Physiological Functions of Curcumin and Its Applications in Livestock and Poultry Production (Postprint)

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Abstract

Curcumin is a yellow pigment extracted from turmeric rhizomes that exhibits antioxidant, anti-inflammatory, and lipid-lowering effects. As a natural feed additive, it holds promising application prospects in livestock production, demonstrating efficacy in improving production performance of livestock and poultry, enhancing product quality, and boosting immune function. This article elaborates on the physiological functions and mechanisms of action of curcumin, and synthesizes the latest research findings from scholars worldwide regarding its application in livestock and poultry production, with the aim of providing a reference for its optimized utilization in animal husbandry.

Full Text

Physiological Functions of Curcumin and Its Application in Livestock and Poultry Production

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Abstract

Curcumin is a yellow pigment extracted from turmeric rhizomes that exhibits antioxidant, anti-inflammatory, and lipid-lowering properties. As a natural feed additive, curcumin holds promising application prospects in animal production, with demonstrated benefits for improving livestock performance, product quality, and immune function. This paper elucidates the physiological functions and mechanisms of curcumin and reviews recent research findings on its application in livestock and poultry production, providing a reference for its optimal utilization.

Keywords: curcumin; plant extracts; physiological function; mechanism; livestock and poultry production; application

Introduction

Curcumin is the active component of turmeric and, as a plant extract, is widely present in the rhizomes of perennial plants in the Zingiberaceae family, such as *Curcuma longa*, *Curcuma zedoaria*, and *Curcuma aromatica* [1]. The curcumin content varies significantly across different geographic origins, typically ranging from 2% to 9% [2]. First discovered in 1815 and chemically characterized in 1910 [3], curcumin research over the past decades has primarily focused on pharmaceutical applications including antioxidant, anti-inflammatory, lipid-lowering, and cancer chemopreventive properties [4]. However, according to Web of Science analysis, only 2.75% of curcumin publications (15,462 total articles) fall under animal science research, indicating that studies on curcumin in livestock production remain in their infancy.

With growing awareness of environmental protection and food safety, coupled with increasing concerns over antibiotic misuse, curcumin has emerged as a promising green plant-derived additive due to its natural origin, lack of residues, and physiological functions such as antioxidant and anti-inflammatory activities. Nevertheless, its widespread adoption remains limited, primarily because optimal dosage levels and mechanisms of action across different livestock species are not yet clearly defined. Therefore, this review aims to summarize recent domestic and international research on curcumin, consolidating its physiological functions and application effects in livestock production to provide a theoretical foundation for its development and utilization.

1. Physicochemical Properties of Curcumin

Curcumin (molecular formula $C_{21}H_{20}O_6$) is a crystalline orange-yellow powder with a melting point of 183°C. It is extremely insoluble in water but readily soluble in organic solvents, remaining stable in acidic and neutral environments while being highly unstable under alkaline conditions [5]. Chemically, curcumin contains an α,β-unsaturated β-diketone moiety, with phenolic hydroxyl and methoxy groups on its two benzene rings [6].

2. Physiological Functions

2.1 Antioxidant Effects

Free radicals are highly oxidative species generated during metabolic processes that regulate cell growth and other physiological functions, but excessive accumulation causes cellular damage. Various antioxidant feed additives have been developed to scavenge these radicals, with curcumin gaining widespread attention as a natural antioxidant.

2.1.1 Mechanism of Curcumin' s Intrinsic Antioxidant Activity in Inhibiting Lipid Peroxidation Research demonstrates that curcumin possesses potent antioxidant activity derived from its molecular structure. The phenolic groups can capture free radicals to form highly stable quinone compounds [7]. Additionally, Osawa et al. [8] and Sugiyama et al. [9] reported that after intestinal absorption, curcumin undergoes hydrogenation in cells to generate tetrahydrocurcumin, a strong antioxidant that degrades into 2' -methoxypropionic acid—another antioxidant-active substance capable of further radical binding, thereby exhibiting dual antioxidant functions. However, the identification of curcumin' s core antioxidant functional groups remains controversial: Jovanovic et al. [10] identified the β-diketone unit as essential; Priyadarsini et al. [6] emphasized phenolic hydroxyl groups with methoxy groups providing synergistic effects; while Miriyala et al. [11] attributed activity to the combination of phenolic and methoxy groups with the 1,3-diketone conjugated diene system.

Studies using the oxidative stress model induced by 2,2' -azobis(2-methylpropionamidine)dihydrochloride (AAPH) show that curcumin supplementation inhibits hemolysis and apoptosis in both human [12] and chicken erythrocytes [13]. This effect likely stems from curcumin' s lipophilicity, enabling it to integrate into cell membranes, scavenge radicals, and inhibit radical-mediated lipid peroxidation, thereby protecting membrane structures. Research also indicates that curcumin significantly alleviates mitochondrial swelling in breast muscle of broilers under chronic heat stress [14]. Mitochondria generate substantial reactive oxygen species (ROS) during metabolism [15], making them primary targets of radical damage, which primarily affects DNA and unsaturated fatty acids in membrane structures [16]. In a cisplatin-induced oxidative damage rat model, Waseem et al. [17] found that curcumin significantly reduced mitochondrial lipid peroxidation and protein carbonyl content, mitigating stress damage. Trujillo et al. [18] similarly observed that curcumin ameliorated oxidative stress-induced fibrosis and reductions in renal tight junction proteins. Furthermore, Dorta et al. [19] discovered that natural flavonoids specifically accumulate in mitochondria after absorption, exerting protective effects. It can thus be inferred that curcumin protects against oxidative damage by scavenging mitochondrial radicals and inhibiting lipid peroxidation.

2.1.2 Activation of the Nrf2-ARE Antioxidant Signaling Pathway The antioxidant response element (ARE) is a critical regulatory component for generating antioxidant proteins in response to ROS damage, activated by nuclear factor erythroid 2-related factor 2 (Nrf2) [20]. Under normal physiological conditions, Nrf2 resides in the cytoplasm and undergoes degradation; during oxidative stress, Nrf2 undergoes conformational changes, translocates to the nucleus, binds to ARE, and activates the expression of antioxidant enzyme genes and phase II detoxification enzymes, enhancing antioxidant capacity [21]. Studies show that in arsenic-induced oxidative damage, curcumin upregulates hepatic expression of Nrf2 downstream genes quinone oxidoreductase (NQO1) and heme oxygenase-1 (HO-1), thereby alleviating oxidative damage [22]. Sahin et al. [23] also found that curcumin mitigated heat stress damage in quail via Nrf2/HO-1 pathway modulation. Additionally, curcumin supplementation significantly increases intracellular glutathione (GSH) content during oxidative stress [24]. Nrf2 knockout mouse studies demonstrate that Nrf2 deficiency reduces hepatic GSH levels [25], suggesting that curcumin' s GSH-enhancing effect may involve Nrf2 pathway activation. Moreover, Zheng et al. [26] reported that curcumin directly induces upregulation of GCL (glutamate-cysteine ligase), the rate-limiting enzyme in GSH synthesis, promoting GSH production and antioxidant capacity. However, some researchers argue that curcumin may not be an absolute antioxidant, as in vitro studies show ROS levels increase significantly when curcumin concentrations rise from 1 µmol/L to 25 µmol/L, possibly due to activation of ROS-producing mitochondrial enzymes [27].

In summary, curcumin exerts antioxidant effects through two primary pathways: first, through its intrinsic structural antioxidant properties, and second, as an inducer that promotes expression of antioxidant signaling pathway genes, stimulating production of antioxidant proteins and enzymes to enhance overall antioxidant capacity.

2.2 Anti-inflammatory Effects

Cyclooxygenase (COX) and lipoxygenase (LOX) catalyze arachidonic acid to form various prostaglandins and other inflammatory mediators, triggering inflammatory responses. Curcumin antagonizes both COX and LOX, limiting inflammatory mediator production and achieving anti-inflammatory effects [28]. Additionally, nitric oxide (NO) is a crucial inflammatory signaling molecule, and curcumin inhibits inducible nitric oxide synthase activity in the conversion of L-arginine to NO [29]. The nuclear factor kappa B (NF- B) signaling pathway is another key inflammatory pathway; excessive inflammatory mediators activate NF- B, causing its dissociation from inhibitor B (I B), nuclear translocation, and activation of inflammatory mediator gene expression, exacerbating inflammation [30]. Tumor necrosis factor-alpha (TNF-α) is a major inflammatory mediator that activates NF- B. Peng et al. [31] reported that curcumin pretreatment of Kupffer cells significantly reduced lipopolysaccharide (LPS)-induced interleukin-1β (IL-1β) and IL-6 levels while markedly suppressing TNF-α protein expression. Reuter et al. [32] similarly found that curcumin inhibits numerous TNF-α activation pathways in cells.

In conclusion, curcumin' s anti-inflammatory mechanisms focus on two aspects: first, inhibiting enzymes that produce inflammatory mediators to reduce their generation, and second, suppressing inflammatory factors such as TNF-α to prevent NF- B pathway activation, thereby decreasing inflammatory factor expression.

2.3 Lipid-Lowering Effects

Since 1971, research has demonstrated curcumin’ s lipid-lowering properties [33]. Subsequent studies showed that 18 weeks of curcumin treatment in mice fed high-cholesterol diets reduced plasma cholesterol, triglycerides, low-density lipoprotein, and apolipoprotein B while increasing high-density lipoprotein and hepatic apolipoprotein A expression [34]. In male C57BL/6 mice fed a high-fat diet (22% fat, 500 mg/kg) for 12 weeks, curcumin inhibited weight gain, an effect attributed to activation of AMPK (adenosine monophosphate-activated protein kinase), the master regulator of energy metabolism and fatty acid β-oxidation in adipocytes. In vitro studies also show that curcumin activates carnitine palmitoyltransferase 1 (CPT-1) to promote β-oxidation while inhibiting lipid biosynthetic enzymes such as glycerol-3-phosphate acyltransferase 1 (GPAT1) and acetyl-CoA carboxylase [35].

2.4 Antimicrobial and Antiparasitic Effects

Since 1949, research has demonstrated curcumin’ s antibacterial activity against *Staphylococcus aureus*, *Trichophyton*, *Salmonella paratyphi*, and *Mycobacterium tuberculosis* [36]. In vitro studies show that 100 µmol/L curcumin reduces *Escherichia coli* by 80% [37], while Lüer et al. [38] reported 100% lethality in *S. aureus* and *Pseudomonas aeruginosa* exposed to 100 µmol/L curcumin, and 80% lethality in *Enterococcus faecalis* treated with 200 µmol/L curcumin for 4 hours. These findings indicate curcumin’ s inhibitory effects on both Gram-positive (*S. aureus*, *E. faecalis*) and Gram-negative (*E. coli*, *P. aeruginosa*) bacteria. Tyagi et al. [39] observed complete killing of *S. aureus* at 10^6 CFU/mL within 2 hours of exposure to 100 µmol/L curcumin, with propidium iodide and calcein fluorescence probes revealing membrane disruption in 94–98% of bacterial cells, demonstrating that curcumin’ s antibacterial mechanism involves bacterial membrane structure destruction.

Bazh et al. [40] also identified anthelmintic activity in curcumin, with efficacy dependent on concentration and exposure time. Khalafalla et al. [41] reported that curcumin reduced *Eimeria tenella* sporozoite infectivity by 41.6% and 72.8% at concentrations of 100 and 200 µmol/L, respectively, without adverse effects on infected cells at doses below 400 µmol/L, suggesting its potential as an antiparasitic agent.

3. Applications in Livestock and Poultry Production

3.1 Application in Poultry Production

Curcumin improves poultry performance and immune function. Studies show that dietary supplementation with 200 and 250 mg/kg curcumin increased broiler weight gain by 4.48% and 1.59% while reducing feed conversion ratio by 7.39% and 6.40%, respectively [42], with the 200 mg/kg dose showing highly significant effects [43]. Platel et al. [44] reported enhanced pancreatic enzyme activity in rats fed 5 g/kg curcumin, suggesting that curcumin may improve broiler growth performance by stimulating intestinal digestive enzyme production or activity, thereby enhancing feed digestibility. Additionally, NO, a key inhibitory neurotransmitter in the intestine that suppresses gastrointestinal motility [45,46], may be reduced through curcumin's inhibition of enzymes involved in L-arginine conversion to NO, thereby promoting gastrointestinal peristalsis and feed intake. Zhang et al. [14] also found that curcumin alleviates stress-induced production losses, indicating that stress mitigation may be another important mechanism for performance improvement.

Curcumin supplementation significantly increases thymus index [47], spleen index [48], antibody levels [47], and total protein concentrations [48] in broilers. The enhanced immune organ indices reflect improved immune organ development, likely mediated by increased total protein levels that enhance protein absorption and utilization, providing conditions for healthy immune organ growth. Elevated antibody levels are associated with curcumin' s promotion of thymus development and T lymphocyte differentiation, which enhances T cell stimulation of B lymphocyte antibody production.

Furthermore, curcumin improves meat color, shelf life [49,50], and muscle nutritional value [42,51]. These effects relate to curcumin' s potent antioxidant activity. Myoglobin, the primary protein regulating meat color in poultry, can cause discoloration upon oxidation [52], while high concentrations of polyunsaturated fatty acids in muscle are vulnerable to radical attack, initiating lipid peroxidation that accumulates oxidative products and compromises meat quality and nutritional content [53]. Curcumin' s strong antioxidant properties prevent excessive myoglobin oxidation and retard oxidative necrosis of muscle cells in fresh meat, while its regulatory effects on lipid metabolism and deposition improve chicken meat nutritional value.

3.2 Application in Pig Production

Dietary curcumin supplementation improves feed digestibility [54] and growth performance in pigs [55], with effects significantly surpassing those of quinolone [56,57]. The mechanism likely involves intestinal regulation; Xun et al. [56] demonstrated that curcumin increased ileal villus height-to-crypt depth ratio and improved ileal epithelial morphology in ETEC-challenged piglets, repairing intestinal damage caused by *E. coli.* This intestinal protection provides the foundation for enhanced nutrient digestion, absorption, and performance. Additionally, curcumin' s antimicrobial, antiparasitic, and stress-reducing functions may contribute to improved pig performance.

Curcumin also modulates pork quality [58]. Zhu et al. [58] found that dietary supplementation with 300 and 400 mg/kg curcumin significantly increased lean percentage and muscle pH while reducing backfat thickness and drip loss, thereby improving post-slaughter shelf life and meat quality. The regulation of lean percentage and backfat thickness may occur through activation of glutathione peroxidase, which inhibits the oxidative pentose phosphate pathway and affects lipid synthesis, or through curcumin' s lipid-lowering function that promotes lipid metabolism and excretion. Muscle pH affects protein charge; post-slaughter pH decline to the isoelectric point causes protein coagulation and contraction, generating free water and drip loss. Therefore, curcumin' s ability to elevate muscle pH reduces drip loss while its antioxidant properties maintain meat freshness.

3.3 Application in Ruminants

Research in ruminants is limited, focusing primarily on improving semen quality and preservation in breeding animals. Studies show that curcumin addition during semen storage significantly enhances sperm antioxidant capacity before freezing and after thawing [59], while improving mitochondrial activity and sperm motility to ensure semen quality [60]. Sperm contain high concentrations of unsaturated fatty acids that are susceptible to radical damage [61]; curcumin likely utilizes its lipophilicity to penetrate sperm cells, scavenge excess radicals generated during freeze-thaw cycles, and protect mitochondrial and sperm membrane structures.

Conclusion

Curcumin possesses important physiological functions and, as a feed additive, can improve livestock performance and product quality. However, research on its application in animal production remains limited, with relatively narrow species coverage and unclear mechanisms. Current global trends toward "antibiotic-free farming" to address safety issues from antibiotic misuse urgently require further investigation into optimal curcumin dosage levels for various livestock species, its effects on different breeds, and its regulatory mechanisms to establish a theoretical foundation for curcumin application in animal production.

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