Efficacy of black cumin in edible film and edible coating formulation -a review

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Abstract **Recent advances in edible films and edible coatings have piqued interest for their ability to offer benefits similar to those of their plastic counterparts, which carry a negative perception due to environmental concern. Abundance of volatile oils, fibres, alkaloids, minerals and vitamins in black cumin (*Nigella sativa*) bestows potential antioxidant, antimicrobial and other health promoting activities that not only increases the nutritional profile of foods, but also enhances shelf life. The integration of black cumin (*Nigella sativa*) derivatives—including extract, essential oil, and seed cake—at concentrations ranging from 0.5% to 12% w/w into biopolymer-based edible film and edible coating matrices comprising protein, polysaccharide, chitosan, and pectin has demonstrated significant enhancement in functional attributes, notably antioxidant activity, antimicrobial potency, and optical barrier efficacy. Nonetheless, precise formulation optimization is imperative to counteract potential deleterious impacts on film structural integrity and organoleptic properties. This review delineates the advancement of *Nigella sativa*-based edible films and edible coatings exhibiting bioactive functionalities conducive to human health and food safety, thereby offering a sustainable alternative to conventional harmful plastic-derived packaging systems.**

Keywords: Black cumin; edible film; edible coating; antioxidant

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1. INTRODUCTION

Plastic-based materials have become predominant in the food packaging sector owing to their cost-effectiveness, heat sealability, shape diversity, degree of elasticity, and mechanical strength [1]. Despite these advantages, such materials exhibit significant limitations, including non-biodegradability, potential health hazards and the propensity to leach toxic substances [2]. To address these issues, edible films and edible coatings have emerged as alternative packaging systems that align with consumer preferences for packaging solutions that are health- promoting, environmentally sustainable and enriched with natural preservatives. The fundamental distinction between edible coatings and edible films lies in their application methodology: edible coatings are applied directly onto the surface of food products in liquid form, whereas edible films are pre-formed, dried layers subsequently affixed to food items [3]. These packaging substances contain nutrients and natural antioxidants that ultimately improve the quality of food products and prolong their shelf life [2]. Since ancient times, spices have been esteemed for their sensory as well as medicinal properties. So, the incorporation of spices in edible packaging has garnered attention from researchers worldwide. Black cumin (*Nigella sativa*) is one such renowned spice belonging to the *Ranunculaceae* family [4]. It is widely cultivated in Asia, Middle-East, North Africa, and the Mediterranean region [4]. Black cumin is rich in volatile oil, amino acids, protein, fatty acids, alkaloids, carbohydrates, vitamins and minerals [4,5]. Furthermore, black cumin exhibits a broad spectrum of pharmacological activities, demonstrating efficacy in the management of asthma, fever, cough, influenza, headache, dizziness, hypertension, eczema, inflammation and diabetes [6]. Therefore, black cumin can be considered a promising natural additive for edible coatings and edible films due to its preservative properties and its ability to extend the shelf life of packaged food products. There is a scarcity of review articles regarding the development and application of spice-based edible packaging [2, 7, 8]. To the best of our knowledge, there is currently no review paper on black cumin-based edible coatings and edible films. Accordingly, the primary objective of this review is to critically evaluate the influence of black cumin on the antioxidant, antimicrobial, barrier, mechanical and thermal properties of edible films and edible coatings, as well as its impact on the storage stability and sensory attributes of food products.

2. INFLUENCE OF BLACK CUMIN ON EDIBLE FILMS AND EDIBLE COATINGS

2.1 ANTIOXIDANT PROPERTIES

Black cumin serves as a potent source of high-quality essential oil, characterized by a rich profile of volatile bioactive constituents including thymoquinone, β-thujene, β-pinene, o-cymene, and cis-4-methoxythujane. The seeds are notably enriched with tocopherol isomers—γ-, β-, and α-tocopherol—alongside a diverse array of amino acids including glutamic acid, leucine, alanine, and aspartic acid. Furthermore, the lipid fraction of black cumin comprises substantial quantities of fatty acids, predominantly linoleic, palmitic, and oleic acids [6].

The antioxidant efficacy of black cumin oil is linked to specific mechanisms, including thymoquinone mediated modulation of enzymatic antioxidants, tocopherol driven inhibition of lipid peroxidation, and phenolic compound chelation of transition metals, rather than a generalized synergistic effect [9]. The incorporation of black cumin oil into polymeric matrices has been shown to enhance the antioxidant potential of edible films and edible coatings. This enhancement is further potentiated by the presence of phenolic compounds, which exhibit radical-scavenging activity by inhibiting reactive oxygen species [10].

Empirical investigations have demonstrated that guava fruits coated with sodium alginate-based edible films supplemented with 0.5–2% black cumin oil exhibited markedly elevated antioxidant capacity compared to uncoated guava fruits. Although a gradual decline in antioxidant content and activity was observed during storage, the coated samples consistently retained superior antioxidant levels. The application of the coating was found to modulate the internal atmosphere of the fruit, elevate ascorbic acid concentration, and delay the onset of ripening [11].

Additionally, increasing the number of coating layers enriched with black cumin oil from 5 to 15 resulted in a progressive enhancement of ABTS radical scavenging activity, rising from 21.36% to 26.79%, thereby underscoring the dose-dependent efficacy of the oil in antioxidant augmentation [9].

Although coatings enriched with black cumin oil improved antioxidant retention, variability in oil stability and polymer compatibility may limit reproducibility across different food matrices.

2.2 ANTIMICROBIAL PROPERTIES

Numerous investigations have elucidated the antimicrobial efficacy of *Nigella sativa* (black cumin) against a broad spectrum of pathogenic microorganisms. Among its phytochemical constituents, phenolic compounds are recognized as the principal antimicrobial agents. These compounds exert their bactericidal action by facilitating the delocalization of conjugated double bonds and adenosine triphosphate (ATP) within bacterial cells. This process is mediated through the proton release, which disrupts membrane integrity, compromises cellular homeostasis, and ultimately culminates in cell wall rupture and microbial lysis [10].

Thymoquinone, a prominent monoterpene quinone found in black cumin oil, has been identified as the most potent antimicrobial constituent [10]. Its mechanism of action involves interference with microbial enzymatic systems and membrane permeability, thereby inhibiting cellular proliferation and metabolic activity. Comparative studies have demonstrated that black cumin extract exhibits heightened antibacterial activity against Gram-positive bacterial strains, which is attributed to the structural differences in the cell wall composition. The cell wall of Gram-negative bacteria exhibits increased complexity owing to the presence of an outer membrane primarily composed of lipopolysaccharide. Additionally, the thin peptidoglycan layer functions as a barrier, limiting the entry of bioactive compounds into the cell. Nonetheless, its efficacy against Gram-negative organisms also increases in a concentration-dependent manner, indicating a broad- spectrum antimicrobial potential [11]. These mechanisms warrant further validation under different food system conditions.

In applied food preservation contexts, the integration of black cumin oil into biopolymeric coatings has yielded promising results. For instance, guava fruits treated with a composite edible coating comprising 1% chitosan and 0.5% black cumin oil exhibited a significantly reduced aerobic mesophilic bacterial count, measured at 1.866 log CFU/mL following a 9-day storage period. In contrast, the uncoated control samples recorded the highest microbial load at 3.5 log CFU/mL, underscoring the protective efficacy of the bioactive coating system [12].

These findings collectively affirm the antimicrobial potency of black cumin-derived compounds, particularly when synergistically combined with chitosan matrices. Such formulations not only inhibit microbial proliferation but also extend the postharvest shelf life of perishable commodities through active barrier functionality and biochemical modulation.

2.3 MECHANICAL PROPERTIES

The mechanical properties of edible coatings and edible films are critical indicators of their structural integrity and functional performance within packaging systems. These properties reflect the degree of polymeric resistance imparted by the matrix, thereby contributing to the protection of food products against physical damage during handling, storage, and transportation [13]. The incorporation of bioactive compounds into the polymeric matrix significantly influences the mechanical behavior of these systems by altering molecular interactions and network architecture.

Several physicochemical parameters govern the mechanical attributes of edible films and coatings, including the chemical nature and physical form of the additive, particle size distribution, concentration, and the extent of intermolecular and intramolecular bonding within the matrix [14]. The integration of black cumin (*Nigella sativa*) essential oil has been shown to induce notable modifications in film mechanics. Specifically, the oil promotes the formation of a polymer–oil interface that enhances elongation at break while concurrently reducing tensile strength. This phenomenon is attributed to the plasticizing effect of the essential oil, which disrupts the continuity of the polymeric network, transitioning it from a homogeneous to a heterogeneous structure. Even at low concentrations, the oil imparts a softening effect, thereby increasing film flexibility and reducing rigidity [13]. While increased elongation enhances flexibility, the simultaneous reduction in the tensile strength may compromise weight-bearing capacity, restricting the suitability for applications requiring high mechanical resistance. Moreover, excessive concentrations or processing interventions (e.g., ultrasound) can disrupt polymer continuity, leading to diminished extensibility.

Moreover, the presence of bioactive constituents within the incorporated ingredients can exert a pronounced influence on the final mechanical profile of the edible film or coating [14]. These compounds may interact with the polymer chains, modulate hydrogen bonding, and alter the viscoelastic behavior of the matrix. Empirical data indicate that the addition of 5% black cumin oil nanoemulsion, in the absence of ultrasound treatment, to orange peel pectin-based edible films significantly elevated the elongation at break (EB) values. Specifically, EB increased from 7.32% in commercial pectin films to 25.68% in films containing the nanoemulsion. However, the application of ultrasound processing and further increases in nanoemulsion concentration resulted in a decline in EB values, suggesting a threshold beyond which structural disruption may compromise film extensibility [15].

These findings underscore the importance of optimizing formulation parameters and processing conditions to tailor the mechanical properties of bioactive-enriched edible films for specific packaging applications.

2.4 BARRIER PROPERTIES

Barrier properties of a packaging material can be classified into three types, namely: (1) water vapor permeability, (2) Opacity and (3) Oxygen permeability.

Water vapor permeability is an important parameter, as it indicates the amount of water transmission. Studies have shown that black cumin-loaded edible films can minimize moisture content and improve their barrier properties. The presence of hydrophobic constituents in black cumin may be responsible for enhancing its barrier properties [16]. Studies have shown that the water vapor permeability decreased from $5.55 \pm 2.01 \times 10^{-10}$ g/ms kPa in control chitosan film to $2.39 \pm 1.63 \times 10^{-10}$ g/ms kPa in black cumin oil-enriched chitosan edible film [16]. Similarly, the addition of black cumin extracts up to 2.5% resulted in a reduction in water vapor permeability from 0.207 ± 0.02 g mm/h m^2 kPa to 0.15 ± 0.07 g mm/h m^2 kPa. However, increasing the concentration of the extract beyond 2.5% escalated the water vapor permeability of the films [17].

Transparency and opacity are critical aspects in food packaging formulation, as it primarily depends on the chemical interactions and color of edible films and edible coatings [15]. In one study, the addition of cumin oil reduced the transparency of soy protein isolate film decreased by 10% - from 79.76% to 72-73%. The addition of nanoemulsion and pickering emulsion of black cumin oil increased the greenness, yellowness, and opacity of the soy protein isolate films due to the presence of naturally colored lecithin, black cumin oil, and whey protein isolate. Furthermore, elevating the concentration of black cumin oil from 5% to 10% resulted in a commensurate reduction of transparency to 67.01% and 71.48% in nanoemulsion and Pickering emulsion-based films, respectively. At higher cumin oil concentrations, the increased size of lipid particles intensifies the light-scattering effect of the film [18]. Conversely, the increased opacity may create challenges as colorless and transparent edible coatings and edible films are desired [19].

Oxygen permeability is another significant property that determines the utility of packaging materials. Inclusion of black cumin oil lowers the oxygen permeability in carboxymethyl cellulose and okra mucilage-based films. The incorporation of 1.29% okra mucilage and 0.43% black cumin oil into the film resulted in a 33.5% reduction in oxygen permeability compared to the control film. The hydrophobic nature of the oil brings down the moisture content, which restricts the oxygen solubility within the film matrix. Additionally, the interaction between the phenolic compounds in black cumin oil, and the biopolymer formed a more compact film structure [18].

Although moderate incorporation of black cumin oil reduces water vapor and oxygen permeability, higher concentrations can reverse these benefits by destabilizing the polymer matrix. Similarly, opacity improvements may protect light- sensitive foods but reduce consumer acceptance where transparency is desired.

Table 1. Application of Black cumin-enriched edible films and edible coatings on various food products

Food Application	**Type of Edible Coating**	**Amount of Addition**	**Outcome**	**Reference**
Lemon	Black cumin seed oil	50% and 100%	Longer shelf life, prevention of weight loss during storage, decrease in pH, titratable acidity and TSS after storage period	[20]
Lemon	Beeswax and coconut oil	90:10 and 80:20	Coating along with modified atmosphere packaging (MAP) increased shelf life, ascorbic acid, titratable acidity, juice content, retention of green color, improved sensory quality, firmness, reduced pH, weight loss	[21]
Lemon	Guar gum, ethanolic and methanolic extract of spices (fennel, black cumin, bay leaf, coriander seeds)	1.5% guar gum, 0.2 ml of each ethanolic and methanolic extract of spices (fennel, black cumin, bay leaf, coriander seeds)	Better Inhibiting activity against bacteria and fungi, reduced chlorophyll and increased carotenoid content, delayed the ripening by lowering the rate of increase in ascorbic acid content, antioxidant activity, phenolic and flavonoid content, fennel extract showed better shelf life than other spice extracts	[22]
Rainbow Trout fish fillet	Quinoa starch, black cumin and mint essential oil	4% quinoa starch, 4.75 ml of black cumin and mint essential oil each	Prolonged shelf life, reduced pH, TBARS and TVB-N values, slower deterioration in fish fillet, lowest in total aerobic mesophilic bacteria plate count	[23]
Rainbow Trout fish fillet	Chitosan, pectin, lemon essential oil, pepper mint	2% chitosan, 2% pectin, lemon essential oil (0.5% and 1%) and peppermint oil	Essential oils delayed spoilage, decreased bacterial count, lowered pH	[24]

	essential oil	(0.5% and 1%)		
Rainbow Trout fish fillet	Chitosan, grape seed extract (GSE)	2% chitosan and 0.1% GSE	Combining chitosan with GSE showed better inhibitory effect against mesophilic and psychrotropic bacteria, reduced pH, peroxide value. Thiobarbituric acid value, better sensory scores than control sample	[25]
Egg	Gum Arabic, black cumin seed oil and rosemary essential oil	20 % gum Arabic (w/v), 2:8(w/w) black cumin seed oil. 1%, 2% and 3% of rosemary essential oil	Increased shell thickness, yolk index, Haugh unit, albumen foaming capacity, delaying foam deterioration, increased shelf life, effective against microorganisms especially Gram-positive bacteria	[26]
Egg	Chitosan and lysozyme	1% chitosan with lysozyme (0,10,20 and 60% w/w)	Increased Haugh unit, yolk index, eggshell breaking strength, albumen viscosity, foaming capacity reduced albumen pH, weight loss, extended shelf life	[27]
Egg	Chitosan and soybean oil	Ratio of soybean oil and chitosan are 60:40, 50:50	Increased Haugh unit, yolk index, emulsion capacity, decrease in albumen pH,	[28]

		and 40:60	weight loss than uncoated sample	
Kashar Cheese	Black cumin oil	2% and 4%	Increased browning, meltability, stretchiness, springiness, chewiness, organic acids, aromatic compounds, reduced pH, hardness, adhesiveness, slowed down the reduction rate of aw	[29]
Kashar Cheese	Whey protein isolate (WPI) and ginger essential oil	5% w/v WPI and 1.5% w/v ginger oil	Increased fat content, decreased pH, hardness, weight loss, microbial load, improved shelf life. Addition of ginger essential oil reduced the water vapor permeability	[30]
Kashar Cheese	Chitosan, sodium caseinate, transglutaminase enzyme	2% Chitosan, 10 % (w/v) sodium caseinate and 10 U/g transglutaminase enzyme	Increased hardness, cohesiveness, chewiness, adhesiveness, Reduced mold and yeast count, springiness, dry matter, pH, total nitrogen content, water soluble nitrogen content, trichloroacetic acid-soluble nitrogen (non protein nitrogen), phosphotung	[31]

			stic acid-soluble nitrogen (amino nitrogen), lipolysis value than the control sample	

2.5 THERMAL PROPERTIES

The glass transition temperature (T_g) is a crucial thermophysical property in evaluating edible films and edible coatings, as it governs the transition from a rigid, glassy state to a flexible, rubbery phase. This transition directly impacts permeability of the material to water vapor and gases. Above the T_g, increased free volume and molecular mobility facilitate greater diffusion of small molecules, thereby influencing the barrier performance of the packaging system [32].

Elevated temperatures enhance polymer chain mobility and vacancy migration, thereby improving the ability of the coating to inhibit environmental stressors. Thus, permeability and protective efficacy are closely tied to the thermal behavior of the polymer matrix, with implications for food preservation and shelf-life extension [13].

In bioactive-enriched systems, the thermal analysis of milk protein-based edible films containing 1. 27% (w/v) black cumin (*Nigella sativa*) essential oil revealed a distinct endothermic peak at approximately 130°C. This peak reflects a phase transition associated with polymer–oil interactions and the energy required to disrupt intermolecular associations. Volatile and phenolic constituents of the oil may contribute to altered thermal stability and plasticization effects within the matrix [13].

Overall, assessing T_g and related transitions is essential for optimizing the barrier and mechanical properties of edible packaging systems, particularly those incorporating functional bioactive substances under varying storage and processing conditions.

2.6 SENSORY EVALUATION

The incorporation of bioactive compounds into packaging matrices may exert unintended effects on the sensory characteristics of food products, primarily due to direct physicochemical interactions with intrinsic food components. Such interactions can influence flavor, aroma, texture, and overall acceptability, necessitating careful formulation strategies [19].

In a recent study, black cumin (*Nigella sativa*) essential oil was incorporated into soy protein isolate-based edible films using both Pickering emulsion and nanoemulsion delivery systems at 5% w/w of soy protein isolate. The sensory properties of 2 cm × 2 cm bread slices wrapped in these films were evaluated over a storage period of 9 days. Although normal staling and oxidative processes caused a progressive reduction of sensory parameters of all bread samples during storage, cumin oil-coated samples consistently exhibited better sensory characteristics relative to the control that was wrapped with low density polyethylene (LDPE). Particularly, the nanoemulsion-based film provided the least deterioration in the organoleptic attributes of the bread; it exhibited a reduction of 1.33 units of overall acceptability- from 5 to 3.67, compared to 3 units for control samples. This suggests that the nanoemulsion-based films may mitigate sensory degradation and retain freshness by facilitating uniform dispersion and controlled release of volatile compounds [19].

Furthermore, the sensory characteristics of pomegranate arils coated with a starch and black cumin oil-based edible coating demonstrated superior taste score compared to the control sample. All samples demonstrated a progressive decrease in sensory scores during the 12-day storage period; however, the coated sample exhibited a markedly lower reduction (20%) compared to the control sample (60%). Nevertheless, elevating the concentration of black cumin oil from 300 ppm to 600 ppm resulted in a decrease in sensory scores [33]

3. FUTURE GOALS

The incorporation of agricultural derivatives into food packaging systems has garnered substantial scientific interest, primarily due to their potential to improve environmental sustainability and reduce dependence on petroleum-based synthetic materials. Edible films and edible coatings developed using spice-derived constituents, notably black cumin (*Nigella sativa*), are increasingly recognized for their reduced ecological footprint and lower toxicological risk profiles when compared to conventional packaging substrates [2].

Despite these advantages, the functional stability of bioactive compounds embedded within such matrices presents a significant challenge. These constituents are prone to degradation under oxidative stress, fluctuating pH conditions, photolytic exposure, and elevated thermal regimes, which may compromise their efficacy and shelf-life [2]. Furthermore, the mechanical robustness of biodegradable edible films and coatings often falls short of that exhibited by synthetic analogues, thereby constraining their utility in commercial packaging applications where tensile strength and barrier performance are critical.

The inclusion of black cumin oil or extract may also introduce pronounced organoleptic attributes—such as intense aroma or flavor—that risk masking or altering the inherent sensory profile of the packaged food. This sensory interference can influence consumer perception and acceptance, specifically in products with delicate or neutral flavor matrices. Particular attention should be directed towards their impact on product color, texture, and flavor, as these parameters are critical to both functional performance and consumer satisfaction [8].

Table 1 summarizes the current applications of black cumin-enriched edible films and coatings across diverse food systems. Although black cumin enriched edible films and edible coatings show promise, several limitations hinder industrial adoption such as,

- **Scalability:** Most studies remain at laboratory scale. Industrial production requires process optimization (casting, extrusion, spray-coating) to ensure reproducibility, stability of bioactive compounds and integration into existing packaging line [34].
- **Regulatory Approval:** Compliance with food safety authorities (FSSAI, FDA, EFSA) is essential. Migration limit, toxicological evaluation and labelling must be clarified, particularly given the dual role of black cumin as flavoring and functional ingredient [34].
- **Industrial Feasibility**: Cost competitiveness with plastics, consumer acceptance of sensory changes, and performance under real storage conditions remain unresolved. Pilot trials and techno-economic analyses are needed to assess shelf life, mechanical and barrier properties [35].

Addressing these issues with process engineering, regulatory alignment and industry academia collaboration will be critical for translating black cumin based edible films from prototypes to viable commercial packaging solutions. Life cycle assessment (LCA) of the edible packaging system is another crucial tool for selecting packaging material, investigating the direct and indirect impact of the packaging system and evaluating the biodegradability of the material. Additionally, market research and consumer acceptability surveys are also essential for comprehending the need for these environmentally friendly packaging options and aligning their traits with expectations of the consumers [35,36].

Therefore, further research is required to elucidate the physicochemical interactions between black cumin-derived bioactive substances and other formulation components. Future investigations should prioritize:

1. Encapsulation strategies (e.g., nanoemulsion, liposome or cyclodextrin complexes) to increase the oxidative and thermal stability of black cumin bioactive substances within edible matrices [37].
2. Advanced mechanical reinforcement approaches, including blending with polysaccharides (chitosan, pectin) or protein-based biopolymers to improve tensile strength and barrier properties [38].
3. Controlled release system that regulates the migration of bioactive compounds, thereby balancing antimicrobial efficacy with minimal sensory interference [37].
4. Systematic sensory evaluation protocols to quantify the influence of black cumin constituents on product aroma, flavor, and consumer acceptance across different food categories [38].
5. Multiscale modelling and simulation studies to determine interactions between spice derived compounds and matrix components under varying storage and processing conditions.

Such targeted methodological improvements will not only strengthen the functional performance of black cumin enriched edible films but also accelerate their translation into scalable, commercially viable packaging solutions [8].

4. CONCLUSION

Recent scientific investigations into the integration of *Nigella sativa* (black cumin) into food packaging matrices have underscored its potential to significantly enhance the functional attributes of packaged food products, particularly in terms of antioxidant activity, antimicrobial efficacy, and shelf-life extension. The incorporation of black cumin-derived bioactive compounds into edible films and edible coatings has demonstrated promising results in modulating oxidative stability, microbial load, and sensory preservation across various food categories.

Beyond its functional contributions, the utilization of black cumin in packaging formulations represents a strategic advancement towards reducing reliance on petroleum-based synthetic materials. By leveraging agricultural derivatives with inherent bioactivity, such systems align with the principles of green chemistry and circular economy, thereby fostering the development of more sustainable and environmentally responsible food packaging technologies.

This review has delineated the multifaceted roles of black cumin in edible packaging systems, including its physicochemical interactions, barrier enhancement capabilities, and influence on mechanical and sensory properties. However, despite these encouraging findings, several challenges persist. The stability of bioactive compounds under processing and storage conditions, potential sensory interference, and limitations in mechanical robustness require further investigation.

Comprehensive, interdisciplinary research is essential to address these constraints and to optimize formulation parameters, delivery systems (e.g., nanoemulsions, encapsulation), and compatibility with diverse food matrices. Future studies should also explore the scalability, regulatory compliance, and consumer acceptance of black cumin-enriched packaging systems to facilitate their transition from experimental prototypes to commercially viable solutions.

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