Advances in Chitosan Regulation of Lipid Metabolism in Poultry: Postprint

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Abstract

Chitosan is a natural amino polysaccharide widely distributed in nature. Research has shown that chitosan possesses antibacterial, anti-inflammatory, antioxidant, antitumor, and immune-enhancing biological functions. This review summarizes the effects of chitosan on lipid digestion, body fat deposition, serum biochemical parameters, and the activity and gene expression of key enzymes in lipid metabolism in poultry, and preliminarily explores the regulatory mechanisms of chitosan on poultry lipid metabolism.

Full Text

Research Progress on Chitosan Regulation of Lipid Metabolism in Poultry

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Abstract: Chitosan is a natural polyglucosamine widely distributed in nature. Studies have shown that chitosan possesses biological functions including antibacterial activity, anti-inflammatory effects, antioxidant properties, antitumor activity, and immune enhancement. This review synthesizes research on the effects of chitosan on fat digestion, body fat deposition, serum biochemical parameters, and the activity of key lipid metabolism enzymes and their gene expression in poultry, and preliminarily explores the regulatory mechanisms of chitosan on poultry lipid metabolism.

Keywords: chitosan; poultry; lipid metabolism; regulation

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Chitosan [(1,4)-2-amino-2-deoxy-β-D-glucan] is a polymeric macromolecule rich in amino groups, obtained through the deacetylation of chitin (primarily derived from discarded shrimp and crab shells from aquatic product processing). It has the characteristic of binding with protons and carrying a positive charge in weakly acidic environments, making it the only naturally occurring macromolecular organic compound with a positive charge. The molecular structure of chitosan is shown in Figure 1 [Figure 1: see original paper] [1].

Since Sugano et al. [2] first reported the cholesterol-lowering effects of chitosan in 1978, its lipid-reducing function has become a focal point of scholarly attention and research. Numerous studies have demonstrated that chitosan can reduce dietary fat absorption, increase lipid excretion in feces, influence blood and liver lipid metabolism, and participate in the deposition and redistribution of animal fat by regulating the activity of key lipid metabolism enzymes and their gene expression [3-4]. As the problem of excessively high fat content in poultry products has become increasingly prominent, chitosan, as a natural, green, and safe lipid-lowering product, has attracted growing attention from poultry enterprises and researchers regarding its effects on avian lipid metabolism. This review begins with the effects of chitosan on dietary fat utilization efficiency in poultry, synthesizes domestic and international research on the impacts of chitosan on poultry body fat and blood lipids, preliminarily analyzes the biochemical and molecular mechanisms underlying chitosan' s regulation of lipid metabolism, and aims to provide a reference for the scientific application of chitosan and the development of high-quality poultry products.

1 Effects of Chitosan on Lipid Metabolism in Poultry

In recent years, numerous studies have shown that chitosan can regulate lipid metabolism by influencing dietary fat absorption, inhibiting fat digestion and metabolic enzyme activities, and reducing the expression levels of key lipid metabolism genes.

1.1 Effects on Dietary Fat Digestibility

Currently, research on the lipid-lowering activity of chitosan has primarily focused on broiler chickens, with few reports on other poultry species. Razdan et al. [5] reported that adding 30 g/kg of chitosan to the diet significantly reduced ileal fat digestibility in broilers, and this reduction was positively correlated with chitosan viscosity. Li Qiuping [6] found that dietary supplementation with 0.75% chitosan significantly increased the excretion of crude fat in feces of Qilin chickens. In studies with geese, Wang Runlian et al. [7] reached similar conclusions, demonstrating that dietary addition of 0.05% to 0.15% chitosan significantly reduced the utilization rate of dietary crude fat in goslings. Therefore, it can be concluded that chitosan reduces dietary fat utilization in poultry by preventing fat degradation by digestive enzymes, thereby increasing excretion rates in the terminal intestine [8].

1.2 Effects on Body Fat Deposition

Body fat is the primary means of energy storage in animals, typically measured by indicators such as abdominal fat percentage, intermuscular fat width, and subcutaneous fat thickness. With changes in Chinese consumer dietary patterns, the issue of excessive body fat percentage in poultry, particularly abdominal fat percentage, has become increasingly prominent. Large amounts of fat are discarded during processing, and high body fat not only causes feed waste and deteriorates poultry product quality but also reduces consumer purchasing willingness [9]. Consequently, developing feed additives that can reduce or regulate lipid metabolism in poultry has been a key focus for researchers. Since Sugano et al. [2] discovered the lipid-lowering efficacy of chitosan, numerous subsequent studies have been conducted on poultry.

Ma Xiaozhen et al. [10] found that dietary chitosan supplementation significantly reduced abdominal fat weight in broilers. Liu Haiying et al. [11] reported that chitosan significantly decreased liver fat percentage and abdominal fat percentage in Avian chickens. Huang Guanqing et al. [12] observed that while dietary supplementation with 0.1%, 0.3%, and 0.5% chitosan had no significant effect on abdominal fat percentage in experimental chickens, it significantly reduced subcutaneous fat weight. Hu Zhongze et al. [13] demonstrated that dietary addition of 0.04% chitosan not only significantly reduced abdominal fat percentage but also decreased intermuscular fat width.

The degree of deacetylation in chitosan can also influence its lipid-lowering efficacy. Lü Danna [14] noted that the deacetylation degree of chitosan had some inhibitory effect on abdominal fat in broilers, though the effect was not significant. In contrast, studies by Li Qiuping [6] and Jiang Guoliang et al. [15] showed that deacetylation degree significantly reduced intermuscular fat width, abdominal fat percentage, and liver fat percentage in broilers. Currently, relevant data on geese are limited. Zhao Ping [16] reported that 100–400 mg/kg of chitosan could reduce intermuscular fat width and thickness, subcutaneous fat thickness, and abdominal fat percentage in Tianshan snow geese. Whether chitosan affects geese consistently with chickens remains to be verified through further experimentation.

1.3 Effects on Blood Lipid Content

Blood lipids refer to the total lipids in blood, typically including triglycerides (TG), total cholesterol (TC), high-density lipoprotein (HDL), and low-density lipoprotein (LDL). TG primarily participates in energy storage and supply, TC is a major component of animal cell membranes and nerve myelin sheaths, HDL is responsible for transporting TC from peripheral tissues and blood to the liver for metabolism, and LDL transports TC synthesized in the liver to extrahepatic tissues [17].

Jiang Guoliang et al. [15] demonstrated that 0.15% chitosan significantly reduced serum triglyceride and total cholesterol levels in broilers. Huang Guanqing et al. [12] found that chitosan at 0.1%, 0.3%, and 0.5% all decreased serum TC and TG content in broilers. Yang Zhengping et al. [18] suggested that even lower doses (100 mg/kg) of chitosan could reduce serum TC and TG levels in experimental chickens ($P<0.05$). Han Jie et al. [19] reported that 2% chitosan not only significantly reduced serum TC content in broilers but also significantly decreased serum free fatty acid (FFA) content.

In studies with laying hens, Zhao Ying et al. [20] found that 20 mg/kg of chitosan oligosaccharide significantly reduced serum TG, LDL, and very low-density lipoprotein content. Wang Runlian et al. [7] observed similar phenomena in geese, where 0.10% chitosan supplementation significantly reduced serum TG and TC levels in experimental geese. In contrast to the aforementioned findings, Li Zhongrong et al. [21] discovered that while 0.3% and 0.5% chitosan significantly reduced serum TG and TC content in female Hetian chickens, they had no significant effects on HDL, LDL, apolipoprotein AI, or apolipoprotein B content.

Liu Mei [22] reported that 150 mg/kg of chitosan had no significant effect on blood TG or FFA content in broilers. Similar to these findings, Zheng Xiaoling et al. [23] found that dietary supplementation with 0.10%-0.50% chitosan had no effect on blood lipid content in 1- to 3-week-old yellow-feathered broilers. In studies on the effect of deacetylation degree on lipid metabolism, Lü Danna [14] found that deacetylation degree could inhibit blood lipid levels in broilers. Further research by Li et al. [24] confirmed that, in addition to deacetylation degree, the molecular weight of chitosan could also affect its lipid-lowering efficacy. Specifically, chitosan with molecular weights of 50 and 5 ku significantly reduced serum TC content in Qilin chickens, while 5 ku chitosan extremely significantly decreased serum TG content.

1.4 Effects on Lipids in Poultry Products

Poultry products encompass both eggs and meat. In egg research, Nogueira et al. [25] reported that supplementation with 2% or 3% chitosan significantly reduced TC content in egg yolks of 28-week-old laying hens, a conclusion also reached by Świątkiewicz et al. [26]. In domestic research, Wang Dun et al. [27] found that dietary addition of 1.0% insect-derived chitosan reduced TC content in egg yolks. Liu Zhiyou [28] demonstrated that 250-500 mg/kg of chitosan could improve the content of saturated fatty acids (SFA), monounsaturated fatty acids (MUFA), polyunsaturated fatty acids (PUFA), n-6 PUFA, n-3 PUFA, and the n-6/n-3 ratio in egg yolks, though the improvement effect diminished at high doses. In contrast, Zhao Ying et al. [20] found that 20 mg/kg of chitosan oligosaccharide had no effect on egg fat content or egg quality.

In poultry meat research, Du Bingwang et al. [29] noted that 0.05%-0.20%

chitosan could reduce muscle fat content in 90-day-old Guifei chickens. Zhou et al. [30] showed that 0.14% and 0.28% chitosan reduced SFA content and increased MUFA content in breast muscle. Wang Shubai et al. [31] reported that TC content in thigh and breast muscles of experimental chickens in the 2% chitosan group decreased by 5.08% and 4.96%, respectively, compared to the control group. Wang Yunxia [32] found that linoleic acid and PUFA content in chicken meat from the 0.1% chitosan group differed extremely significantly from the control group. Chang Bin et al. [33] and Xia Dangrong et al. [34] suggested that, similar to chickens, dietary chitosan supplementation can also reduce fat content in goose meat.

2.1.1 Adsorption

Similar to plant cellulose, as an animal fiber, chitosan possesses strong adsorption capacity for lipid substances. By adsorbing dietary fats and bile acids, chitosan reduces contact between dietary lipids and digestive enzymes, increases lipid excretion in feces, decreases dietary fat utilization efficiency, and reduces fat deposition [3]. Research has shown that the adsorption capacity of chitosan is closely related to its molecular structure, with high molecular weight and high viscosity chitosan exhibiting relatively stronger adsorption ability [6].

2.1.2 Electrostatic Interaction

Chitosan molecules are rich in amino groups that become protonated and exist in the -NH3+ form in the acidic gastric environment. The -NH3+ can bind with negatively charged fats or bile acids through electrostatic interactions, further reducing fat absorption and utilization by the body. This hypothesis has been confirmed in both in vitro and in vivo experiments [35-36]; however, Sugano et al. [2] inferred from the observation that neutral steroid excretion increased while acidic steroid excretion remained unchanged in experimental rats that electrostatic interaction may not be the primary mechanism of chitosan' s lipid-lowering action.

2.1.3 Encapsulation

In acidic gastric fluid, chitosan can exist in water-soluble form and mix with lipid substances to create an emulsion. Upon entering the small intestine, the emulsion aggregates and precipitates in the alkaline environment, hindering contact between fat droplets and lipases in the intestinal tract, reducing decomposition and increasing excretion [3].

2.2.1 Regulation of Serum Hormone Levels

Hormones are important mediators that regulate lipid metabolism. They modulate lipid metabolism by regulating the expression of lipid metabolism-related genes or phosphorylation of key enzymes at the molecular or protein level through receptor-mediated pathways or by interfering with other hormone signaling pathways [37]. In poultry lipid metabolism research, insulin, leptin, and adiponectin have been relatively well studied. Insulin can influence the rate of fat decomposition by regulating hormone-sensitive lipase activity; leptin controls poultry feed intake by binding to leptin receptors on hypothalamic neurons, stimulating the brain to release satiety signals [38]; adiponectin regulates lipid metabolism by improving insulin sensitivity [39]. Liu Zhiyou [28] found that 250–500 mg/kg of chitosan decreased serum leptin and increased insulin content in breeding hens, while doses of 1,000–2,000 mg/kg produced opposite effects, which aligns with experimental results showing that low-dose chitosan promotes while high-dose chitosan inhibits hepatic fatty acid synthesis. Miao Zhiguo et al. [40] reported that 0.10% and 0.20% chitosan increased insulin content in experimental chicken serum by 4.30% and 6.45%, respectively, leading them to conclude that chitosan influences animal growth and lipid metabolism by regulating blood insulin secretion.

2.2.2 Regulation of Digestive Tract Lipase Activity

Several studies have found that chitosan can inhibit dietary fat digestion and absorption in the digestive tract by regulating lipase activity in the gastrointestinal tract of poultry, thereby achieving lipid-lowering effects. Khambualai et al. [41] discovered that dietary supplementation with 0.5% chitosan reduced small intestinal lipase activity in broilers, decreased fat absorption, and lowered body fat deposition. Li Zongnan [8] showed that dietary addition of 250–2,000 mg/kg chitosan caused a linear decrease in jejunal lipase and a significant quadratic curve reduction in ileal lipase in broilers on days 28 and 56 of the experiment. Li Qiuping [6] found that chitosan of different molecular weights could all reduce pancreatic lipase activity in Qilin chickens.

2.2.3 Regulation of Key Lipid Metabolism Enzyme Activity and Gene Expression

In poultry, the liver plays a decisive role in fatty acid synthesis, producing 85% of all fatty acids. Acetyl-CoA carboxylase (ACC) in the liver is the first rate-limiting enzyme in fatty acid synthesis, catalyzing the synthesis of malonyl-CoA from acetyl-CoA, adenosine triphosphate, and carbon dioxide. Fatty acid synthase (FAS) catalyzes the de novo synthesis of fatty acids from malonyl-CoA and acetyl-CoA. Studies in rats have shown that after being degraded by digestive enzymes, chitosan primarily enters the blood, liver, kidneys, and adipose tissue, regulating lipid metabolism by affecting the activity of key lipid metabolism enzymes and the expression of key genes [3]. In poultry research, Li Qiuping [6] and Jiang Guoliang et al. [15] found that chitosan did not affect hepatic FAS activity in broilers. Liu Zhiyou [28] further confirmed this finding, showing that dietary supplementation with 250–2,000 mg/kg chitosan had no significant effect on hepatic FAS activity or its mRNA expression in breeding hens. However, he also noted that 250–500 mg/kg chitosan enhanced hepatic ACC activity in breeding hens on day 28, suggesting that the regulatory mechanisms of chitosan on lipid metabolism in poultry differ from those in rats and warrant further poultry-specific investigation.

Lipoprotein lipase (LPL) and hepatic lipase (HL) catalyze lipoprotein degradation and play important roles in TG metabolism. Jiang Guoliang et al. [15] showed that dietary chitosan supplementation increased LPL activity in adipose tissue of experimental chickens. Li et al. [24] found that medium and low molecular weight chitosan (5 and 2 ku) significantly increased hepatic LPL and HL activities in Qilin chickens, implying that chitosan may regulate lipid metabolism in broilers by enhancing body fat decomposition. However, Liu Zhiyou [28] reported that 250–500 mg/kg chitosan inhibited hormone-sensitive lipase (HSL) activity in abdominal fat and blood LPL activity, while these activities showed an upward trend with increasing supplementation levels. This indicates that the effects of chitosan on lipase activity vary depending on chitosan properties, supplementation levels, and research subjects.

Peroxisome proliferator-activated receptors (PPARs) are important transcription factors in lipid metabolism, closely associated with various diseases including lipid metabolism disorders, obesity, and diabetes. Evidence shows that chitosan can upregulate the gene and protein expression of hepatic PPARα in experimental animals, enhancing fatty acid β-oxidation and reducing body fat deposition [42]. In studies with breeding hens, Liu Zhiyou [28] found that 250–500 mg/kg of chitosan promoted hepatic PPARγ protein expression, though this promoting effect weakened with increasing dosage.

2.3 Other Mechanisms

Studies have shown that chitosan can reduce malondialdehyde content in serum and liver, suggesting that chitosan may regulate lipid metabolism by modulating lipid peroxidation levels in the body [43].

3 Summary

Lipid metabolism is a complex, multi-factorial, and multi-pathway process influenced by numerous factors. In summary, chitosan can reduce abdominal fat deposition and achieve fat redistribution in poultry products by affecting lipase and lipid metabolism enzyme activities, inhibiting the expression of key lipid metabolism genes, reducing fat absorption and utilization, and lowering blood lipid levels. Moreover, low molecular weight chitosan (<50 ku) tends to exert its lipid-lowering effects through physiological and biochemical mechanisms, whereas high molecular weight chitosan tends to act through physical mechanisms.

References:

[1] GEORGE Z K, DIMITROS N B. Recent modifications of chitosan for adsorption applications: a critical and systematic review[J]. Marine Drugs, 2015, 13(1): 312–337.

[2] SUGANO M, FUJIKAWA T, HIRATSUJI Y, et al. Hypocholesterolemic effects of chitosan in cholesterol fed rats[J]. Nutrition Reports International, 1978, 18(5): 531–537.

[3] LIU Jingna. Study on the Mechanism of Chitosan' s Lipid-Lowering Effects[D]. PhD Dissertation. Wuxi: Jiangnan University, 2008.

[4] HUANG Guidong. Study on the Lipid-Lowering Activity and Mechanism of Chitosan and Related Products[D]. Master' s Thesis. Guangzhou: Guangdong Pharmaceutical University, 2015.

[5] RAZDAN A, PETTERSSON D. Effect of chitin and chitosan on nutrient digestibility and plasma lipid concentrations in broiler chickens[J]. British Journal of Nutrition, 1994, 72(2): 277–288.

[6] LI Qiuping. Effects of Different Molecular Weight Chitosan on Lipid Metabolism in Qilin Chickens and Its Mechanism[D]. Master' s Thesis. Zhanjiang: Guangdong Ocean University, 2015.

[7] WANG Runlian, CHANG Bin, DU Bingwang, et al. Effects of Chitosan on Growth Performance, Nutrient Metabolism, and Blood Biochemical Indices in Broiler Geese[J]. China Herbivore Science, 2008, 28(2): 25–27.

[8] LI Zongnan. Effects of Chitosan on Nutrient Metabolism and Intestinal Related Indices in Breeding Hens[D]. Master' s Thesis. Hohhot: Inner Mongolia Agricultural University, 2016.

[9] SHENG Dongfeng, ZHU Zixue, WU Anquan. Study on the Effects of Dietary Nutrients on Abdominal Fat Deposition in Waterfowl[J]. Chinese Journal of Animal Nutrition, 2016, 28(2): 312–318.

[10] MA Xiaozhen, YANG Ye, XIE Xindong, et al. Effects of Chitosan on Growth Performance and Lipid Metabolism in Broiler Chickens (Roosters)[J]. Journal of Fujian Agricultural University, 2001, 16(4): 30–34.

[11] LIU Haiying, YU Miao, YANG Guiqin. Effects of Chitosan on Growth Performance and Lipid Metabolism in Broiler Chickens[J]. Feed Review, 2003(5): 1–4.

[12] HUANG Guanqing, HUANG Xiaoliang, WANG Runlian. Effects of Chitosan on Fat Deposition in Yellow-Feathered Broiler Chickens[J]. Feed Research, 2007(2): 5–7.

[13] HU Zhongze, YUE Yijia, QIU Wei. Effects of Chitosan on Meat Quality of Huainan Partridge Chickens[J]. Feed Research, 2013(12): 57–59, 79.

[14] LÜ Danna. Study on the Application of Chitosan with Different Degrees of Deacetylation in Broiler Chicken Feed[D]. Master' s Thesis. Harbin: Northeast Agricultural University, 2015.

[15] JIANG Guoliang, PAN Wen, WANG Runlian, et al. Effects of Chitosan with Different Degrees of Deacetylation on Growth, Carcass Performance, and Lipid Metabolism in Broiler Chickens[J]. Guangdong Agricultural Sciences, 2014, 41(14): 106–109.

[16] ZHAO Ping. Effects of Different Levels of Chitosan on Growth Performance and Fat Deposition in Tianshan Snow Geese[J]. Rural Science and Technology, 2011(5): 61–62.

[17] MA Jianshuang, CHANG Wenhuan, ZHANG Shu, et al. Effects of Betaine on Growth Performance, Lipid Metabolism, and Muscle Flavor Quality in Broiler Chickens[J]. Chinese Journal of Animal Nutrition, 2015, 27(1): 185–195.

[18] YANG Zhengping, LIU Fuzhu, DENG Xingzhao, et al. Effects of Chitosan on Growth Performance and Serum Biochemical Indices in Broiler Chickens[J]. China Animal Husbandry & Veterinary Medicine, 2007, 43(7): 28–31.

[19] HAN Jie, YU Ning. Effects of Chitosan on Growth Performance and Lipid Metabolism in Broiler Chickens[J]. Cereal & Feed Industry, 2007(2): 31–32.

[20] ZHAO Ying, QIAO Lihong, WU Dawei, et al. Effects of Chitosan Oligosaccharide on Lipid Metabolism and Egg Quality in Laying Hens[J]. Cereal & Feed Industry, 2013, 12(1): 45–48.

[21] LI Zhongrong, FENG Yulan. Effects of Chitosan on Fat Deposition in Hetian Chickens[J]. Chinese Journal of Animal Science, 2010, 46(3): 39–41.

[22] LIU Mei. Effects of Chitosan on Growth Performance and Immune Organ Indices in Broiler Chickens[J]. Journal of Zaozhuang University, 2010, 27(2): 117–120.

[23] ZHENG Xiaoling, HUANG Guanqing, LIU You, et al. Effects of Chitosan on Early Growth Performance and Lipid Metabolism in Yellow-Feathered Broiler Chickens[J]. Feed Wide Angle, 2007(5): 27–28, 30.

[24] LI Q P, GOONERATNE S R, WANG R L, et al. Effect of different molecular weight of chitosans on performance and lipid metabolism in chicken[J]. Animal Feed Science and Technology, 2016, 211: 174–180.

[25] NOGUEIRA C M, ZAPATA J F F, FUENTES M F F, et al. The effect of supplementing layer diets with shark cartilage or chitosan on egg components and yolk lipids[J]. British Poultry Science, 2003, 44(2): 218–223.

[26] ŚWIATKIEWICZ S, ARCZEWSKA-WŁOSEK A, KRAWCZYK J, et al. Effects of selected feed additives on the performance of laying hens given a diet rich in maize dried distiller' s grains with solubles (DDGS)[J]. British Poultry Science, 2013, 54(4): 475–485.

[27] WANG Dun, XU Yingnan, ZHAI Shaowei. Effects of Insect-Derived Chitosan on Production Performance and Egg Quality in Laying Hens[J]. China Poultry, 2004, 26(17): 7-9.

[28] LIU Zhiyou. Effects of Dietary Chitosan Supplementation on Lipid Metabolism in Breeding Hens and Its Mechanism[D]. PhD Dissertation. Hohhot: Inner Mongolia Agricultural University, 2016.

[29] DU Bingwang, WANG Runlian, CHANG Bin, et al. Effects of Chitosan on Meat Quality of Guifei Chickens[J]. Chinese Journal of Animal Nutrition, 2009, 21(1): 113-117.

[30] ZHOU T X, CHEN Y J, YOO J S, et al. Effects of chitooligosaccharide supplementation on performance, blood characteristics, relative organ weight and meat quality in broiler chickens[J]. Poultry Science, 2009, 88(3): 593-600.

[31] WANG Shubai, WANG Baowei, ZHANG Liying, et al. Study on the Effects of a New Additive–Chitosan on Cholesterol in Broiler Chicken Muscle[J]. Feed Research, 1998(5): 9-10.

[32] WANG Yunxia. Study on the Effects of Low Chitosan on Growth Performance and Meat Quality in Broiler Chickens[J]. Feed Wide Angle, 2012(15): 34-35, 38.

[33] CHANG Bin, WANG Runlian, HUANG Xiaoliang, et al. Effects of Chitosan on Slaughter Performance and Meat Quality in Meat Geese[J]. China Herbivore Science, 2008, 28(3): 23-25.

[34] XIA Dangrong, ZHAO Jie. Effects of Chitosan on Slaughter Performance and Meat Quality in Tianshan Snow Geese[J]. China Feed, 2010(17): 22-24.

[35] HELGASON T, GISLASON J, CLEMENTS D, et al. Influence of molecular character of chitosan on the adsorption of chitosan to oil droplet interfaces in an in vitro digestion model[J]. Food Hydrocolloids, 2009, 23(8): 2243-2253.

[36] DIMZON I K D, EBERT J, KNEPPER T P. The interaction of chitosan and olive oil: Effects on polymerization[J]. Carbohydrate Polymers, 2013, 92(1): 564-570.

[37] HUANG Jianzhen. Screening of Key Factors in Hepatic Lipid Metabolism in Broiler Chickens During Embryonic Period and Regulation by DHEA[D]. PhD Dissertation. Nanjing: Nanjing Agricultural University, 2008.

[38] BALOGH O, STAUB L P, GRAM A, et al. Leptin in the canine uterus and placenta: Possible implications in pregnancy[J]. Reproductive Biology and Endocrinology, 2015, 13(1): 13.

[39] LIM S, QUON M J, KOH K K. Modulation of adiponectin as a potential therapeutic strategy[J]. Atherosclerosis, 2014, 233(2): 721-728.

[40] MIAO Zhiguo, LI Guowang, XIE Hongbing, et al. Effects of Chitosan on Immune Function in Huoyan Geese[J]. China Feed, 2011(12): 70-71.

[41] KHAMBUALAI O, YAMAUCHI K E, TANGTAWEEWIPAT S, et al. Effects of dietary chitosan diets on growth performance in broiler chickens[J]. The Journal of Poultry Science, 2008, 45(3): 206–209.

[42] PAN H T, YANG Q Y, HUANG G D, et al. Hypolipidemic effects of chitosan and its derivatives in hyperlipidemic rats induced by a high-fat diet[J]. Food & Nutrition Research, 2016, 60: 31137.

[43] ZHAO Qilong. Effects of Chitosan on Laying Performance, Immune and Antioxidant Functions, and Related Serum Biochemical Indices in Breeding Hens[D]. Master' s Thesis. Hohhot: Inner Mongolia Agricultural University, 2015.

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