

# METABOLISM AND NUTRITION

## Mineral requirements in ducks: an update

H. Wang,<sup>1</sup> W. Gao,<sup>1</sup> L. Huang, J. J. Shen, Y. Liu, C. H. Mo, L. Yang,<sup>2</sup> and Y. W. Zhu<sup>2</sup>

*Guangdong Provincial Key Laboratory of Animal Nutrition and Regulation, College of Animal Science, South China Agricultural University, Guangzhou 510000, China*

**ABSTRACT** Mineral nutrition plays a critical role in growth and bone mineralization in meat ducks as well as reproductive performance in duck layers and duck breeders. In addition to improving production performance parameters, minerals are also essential to support several enzymatic systems to enhancing antioxidant ability and immune function. This review explores the biological function and metabolism of minerals in the body, as well as mineral feeding strategy of various species of ducks. Topics range from mineral requirement to the physiological role of macroelements such as calcium and phosphorus and microelements such as zinc and selenium, etc. As with the improvement of genetic evolution and upgrade of rearing system in duck production, mineral requirements and electrolyte balance are urgent to be re-evaluated using sensitive biomarkers for the modern duck breed characterized by the rapid growth rate and inadequate bone development and mineralization. For duck breeders, mineral nutrition is not only required for maximal egg production performance but

also for maintaining normal embryonic development and offspring's performance. Therefore, the proper amounts of bioavailable minerals need to be supplemented to maintain the mineral nutritional state of duck species during all phases of life. In addition, more positive effects of high doses microelements supplementations have been revealed for modern meat ducks subjected to various stresses in commercial production. The nutritional factors of mineral sources, supplemental enzymes, and antinutritional factors from unconventional ingredients should be emphasized to improve the effectiveness of mineral nutrition in duck feed formulation. Organic mineral sources and phytase enzymes have been adopted to reduce the antagonistic action between mineral and antinutritional factors. Therefore, special and accurate database of mineral requirements should be established for special genotypes of ducks under different rearing conditions, including rearing factors, environmental stresses and diets supplemented with organic sources, phytase and VD<sub>3</sub>.

**Key words:** duck, mineral requirement, mineralization, organic source, sensitive biomarker

2020 Poultry Science 99:6764–6773

<https://doi.org/10.1016/j.psj.2020.09.041>

## INTRODUCTION

Duck meat consumption generally escalated during the past few decades because of its high nutrient content with an optimum essential amino acid, proper composition of fatty acid with a high polyunsaturated fatty acid, and a balanced ratio of omega-6 and omega-3 (Pingel and Germany, 2011). In 2019, Food and Agriculture Organization of the United Nations estimated that the annual duck slaughter has reached 6.42 billion birds in the world. Asia is the leading continent in duck production with a share of 82.2%, followed by Europe with

12.4% (Sumarmono, 2019). However, the improvement and update of feed nutrition and management system are lagging behind the demand of duck production (Baeza, 2016). So far, many studies have been conducted on macronutrients (metabolizable energy, crude protein, and amino acid), whereas the information on mineral nutrition of ducks was relatively in shortage. During 2005–2020, studies of mineral nutrition were mainly focused on macroelement of Ca and P nutrition (Table 1), with limited information on microelement nutrition of Cu, Fe, Mn, Zn, and Se in ducks (Table 2). The optimum Ca and P levels (0.65% Ca and 0.40% non-phytate phosphorus (NPP) for 0–2 wk; 0.60% Ca and 0.30% NPP for 2–7 wk) have been recommended for Pekin ducks at 0 to 7 wk of age by NRC (1994). However, these data sourced from previous studies over 5 decades (Dean et al., 1967; Lin and Shen, 1979) may not be applicable to modern duck breeds/varieties with the greater changes in growth potential and management. For example, owing to the

© 2020 Published by Elsevier Inc. on behalf of Poultry Science Association Inc. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

Received May 15, 2020.

Accepted September 11, 2020.

<sup>1</sup>These authors contributed equally to the present study.

<sup>2</sup>Corresponding authors: [ylin898@126.com](mailto:ylin898@126.com) (LY); [408034085@qq.com](mailto:408034085@qq.com) (YZ)

**Table 1.** Summary of the recommended requirement of calcium and phosphorus in ducks during 2005-2020.

Minerals	Breed	Age	Dietary Ca and P levels	Evaluation indicator	Recommended level	References
Ca	Pekin duck	7-18 d	Ca: 0.74, 0.85, 0.95, 1.11%; NPP: 0.40%	Weight gain	0.95%	Rush et al., 2005
	Pekin duck	0-2 wk	Ca: 0.40, 0.60, 0.80, 1.00, 1.20%; NPP: 0.40%	Weight gain and feed/gain	0.796–0.806%	Xie et al., 2009a
	Pekin duck	3-6 wk	Ca: 0.36, 0.48, 0.66, 0.84%; NPP: 0.37%	Weight gain	0.72%	Xie et al., 2009b
	Pekin duck	0-3 wk	Ca: 0.55, 0.75, 0.95, 1.15%; TP: 0.60%	Weight gain and feed/gain	0.75%	Zhu et al., 2018
	Sheldrake	0-3 wk	Ca: 0.45, 0.60, 0.75, 0.90, 1.05, 1.20%; NPP: 0.40%	Weight gain and bone mineralization	0.60–0.87%	Zhu et al., 2019
	Cherry Valley duck	15-35 d	Ca: 0.5, 0.7, 0.9, 1.1%; NPP: 0.40%	Bone turnover and tibia quality	0.70%	Zhang et al., 2018
	Linwu duck	30-38 wk	Ca: 2.0, 2.5, 3.0, 3.5, 4.0%; NPP: 0.29%	Egg qualified rate and eggshell strength	3.50%	Huang et al., 2017
	Linwu duck	22-28 wk	Ca: 1.5, 2.0, 2.5, 3.0, 3.5%; NPP: 0.29%	Egg weight, tibial Ca content, and tibial ash content	2.79–2.98%	Huang et al., 2016
	Longyan duck	21-33 wk	Ca: 2.8, 3.2, 3.6, 4.0, 4.4%; NPP: 0.40%	Serum ALP activity and tibial fresh weight	3.20–3.60%	Xia et al., 2015
P	Pekin duck	1-14 d	NPP: 0.20, 0.30, 0.40, 0.50%; Ca: 0.80%	Weight gain and feed/gain	0.379–0.403%	Xie et al., 2009a
	Pekin duck	3-6 wk	NPP: 0.17, 0.25, 0.33, 0.41%; Ca: 0.66–0.72%	Weight gain and tibial P content	0.37%	Xie et al., 2009b
	Pekin duck	1-21 d	TP: 0.409, 0.476, 0.532, 0.563, 0.659, 0.710, 0.796, 0.863%; Ca: 0.56%	Weight gain	0.56%;	Rodehutsord et al., 2003
	Pekin duck	21-49 d	TP: 0.377, 0.415, 0.493, 0.539, 0.585, 0.681, 0.817, 0.949%; Ca: 0.61%	Weight gain	0.51%;	Rodehutsord et al., 2003
	Cherry Valley duck	1-21 d	NPP: 0.22, 0.34, 0.40, 0.46, 0.58%; Ca: 0.90%	Weight gain and feed intake	0.34%	Dai et al., 2018

considerable improvement of genetics between 1988 and 2014, modern Cherry Valley duck breeds had greater feed intake, growth rate, and feed efficiency than before (e.g., live weight at 44 d, 2.95 kg vs 3.50 kg; FCR at

3.25 kg live weight, 2.65 vs 1.85; market age, 49 d vs 42 d). In addition, the enhanced performance capacity of birds has necessitated an increasing mineral requirement to ensure the bone health. Zhang et al. (2019)

**Table 2.** Summary of the recommended requirement of microelement in ducks during 2005-2020.

Microelements	Breed	Age	Microelement content in basal diet	Dietary supplemental level	Evaluation indicator	Recommended level	References
Copper	Pekin duck	1-56 d	7.0 mg/kg	0, 4, 8, 12, 150 mg/kg	Growth performance	8 mg/kg	Attia et al., 2012
	Shanma duck	17-45 wk	4.63 mg/kg	0, 4, 8, 12, 16, 20, 24 mg/kg	Laying performance and egg quality	5 mg/kg	Fouad et al., 2016a
Zinc	Pekin duck	1-56 d	26 mg/kg	0, 30, 60, 120 mg/kg	Growth rate and Zn excretion.	30 mg/kg	Attia et al., 2013
	Longyan duck	21-41 wk	27.7 mg/kg	0, 10, 20, 40, 80, 160 mg/kg	Productive performance and Zn deposition	70-80 mg/kg	Zhang et al., 2020
	Longyan duck	23-43 wk	37 mg/kg	0, 15, 30, 45, 60, 75, 90 mg/kg	Productive performance and antioxidant capacity	30-45 mg/kg	Chen et al., 2017
Manganese	Shanma duck	17-36 wk	19.1 mg/kg	0, 15, 30, 45, 60, 75, 90 mg/kg	Laying performance and egg quality	90 mg/kg	Fouad et al., 2016b
Iron	Shanma duck	17-30 wk	52.2 mg/kg	0, 15, 30, 45, 60, 75 mg/kg	Egg weight	45-75 mg/kg	Xia. et al., 2016
	Linwu duck	50-60 wk	77,34 mg/kg	0, 20, 40, 60, 80 mg/kg	Laying performance and egg quality	71.88-84.50 mg/kg	Huang et al., 2015
Selenium	Cherry Valley duck	1-49 d	0.041 mg/kg	0, 0.2, 0.4, 0.6 mg/kg	Growth performance	0.40 mg/kg	Baltić et al., 2017
	Shanma duck	22-48 wk	0.042 mg/kg	0, 0.08, 0.16, 0.24, 0.32, 0.40 mg/kg	Egg production	0.18-0.24 mg/kg	Chen et al., 2015a

reported that intensive selection for growth rate in ducks resulted in tibial morphology changes, displaying rapid bone growth (e.g., bone length, approximately from 40 mm to 117 mm; bone width, approximately from 1.50 to 8.70 mm) and mineralization (e.g., tibia density, approximately from 0.26 to 0.67 g/cm<sup>3</sup>) in ducks from day 1 to day 35. Moreover, ducks rearing in the plated or caged systems were lacked of exercise than the litter floor system (Rodenburg et al., 2005). Therefore, mineral nutrition should be paid more attention to bone development and mineralization of ducks under the update rearing systems with limited space.

In NRC (1994), the recommended requirements of Mn (60 mg/kg), Zn (40 mg/kg), Fe (80 mg/kg), and Se (0.15 mg/kg) were sourced from the values in chicken. However, there are huge differences in digestive physiology (Jamroz et al., 2002), mineral digestibility (Adeola, 2006), and mineral deposition (Rodehutscord and Dieckmann, 2005) between chickens and ducks. Unlike chickens, ducks have a spindle-shaped widening of the esophagus and fusiform proventriculus and a quicker transit rate of chyme, resulting in a lower mineral availability (Fan, 2003). For special duck types, mineral requirement recommendations from INRA (1989) and NRC (1994) were mainly focused on large type meat ducks, such as Muscovy ducks and Pekin ducks. It is not clear whether these data were applied to small type meat ducks and duck layers due to the great differences in growth curve, digestive physiology and nutrient digestibility (Wasilewski et al., 2015). Therefore, as a result of changes in genetics, sex, and rearing factors of birds, the mineral requirements in ducks at different growth periods need be further reevaluated. In China, the standard of nutrient requirements of meat-type duck has been published by the national waterfowl industry system in 2012, covering the duck species of Pekin ducks, Muscovy ducks, and local meat-egg-type ducks at the starter, growth-finisher, and breeder periods (NY/T, 2012). However, some values of microelement requirements in the standard were recommended based on the data from duck production experiences, which need to be confirmed and reevaluated. Therefore, it is necessary to establish the database and feeding standard for the mineral requirement of special duck species at the different growth phases.

## Calcium

Calcium, as the most abundant mineral in the body, plays an important role in growth development and bone mineralization in animals (Selle et al., 2009). The Ca requirement of Pekin duck but not duck breeder (laying period) was recommended by NRC (1994). Dietary Ca deficiency induced rickets in broilers and impaired eggshell quality in laying hens. Four series of experiments conducted by Dean et al. (1967) indicated that rickets occurred in ducks fed a corn-soybean meal diet with a Ca level of 0.17% while maximum weight gain and normal bone ash were achieved when the Ca level was increased to 0.56%. Lin and Shen (1979)

reported that the minimum Ca requirements were 0.48% and 0.58%, respectively, for maximum growth and optimum tibia ash content in mule ducks as determined by regression analysis. Leclercq et al. (1990) recommended that the optimum Ca requirements were 0.46% and 0.42% in Muscovy ducks at 3 to 8 wk and 8 to 12 wk of age, respectively. During 1989–2008, the studies of Ca and P nutrition on ducks have not shown much progress. However, the production potential of modern duck breed was improved by the genetic breeding improvement as well as the feed pattern of rearing ducks was changed from on ground to on netting bed or on cage during this time, which may have caused a change in the requirements of the modern-type meat ducks. Therefore, the applicability of values from NRC (1994) needs to be reevaluated in modern duck breeds/varieties.

Over the past decade, Xie et al. (2009a) investigated the interaction between dietary Ca and NPP levels on growth performance and bone ash in White Pekin ducks. The predicted requirements were 0.80% Ca and 0.38–0.40% NPP in Pekin ducklings from hatch to 2 wk of age (Xie et al., 2009a) as well as 0.72% Ca and 0.37% NPP in ducks from 3 to 6 wk of age (Xie et al., 2009b) based on body weight gain (BWG). These values were higher than those recommended by NRC (1994) (0.65% Ca and 0.40% NPP for 0–2 wk; 0.60% Ca and 0.30% NPP for 2–7 wk). In addition, both genetic selection and increasing nutrient density priority to improving growth performance resulted in the increased leg problems of meat ducks. Moreover, the welfare problems also were inadvertently involved in the genetic evolution with poor bone quality and mineralization in meat ducks. Zhang et al. (2018) found that above 0.7% Ca supplementation in a low-nutrient density diet decreased bone turnover and subsequently increased tibia quality by downregulating the expression of osteoclast differentiation genes. Therefore, the demands for supplemental Ca level could be greater than before to ensure bone development and quality of modern meat ducks. For local meat-egg-type ducks, Zhu et al. (2019) estimated that the 0.60 to 0.87% Ca was required to optimize BWG and bone mineralization in Sheldrake ducks from hatch to 21 d of age.

Huang et al. (2016, 2017) showed that local Linwu ducks required 2.79 to 2.98% Ca and 3.50% Ca to support laying performance and egg quality in the early- and peak-laying periods, respectively. The optimal laying performance and bone quality could be achieved in Shanma laying ducks fed diets containing 3.2 to 3.6% at the peak-laying period (Xia et al., 2015). Wang et al. (2014) examined the influence of Ca source (limestone vs oyster shell) and particle size (<0.1 mm vs 0.85 to 2 mm) on laying performance, egg quality, and bone properties in duck layers, indicating that a diet supplemented with limestone with a large particle size provided for superior eggshell and bone quality. Chen et al. (2015b) found that dietary Ca supplementation increased both *secreted phosphoprotein 1* and *carbonic anhydrase 2* mRNA expressions in the uterus and then

improve eggshell quality and microarchitecture partly by strengthening shell biomineralization, which might be influenced by Ca source and particle size. Therefore, the precise Ca requirement of ducks could be varied in the diets supplemented with different Ca sources.

## Phosphorus

Phosphorus is essential for poultry to attain their optimum genetic potential in growth and skeletal development involving in the metabolic and structural processes. In practical duck feed formulation, an excess P level was added to the diets to ensure a safety factor and prevent P deficiency in ducks, leading to the waste of resources and serious pollution. The studies involved P requirements and availabilities are limited on ducks. The P requirement (0.40% NPP for 0–2 wk and 0.30% NPP for 2–7 wk) recommended by NRC (1994) was estimated based on values obtained from chicken, which were lacked of experimental data on ducks. In fact, the P availability was significantly different between duck and chicken species. As reported by Rodehutsord and Dieckmann (2005), the maximum in marginal efficiency of supplemented P as monobasic calcium phosphate source was 96% in White Pekin ducks and 74% in broiler chickens at 3 wk of age. In studies with graded P levels, Pekin ducks achieved a plateau BWG in the P concentration of 5.6 g/kg at 2 wk old, while the value was slightly lower (5.1 g/kg) at 5 wk old (Rodehutsord et al., 2003). However, these P recommendations in duck diets were much lower than the result of 0.72 to 0.79% (NPP 0.34–0.40%) reported by Dai et al. (2018). These inconsistent results implied that the applicability of P requirement of NRC (1994) for ducks needs to be further confirmed.

For the aspect of P availability from different inorganic P sources, Wendt et al. (2004) found that P availabilities were 100, 96, 92, 91, and 86% for monosodium phosphate, anhydrous dibasic calcium, calcium sodium magnesium phosphate, monodibasic calcium phosphate, and dihydrated dibasic calcium phosphate using low-P diet, respectively. Li et al. (2018) indicated that P availability of monocalcium phosphate was 109.85% higher than dicalcium phosphate based on BWG and tibia mineralization. These data suggested that the amounts of different P sources should be adjusted appropriately for feed formulations due to the different P availabilities.

## Nutritional Factors on Ca and P Utilization

Many studies have indicated that Ca and P utilization in poultry is affected by nutritional factors, such as Ca:P ratio and the levels of phytase and  $VD_3$  additions (Rodehutsord, 2006). For dietary Ca:P ratio, Rodehutsord and Dieckmann (2005) and Rush et al. (2005) recommended the appropriate Ca:TP ratio varied between 1.6 and 1.9 based on the level of dietary Ca requirement. Xie et al. (2009a,b) recommended that requirements of Ca and NPP ratio for maximum weight gain were 2.0 (Ca 0.806% vs NPP 0.403%) and

1.94 (Ca 0.72% vs NPP 0.37%) in Pekin ducks at starter and growth-finisher periods, respectively. Zhu et al. (2018) reported that as dietary Ca:TP ratio was increased ranging from 1.2 to 2.5, the growth rate and bone mineralization were decreased in ducks fed the low-P diet with 0.45% TP. Therefore, it is important to consider the Ca:P ratio as a determinant of Ca and P requirements in the duck diet.

Supplementing phytase is an effective way of improving the utilization of phytate P and reducing the amount for P supplementation and P excretion (Bedford and Schulze, 1998). Rodehutsord et al. (2006) found that the addition of phytase (0, 250, 500, 750, 1,000, 1,500, and 2,000 U) could linearly increase the utilizations of Ca and P, and a plateau in response was reached above 1500 U/kg in duckling diets in accordance with the results of 2 balance studies. Similarly, Orban et al. (1999) found that the addition of phytase can increase the phytate P utilization (0.06–0.08%) resulting in the greater growth performance and bone quality in meat ducks at 3 to 6 wk old. Adeola (2010, 2018) indicated that supplementing the low-P duck diet with phytase resulted in both linear and quadratic increases in ileal digestibility and retention of P in both the starter and growth phases. Yang et al. (2009) found that adding 500 U/kg phytase reduced supplemental NPP level from 0.45 to 0.25% in duck layers diets without affecting the laying performance and bone mineral deposits. The mean P equivalency values of phytase supplemented with graded levels of inorganic P or phytase for 500, 1,000, and 1,500 phytase U/kg of diet were 0.453, 0.847, and 1.242 g/kg of duck diet, respectively (Adeola, 2010, 2018). Moreover, studies on broilers have found that high dose of phytase addition could degrade phytic acid to the greatest extent and obtain better production performance (Manobhavan et al., 2016). Therefore, it is necessary to determine the content of phytate P in feed ingredients and P equivalency values between phytase and inorganic P.

Supplementation of  $VD_3$  in diets can increase Ca deposition, bone density, and immune function, which plays a great role in maintaining the normal growth and development of poultry (Świątkiewicz et al., 2017). With the increase of  $VD_3$  levels (0, 250, 500, 1,000, 2,000, 3,000 IU/kg), feed intake and BWG were increased linearly and the maximum value was reached at 2,000 IU/kg in Pekin ducklings fed low Ca:NPP ratio diets (0.4% Ca vs 0.2% NPP) at 1 to 14 d of age, whereas the addition of  $VD_3$  had no effect on growth performance in ducklings fed the normal Ca:NPP ratio diets (0.8% Ca vs 0.4% NPP) (Wang et al., 2010). Rush et al. (2005) observed that there was no response to increasing concentrations of  $VD_3$  from 826 to 8,260 IU/kg on performance characteristics or bone ash contents in drakes during 0 to 13 d of age. The above inconsistent results implied that the positive effect of  $VD_3$  on Ca and P metabolism is closely related to Ca and P contents in diets as well as nutritional status of Ca and P in ducks. Currently, the use of 25-hydroxycholecalciferol (25-OH- $D_3$ ) as biologically active metabolite of  $VD_3$  is

more popular in poultry diets (Soares et al., 1995). The relative biological value of 25-OH-D<sub>3</sub> in comparison to VD<sub>3</sub>, calculated using slope ratio based on tibia compressive strength and daily weight gain, were 1.44 and 1.37 times in Pekin ducks at 1 to 21 d and 22 to 42 d of age, respectively (Shi, 2013). Ren et al. (2016, 2017) confirmed that the inclusion of the mixture of 25-OH-D<sub>3</sub> and canthaxanthin in a diet increased antioxidant ability and serum P level in newly hatched ducklings. The enhanced P absorption and skeletal P deposition might be due to that VD<sub>3</sub> supplementation could increase the *NaP-IIb* and *PiT-2* mRNA expressions and decrease *PiT-1* mRNA expression in the small intestine of broilers (Shao et al., 2019). Although recent studies have paid more attention on the Ca and P requirements of different duck breeds at different growth stages, it is unclear that Ca and P requirements for the growth performance were enough to meet the need of skeletal development of ducks. Moreover, the databases of Ca and P supplementation should be established for feed formulation with addition of different Ca and P sources as well as supplemental 25-OH-D<sub>3</sub> and phytase.

### Electrolyte Balance

Dietary electrolyte balance influences the nutrient metabolism by affecting the acid–base balance and pH in the microenvironment. When the acid–base balance is destroyed in the organism, the catalytic efficiency of enzymes is reduced and then results in metabolic abnormalities (Mushtaq et al., 2013). Most commonly, the electrolyte balance is described by a simple formula Na + K–Cl and expressed as mEq/kg meal. Adeola (2006) recommended 0.18 and 0.16% for Na requirement of meat ducks during 0 to 2 and 2 to 7 wk old, respectively. Dean (1972) suggested that ducklings require approximately 0.14% Na and 0.12% Cl for maximum weight gain, which was close to the recommendations of Pekin ducks in NRC (1994) (0.15% Na and 0.12% Cl) and NY (2012) (0.15% Na and 0.12% Cl). INRA (1989) recommended Na and Cl requirements to be 0.16 and 0.14% for Muscovy ducks, respectively, which are close to those for Pekin ducks. On transfer to saline drinking water (284 mmol/L Na<sup>+</sup>, 6.0 mmol/L K<sup>+</sup>), there was a gradual loss of body weight accompanied by a reduction in the food and water intake (Fletcher and Holmes, 1968). Numerous studies have shown that the amount 250 mEq/kg is considered optimal for normal physiological function in broilers, but limited information in meat ducks (Mushtaq et al., 2013). Liu and Wang (2005) recommended 250–350 mEq/kg for duck layer diets (CP 16%) at growth–finisher period. Birds covered with a feather without sweat glands are susceptible to heat stress and respiratory alkalosis occurs at high temperatures consequent to the excessive loss of carbon dioxide induced by panting (Farghly et al., 2017; Rizk et al., 2019). Treatment with aqueous electrolyte solutions eliminates the adverse effects on broilers and layers (Ahmad and Sarwar, 2006). Subjected to high-temperature environment in summer, the electrolyte

balance of 250–300 mEq/kg was recommended for caged duck layers at the early laying stage (Wang et al., 2011). Therefore, heat-stressed condition results in poor growth rate and poor eggshell quality of highly productive layers (Nawab et al., 2018).

In addition, NRC (1994) recommended magnesium was 500 mg/kg diet for Pekin ducks. Ding and Shen (1992) reported that dietary excess Mg level (690, 1,070, 1,690, 2,150, 2,380 mg/kg) did not affect laying performance in Tsaiya ducks, whereas there was a negative correlation between eggshell thickness and eggshell Mg content, revealing that the increase in eggshell magnesium content probably associated with the impairment of eggshell quality. However, no significant correlation was observed in Leghorn hens. The inconsistent results suggested that there might be some differences on the mineral deposition and microstructure in eggshell between duck and chicken species.

### Copper

Copper is a necessary mineral in poultry nutrition as being a cofactor for many enzymes, for example, cytochrome oxidase, lysyl oxidase, tyrosinase, phydroxyphenyl pyruvate hydrolase, and CuZnSOD (Leeson, 2009). However, Cu requirement in meat duck was not given by NRC (1994). INRA (1989) recommended 5, 4, and 3 mg Cu/kg diet for Muscovy ducks at starter, growth, and finisher phases, respectively, whereas Adeola (2006) recommended 8 mg Cu/kg diet for Pekin ducks at 0 to 7 wk of age. Fouad et al. (2016a) reported that a basal diet containing 5 mg Cu/kg was sufficient for laying performance and egg quality of Shanma laying ducks from 17 to 45 wk of age. In addition, dietary high Cu level of 150 mg/kg supplementation decreased plasma lipids, triglycerides, and cholesterol contents and increased plasma AST and ALT activities (Fouad et al., 2016a). Similarly, dietary 60 mg Cu/kg also decreased the cholesterol contents in plasma and egg yolk, which will help prevent cardiovascular disease for human health (Attia et al., 2011). However, it cannot be recommended due to its toxic effect on organ morphology and EU regulation of 35 mg/kg as the maximum permitted level.

Owing to the limited supplemental Cu level, organic Cu sources have recently received much more attention due to their higher electrical and melting points and bioavailability as well as low electrochemical migration and feed cost in poultry. For instance, Attia et al. (2012) have shown that organic lysine-Cu was more potent for decreasing plasma triglycerides than the inorganic source. Cu nanoparticles with larger surface area and greater capability to cross the small intestine could avoid antagonism with other nutrients and improve growth performance effectively, which was confirmed in piglets, fish, and broilers (Scott et al., 2018). Zhang (2004) found that Cu nanoparticles supplementation improved feed intake and immunity and increased the secretion of GnRH and GH to promote the growth and carcass quality of meat ducks.

## Zinc

Zinc is a nutritionally essential mineral needed for catalytic, structural, and regulatory functions in animals. [Wight and Dewar \(1976\)](#) have reported that the growing ducks fed Zn-deficient maize starch-spray-dried egg albumen displayed the retarded growth and severe lesions of pedal epidermis. Severe Zn deficiency in diets results in a lower hatchability rate, abnormal embryonic development, and poor performing offspring ([Kienholz et al., 1961](#)). A 60 mg Zn/kg diet is required to maintain the optimum productive performance of Pekin ducks at 0 to 7 wk of age by [NRC \(1994\)](#). [INRA \(1989\)](#) recommended that the Zn requirements of Muscovy ducks were 40, 30, and 20 mg/kg at starter, growth, and finisher periods, respectively. [Wen et al. \(2018\)](#) found that Zn content in the traditional corn-soybean meal diet was inadequate to support optimum growth of Pekin ducks. [Attia et al. \(2013\)](#) showed that supplementation with 30 mg Zn/kg in corn-soybean meal basal diet (containing 26 mg Zn/kg) was optimal for growth performance of Pekin ducks from hatching to 56 d of age. In addition, Zn as an essential cofactor for thymulin can enhance the immune system and infectious disease resistance in poultry ([Park et al., 2004](#)). Zn deficiency could inhibit the growth and development of immune organs, leading to the decline of immune function, which was attributed to the apoptosis of immune cells via Fas/Fas-L pathway. For duck layers, addition of 30 to 45 and 70 to 80 mg Zn/kg to the corn-soybean basal diets could maintain the productive performance and improve immune function at the growing and breeder phases, respectively ([Chen et al., 2017](#); [Zhang et al., 2020](#)). These varies suggested that Zn requirements still need to be reevaluated precisely in special duck species at different growth stages.

Recent study has demonstrated that dietary high level of 120 mg Zn/kg exhibited growth-promoting effect and improved the intestinal morphology and barrier integrity on Pekin ducks from 1 to 35 d of age ([Wen et al., 2018](#)). In caged systems, dietary high level of 140 mg Zn/kg level increased the ultrastructural palisade layer thickness contributing to greater eggshell thickness of duck breeders than 40 mg Zn/kg ([Huang et al., 2020](#)). Owing to the higher bioavailability organic Zn, the greater improvement achieved by organic Zn supplementation has been reported in broilers and hens ([Huang et al., 2019](#)). [Guo et al. \(1999\)](#) reported that organic Zn of Met-Zn exhibited greater laying performance of local Jingjiang ducks at laying period. However, [Attia et al. \(2013\)](#) showed that a level of 30 mg Zn/kg from inorganic source displayed better effects of growth rate and Zn excretion than organic source. Because studies in broilers have demonstrated that the bioavailability of Zn might be depended on the chelation strengths, and organic Zn with moderate or strong chelation strength exhibits higher bioavailability compared to inorganic Zn as determined by tissue *MT* mRNA expression ([Huang et al., 2009](#)). One hypothesis is that organic Zn sources with moderate or strong chelation

strength could resist interference from dietary competitive ligands in the digestive tract and directly reach the intestinal brush border, displaying greater Zn bioavailability. Therefore, it is necessary to determine whether the improvements in productive performance were related to the higher Zn bioavailability of organic Zn with optimal chelation strength.

## Manganese

Biochemically, Mn functions as an integral component of the enzymes pyruvate carboxylase, arginase, and superoxide dismutase. [NRC \(1994\)](#) and [Adeola \(2006\)](#) recommended a diet containing a minimum of 60 mg Mn/kg for growing Pekin ducks at 0 to 7 wk of age. Ducks fed a basal diet containing 11.62 mg Mn/kg for 2 wk presented the slipped tendon or perosis symptoms of Mn deficiency, characterized by swelling and flattening of the hock joint, along with subsequent slipping of the Achilles tendon from the condyles, whereas a 40 mg Mn/kg of diet was adequate for normal growth and prevention of perosis of ducks ([Van Reen and Pearson, 1955](#)). However, [Zhu et al. \(1999\)](#) indicated that dietary Mn levels had no effect on growth performance and increased tissue Mn contents. The differences between the studies may depend on the differences in the Mn content in basal diets, experimental periods and the genetic differences, ages, and physiological states of the birds. [Fouad et al. \(2016b\)](#) reported that a corn-soybean meal diet containing 19.2 mg Mn/kg was sufficient for laying performance and egg quality and adding 90 mg Mn/kg basal diet is required to increase Mn-containing superoxide dismutase (**MnSOD**) activity and yolk Mn content in Shanma laying ducks, suggesting that a higher Mn requirement was estimated for ducks by using some sensitive biomarkers (e.g., heart MnSOD activity as well as *MnSOD* mRNA and protein expressions). In addition, Mn is essential for embryonic development, normal growth of bones, and reproduction. For laying hens and breeding hens, some researchers have demonstrated that Mn deficiency marginally showed little or no effect on egg production and eggshell quality, the offspring performance was negatively influenced accompanying with the slipped tendon or perosis symptoms ([Olgun, 2017](#)). It is suggested that dietary Mn requirement for egg production might not be sufficient to maintain the optimal embryonic development and offspring performance in duck breeders. Therefore, the optimal Mn requirement in duck breeders needs to be reevaluated for egg production as well as embryonic development and offspring performance in the future.

## Iron

Iron has a very specific function in animals as a component of the protein heme in the red blood cell's protein hemoglobin and in the muscle cell's protein myoglobin ([Theil, 2004](#)). So far, iron requirement of meat ducks was not recommended by [NRC \(1994\)](#). [Adeola \(2006\)](#) recommended a diet required 80 mg

Fe/kg for growing Pekin ducks at 0 to 7 wk of age. INRA (1989) recommended that the Fe requirements of Muscovy ducks were 40, 30, and 20 mg/kg at starter, growth, and finisher periods respectively. However, these values were lacked of experimental evidence in meat ducks. Therefore, studies about Fe nutrition in meat duck need to be further strengthened. In laying ducks, Xia et al. (2016) showed that 52.2, 97.2, and 127.2 mg Fe/kg are required to maintain performance and enhance hemoglobin and hematocrit levels of local Shanma ducks, respectively. Huang et al. (2015) shown that dietary supplemented with 71.9 to 84.5 mg Fe/kg were estimated to obtain the better egg production performance and egg quality of local Linwu laying ducks at 50 to 60 wk old. These data about Fe requirement were evaluated based on traditional conventional indicators for maximal performance, which may not be able to effectively reflect the sensitive response of iron nutritional status in ducks. Therefore, in broilers, some sensitive and specific indicators, such as enzymes (e.g., succinate dehydrogenase) and genes expression (e.g., cytochrome C oxidase) related to iron metabolism, have been selected to reevaluated Fe requirement, which tended to be higher than those from maximal performance (Ma et al., 2016).

Some antinutritional factors in feedstuffs have antagonistic effects on iron absorption, such as phytic acid (Hunter, 1981), pectin (Miyada et al., 2011), and tannin (Delimont et al., 2017). For example, iron can bind to cellulose or tannins to form insoluble complexes to inhibit the Fe absorption in animals. Recently, more unconventional ingredients with high contents of antinutritional factors tended to be used in feed formulation of meat ducks than broilers. Therefore, supplemental Fe levels in duck diet should not be referred to the data from studies in broilers. Organic sources with higher bioavailability could prevent antagonistic action between Fe and antinutritional factors as well as reduce fecal Fe excretion and environmental pollution.

## Selenium

Selenium as an integral part of selenoproteins participated in the regulation of various physiological processes in the body. Se deficiency damaged fibroblast membranes and decreased collagen synthesis, resulting in myodegeneration in ducks (Brown et al., 1982). Se requirements were 0.2 and 0.1 mg/kg in Pekin ducks and Muscovy ducks, respectively. Chen et al. (2015a) indicated that Se requirement based on daily egg production were 0.18 and 0.24 mg/kg for duck layers at early-laying and peak-laying periods, respectively. Generally speaking, there are 2 major Se sources for poultry, namely inorganic Se (selenite) and organic Se in the form of selenomethionine (Se-yeast). Organic Se sources shows greater bioavailability (75.7%) than Se bound in the inorganic form (49.9%) (Mahan and Peters, 2004), augmenting antioxidant defense against free radicals and natural immunity of the organism (Surai, 2002).

Compared with inorganic Se, diet required 0.40 mg Se/kg as Se-yeast source to improve the growth rate of Cherry Valley ducks from 1 to 49 d of age (Baltić et al., 2017). Zhang (2013) reported that adding 0.19 mg Se/kg in a basal diet containing 0.042 mg Se/kg was sufficient to maintain growth rate and improve the antioxidant ability and immune function of ducklings at the starter period. Considering the enhanced antioxidant ability due to Se supplementation, He et al. (2013) have demonstrated that Se-yeast + VE could reduce negative effects of AFB1 on growth and hepatic function. Li (2008) found that dietary higher level of 0.4 mg Se/kg could alleviate the cold-stressed effect on growth performance of ducklings. Therefore, the beneficial effect and mechanism of organic Se sources and levels should be examined in further studies in ducks subjected to the stress and disease conditions.

## SUMMARY

Over the past 60 yr, most mineral nutrition studies have been limited to the effects of Ca, P, Zn, and Se on growth performance of meat ducks and laying performance of duck layers. Thus, more studies should be conducted to determine the requirements of Cu, Fe, and Mn and electrolyte balance of meat ducks and duck breeders. Especially, mineral nutrition in female duck breeder is not only required for maximal egg production performance but also for maintaining normal embryonic development and offspring's performance. As with the improvement of genetic evolution and upgrade of rearing systems in duck production, mineral requirements should be urgent to be reevaluated for modern duck breed characterized by the rapid growth rate and inadequate bone development and mineralization. It is also suggested that sensitive and specific enzymes and target genes related to mineral metabolism should be used to determine mineral requirements of ducks. In addition, considering the high susceptibility of modern poultry to various stresses in commercial production, more attention should be paid for the positive effects of high doses addition for meat ducks subjected to the stressed challenges. Recently, some unconventional ingredients with antinutritional factors were preferred to be used in feed formulation of ducks, some nutritional strategies with supplemental enzymes (e.g., phytase and NSP enzymes) or organic sources could be adopted to reduce the antagonistic action between mineral and antinutritional factors. It is necessary to clarify how to adjust the mineral addition in diets supplementations of phytase and VD<sub>3</sub>. Therefore, special and accurate database of mineral requirements should be established for different genotypes of ducks (meat-type vs egg-type) under different rearing conditions, including rearing factors (caged system and litter floor), environmental stresses (heat stress vs cold stress) and diets supplemented with different mineral sources (inorganic source vs organic source), phytase and VD<sub>3</sub>.

## ACKNOWLEDGMENTS

This study was sponsored by National Natural Science Foundation of China (31802080), Guangdong Provincial Natural Science Foundation (2018A030310202) and Provincial Natural Science Foundation for Cooperation with WENS Group (2019B1515210031), and China Agriculture Research System (CARS-42-15).

## DISCLOSURES

The authors declare that there is no conflict of interest related to the preparation and publication of this article.

## REFERENCES

- Adeola, O. 2006. Review of research in duck nutrient utilization. *Int. J. Poult. Sci.* 5:201–218.
- Adeola, O. 2010. Phosphorus equivalency value of an *Escherichia coli* phytase in the diets of White Pekin ducks. *Poult. Sci.* 89:1199–1206.
- Adeola, O. 2018. Phytase in starter and grower diets of White Pekin ducks. *Poult. Sci.* 97:592–598.
- Ahmad, T., and M. Sarwar. 2006. Dietary electrolyte balance: implications in heat stressed broilers. *Worlds Poult. Sci. J.* 62:638–653.
- Attia, Y., A. Abdalah, H. Zeweil, F. Bovera, A. T. El-Din, and M. Araft. 2011. Effect of inorganic or organic copper additions on reproductive performance, lipid metabolism and morphology of organs of dual-purpose breeding hens. *Arch. Geflugelk* 3:169–178.
- Attia, Y., A. A. Al-Hamid, H. Zeweil, E. Qota, F. Bovera, G. Monastra, and M. Sahledom. 2013. Effect of dietary amounts of inorganic and organic zinc on productive and physiological traits of White Pekin ducks. *Animal* 7:895–900.
- Attia, Y. A., E. M. Qota, H. S. Zeweil, F. Bovera, A. A. Abd, and M. D. Sahledom. 2012. Effect of different dietary concentrations of inorganic and organic copper on growth performance and lipid metabolism of White Pekin male ducks. *Br. Poult. Sci.* 53:77–88.
- Baeza, E. 2016. Nutritional requirements and feed management of meat type ducks. *Worlds Poult. Sci. J.* 72:5–19.
- Baltić, M. Z., M. D. Starčević, M. Bašić, A. Zenunović, J. Ivanović, R. Marković, J. Janjić, H. Mahmutović, and N. Glamočlija. 2017. Effects of dietary selenium-yeast concentrations on growth performance and carcass composition of ducks. *Anim. Prod. Sci.* 57:1731–1737.
- Bedford, M. R., and H. Schulze. 1998. Exogenous enzymes for pigs and poultry. *Nutr. Res. Rev.* 11:91–114.
- Brown, R., P. Sweeny, and E. Moran, Jr. 1982. Collagen levels in tissues from selenium deficient ducks. *Comp. Biochem. Phys. A.* 72:383–389.
- Chen, W., S. Wang, H. X. Zhang, D. Ruan, W. Xia, Y. Cui, C. T. Zheng, and Y. C. Lin. 2017. Optimization of dietary zinc for egg production and antioxidant capacity in Chinese egg-laying ducks fed a diet based on corn-wheat bran and soybean meal. *Poult. Sci.* 96:2336–2343.
- Chen, W., H. Zhang, S. Wang, D. Ruan, X. Xie, D. Yu, and Y. Lin. 2015a. Estimation of dietary selenium requirement for Chinese egg-laying ducks. *Anim. Prod. Sci.* 55:1056–1063.
- Chen, W., F. Zhao, Z. M. Tian, H. X. Zhang, D. Ruan, Y. Li, S. Wang, C. T. Zheng, and Y. C. Lin. 2015b. Dietary calcium deficiency in laying ducks impairs eggshell quality by suppressing shell biomineralization. *J. Exp. Biol.* 218:3336–3343.
- National Research Council. (NRC) 1994. *Nutrient Requirements of Poultry*: 1994. National Academies Press.
- Dai, S. J., K. Zhang, X. Ding, S. Bai, Y. Luo, J. Wang, and Q. Zeng. 2018. Effect of dietary non-phytate phosphorus levels on the diversity and structure of cecal microbiota in meat duck from 1 to 21 d of age. *Poult. Sci.* 97:2441–2450.
- Dean, W., M. Scott, R. Young, and W. Ash. 1967. Calcium requirement of ducklings. *Poult. Sci.* 46:1496–1499.
- Dean, W. F. 1972. Recent findings in duck nutrition. *Cornell Nutr. Conf. Feed Manufacturers Proc.* 77–85.
- Delimont, N. M., M. D. Haub, and B. L. Lindshield. 2017. The impact of tannin consumption on iron bioavailability and status: a narrative review. *Curr. Dev. Nutr.* 1:1–12.
- Ding, S., and T. F. Shen. 1992. The effect of dietary magnesium level on the eggshell quality in laying Tsaiya duck and Leghorn hen. *Asian Australas. J. Anim. Sci.* 5:217–224.
- Fan, H. P. 2003. *Comparative Study of the Digestion of Feed Nutrients between Cockerel and Drake*. Chinese Academy of Agricultural Sciences, Beijing.
- Farghly, M. F. A., K. M. Mahrose, Z. Ullah, Z. U. Rehman, and C. Ding. 2017. Influence of swimming time in alleviating the deleterious effects of hot summer on growing Muscovy duck performance. *Poult. Sci.* 96(11):3912–3919.
- Fletcher, G. L., and W. N. Holmes. 1968. Observations on the intake of water and electrolytes by the duck (*Anas platyrhynchos*) maintained on fresh water and on hypertonic saline. *J. Exp. Biol.* 49:325–339.
- Fouad, A., Y. Li, W. Chen, D. Ruan, S. Wang, W. Xia, Y. Lin, and C. Zheng. 2016a. Effects of dietary copper supplementation on laying performance, egg quality and plasma cholesterol fractions in laying ducks. *Pak. J. Nutr.* 15:878–882.
- Fouad, A. M., Y. Li, W. Chen, D. Ruan, S. Wang, W. Xie, Y. C. Lin, and C. T. Zheng. 2016b. Effects of dietary manganese supplementation on laying performance, egg quality and antioxidant status in laying ducks. *Asian J. Anim. Vet. Adv.* 11:570–575.
- Guo, R. F., K. L. Chen, and C. Y. Zhang. 1999. A study on bioavailability of organic zinc source in meat duck. *Feed Res.* 11:9–11.
- He, J., K. Zhang, D. Chen, X. Ding, G. Feng, and X. Ao. 2013. Effects of vitamin E and selenium yeast on growth performance and immune function in ducks fed maize naturally contaminated with aflatoxin B1. *Livest. Sci.* 152:200–207.
- Huang, L., X. Li, W. Wang, L. Yang, and Y. W. Zhu. 2019. The role of zinc in poultry breeder and hen nutrition: an update. *Biol. Trace Elem. Res.* 192:308–318.
- Huang, L., J. Shen, Y. Feng, D. Li, W. Wang, L. Yang, and Y. Zhu. 2020. Effect of dietary zinc level on egg production performance and eggshell quality characteristics in laying duck breeders in furnished cage system. *Biol. Trace Elem. Res.* 196:597–606.
- Huang, X., C. Li, G. Jiang, X. Zhang, X. Wang, and Q. Dai. 2016. Dietary calcium requirement of Linwu ducks in early laying period. *Chin. J. Anim. Nutr.* 28:3437–3444.
- Huang, X., C. Li, X. Zhang, G. Jiang, X. Wang, Y. Hu, and Q. Dai. 2015. Effects of dietary iron supplementation on egg production performance and egg quality of Linwu ducks at 50-60 weeks old. *China Feed* 19:20–22.
- Huang, X., C. Li, X. Zhang, G. Jiang, X. Wang, Y. Hu, and Q. Dai. 2017. Effect of dietary calcium level on laying performance, egg quality and serum biochemical indexes of Linwu duck at the peak of laying period. *China Feed* 17:24–27.
- Huang, Y., L. Lu, S. F. Li, X. Luo, and B. Liu. 2009. Relative bioavailabilities of organic zinc sources with different chelation strengths for broilers fed a conventional corn-soybean meal diet. *J. Anim. Sci.* 87:2038–2046.
- Hunter, J. E. 1981. Iron availability and absorption in rats fed sodium phytate. *J. Nutr.* 111:841–847.
- Institut National de la Recherche Agronomique (INRA). *L'alimentation des animaux monogastriques: porc, lapin, volailles*, 1989. Pages 123–131 in Editions Quae, Paris, France.
- Jamroz, D., A. Wiliczekiewicz, J. Orda, T. Wertelecki, and J. Skorupinska. 2002. Aspects of development of digestive activity of intestine in young chickens, ducks and geese. *J. Anim. Physiol. Anim. Nutr.* 86:353–366.
- Kienholz, E., D. Turk, M. Sunde, and W. Hoekstra. 1961. Effects of zinc deficiency in the diets of hens. *J. Nutr.* 75:211–221.
- Leclercq, B., H. De Carville, and G. Guy. 1990. Calcium requirement of male Muscovy ducklings. *Br. Poult. Sci.* 31:331–337.
- Leeson, S. 2009. Copper metabolism and dietary needs. *Worlds Poult. Sci. J.* 65:353–366.
- Li, R. 2008. *The Effect of Low Temperature and Selenium on Growth and Biochemical Indexes of Breeding Ducks in Cage*. Master Diss. Northeast Agricultural University, Haerbin.
- Li, W. J., L. W. H. Chang, Z. M. Chen, A. J. Zheng, and G. H. Liu. 2018. A study of relative bioavailability of mono-



- dicalcium phosphate on meat ducks. *Chin. J. Anim. Nutr.* 30:3364–3376.
- Lin, I., and T. Shen. 1979. Studies on duck nutrition. II. Calcium and phosphorus requirements of mule ducklings. *Poult. Sci.* 58:124–130.
- Liu, Y. X., and A. Wang. 2005. Effect of dietary protein on acid-base balance of cage-rearing ducks. *J. Northeast Agric. Univ.* 36:336–341.
- Ma, X., X. Liao, L. Lu, S. F. Li, L. Zhang, and X. Luo. 2016. Determination of dietary iron requirements by full expression of iron-containing enzymes in various tissues of broilers. *J. Nutr.* 146:2267–2273.
- Mahan, D., and J. Peters. 2004. Long-term effects of dietary organic and inorganic selenium sources and levels on reproducing sows and their progeny. *J. Anim. Sci.* 82:1343–1358.
- Manobhavan, M., A. Elangovan, M. Sridhar, D. Shet, S. Ajith, D. Pal, and N. Gowda. 2016. Effect of super dosing of phytase on growth performance, ileal digestibility and bone characteristics in broilers fed corn-soya-based diets. *J. Anim. Physiol. Anim. Nutr.* 100:93–100.
- Miyada, T., A. Nakajima, and K. Ebihara. 2011. Iron bound to pectin is utilised by rats. *Br. J. Nutr.* 106:73–78.
- Mushtaq, M. H., T. N. Pasha, T. Mushtaq, and R. Parvin. 2013. Electrolytes, dietary electrolyte balance and salts in broilers: an updated review on growth performance, water intake and litter quality. *Worlds Poult. Sci. J.* 69:789–802.
- Nawab, A., F. Ibtisham, G. Li, B. Kieser, J. Wu, W. Liu, Y. Zhao, Y. Nawab, K. Li, and M. Xiao. 2018. Heat stress in poultry production: Mitigation strategies to overcome the future challenges facing the global poultry industry. *J. Therm. Biol.* 78:131–139.
- NY/T 2012. Nutrient Requirement of Meat-type Ducks (NY/T 2122–2012). China Agricultural Industry Standards, Beijing.
- Olgun, O. 2017. Manganese in poultry nutrition and its effect on performance and eggshell quality. *Worlds Poult. Sci. J.* 73:45–56.
- Orban, J. I., O. Adeola, and R. Strohshine. 1999. Microbial phytase in finisher diets of White Pekin ducks: effects on growth performance, plasma phosphorus concentration, and leg bone characteristics. *Poult. Sci.* 78:366–377.
- Park, S., S. Birkhold, L. Kubena, D. Nisbet, and S. Ricke. 2004. Review on the role of dietary zinc in poultry nutrition, immunity, and reproduction. *Biol. Trace Elem. Res.* 101:147–163.
- Pingel, H., and L. Germany. 2011. Waterfowl production for food security. *Lohmann Information* 46:32–42.
- Ren, Z. Z., S. Jiang, Q. Zeng, X. Ding, S. Bai, J. Wang, Y. Luo, Z. W. Su, Y. Xuan, and K. Zhang. 2017. Effect of maternal canthaxanthin and 25-hydroxycholecalciferol supplementation on the performance of ducklings under two different vitamin regimens. *J. Anim. Physiol. Anim. Nutr.* 101:359–368.
- Ren, Z. Z., J. Wang, Q. Zeng, X. Ding, S. Bai, Y. Luo, Z. W. Su, Y. Xuan, and K. Zhang. 2016. The effects of maternal dietary vitamin premixes, canthaxanthin, and 25-hydroxycholecalciferol on the performance of progeny ducklings. *Poult. Sci.* 95:630–635.
- Rizk, Y. S., H. N. Fahim, M. M. Beshara, K. M. Mahrose, and A. L. Awad. 2019. Response of duck breeders to dietary L-Carnitine supplementation during summer season. *Acad. Bras Cienc* 91:e20180907.
- Rodehutsord, M. 2006. Optimising the use of phosphorus sources in growing meat ducks. *Worlds Poult. Sci. J.* 62:513–523.
- Rodehutsord, M., and A. Dieckmann. 2005. Comparative studies with three-week-old chickens, turkeys, ducks, and quails on the response in phosphorus utilization to a supplementation of monobasic calcium phosphate. *Poult. Sci.* 84:1252–1260.
- Rodehutsord, M., R. Hempel, and P. Wendt. 2006. Phytase effects on the efficiency of utilisation and blood concentrations of phosphorus and calcium in Pekin ducks. *Br. Poult. Sci.* 47:311–321.
- Rodehutsord, M., R. Timmler, and P. Wendt. 2003. Response of growing Pekin ducks to supplementation of monobasic calcium phosphate to low-phosphorus diets. *Poult. Sci.* 82:309–319.
- Rodenburg, T. B., M. Bracke, J. Berk, J. Cooper, J. Faure, D. Guémené, G. Guy, A. Harlander, T. Jones, and U. Knierim. 2005. Welfare of ducks in European duck husbandry systems. *Worlds Poult. Sci. J.* 61:633–646.
- Rush, J. K., C. R. Angel, K. M. Banks, K. L. Thompson, and T. J. Applegate. 2005. Effect of dietary calcium and vitamin D3 on calcium and phosphorus retention in white Pekin ducklings. *Poult. Sci.* 84:561–570.
- Scott, A., K. P. Vadalasetty, A. Chwalibog, and E. Sawosz. 2018. Copper nanoparticles as an alternative feed additive in poultry diet: a review. *Nanotechnol. Rev.* 7:69–93.
- Selle, P. H., A. J. Cowieson, and V. Ravindran. 2009. Consequences of calcium interactions with phytate and phytase for poultry and pigs. *Livest. Sci.* 124:126–141.
- Shao, Y., Q. Wen, S. Zhang, L. Lu, L. Zhang, X. Liao, and X. Luo. 2019. Dietary supplemental vitamin D3 enhances phosphorus absorption and utilisation by regulating gene expression of related phosphate transporters in the small intestine of broilers. *Br. J. Nutr.* 121:9–21.
- Shi, W. B. 2013. Studies on Vitamin D<sub>3</sub> and 25-hydroxyvitamin D<sub>3</sub> Requirements and Relative Bioavailability in White Pekin Ducks. Master Diss. Chinese Academy of Agricultural Sciences, Beijing.
- Soares, J. H., J. M. Kerr, and R. W. Gray. 1995. 25-Hydroxycholecalciferol in poultry nutrition. *Poult. Sci.* 74:1919–1934.
- Sumarmono, J. 2019. Duck production for food security. *IOP Conf. Ser. Earth Environ. Sci.* 372:1–11.
- Surai, P. 2002. Selenium in poultry nutrition I. Antioxidant properties, deficiency and toxicity. *Worlds Poult. Sci. J.* 58:333–347.
- Świątkiewicz, S., A. Arczewskawłosek, D. Bederskałojewska, and D. Jozefiak. 2017. Efficacy of dietary vitamin D and its metabolites in poultry - review and implications of the recent studies. *Worlds Poult. Sci. J.* 73:57–68.
- Theil, E. C. 2004. Iron, ferritin, and nutrition. *Annu. Rev. Nutr.* 24:327–343.
- Van Reen, R., and P. B. Pearson. 1955. Manganese deficiency in the duck. *J. Nutr.* 55:225–234.
- Wang, S., S. S. Hou, M. Xie, W. Huang, and J. Y. Yu. 2010. Effect of different concentrations of vitamin D3 on growth performance, blood biochemistry and tibia parameter for white pekin ducklings. *Acta Vet. Zootech. Sin.* 41:1414–1420.
- Wang, A., C. H. Fang, and H. Q. Wang. 2011. Regulation of dietary electrolyte balance in summer on blood acid-base balance and growth performance of duck layer in caged system. *Feed Ind.* 32:50–53.
- Wang, S., W. Chen, H. X. Zhang, D. Ruan, and Y. C. Lin. 2014. Influence of particle size and calcium source on production performance, egg quality, and bone parameters in laying ducks. *Poult. Sci.* 93:2560–2566.
- Wasilewski, R., D. Kokoszyński, A. Mieczkowska, Z. Bernacki, and A. Górka. 2015. Structure of the digestive system of ducks depending on sex and genetic background. *Acta Vet. Brno* 84:153–158.
- Wen, M., H. Zhao, G. Liu, X. Chen, B. Wu, G. Tian, J. Cai, and G. Jia. 2018. Effect of zinc supplementation on growth performance, intestinal development, and intestinal barrier-related gene expression in Pekin ducks. *Biol. Trace Elem. Res.* 183:351–360.
- Wendt, P., and M. Rodehutsord. 2004. Investigations on the availability of inorganic phosphate from different sources with growing White Pekin ducks. *Poult. Sci.* 83:1572–1579.
- Wight, P., and W. Dewar. 1976. The histopathology of zinc deficiency in ducks. *J. Pathol.* 120:183–191.
- Xia, W. G., Y. C. Lin, C. T. Zheng, W. Chen, D. Ruan, S. Wang, and G. Li Y. 2016. Effects of dietary iron level on laying performance, egg quality, liver and blood indices of shanma laying ducks. *Chin. J. Anim. Nutr.* 1:71–78.
- Xia, W., H. Zhang, Y. Lin, and C. Zheng. 2015. Evaluation of dietary calcium requirements for laying Longyan shelducks. *Poult. Sci.* 94:2932–2937.
- Xie, M., S. Wang, S. Hou, and W. Huang. 2009a. Interaction between dietary calcium and non-phytate phosphorus on growth performance and bone ash in early White Pekin ducklings. *Anim. Feed Sci. Technol.* 151:161–166.
- Xie, M., S. Wang, S. Hou, W. Huang, L. Zhao, and J. Yu. 2009b. Calcium and phosphorus requirements of pekin ducks from 3 to 6 week of age. *Chin. J. Anim. Nutr.* 21:25–30.
- Yang, Z., Z. Y. Huang, J. P. Zhou, W. Yang, S. Z. Jiang, and G. G. Zhang. 2009. Effects of a new recombinant phytase on performance and mineral utilization of laying

- ducks fed phosphorus-deficient diets. *J. Appl. Poult. Res.* 18:284–291.
- Zhang, L. H. 2004. The Effect of Nano-Copper on the Production Performance and Serum Biochemical Indices of Meat Duck. Master Diss. Shanxi Agricultural University, Jinzhong.
- Zhang, H., Q. Zeng, S. Bai, J. Wang, X. Ding, Y. Xuan, Z. Su, and K. Zhang. 2018. Effect of graded calcium supplementation in low-nutrient density feed on tibia composition and bone turnover in meat ducks. *Br. J. Nutr.* 120:1217–1229.
- Zhang, W. M. 2013. Effects of Selenium on Growth and Biochemical Indexes of Caged Egg-type Ducklings. Master Diss. Northeast Agricultural University, Haerbin.
- Zhang, Y. N., S. Wang, K. C. Li, D. Ruan, W. Chen, W. G. Xia, S. L. Wang, K. F. M. Abouelezz, and C. T. Zheng. 2020. Estimation of dietary zinc requirement for laying duck breeders: effects on productive and reproductive performance, egg quality, tibial characteristics, plasma biochemical and antioxidant indices, and zinc deposition. *Poult. Sci.* 99:454–462.
- Zhang, H. Y., Q. F. Zeng, S. P. Bai, J. P. Wang, X. M. Ding, Y. Xuan, Z. W. Su, G. S. Fraley, and K. Y. Zhang. 2019. Study on the morphology and mineralization of the tibia in meat ducks from 1 to 56 d. *Poult. Sci.* 98:3355–3364.
- Zhu, Z. Y., Y. T. Bao, and A. H. Shen. 1999. A study on dietary manganese requirement of ducklings. *Feed Res.* 3:3–4.
- Zhu, Y., X. Jiang, J. Wen, W. Wang, and L. Yang. 2019. Dietary calcium requirements of Sheldrake ducklings from 1 to 21 days of age. *Anim. Prod. Sci.* 59:887–890.
- Zhu, Y. W., J. Wen, X. X. Jiang, W. C. Wang, and L. Yang. 2018. High calcium to phosphorus ratio impairs growth and bone mineralization in Pekin ducklings. *Poult. Sci.* 97:1163–1169.