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The Influence of Black Cumin Seed (*Nigella sativa*) Supplementation on Growth Performance, Carcass Characteristics, and Meat Quality in Poultry: A Comprehensive Review

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Abstract

Over the last decade, there has been a surge of interest in natural feed additives as sustainable alternatives to antibiotics in poultry nutrition. The global restriction on the use of antibiotic growth promoters (AGPs) in animal nutrition has accelerated the search for safe, effective natural alternatives. Among various phytogenic additives, *Nigella sativa* (black cumin) has emerged as a promising alternate owing to its diverse pharmacologically active compounds, including thymoquinone, dithymoquinone, thymol, carvacrol, nigellicine, and nigellidine. These bioactive constituents exhibit a broad spectrum of biological activities, such as antibacterial, antioxidant, anti-inflammatory, immunomodulatory, hepatoprotective, and digestive-enhancing effects. In poultry, dietary supplementation with *Nigella sativa* seeds has demonstrated considerable improvements in growth performance, feed conversion ratio, carcass yield, and meat quality, as well as enhanced immune responses and intestinal health. It effectively reduces intestinal pH and pathogenic load while promoting beneficial gut microbiota. In layer birds, supplementation is associated with enhanced egg quality and improved overall health status. Beyond productivity metrics, the antioxidant properties of black cumin contribute to better meat preservation and shelf-life by reducing oxidative spoilage. Its antimicrobial activity against both Gram-positive and Gram-negative bacteria highlights its potential as a natural substitute for synthetic antibiotics and preservatives. Optimal inclusion levels ranging from 1–2% have been shown to yield beneficial outcomes without adverse effects. This review consolidates current findings on the efficacy of *Nigella sativa* in poultry diets, emphasizing its role in promoting growth, improving meat and egg quality, and supporting sustainable poultry production. Future research should aim to standardize inclusion levels, investigate synergistic effects with other natural additives like probiotics, and evaluate its long-term effects under diverse management systems.

Key Words: *Nigella sativa, black cumin, poultry nutrition, growth performance, meat quality, natural antioxidants, gut health, feed efficiency, sustainability*

Introduction

Text The global poultry industry serves as a vital source of high-quality animal protein, facing increasing demands as world population growth necessitates 60% greater food production by 2050 (Asghar et al., 2021; Akram et al., 2019; Al-Beitawi et al., 2008; Hanboonsong et al., 2013). This protein crisis has led to concerning practices, including the widespread use of synthetic chemicals and antibiotics as growth promoters in poultry production (Asghar et al., 2022; Akram et al., 2021; Güler and Dalkiliç, 2009; Miles et al., 2006; Naımatı et al., 2022). While these substances effectively control pathogenic microorganisms like Salmonella, Escherichia coli, and Enterococci, their routine use has led to alarming consequences including antibiotic resistance and tissue residues in animal products (Schwarz et al., 2001; Sierżant et al., 2023; Tauseef et al., 2017).

In recent years, the poultry industry has witnessed growing interest in phytogenic feed additives, driven by consumer demand for natural and residue-free animal products. Among these, *Nigella sativa* (black cumin) has emerged as particularly noteworthy due to its rich phytochemical composition and multifaceted therapeutic properties. With a history of traditional use in herbal medicine, this remarkable botanical has demonstrated antioxidant, antimicrobial, immunomodulatory, and growth-promoting characteristics that position it as an ideal candidate for sustainable poultry nutrition (Asghar et al., 2022)

The European Union's 2006 ban on antibiotic growth promoters Toghyani et al., (2010) has accelerated research into natural alternatives, particularly following evidence linking antibiotic residues in meat and eggs to human health risks (Rahmatnejad et al., 2009; Issa et al., 2012). This regulatory shift has forced the industry to reconcile production efficiency with evolving consumer preferences for food products containing beneficial bioactive compounds (Asghar et al., 2024; Cofrades et al., 2008; Sajid et al., 2023; Jia et al., 2021). Modern consumers increasingly prioritize not only food safety but also nutritional quality seeking products with natural antioxidants,

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optimal fatty acid profiles, and reduced chemical additives (Hygreeva et al., 2014; Pisulewski et al., 2005; Capitani et al., 2013; Decker et al., 2010).

Scientific investigations have consequently focused on various natural alternatives including essential oils, phytobiotics, and medicinal plants (Elgayyar et al., 2001; Valero et al., 2003; Jamroz et al., 2002; Jang et al., 2004; Ramakrishna et al., 2003). These substances offer the dual advantage of antimicrobial activity without promoting resistance while potentially enhancing digestive function (Jamroz et al., 2002; Jang et al., 2004; Ramakrishna et al., 2003). The search for effective alternatives has gained urgency as dietary patterns shift toward healthier options that may reduce risks of cardiovascular disease, cancer, and obesity (Hygreeva et al., 2014; Pisulewski et al., 2005; Capitani et al., 2013; Decker et al., 2010).

Nigella sativa distinguishes itself among phytogenic options through its exceptional nutritional profile, containing high-quality proteins, essential amino acids, vital minerals (calcium, potassium, phosphorus, magnesium) El-Ghorab et al. (2003); Sultan et al. (2009), and an impressive array of bioactive compounds including thymoquinone, carvacrol, and thymol (Nasir, 2005). These components confer numerous benefits including antimicrobial activity (Oroojalian et al., 2010), antioxidant capacity (Attia et al., 2019; Baghban-Kanani et al., 2019; Khoobani et al., 2019), gastrointestinal protection (Jamroz et al., 2002), and growth promotion potential (Al-Beitawi et al., 2009).

The essential oil fraction of black cumin contains at least 18 bioactive compounds, predominantly carvone (66%) and limonene (50%), along with gamma-terpinene, cuminaldehyde, and various flavonoids (Jalilzadeh-Amin et al., 2011; Moghtader et al., 2009; Yalçın et al., 2009)[27-29]. These compounds exhibit diverse pharmacological activities including antimicrobial (Oroojalian et al., 2010), anti-inflammatory (Hajhashemi et al., 2011), and muscle relaxant effects (Jalilzadeh-Amin et al., 2011), making *Nigella sativa* a comprehensive natural solution for poultry production challenges.

This review systematically evaluates current knowledge regarding *Nigella sativa* supplementation in poultry nutrition, with particular emphasis on its effects on growth performance, carcass characteristics, and meat quality parameters in broiler chickens and laying hens. By synthesizing existing research, we aim to clarify the mechanisms of action, optimal inclusion levels, and practical applications of this promising phytogenic additive in modern poultry production systems.

Phytochemical Composition of *Nigella sativa*

Nigella sativa, commonly known as black cumin, is a flowering plant of the Ranunculaceae family that has garnered considerable scientific attention due to its complex and potent phytochemical profile. The seeds of N. sativa contain a wide array of biologically active compounds that contribute to its therapeutic efficacy and functional role as a phytogenic feed additive in poultry nutrition. The most significant constituent of N. sativa seeds is thymoquinone (TQ), a monoterpene compound that accounts for the majority of its pharmacological activity. Thymoquinone exhibits strong antioxidant, antimicrobial, anti-inflammatory, anticancer, and immunomodulatory effects, making it a key contributor to the plant's functional applications (Nasir, 2005; Attia et al., 2019; Baghban-Kanani et al., 2019; Khoobani et al., 2019). In addition to thymoquinone, other notable constituents include dithymoquinone, thymohydroquinone, thymol, carvacrol, nigellidine, nigellicine, and α-hederin, all of which have demonstrated bioactivity in both in vitro and in vivo studies (Al-Beitawi et al., 2009; Jalilzadeh-Amin et al., 2011; Moghtader et al., 2009). The essential oil content of N. sativa seeds ranges from 0.4% to 2.5%, and its composition varies depending on geographical origin, cultivation conditions, and extraction methods. Major volatile compounds include carvone (up to 66%), limonene (approximately 50%), p-cymene, γ-terpinene, trans-anethole, cuminaldehyde, and β-pinene, many of which contribute to the plant's antimicrobial, digestive-stimulant, and anti-inflammatory properties (Jalilzadeh-Amin et al., 2011; Moghtader et al., 2009; Yalçın et al., 2009; Oroojalian et al., 2009).

Apart from volatile oils, N. sativa seeds are also a rich source of fixed oils (up to 35–38%), composed primarily of unsaturated fatty acids such as linoleic acid (50–60%), oleic acid (20–30%), and smaller quantities of palmitic and stearic acids (Hajhashemi et al., 2011). These fatty acids contribute to the plant's nutritional value and are beneficial for energy metabolism, lipid regulation, and cellular function in poultry. Additionally, the seeds contain significant amounts of proteins (20–25%), dietary fiber, saponins, alkaloids, and phenolic compounds, including flavonoids and tannins. These molecules play important roles in modulating oxidative stress, enhancing nutrient absorption, and improving gut health (Gilani et al., 2004; Ferdous et al., 1992; ElKamali et al., 1998). Mineral content is also substantial in N. sativa, with appreciable levels of calcium, potassium, magnesium, iron, phosphorus, zinc, and selenium, which are essential for skeletal development, enzyme function, and overall physiological balance in poultry (El-Ghorab et al., 2003; Sultan et al., 2009).

In summary, the phytochemical richness of N. sativa underpins its multifaceted biological activities. The synergistic action of its bioactive compounds supports its efficacy as a natural growth promoter, antimicrobial agent, antioxidant, and immune enhancer, reinforcing its potential as a sustainable alternative to conventional feed additives in poultry nutrition.

Effects of N. sativa on Feed intake and Growth Performance

Numerous studies have demonstrated that dietary supplementation with *Nigella sativa* (commonly referred to as black cumin seed, BCS) positively influences average daily weight gain (ADWG) and overall growth performance in poultry. Research conducted over the past two decades consistently indicates improved body weight parameters across various poultry species and production systems following BCS inclusion in feed (Osman, 2002; El-Bagir et al., 2006; Guler et al., 2006; Durrani et al., 2007; Abu-Dieyeh and Abu-Darwish, 2008; Al-Beitawi et al., 2009; Ashayerizadeh et al., 2009; Erener et al., 2010; Ismail, 2011; Khan et al., 2012; Yatoo et al., 2012; Saleh, 2014; Jahan et al., 2015). For instance, Osman (2002) reported a significant increase in ADWG in broiler chickens supplemented with BCS oil. El-Bagir et al. (2006) found that the inclusion of BCS at levels of 10 or 30 g/kg significantly improved final body weight in laying hens. Guler et al. (2006) observed that broilers fed diets containing both BCS (10 g/kg) and antibiotics achieved the highest ADWG compared to the control. Likewise, Abu-Dieyeh and Abu-Darwish (2008) showed that diets containing 10 and 15 g/kg BCS led to significantly enhanced ADWG over a four-week feeding period. Similar improvements were reported by Erener et al. (2010), Khan et al. (2012), and Yatoo et al. (2012), with the latter highlighting the highest gains in groups receiving 0.5% BCS.

These growth-enhancing effects are potentially linked to improved nutrient digestibility, stimulated bile secretion, and activation of pancreatic enzymes, resulting in more efficient fat digestion and nutrient absorption (Kumar et al., 2017a). Key active components of BCS, including thymoquinone (approx. 60%), carvone, anethole, carvacrol, and 4-terpineol, exert antibacterial and antioxidant actions, while simultaneously stimulating digestive enzyme activity in both intestinal mucosa and pancreas (Abu-Dieyeh and Abu-Darwish, 2008). Additionally, Mandour et al. (1998) suggested that BCS may elevate thyroxine levels, thereby enhancing basal metabolic rate and contributing to growth.

The feed intake response to BCS supplementation, however, remains inconsistent across the literature. Some studies reported a significant increase in average daily feed intake (ADFI) following BCS inclusion (Osman and El-Barody, 1999; Abou-El-Soud, 2000; Erener et al., 2010; Ismail, 2011; Yatoo et al., 2012). For example, Osman and El-Barody (1999) noted increased ADFI with powdered BCS at inclusion levels ranging from 2 to 10 g/kg. Similarly, Yatoo et al. (2012) observed increased feed intake across all growth phases in broilers fed 1% BCS, while Abou-El-Soud (2000) reported the highest ADFI in quail chicks supplemented with 2% whole crushed BCS. In contrast, other investigations documented a decline in ADFI upon BCS supplementation. Osman (2002) and Abbas and Ahmed (2010) noted reduced feed intake in broilers receiving 1–2% BCS oil, while Szczerbińska et al. (2012) and Çetin et al. (2008) observed dose-dependent decreases in ADFI in quail and partridges, respectively. Durrani et al. (2007) and Shewita and Taha (2011) also reported significant reductions in feed intake at higher BCS inclusion levels. Several other studies found no significant impact of BCS supplementation on feed intake (Denli et al., 2004; Guler et al., 2006; Ashayerizadeh et al., 2009; Khalaji et al., 2011; Ghasemi et al., 2014; Al-Mufarrej, 2014; Saleh, 2014). These divergent findings may be attributed to variations in BCS form (whole seed, oil, extract), dosage, poultry species, and experimental conditions, including feed composition and rearing environment.

With regard to feed conversion ratio (FCR), most studies indicate a favorable effect of BCS supplementation. Significant improvements in FCR have been reported in trials by Guler et al. (2006), Durrani et al. (2007), Abu-Dieyeh and Abu-Darwish (2008), Erener et al. (2010), Toghyani et al. (2010), Yatoo et al. (2012), and others. Guler et al. (2006) showed that 1% BCS improved FCR by approximately 5% over the control group, while Abu-Dieyeh and Abu-Darwish (2008) achieved the best efficiency with 1.5% BCS supplementation. Nonetheless, not all studies found a consistent or significant effect on FCR. For instance, Nasir and Grashorn (2010) and Abbas and Ahmed (2010) reported non-significant improvements, and Majeed et al. (2010) even observed a deterioration in FCR with 0.25% BCS inclusion. Similarly, Al-Beitawi and El-Ghousein (2008) reported dose-dependent declines in feed efficiency at BCS inclusion rates above 1.5%. The variability in FCR responses may relate to several factors, including baseline diet composition, bird health status, housing conditions, and potential interactions between BCS bioactives and gut microbiota. It has been proposed that the benefits of phytogenic additives such as BCS are more pronounced under suboptimal conditions, where the antimicrobial and digestive-stimulatory effects may compensate for environmental or dietary challenges (Lee et al., 2003).

In conclusion, while the majority of studies support the growth-promoting and feed efficiency-enhancing effects of *Nigella sativa* supplementation in poultry, the impact on feed intake appears to be context-dependent. Differences in experimental design, dietary formulations, and the form and level of BCS supplementation likely account for the observed inconsistencies. Further research is warranted to define optimal inclusion rates and to elucidate the mechanisms underpinning these performance improvements.

Effects on Carcass Traits

The inclusion of *Nigella sativa* (Black Cumin Seed, BCS) in poultry diets has demonstrated variable yet generally beneficial effects on carcass traits and internal organ development. Several studies have reported improvements in dressing percentage, breast muscle yield, and reductions in abdominal fat deposition, suggesting enhanced protein metabolism and modulation of lipid pathways. For instance, Guler et al. (2006) and Toghyani et al. (2010) observed significant increases in carcass yield, as well as the weights of the liver, breast, thigh, wing, and neck in broilers supplemented with 1% BCS. However, heart weight remained unaffected. Similarly, studies such as those by Erener et al. (2010) and Saleh (2014) confirmed increases in carcass and breast muscle weights, though some found no significant changes in liver or edible organ weights. On the contrary, several researchers have reported inconsistent or non-significant effects. For example, El-Ghammry et al. (2002) and Abbas and Ahmed (2010) observed a decrease in dressing percentage with BCS inclusion, while Ismail (2011) noted no significant changes in most carcass parameters, including dressing yield, edible organ weight, and abdominal fat.

In terms of fat metabolism, Durrani et al. (2007) and Abaza et al. (2008) highlighted BCS's lypolytic effects, especially the significant reduction in abdominal fat when BCS oil was added at low concentrations (e.g., 0.1%), indicating a potential diversion of energy from fat deposition toward more beneficial physiological processes. Nonetheless, conflicting evidence also exists. Some studies, such as those by Al-Beitawi and El-Ghousein (2008) and Khalaji et al. (2011), reported no significant differences in internal organ weights or carcass traits across varying levels of crushed or uncrushed BCS. Moreover, while an increase in breast meat weight was consistently observed in multiple studies (Jahan et al., 2015), parameters like thigh and wing weights, skin, and drumstick weights often varied depending on BCS concentration, bird age, and experimental conditions.

Additionally, several studies have indicated that while meat composition—such as protein and fat content—might be altered positively by BCS supplementation (Hermes et al., 2009, 2011), there are often no significant effects on attributes like meat tenderness, pH, shear force, or electrical conductivity (Majeed et al., 2010; Khan et al., 2012). Some negative impacts were also reported, such as increased cooking losses and decreased dressing percentage with 1% whole-ground black cumin (Ismail, 2011). The disparities in results may be attributed to differences in BCS form (oil, meal, crushed or uncrushed seeds), inclusion levels, bird genetics, and environmental or management factors. Nevertheless, the frequent observation of increased breast muscle yield suggests that BCS positively influences protein metabolism and mineral bioavailability in poultry, making it a promising natural additive for improving carcass traits under controlled dietary strategies.

Effects on Meat Quality, Chemical Composition, and Antioxidant Properties in Poultry

The inclusion of BCS in poultry diets has shown a promising impact on meat quality attributes, primarily through its antioxidant mechanisms. These effects are attributed to bioactive compounds such as thymoquinone, carvacrol, anethole, and 4-terpineol, which help delay lipid oxidation, reduce microbial load, and extend shelf life. Improvements in meat quality parameters have been consistently reported, including enhanced meat color—likely due to the stabilization of myoglobin—better water-holding capacity and tenderness, and reduced lipid peroxidation. Studies have demonstrated that BCS supplementation leads to increased dry matter (DM), crude protein (CP), and ether extract (EE) content in breast and thigh muscles, with the most significant results observed at 10 g/kg diet (Kumar et al., 2018). Similar findings were reported by Al-Beitawi and El-Ghousein (2008), who noted improved DM and CP levels in breast meat with 15 g/kg BCS inclusion, though leg meat was less responsive.

The antioxidant effects of BCS are also evident at the biochemical level. Supplementation has been shown to elevate antioxidant enzyme activities such as glutathione peroxidase and superoxide dismutase in thigh muscle, while simultaneously decreasing malondialdehyde (MDA) levels, a key marker of lipid peroxidation (Rahman and Kim, 2016; Guler et al., 2007). Kumar et al. (2018) observed increased ferric reducing antioxidant power (FRAP) in serum and meat, suggesting an improved oxidative stability, especially after storage at 4°C. While the peroxide values in thigh meat remained largely unaffected, breast meat showed decreased lipid peroxidation when ether extract content was considered, reinforcing the meat-protective effects of BCS. Moreover, these antioxidant properties may be linked to the influence of BCS on endocrine function, particularly thyroid activity, which affects protein synthesis and energy metabolism (Hermes et al., 2011).

In addition to improving oxidative stability, BCS influences the fatty acid profile of poultry meat. Though research is limited, some studies indicate increased polyunsaturated fatty acid (PUFA) content and reduced fat oxidation in BCS-treated meat (Kumar et al., 2018). PUFA enrichment is particularly beneficial, given its susceptibility to oxidative degradation and its importance in human nutrition. Methanolic extracts of BCS have revealed high phenolic content—such as syringic acid, hydroxybenzoic acid, and p-coumaric acid—which exhibit potent in vitro antioxidant activity (Mariod et al., 2009). The capacity of BCS to scavenge free radicals, inhibit cyclooxygenase and lipoxygenase pathways, and regulate enzymes like glutathione S-transferase and catalase has been confirmed in both poultry and rodent models (Badary et al., 2003; Tuluce et al., 2009). Notably, diets containing 0.5–1% BCS significantly reduced erythrocyte MDA levels and increased glutathione concentrations, reflecting decreased oxidative stress and enhanced cellular defense mechanisms.

Collectively, these findings underscore the potential of *Nigella sativa* as a natural feed additive to enhance meat quality in broilers. Its integration into poultry diets not only improves physicochemical properties and nutritional value of meat but also supports oxidative stability, thereby contributing to better shelf life and consumer acceptability.

Effects on Immunity and Health Status

Numerous studies have investigated the immuno-potentiative activity of Black Cumin Seed (BCS) in poultry, highlighting its potential role in enhancing immune responses and overall health. Kumar et al. (2017a) demonstrated a quadratic increase in antibody titres against Newcastle Disease Virus (NDV) in broiler chickens supplemented with BCS at 5, 10, and 20 g/kg diet at 35 days of age, although no significant difference was observed at 28 days. Similarly, Al-Beitawi et al. (2009) reported a significant enhancement in antibody titres against NDV and Infectious Bursal Disease Virus (IBDV) at 42 days of age following BCS supplementation in chickens vaccinated at appropriate intervals. Durrani et al. (2007) also noted increased antibody production when BCS was included at 40 g/kg diet. In contrast, other studies (Toghyani et al., 2010; Shewita and Taha, 2011) reported no significant changes in antibody titres against NDV and influenza virus, attributing these results to the use of lower BCS doses or reduced concentrations of active compounds in the BCS formulations used.

In terms of lymphoid organ development, findings remain inconsistent across studies. Kumar et al. (2018) observed that spleen weight decreased linearly while bursa weight increased linearly with increasing BCS supplementation. Toghyani et al. (2010) found that lymphoid organ weights were positively influenced at 2 and 4 g/kg of BCS. Al-Mufarrej (2014) reported enhanced immune responsiveness with 10 or 14 g/kg BCS supplementation; however, no significant differences in bursa or spleen weights were observed at 21 and 35 days post-vaccination. Other investigations, such as those by El-Deek et al. (2009) and Yatoo et al. (2012), failed to find statistically significant differences in immune organ weights, although some variation was noted, possibly due to external factors such as feed contamination by mycotoxins (Cazaban et al., 2015).

Several bioactive compounds in BCS, including thymoquinone, carvacrol, nigellimine, thymol, and nigellicine, are believed to contribute to its immunomodulatory effects due to their antibacterial, antioxidant, and anti-inflammatory properties. These compounds likely stimulate immune cell activity, promote antibody production, and offer protection against oxidative stress and pathogenic microorganisms. Supporting this, El-Tahir et al. (1993) found that supplementation of BCS in human volunteers enhanced immune function by improving the helper T cell to suppressor T cell ratio and increasing natural killer cell activity. Similarly, Dorucu et al. (2009) observed significantly elevated serum protein and immunoglobulin levels in rainbow trout fed with BCS.

BCS also demonstrated the potential to reduce poultry mortality rates. Supplementation with 1.5% BCS in layer diets decreased mortality from 16.67% to 4.17%, while 1% BCS in broiler diets reduced mortality from 3.5% to 2% (Al-Jabre et al., 2003). Moreover, Hermes et al. (2011) noted improved bird survival and health under heat stress conditions with BCS supplementation, attributing the effects to enhanced immunity and antimicrobial action. However, some studies, such as Ismail (2011), reported no significant effect on mortality rates, reflecting the variability in outcomes depending on the dosage, environmental factors, and health status of the flock.

In summary, while the immunomodulatory potential of BCS is supported by several studies—particularly in enhancing NDV and IBDV antibody titres, supporting lymphoid organ development, and reducing mortality—the findings are not universally consistent. Variations in dosage, form of BCS used, bird age, vaccination schedule, and environmental conditions appear to significantly influence the outcomes. These inconsistencies underscore the need for standardized protocols in future research to better elucidate the immunological benefits of BCS in poultry nutrition.

Effects of *Nigella sativa* on Egg Production and Quality in Laying Poultry

The impact of *Nigella sativa* (black cumin) on egg production and quality in laying poultry has been widely studied, with results often showing variation depending on the dosage, form, and species involved. Several studies have reported positive outcomes; for instance, supplementation with 1.5% powdered black cumin or 3% whole seeds has significantly enhanced egg production in laying hens. Conversely, El-Bagir et al. (2006) observed a reduction in egg production by approximately 9% and 16% with the inclusion of 1% and 3% black cumin, respectively, without any influence on egg dimensions. This decline was attributed to increased final body weight, suggesting that the energy from N. sativa oil may be directed more towards weight gain than egg output. Another possible explanation is the associated decrease in egg yolk cholesterol, as lower cholesterol levels—essential for egg formation—can negatively affect egg production. Elkin et al. (1993) demonstrated that a 30% reduction in yolk cholesterol via a synthetic HMG-CoA reductase inhibitor resulted in a 20% drop in egg production, implying a critical threshold for cholesterol levels below which normal egg production cannot be sustained.

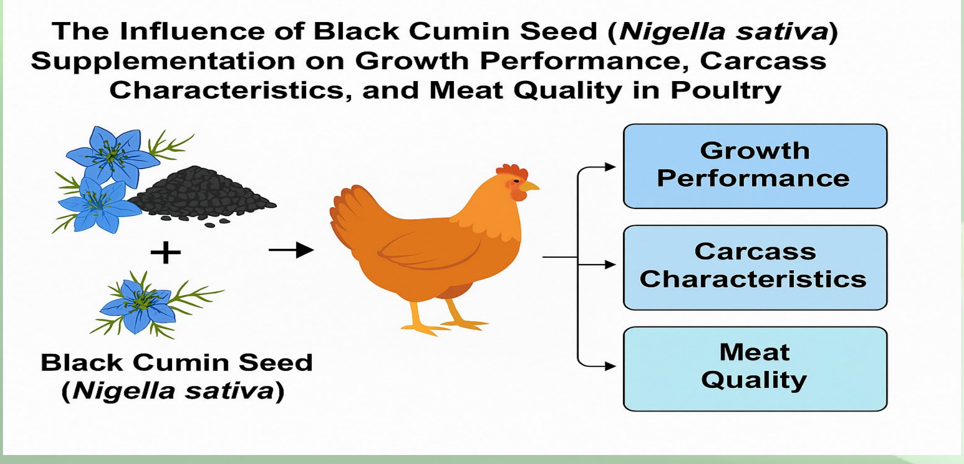
In terms of egg quality, supplementation with black cumin has shown promising results. A 1.5% inclusion increased egg weight from 54 to 58 grams, and 1% black cumin extract was effective in enhancing both egg weight and shell characteristics in quails. Additionally, diets with 2–3% black seed were associated with significant improvements in shell thickness and strength, whereas 1% or lower did not yield similar benefits. However, some studies reported no significant effect on egg production or composition. For example, Bolukbasi et al. (2009) found that N. sativa oil did not influence egg weight, production, or the proportion of yolk, albumen, and shell, although a 3 ml/kg inclusion reduced the Haugh unit, a measure of egg albumen quality. Notably, a 3% black cumin seed diet resulted in reductions in egg yolk total lipids, cholesterol, phospholipids, and triacylglycerols by 34%, 45%, 11%, and 20%, respectively—an outcome considered beneficial for human consumption. The exact mechanism of cholesterol reduction remains unclear, though it is hypothesized that N. sativa inhibits de novo cholesterol synthesis or lowers serum cholesterol levels.

Albumin quality has also been reported to improve with N. sativa supplementation, although its effect on yolk index appears to be negligible. Medicinal plants like N. sativa, known for their bioactive compounds, have the potential to support reproductive tissue health in laying poultry. For example, Boka et al. (2014) demonstrated that black cumin seed supplementation (1–3%) did not significantly affect laying rate or yolk cholesterol but positively influenced intestinal E. coli counts, blood biochemistry, and immune parameters. At doses above 2%, enhancements in egg production, weight, and shell strength were observed. On the other hand, Yalçin et al. (2012) reported a significant reduction in egg weight following N. sativa supplementation, with no notable changes in shell thickness, egg index, albumen height, or Haugh unit. Similarly, studies by Aydin et al. (2008) and Szczerbińska et al. (2012) found no effects on the live weight of hens.

Other researchers have highlighted the favorable influence of N. sativa on overall hen performance and egg quality parameters. Rich in unsaturated fatty acids like linoleic and oleic acids, black cumin seed inclusion up to 15 g/kg has been associated with improvements in egg weight, cholesterol levels, and yolk fatty acid composition. Bölükbaşi et al. (2009) confirmed that N. sativa oil can reduce intestinal E. coli, although its administration at 3 mg/kg may adversely affect the Haugh unit. In Aydin et al. (2008) trial, laying hens fed 3% black cumin seeds produced more eggs compared to controls, and eggs from hens fed 2–3% black cumin exhibited superior shell thickness and strength. Additionally, eggs from these groups showed a significant reduction in cholesterol content. As dietary fatty acid composition plays a key role in modifying egg lipid profiles, N. sativa proves to be a promising feed additive. Elkin et al. (1993) previously noted a cholesterol reduction from 30% to 20% through dietary modification without compromising egg weight. Supporting these findings, Hossain et al. found that dietary supplementation with 1.5%–2% black cumin significantly decreased yolk cholesterol without adverse effects on egg production or weight. Overall, evidence suggests that black cumin can positively influence various aspects of egg quality and production, although inconsistencies across studies highlight the need for further controlled investigations.

Optimal Inclusion Levels and Safety

In poultry nutrition, determining the optimal inclusion levels of additives like Black Cumin Seed (*Nigella sativa*) is crucial to maximizing their benefits while ensuring safety. Research on *Nigella sativa* supplementation in poultry diets suggests that inclusion levels typically range from 0.5% to 2%, depending on the desired outcomes and specific poultry species. These levels are generally considered safe and effective, providing significant improvements in growth performance, carcass characteristics, and meat quality without compromising feed intake or bird health. At lower inclusion levels (0.5% - 1%), Black Cumin Seed supplementation tends to offer benefits without adversely affecting feed palatability, while higher inclusion levels (1% - 2%) may enhance performance but could lead to reduced palatability or even potential negative effects if overused. Excessive inclusion can result in undesirable outcomes such as digestive disturbances, reduced feed consumption, or toxicity from exceeding safe nutrient thresholds (Asghar et al., 2022). Therefore, ensuring proper formulation of poultry diets with Black Cumin Seed is essential to achieve the desired effects on growth and meat quality without compromising safety. This requires careful calculation of inclusion levels based on the birds' age, growth stage, and environmental factors. Formulating diets with the appropriate balance, along with considering the bioavailability of the active compounds in *Nigella sativa*, ensures that the supplementation promotes optimal performance. Adhering to regulatory guidelines and safety protocols set by authorities like the FDA or EFSA is also critical in determining safe inclusion levels. In conclusion, optimizing the inclusion levels of Black Cumin Seed in poultry diets is key to improving growth performance, carcass traits, and meat quality while maintaining bird health and productivity.



This graphical abstract illustrates the impact of dietary supplementation with *Nigella sativa* (black cumin seed) on poultry performance, carcass characteristics, and meat quality. The diagram highlights the functional bioactive compounds of *Nigella sativa* and their physiological roles in enhancing digestion, immunity, and antioxidant status. These effects collectively contribute to improved growth performance, better feed efficiency, enhanced carcass yield, and superior meat quality in poultry production systems.

Challenges and Future Perspectives

Despite the well-documented benefits of *Nigella sativa* supplementation in poultry nutrition, several challenges continue to limit its widespread and standardized use in commercial production systems. One of the primary concerns is the lack of standardization in the active compounds, such as thymoquinone, which can vary significantly between different seed sources and extraction methods. This variability makes it difficult to ensure consistent efficacy across studies and applications. Additionally, geographic and environmental factors play a significant role in influencing seed quality, composition, and potency, further contributing to inconsistencies in performance outcomes. Another practical challenge is the cost-effectiveness of *Nigella sativa* supplementation at a commercial scale, particularly when high-quality or processed forms such as oils or extracts are used. These issues highlight the need for continued research and innovation in this area. Future studies should explore advanced delivery systems, such as nano-formulations or encapsulated extracts, to improve the bioavailability and stability of active compounds in the digestive tract. Moreover, the potential synergistic effects of combining *Nigella sativa* with other feed additives such as probiotics, enzymes, or other phytogenics should be investigated to enhance overall efficacy and reduce costs. In addition, molecular and genetic expression studies are essential to gaining deeper insight into the metabolic and physiological mechanisms through which *Nigella sativa* exerts its effects on growth performance and meat quality. Such research could pave the way for precision feeding strategies and the development of optimized formulations tailored to specific production goals. Overall, addressing these challenges through targeted research and innovation will be key to fully realizing the potential of *Nigella sativa* in modern poultry production.

Conclusion

In conclusion, *Nigella sativa* represents a highly promising natural feed additive with substantial potential to enhance poultry growth performance, carcass yield, meat quality, and overall health status. Its rich profile of bioactive compounds, particularly thymoquinone, contributes to its antimicrobial, antioxidant, immunomodulatory, and growth-promoting effects, positioning it as a compelling alternative to synthetic growth promoters. The multifaceted benefits observed across various studies highlight its role in improving not only production efficiency but also the quality and safety of poultry products. However, for *Nigella sativa* to gain wider acceptance in commercial poultry production, key challenges such as the standardization of active constituents, variability in seed quality, and cost-effective inclusion strategies must be addressed. Continued research focusing on improved formulations, such as nano-delivery systems and synergistic combinations with other phytogenics or probiotics, will be crucial in optimizing its efficacy. Ultimately, with proper standardization and strategic application, *Nigella sativa* holds strong potential to become an integral component of sustainable and health-oriented poultry nutrition programs.

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