57–72 weeks), showing better effects than zinc sulfate [46]. Thus, zinc positively affects immune function, though studies in laying ducks and breeding birds are lacking. Based on immune performance, recommended additional zinc is 30–60 mg/kg for pre-lay ducks and 40–70 mg/kg for laying hens when basal dietary zinc is ~30 mg/kg.

2.4 Zinc Nutritional Requirements for Laying Birds

The NRC (1994) general recommendation for poultry dietary zinc is 30–40 mg/kg. Zinc deficiency increases cellular oxidative damage [2,47], reduces appetite and feed efficiency [7], decreases laying rate and hatchability [48], impairs eggshell quality [19,22], and causes economic losses. Zinc deficiency in breeding eggs causes embryonic skeletal deformities, with hatched chicks unable to stand, eat, or drink [49]. Zinc is primarily absorbed passively in the duodenum. When body zinc is high, intestinal cells secrete large amounts of MT that tightly bind zinc, preventing its transport to blood and causing toxicity [8]. Thus, mature laying birds can tolerate certain zinc levels, though 2 g/kg (as zinc propionate) inhibits laying and causes feather loss [50].

Commercial laying hen diets are generally recommended to contain 70–140 mg/kg zinc [11-12,51]; higher levels (150 or 200 mg/kg as zinc sulfate) do not improve eggshell quality [52], while excessive levels (137–655 mg/kg as chelated zinc) reduce laying performance and eggshell weight [15]. Using bone zinc as the evaluation criterion, the optimal zinc supplementation was 44 mg/kg for Brown laying hens (20–40 weeks) fed basal diets containing 27.95 mg/kg zinc [38]. Although slightly excessive zinc does not negatively affect production or egg quality, it increases zinc excretion [51], affecting environmental health. Considering all factors, recommended dietary zinc for laying hens is basal diet (25–30 mg/kg) plus an additional 60–80 mg/kg.

Appropriate zinc supplementation (30–45 mg/kg as zinc sulfate) improves laying rate, feed conversion, and antioxidant function in laying ducks, with no further improvement at higher doses (45–90 mg/kg) [10]. Basal diets (32.9 mg/kg zinc) with 30–60 mg/kg added zinc (as zinc sulfate) meet growth requirements for growing ducks (4–10 weeks) [39]. Comprehensive evaluation of growth performance, antioxidant function, hormone metabolism, and immune function recommends 51.8–53.0 mg/kg additional zinc (as zinc sulfate) for 0–4 week-old ducklings fed basal diets containing 33.3 mg/kg zinc [45]. Overall, recommended dietary zinc for laying ducks is basal diet (~30 mg/kg) plus 30–50 mg/kg zinc.

Recent research on zinc requirements for breeding birds is limited. Early studies indicated that basal diets containing 28 mg/kg zinc met production and progeny development needs in breeding hens, with no significant benefits from additional zinc carbonate (10, 20, or 40 mg/kg) [53] or even higher zinc sulfate doses (20, 200, or 2,000 mg/kg) [54]. However, other studies showed that zinc deficiency reduced hatchability and embryonic development [48]. Thus, results vary. Research on zinc requirements for breeding ducks is scarce, with no established standards. One study showed that different zinc sources (zinc oxide, nano-zinc oxide, basic zinc chloride, amino acid chelated zinc) and levels (20 or 80 mg/kg) did not significantly affect egg weight, laying rate, feed conversion, fertility, or hatchability in Shanma ducks [55], though the research was not systematic. With advances in breeding technology and changes in rearing systems, zinc requirements for breeding birds need further investigation.

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3. Summary

In summary, appropriate zinc levels can improve production performance, product quality, and immune and antioxidant functions in laying birds. Despite significant research progress, several issues remain: (1) Most studies focus on laying birds, lacking systematic research on zinc application in breeding birds. Zinc requirements for breeding birds need determination, and research is needed on zinc deposition in yolk or embryonic zinc provision effects on hatchability, embryonic survival, and progeny development. (2) Compared with chickens, research on zinc effects in ducks is limited. Duck production is an important component of animal agriculture in China, with multiple breeds. In-depth research on nutrient regulation of duck production and quality could better promote healthy duck industry development, such as zinc-enriched duck eggs and mechanisms of zinc' s effects on duck eggshell quality. (3) Research on zinc application lacks mechanistic exploration. Literature review often reveals similar experimental designs with different results, fundamentally due to lack of mechanistic discussion. Investigating mechanisms of zinc' s effects on production performance and immune function could better explain results and differences, yielding more valuable findings to guide production.

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Note: Figure translations are in progress. See original paper for figures.