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Quality evaluation of chicken nuggets incorporated with black cumin (*Nigella sativa*) Essential Oil

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Abstract

The present study was envisaged to assess the changes in quality of chicken nuggets prepared by incorporation of black cumin seed essential oil (BCEO) as natural preservative. The chicken nuggets containing different levels of BCEO viz., 0.05% (T₁), 0.10% (T₂), 0.25% (T₃) along with control (without BCEO) were prepared and packed in LDPE plastic bags. The control and treated products were evaluated for physico-chemical (emulsion pH, product pH, emulsion stability, cooking yield, shear force value, moisture and fat retention, DPPH radical scavenging activity and total phenolic content) and sensory evaluation. Incorporation of BCEO produced non-significant ($P>0.05$) changes in all physico-chemical parameters among the treatment groups. There was gradual but significant ($P<0.01$) in DPPH scavenging activity and total phenolic content of the chicken nuggets as the level of BCEO level increases in dose-dependent manner, confirming that the bioactive phenolics of BCEO are effectively retained in the steam-cooked meat matrix and deliver measurable antioxidant benefit. All sensory attributes scored above 6.0 and remained statistical. From this study, it can be concluded that 0.10% black cumin essential oil added chicken nugget can be prepared without compromising physico-chemical properties and sensory quality of the product.

Keywords: Black cumin essential oil, thymoquinone, chicken nuggets, DPPH radical scavenging, total phenolic content, sensory evaluation

Introduction

India's poultry sector is one of the fastest-growing segments of its livestock economy, contributing approximately 46.7% of total meat production annually, around 3.29 million tonnes of broiler meat, while the FAO projected that chicken would constitute over 42% of worldwide meat consumption by 2020 (DAHDF, 2016; Prabakaran, 2012) [12, 31]. Poultry meat is appreciated for its lean protein profile, B-complex vitamins, essential amino acids and unsaturated fatty acids and its freedom from religious dietary restrictions has made it the preferred raw material for a wide range of value-added ready-to-eat (RTE) products (Barbut, 2005) [4]. Chicken nuggets, an emulsion-based, heat-processed, convenient RTE products, have gained rapid acceptance among urban consumers across all age groups.

Despite their commercial popularity, nuggets are inherently perishable because their high moisture, protein and fat content creates conditions that favour microbial growth, lipid oxidation and proteolytic deterioration during refrigerated storage, ultimately causing off-flavour development, colour changes and reduced shelf life (Casaburi *et al.*, 2011; Dave and Ghaly, 2011) [11, 13]. Synthetic antioxidants such as butylated hydroxyanisole (BHA), butylated hydroxytoluene (BHT), propyl gallate and nitrite-based preservatives have long been used to manage these pathways. However, growing consumer concern over the potential toxicological effects of these synthetic additives has driven strong demand for clean-label, plant-derived preservation alternatives and this shift is now well-documented across the processed meat sector (Naveena *et al.*, 2008; Ji *et al.*, 2021; Campolina *et al.*, 2023) [29, 17, 9].

Plant essential oils are classified as generally recognised as safe (GRAS) by the US FDA offer a broad spectrum of antimicrobial, antioxidant and flavour modifying properties without inducing microbial resistance (Burt, 2004; Ji *et al.*, 2021) [8, 17]. Research on essential oils in chicken meat products has been dominated by classical Lamiaceae oils such as rosemary, thyme and oregano which are well documented as natural preservatives (Sutha *et al.*, 2018; Sutha and Gaudaman, 2024) [36, 35]. Despite having a strong bioactivity profile, black cumin seed oil, has gotten relatively little attention in this regard.

Arıcı *et al.* (2005) ^[1] reported that black cumin seed (*Nigella sativa*) is native to parts of the Mediterranean region. Black cumin oil has been shown to demonstrate antibacterial and antioxidant activities (Luther *et al.*, 2007) ^[25]. Its essential oil is rich in thymoquinone, the principal bioactive constituent also contain thymohydroquinone, carvacrol, *l*-anethole and 4-terpineol, which together confer antioxidant and anti-inflammatory activity (Burits and Bucar, 2000; Bourgou *et al.*, 2010; Aslani *et al.*, 2024) ^[7, 6, 2]. In chicken based meat products, Zwolan *et al.* (2020) ^[40] demonstrated that *N. sativa* ethanolic extracts significantly retarded lipid oxidation and stabilised colour in refrigerated chicken meatballs, while Muzolf-Panek *et al.* (2020) ^[28] confirmed that *N. sativa* extracts improved oxidative stability in raw ground chicken legs. Hassanien *et al.* (2013) ^[16] used black cumin seed essential oil at 0.1-0.2% in soft cheese and confirmed antibacterial activity without compromising sensory quality. Ozpolat and Duman (2016) ^[30] used black cumin seed essential oil at 0.2-0.6% in fish fillets and found no adverse effect on quality, with 0.6% yielding the longest shelf life and best sensory scores.

Despite this emerging evidence from dairy and fish sectors, no systematic published investigation has characterised the physico-chemical and sensory behaviour of black cumin seed essential oil specifically within a steam-cooked emulsion-type chicken meat product. The present study was therefore undertaken to evaluate three inclusion levels of BCEO (0.05%, 0.10% and 0.25%) in standardised chicken nuggets, with the objective of identifying the optimum concentration based on physico-chemical and sensory evaluation.

Materials and Methods

Procurement of raw materials

Dressed broiler carcasses were procured from retail outlets in the vicinity of VCRI, Tirunelveli town, Tamil Nadu. The carcasses were trimmed of visible adipose and connective tissues and hygienically deboned in the meat processing unit of the department. The deboned meat was minced using an 8 mm plate in a MADO Junior meat mincer (Model 71382) and stored at $-18 \pm 2^\circ\text{C}$ in LDPE (low density polyethylene) pouches until use. Certified food-grade black cumin seed essential oil (*Nigella sativa*) was purchased from M/s. Akay Flavour and Aromatics Pvt. Ltd., Kochi, India. Its physico-chemical purity was verified against food-grade specifications before inclusion in the experiment. Refined vegetable oil, refined wheat flour (maida), iodised salt, onion, garlic and ginger were procured from the local market of Tirunelveli town.

Preparation of chicken nuggets

Based on preliminary trials, the basic formulation of chicken nuggets was standardised. For 1 kg of lean chicken meat the following ingredients were added: salt 2%, vegetable oil 5%, dry spice mix 2.5%, wet condiments (onion: garlic: ginger = 1:1:1) 2.5%, refined wheat flour 3% and ice flakes 5%. The dry spice mix comprised of coriander 40%, red chilli 20%, fennel seeds 10%, black pepper 10%, cumin seeds 6%, dried ginger 6%, cloves 2%, turmeric 1%, cinnamon 1%, poppy seeds 2%, cardamom 0.5%, nutmeg 0.5%, bay leaf 0.4%, star anise 0.1% and mace 0.5%. Four

treatment groups were prepared: Control (C, no essential oil), T₁ (0.05% BCEO), T₂ (0.10% BCEO) and T₃ (0.25% BCEO) and BCEO was blended into the emulsion at the commencement of chopping. Emulsification was carried out in a bowl chopper (Scharfen, Model TC11) in a defined sequence; meat with salt and 30% water; then oil with 20% water; then wet condiments; then dry spice mix with the remaining water; then maida, maintaining emulsion temperature below 12°C through the addition of slushed ice. The emulsion was filled into parchment paper-lined stainless steel moulds and steam-cooked to an internal temperature of $80 \pm 2^\circ\text{C}$ for 40 minutes. After cooling to room temperature, blocks were cut into nuggets ($4 \times 1.5 \times 1.5$ cm) and evaluated immediately. Six independent trials were conducted per treatment.

Physico-chemical analysis

The pH of emulsion and product was measured using a digital pH meter (Model 361, Systronics, India) following Trout *et al.* (1992) ^[37]. Emulsion stability was determined by the method of Baliga and Madaiah (1971) ^[3] as modified by Kondaiah *et al.* (1985) ^[22]. Cooking yield was expressed as the percentage of cooked nugget weight to raw emulsion weight. Shear force value was determined using a Warner-Bratzler shear press as per Berry and Stiffler (1981) ^[5], expressed in kg/cm². The moisture retention value represents the amount of moisture retained in the cooked product per 100gm of sample and was determined as per (Ei-Magoli *et al.*, 1996) ^[15]. Fat retention was calculated according to (Murphy *et al.*, 1975) ^[27]. DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging activity was measured by the method of Wu *et al.* (2003) ^[38] using a BECKMAN DU-640 UV-VIS spectrophotometer at 517 nm, expressed as percentage inhibition. Total phenolic content was quantified by the Folin-Ciocalteu method of Yuan *et al.* (2005) ^[39] at 760 nm using a SYSTRONICS Double Beam UV-Vis Spectrophotometer, expressed as gallic acid equivalents (µg/g).

Sensory evaluation

Sensory attributes such as appearance, flavour, spiciness, texture, juiciness and overall acceptability were evaluated by a panel of eight semi-trained judges using an 8-point hedonic scale (Keeton, 1983) ^[21], where 8 = extremely acceptable and 1 = extremely unacceptable. Nuggets were reheated for two minutes in a microwave before serving. Panellists received plain water between samples and evaluated in neutral-lighting individual booths. Three replication sessions yielded $n = 21$ observations per treatment.

Statistical analysis

Data were subjected to one-way analysis of variance (ANOVA) and means were compared using Duncan's Multiple Range Test (DMRT) using SPSS software (Snedecor and Cochran, 1995) ^[34].

Results and Discussion

Physico-chemical Characteristics

The mean ($\pm$ SE) values of all physico-chemical parameters are presented in Table 1.

Table 1: Mean ($\pm$ SE) values of physico-chemical characteristics of chicken nuggets incorporated with black cumin seed essential oil (BO)

Parameter	Control	BCEO 0.05% (T ₁)	BCEO 0.10% (T ₂)	BCEO 0.25% (T ₃)
Emulsion pH	6.11 $\pm$ 0.02	6.13 $\pm$ 0.03	6.15 $\pm$ 0.02	6.17 $\pm$ 0.02
Product pH	6.19 $\pm$ 0.02	6.21 $\pm$ 0.03	6.22 $\pm$ 0.03	6.26 $\pm$ 0.02
Emulsion stability (%)	93.66 $\pm$ 0.52	94.44 $\pm$ 0.50	94.72 $\pm$ 0.47	94.38 $\pm$ 0.50
Cooking yield (%)	92.58 $\pm$ 0.75	93.62 $\pm$ 0.56	93.67 $\pm$ 0.52	93.04 $\pm$ 0.52
Shear force (kg/cm ²)	0.42 $\pm$ 0.04	0.41 $\pm$ 0.04	0.39 $\pm$ 0.03	0.40 $\pm$ 0.09
Moisture retention (%)	65.79 $\pm$ 0.47	67.01 $\pm$ 0.98	68.34 $\pm$ 0.59	66.70 $\pm$ 0.71
Fat retention (%)	74.59 $\pm$ 0.24	75.29 $\pm$ 0.71	76.16 $\pm$ 1.01	74.62 $\pm$ 0.96
DPPH - BCEO (%)	NA	45.48 ^a $\pm$ 1.01	50.42 ^b $\pm$ 2.64	50.96 ^b $\pm$ 1.39
DPPH - product (%)	10.74 ^a $\pm$ 1.25	19.31 ^b $\pm$ 2.21	24.70 ^b $\pm$ 3.78	26.18 ^b $\pm$ 0.67
Total phenolics (μ g/g)	606.17 ^a $\pm$ 5.24	620.00 ^a $\pm$ 5.39	632.83 ^b $\pm$ 7.02	657.50 ^c $\pm$ 6.91

Means bearing different superscripts in a row differ significantly ($p < 0.05$).

Emulsion pH and Product pH

In the present study, addition of black cumin seed essential oil did not show any significant effect on emulsion pH and product pH ($P > 0.05$). This was similar to the results of Ozpolat and Duman (2016) [30] who found the same non-significant pH effect in black cumin treated fish fillets. The slight alkaline drift with increasing BCEO concentration is attributable to the mildly alkaline character of thymoquinone, which interacts with the meat protein without causing any substantive shift in its buffering environment. This pattern is widely reported for essential oil inclusion in emulsion-type chicken products; Can (2012) [10] recorded no meaningful change in pH of thyme oil-treated chicken balls and Sharma *et al.* (2017) [33] observed comparable non-significant responses for multiple essential oils in chicken sausages. Zwolan *et al.* (2020) [40] similarly found that *N. sativa* seed extracts did not significantly alter pH in chicken meatballs. All product pH values (6.19-6.26) fell within the expected range (6.0-6.4) for steam-cooked emulsion-type chicken products, confirming that BCEO at any tested level causes no adverse change to the protein chemistry of the formulation.

Emulsion Stability and Cooking Yield

Addition of BCEO in different levels during emulsion preparation did not reveal any significant ($p > 0.05$) effect on emulsion stability and cooking yield. Emulsion stability ranged from 93.66 $\pm$ 0.52% in the control to a peak of 94.72 $\pm$ 0.47% at T₂, settling at 94.38 $\pm$ 0.50% at T₃. Cooking yield tracked a parallel pattern, rising from 92.58 $\pm$ 0.75% (C) to 93.67 $\pm$ 0.52% (T₂). Similar findings were reported by Kalaikannan (2014) [19], who observed non-significant changes in emulsion stability and cooking yield of clove oil-treated chicken patties. The mild numerical improvement at moderate BCEO inclusion reflects the surface-active properties of thymoquinone, which can reinforce the protein-fat interfacial film within the emulsion matrix, improving resistance to heat-induced phase separation. Naveena *et al.* (2008) [29] reported an analogous non-significant improvement in chicken patties treated with pomegranate rind powder, attributing it to similar phenolic reinforcement of the interfacial structure. The marginal reversal at T₃ suggests that excess phenolics at higher concentrations begin to compete with myofibrillar proteins for interfacial sites, a concentration-dependent effect noted with multiple essential oils in emulsion meat systems (Kalaikannan, 2014) [19]. All cooking yield values exceeded 92.5%, confirming satisfactory processing efficiency irrespective of treatment.

Shear Force Value: Shear force value of black cumin seed oil treated chicken nuggets revealed non-significant

variation between treated nuggets and control. A subtle declining tendency was apparent up to T₂, consistent with the known capacity of phenol-rich essential oil constituents to partially modify the myofibrillar protein network within the cooked meat emulsion, generating mild matrix-softening without structural compromise. The result was in coincidence to Kanimozhi (2012) [20], who observed a significant decrease in shear force value in rosemary extract-incorporated chicken nuggets. The lowest shear force recorded (T₂: 0.39 $\pm$ 0.03 kg/cm²) remains well within the accepted range for steam-cooked emulsion-type nuggets and does not signal any adverse textural outcome.

Moisture Retention and Fat Retention

Moisture retention of C, T₁, T₂ and T₃ was 65.79 $\pm$ 0.47%, 67.01 $\pm$ 0.98%, 68.34 $\pm$ 0.59% and 66.70 $\pm$ 0.71% respectively, with no significant difference among treatments. Fat retention was 74.59 $\pm$ 0.24%, 75.29 $\pm$ 0.71%, 76.16 $\pm$ 1.01% and 74.62 $\pm$ 0.96% for C, T₁, T₂ and T₃. The improved moisture and fat retention at T₂ is mechanistically connected to the emulsion stability improvement, a more stable emulsion matrix restricts the release of water and fat during cooking, retaining both at higher proportions in the finished product. A similar increase in moisture content was observed in ginger essential oil-added beef patties by Dzudie *et al.* (2004) [14], attributed to the same emulsion-stabilising mechanism. Higher moisture retention is practically significant because it is directly associated with improved juiciness perception in consumers. The reversal at T₃ mirrors the emulsion stability pattern and reinforces the identification of 0.10% as the functional optimum within the tested range.

DPPH Radical Scavenging Activity

DPPH scavenging activity of black cumin seed oil was high in 0.25% BO, followed by 0.10% and 0.05%. However, there was no significant ($P > 0.05$) difference between 0.25% and 0.10% ($p > 0.05$). DPPH scavenging activity of black cumin seed oil in product was significantly ($p < 0.01$) higher at 0.25% and 0.10% compared to control (10.74 $\pm$ 1.25%), with values of 19.31 $\pm$ 2.21% (T₁), 24.70 $\pm$ 3.78% (T₂) and 26.18 $\pm$ 0.67% (T₃). The principal mechanism behind these results is the hydrogen-donating capacity of thymoquinone, which quenches DPPH radicals by supplying an active hydrogen atom that converts the stable radical to its non-radical DPPH-H form, thereby interrupting lipid peroxidation chain reactions (Burits and Bucar, 2000; Aslani *et al.*, 2024) [7, 2]. Mizuno and Fukuhara (2022) [26] confirmed this mechanism specifically for thymoquinone and its hydroquinone metabolite. In a directly comparable food application, Zwolan *et al.* (2020) [40] found that *N.*

sativa ethanolic extracts significantly reduced TBARS (Thiobarbituric Acid Reactive Substances) accumulation in refrigerated chicken meatballs, demonstrating that the antioxidant capacity of *N. sativa* translates directly into oxidative protection in chicken matrices. This result was similar to that of Lawrence and Lawrence (2011) [23], who found an increase in DPPH scavenging activity with the increase in concentration of garlic essential oil. The intrinsic DPPH activity of BCEO (45-51%) considerably exceeded that of rosemary oil (8.82-23.30%) at equivalent concentrations as reported by Sutha *et al.* (2018) [36]. Though in the cooked product BCEO at 0.10% (24.70%) fell below thyme oil (55.67%) and oregano oil (39.11%) at the same level (Sutha and Gawdaman, 2024) [35]. This reflects differential thermal stability of each oil's phenolics in the steam-cooked matrix. The highly significant positive dose-response for product DPPH activity provides robust experimental evidence for BO's antioxidant utility in processed chicken products.

Total Phenolic Content

There was a significant ($p < 0.01$) increase in total phenolic content in nuggets with increasing concentration of BCEO. This stepwise accumulation confirms that the bioactive phenolics of *Nigella sativa* - principally thymoquinone, with secondary contributions from carvacrol, 4-terpineol and α -anethole - survive the 80°C steam-cooking process and integrate into the product matrix in proportion to the oil added. This result was in concurrent with Rathod (2015) [32], who found a similar result in lemon peel and lemon pulp incorporated chicken nuggets. The direct correspondence between rising total phenolics and rising DPPH scavenging activity echoes the well-established relationship documented by Lim *et al.* (2007) [24], who demonstrated that higher phenolic content in plant extracts invariably drove stronger radical quenching capacity. In comparative terms, thyme oil at 0.10% yielded $760.33 \pm 4.16 \mu\text{g/g}$ and oregano oil $728.67 \pm 4.94 \mu\text{g/g}$ in the same nugget system (Sutha and Gawdaman, 2024) [35], positioning BCEO as a meaningful but quantitatively moderate phenolic contributor at equivalent concentrations.

Sensory Attributes

Mean sensory scores of chicken nuggets incorporated with black cumin seed essential oil (BCEO) are presented in Table 2.

Table 2: Mean ($\pm$ SE) sensory scores of chicken nuggets incorporated with black cumin seed essential oil (BCEO)

Sensory Attribute	Control	BCEO 0.05% (T ₁)	BCEO 0.10% (T ₂)	BCEO 0.25% (T ₃)
Appearance	6.77 $\pm$ 0.14	6.72 $\pm$ 0.16	6.69 $\pm$ 0.17	6.66 $\pm$ 0.17
Flavour	6.24 $\pm$ 0.13	6.21 $\pm$ 0.13	6.18 $\pm$ 0.10	6.12 $\pm$ 0.13
Spiciness	6.45 $\pm$ 0.08	6.43 $\pm$ 0.13	6.39 $\pm$ 0.08	6.17 $\pm$ 0.16
Texture	6.74 $\pm$ 0.23	6.62 $\pm$ 0.22	6.52 $\pm$ 0.17	6.43 $\pm$ 0.16
Juiciness	6.42 $\pm$ 0.21	6.37 $\pm$ 0.22	6.33 $\pm$ 0.20	6.07 $\pm$ 0.18
Overall acceptability	6.54 $\pm$ 0.16	6.43 $\pm$ 0.13	6.41 $\pm$ 0.19	6.23 $\pm$ 0.16

No significant difference ($p > 0.05$) among any treatment groups for any attribute.

Appearance

The mean value for appearance did not differ significantly ($p \geq 0.05$) between treatments and control. However, there was a gradual decrease in sensory score with increase in the

level of incorporation of black cumin seed oil. The appearance score for control (6.77 ± 0.14) was higher compared to all treatment groups. The marginal reduction in appearance with increasing BCEO concentration is attributable to the characteristic dark pigmentation of *Nigella sativa* oil, which imparts a progressively deeper surface colour to the nuggets as inclusion level rises. This is consistent with observations by Zwolan *et al.* (2020) [40], who noted that *N. sativa* additions negatively influenced colour appearance in chicken meatballs. Unlike thyme and oregano oils which at 0.10% improved appearance scores in this research series (Sutha and Gawdaman, 2024) [35] BCEO darker pigments do not contribute a visually appealing amber or golden surface tone. Despite this, all groups scored between 6.66 and 6.77, placing them in the 'liked moderately to liked very much' range. Equivalent non-significant appearance responses to essential oil incorporation have been widely reported, Can (2012) [10] for thyme oil and Sutha *et al.* (2018) [36] for rosemary oil, among others.

Flavour

Addition of black cumin seed oil decreased the flavour scores over the other levels of addition and control. Flavour scores were 6.24 ± 0.13 (C), 6.21 ± 0.13 (T₁), 6.18 ± 0.10 (T₂) and 6.12 ± 0.13 (T₃), with no significant difference among the treatments. This outcome contrasts sharply with thyme oil at 0.10%, which produced a significantly elevated flavour score of 7.09 ± 0.14 , and oregano oil which reached 7.05 ± 0.17 — both significantly above their respective controls (Sutha and Gawdaman, 2024) [35]. The difference is rooted in the distinct organoleptic character of *Nigella sativa* oil: thymoquinone imparts a warm, slightly bitter-pungent note that, unlike the bright savoury-herbal character of thymol and carvacrol, does not integrate additively into the spice blend of the nugget formulation. Rather than generating a hedonic improvement, BCEO operates flavour-neutrally at 0.10%. Conversely, this result was dissimilar to Ozpolat and Duman (2016) [30], who found that black cumin treated fish flesh was highly preferred by panelists, likely reflecting the very different flavour context of marinated fish versus a spiced chicken nugget formulation. Hassanien *et al.* (2013) [16] similarly found that BCEO maintained but did not enhance product acceptability in soft cheese, consistent with the present findings.

Spiciness, Texture and Juiciness

Spiciness, Texture and Juiciness had not shown any significant ($P > 0.05$) difference between treatment and control. The most notable numerical movement was in spiciness at T₃, where the warm-bitter aromatic character of BCEO at 0.25% began to compete with the established spice blend, muting perceived spiciness. The progressive texture softening is consistent with the shear force data and reflects mild matrix-loosening by phenolic compounds at increasing concentrations. Juiciness scores remained above 6.0 throughout; since moisture retention was numerically highest at T₂ ($68.34 \pm 0.59\%$), the numerical decline in juiciness at T₃ likely reflects holistic sensory perception rather than an actual reduction in retained moisture - a distinction noted by Juntachote *et al.* (2007) [18] in essential oil-treated pork products.

Overall Acceptability

Inclusion of black cumin oil did not influence sensory characteristics significantly ($p > 0.05$) for overall

acceptability. Every group scored above 6.0 on the hedonic scale throughout. Scoring above 6.0 corresponds to at least 'liked slightly' and represents a commercially viable threshold of consumer acceptance for processed chicken products. The T₂ group (0.10% BCEO) achieved an overall acceptability score of 6.41 - only 0.13 units below control while simultaneously delivering significantly superior antioxidant protection: DPPH 24.70% vs. 10.74% in control, and total phenolics 632.83 vs. 606.17 µg/g. This antioxidant gain at negligible sensory cost makes 0.10% the most practically optimal inclusion level. Sutha and Gawdaman, 2024)^[35], driven by the hedonic enhancement of thymol and carvacrol. Black cumin seed oil, by contrast, preserves the existing sensory profile rather than augmenting it, delivering antioxidant functionality as its primary benefit. This positions BCEO as suitable in formulations where oxidative protection is the primary objective and flavour enhancement is secondary.

Conclusion

Based on the findings of present study it may be concluded that chicken nuggets containing 0.10% BCEO can be prepared without any deterioration in qualities. Use of BCEO as natural preservatives in chicken nuggets has not only imparted antioxidant properties but also improved the sensory property. On the combined basis of antioxidant efficacy and sensory compatibility, 0.10% black cumin seed essential oil is identified as the optimal inclusion level for chicken nuggets. These findings establish BCEO as a viable clean-label natural antioxidant for ready-to-eat emulsion-based chicken products. Future research should evaluate the antimicrobial efficacy and oxidative stability of 0.10% BCEO during refrigerated storage, and explore potential synergistic effects when BCEO is combined with thyme or oregano essential oils within a multi-hurdle preservation framework.

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