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Original Scientific Paper

Chia mucilage-based nanoemulsion coatings with sage essential oil for improving the oxidative stability and shelf life of fresh turkey breast

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A R T I C L E I N F O

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A B S T R A C T

This study evaluated chia mucilage (CM)-based edible coatings enriched with sage essential oil (SEO) nanoemulsions for improving oxidative stability, microbial safety, and quality of turkey breast strips during refrigerated storage. Coating solutions (C, CS1: CM + 0.5% SEO, CS2: CM + 1% SEO, CS3: CM + 1.5% SEO) were analyzed for total phenolic content (TPC), total antioxidant activity (TAA), and antimicrobial activity. TPC and TAA values increased with SEO concentration, with CMS3 reaching 139.13 mg GAE/g and 55.53% scavenging activity. Although disk diffusion assays showed limited direct antimicrobial activity, the controlled release of SEO during storage provided effective microbial inhibition. In turkey meat samples, the evaluated parameters included coating yield, color parameters (L*, a*, b*), lipid oxidation (TBARS), total mesophilic aerobic bacteria (TMAB) counts, and sensory attributes. CMS2 and CMS3, compared with the other coating solutions, exhibited higher coating yield (96.24% and 94.68%), better color stability, and lower lipid oxidation. After 12 days at 1 °C under MAP, CMS3 reduced TBARS by ~60% (0.41 vs. 1.03 mg MDA/kg) and TMAB counts by 1 log unit, supporting its potential as a clean-label preservation strategy.

1. Introduction

The limited shelf life of poultry products, particularly turkey meat, is primarily attributed to its high moisture and protein content, which accelerates microbial spoilage and oxidative deterioration (*Baltic et al.*, 2019). As a valuable source of high-quality dietary protein with low fat content, essential amino acids, and beneficial long-chain polyunsaturated fatty acids, turkey meat is increasingly favored by health-conscious consumers (*Marangoni et al.*, 2015; *Keykhosravy et al.*, 2020). However, due to regulatory restrictions, the use of synthetic preservatives is not permitted in fresh meat products, which renders them more vulnerable to spoilage and underscores the need for the development of effective and natural preservation approaches (*Shaltout*, 2024).

In recent years, edible coatings have gained attention as an innovative approach to improving the quality, safety, and shelf life of perishable foods. These coatings form a thin, protective layer on the surface of food, which can modulate gas exchange, reduce moisture loss, and serve as a carrier for bioactive compounds such as antioxidants and antimicrobials (*Valencia-Chamorro et al.*, 2011; *Chen et*

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al., 2021). Among natural bioactives, essential oils have been widely studied for their potent antimicrobial and antioxidant properties; however, their direct incorporation into foods is limited due to volatility, hydrophobicity, and strong sensory attributes (*Prakash et al.*, 2018; *Sharma et al.*, 2022).

To address these challenges, essential oils are increasingly being encapsulated in nanoemulsion-based coatings, which improve their stability, dispersion, and controlled release (*Choi & McClements*, 2020; *Thakur et al.*, 2024). Such nanoemulsion coatings not only preserve the transparency and appearance of foods, but also effectively slow down oxidative rancidity and microbial growth during storage (*Shokri et al.*, 2020; *Mushtaq et al.*, 2023). Moreover, plant-derived hydrocolloids like chia mucilage have demonstrated excellent water-holding capacity and matrix-forming ability, further enhancing the structural and functional properties of these coatings (*Baraketi & Khwaldia*, 2024).

In this context, the present study investigates the application of chia mucilage-based edible coatings enriched with varying concentrations of sage essential oil (SEO) nanoemulsions, applied via the dipping method, on turkey breast meat. The study evaluates their effects on oxidative stability, microbial quality, and sensory attributes during refrigerated storage, offering valuable insights for the development of sustainable, natural, and clean-label preservation strategies for poultry products.

2. Materials and methods

Materials: Fresh turkey breast fillets were purchased from a local butcher shop in İzmir, Türkiye, on the day of processing. Sage essential oil (SEO) was obtained from Doğal Yağlar A.Ş. (İstanbul, Türkiye). Chia seeds (*Salvia hispanica* L.) were sourced from Organik Tarım Ürünleri Ltd. (İzmir, Türkiye) for mucilage extraction. Tween 80 (HLB 15) and all analytical grade chemicals were supplied by Sigma-Aldrich (St. Louis, MO, USA).

Preparation of Chia Mucilage and Nanoemulsions: Chia mucilage (CM) was prepared following the method of *Akhavan et al.* (2022) with minor modifications. Chia seeds were hydrated in distilled water (1:10, w/v) at 45 °C under constant stirring for 15 min, followed by centrifugation (4100 rpm, 15 min). The viscous mucilage layer was collected, filtered, and stored at 4 °C until use. Nanoemulsions containing SEO (0.5%, 1%, or 1.5%, w/w) were produced by blending SEO with Tween 80 (1%, w/w) and distilled water, pre-homogenizing (Ultra-Turrax, 12,000 rpm, 2 min), and then applying high-pressure homogenization (120 MPa, 3 passes) to achieve submicron droplet sizes (*Ghosh et al.*, 2013). The nanoemulsions were subsequently mixed with 10% (w/w) CM and stored at 4 °C for 12 h before coating.

Coating Application: Turkey breast strips (1 cm thick) were trimmed of visible fat and connective tissue and immersed in the coating solutions (1:3 sample-to-solution ratio) for 10 min at 4 ± 1 °C to ensure that the cold chain was maintained throughout the process. Excess solution was allowed to drain on stainless-steel racks for 30 min (chilled condition). Control samples (CONT) were immersed in distilled water. All samples were packaged using modified atmosphere packaging (MAP; 50% CO_2, 50% N_2) with a Henkelman Boxer42 system and stored at 1 °C for 12 days. Five experimental groups were prepared: CONT (control, distilled water), CM (10% chia mucilage), CMS1 (10% CM + 0.5% SEO), CMS2 (10% CM + 1% SEO), and CMS3 (10% CM + 1.5% SEO).

Analyses: Coating solutions were evaluated for total phenolic content (TPC) using the Folin-Ciocalteu method, expressed as mg gallic acid equivalent (GAE)/g (*Singleton et al.*, 1999), total antioxidant activity (TAA) using the DPPH radical scavenging assay (*Brand-Williams et al.*, 1995), and minimum inhibitory concentration (MIC) against *Escherichia coli* and *Staphylococcus aureus* using the broth microdilution method (*CLSI*, 2018). Meat samples were assessed for coating yield (*Shokri et al.*, 2020), color parameters (L*, a*, b*) using a colorimeter (*Hunt et al.*, 1991), lipid oxidation by thiobarbituric acid reactive substances (TBARS) expressed as mg MDA/kg (*Tarladgis et al.*, 1960), and total mesophilic aerobic bacteria (TMAB) counts on Plate Count Agar incubated at 30 °C for 48 h (*ISO*, 2013). Sensory evaluation was performed by a trained panel (n=10) to assess appearance, color, texture, juiciness, and overall acceptability on a 9-point hedonic scale. All measurements were performed in triplicate, and data were analyzed by ANOVA and Tukey's test at a significance of $p < 0.05$.

3. Results and discussion

Coating solution analyses: The total phenolic content (TPC) and total antioxidant activity of the coating solutions increased significantly with the rising concentration of sage essential oil (Table 1).

Due to its high content of phenolic compounds and terpenoids, SEO markedly enhanced the antioxidant potential of the coating matrix. Particularly, the coatings containing 1% and 1.5% SEO exhibited significantly higher TPC values compared to the CM (chia mucilage only) formulation ($p < 0.05$). Similarly, DPPH radical scavenging activity (TAA) showed a concentration-dependent increase, indicating that lipid-soluble phenolic constituents and volatile components in the nanoemulsions improved the radical-quenching ability of the coatings. The antioxidant properties of the coatings are linked bioactive compounds such as borneol, monoterpenes (α- and β-thujenes), eucalyptol, α-caryophyllene (humulene), and β-caryophyllene (*Ghorbani & Esmaeilizadeh*, 2017).

The disk diffusion assay revealed that the coating solutions exhibited limited or no direct antimicrobial effect (Figure 1). This can be attributed to the low diffusion capacity of hydrophobic compounds in the agar medium and the encapsulation of SEO within the nanoemulsion matrix, which restricts its immediate release. Therefore, the antimicrobial efficiency of the coatings is expected to be more pronounced on the surface of meat products through a controlled release mechanism during storage.

Table 1. Total Antioxidant Activity and Total Phenolic Content (TPC) of Coating Solutions

Coating Solution	DPPH(%)	Total phenolic compounds(mg GAE/g)
C	50.20± 0.61^{c}	3.54±0.32^{d}
CS1	50.94±0.57^{c}	23.8±0.23^{c}
CS2	53.4±0.23^{b}	77.8±0.17^{b}
CS3	55.53±0.19^{a}	139.13±0.5^{a}

C: Chia mucilage only; CS1: 10% CM + 0.5% sage essential oil (SEO); CS2: 10% CM + 1% SEO; CS3: 10% CM + 1.5% SEO. Different letters (a–d) within the same column indicate statistically significant differences ($p < 0.05$).

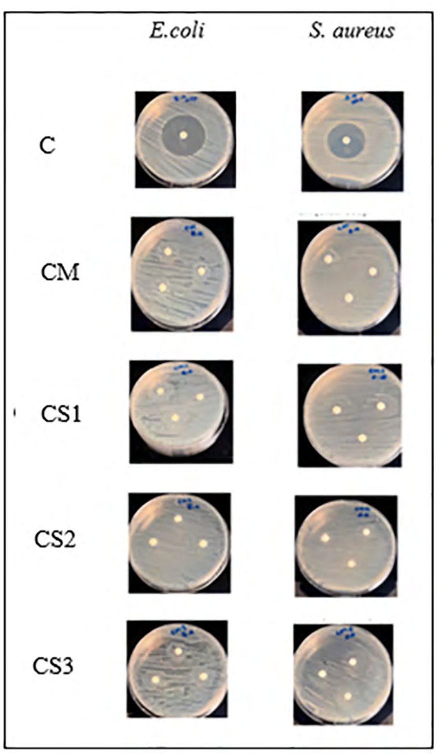

Figure 1. Antimicrobial activity of coating solutions against *Escherichia coli* and *Staphylococcus aureus*. C: Chia mucilage only; CS1: 10% CM + 0.5% sage essential oil (SEO); CS2: 10% CM + 1% SEO; CS3: 10% CM + 1.5% SEO.

Turkey breast analyses: The coating yield ranged from 93.60% (K) to 96.24% (CMS2). The highest yield was recorded in CMS2 (10% chia mucilage + 1% SEO), which was significantly higher than the control and CM groups ($p < 0.05$). The presence of chia mucilage and SEO nanoemulsions likely enhanced the adhesion of the coating film onto the meat surface due to increased viscosity and emulsifying capacity. Conversely, the control group had the lowest yield, as it lacked a polysaccharide matrix to retain the coating solution. On day 0, L* values (lightness) ranged from 44.58 (CMS3) to 48.56 (CM) (Table 2). The inclusion of SEO, particularly at 1.5%, slightly reduced lightness (lower L*), indicating a mild darkening effect likely due to the inherent color of the essential oil. The a* (redness) values showed a slight decrease in all coated groups compared to the CONT, possibly due to the coating acting as a barrier to oxygen, thereby slowing the formation of oxymyoglobin. These findings are consistent with previous reports, where oregano essential oil coatings (*Zheng et al.*, 2023) and cinnamon essential oil nanoemulsions (*Wang et al.*, 2021) also maintained color stability in chicken fillets. The b* (yellowness) values decreased with higher SEO levels, with CMS3 showing the lowest b* value (2.02), indicating that SEO incorporation can subtly shift surface color, but not to an unacceptable degree.

Table 2. Coating yield and color parameters of turkey breast meat coated with chia mucilage based nanoemulsions

Sample	Coating yield (%)	L*	a*	b*
cont	93.60 ± 0.20^{c}	45.85±0.36^{b}	4.14±0.13^{a}	4.01±0.93^{a}
CM	94.38 ± 0.48 ^{bc}	48.56±0.63^{a}	3.54±0.37^{b}	3.12±0.22^{ab}
CMS1	94.82 ± 1.02 ^{bc}	48.50±0.50^{a}	3.64±0.09^{b}	3.40±0.80^{b}
CMS2	96.24 ± 0.89 ^{a}	47.31±0.45^{ab}	3.42±0.59^{b}	2.34±0.44-^{c}
CMS3	94.68 ± 0.58 ^{bc}	44.58±0.85^{c}	3.62±0.75^{b}	2.02±0.35^{c}

Legend: **CONT:** Turkey breast strips coated with water, **CM:** Turkey breast strips coated with 10% chia mucilage, **CMS1:** Turkey breast strips coated with 10% chia mucilage + 0.5% sage essential oil, **CMS2:** Turkey breast strips coated with 10% chia mucilage + 1% sage essential oil, **CMS3:** Turkey breast strips coated with 10% chia mucilage + 1.5% sage essential oil. Different letters (a–e) within the same column indicate statistically significant differences ($p < 0.05$).

TBARS values, reflecting lipid oxidation via malondialdehyde (MDA) formation, increased during refrigerated storage for all groups (Figure 2). On day 0, values were 0.22–0.24 mg MDA/kg with no significant differences ($p > 0.05$). By day 12, the control group reached 1.03 mg MDA/kg, about 2.5 times higher than its initial value, indicating advanced oxidation. In contrast, SEO-coated samples (CMS1–CMS3) showed strong inhibition, with CMS3 (1.5% SEO) achieving the lowest value (0.41 mg MDA/kg), a ~60% reduction compared to the control. This effect results from the antioxidant phenolics in SEO and the oxygen-barrier properties of chia mucilage. While storage time significantly affected TBARS ($p < 0.05$), coated groups, especially CMS2 and CMS3, displayed much slower oxidation, confirming the synergistic protection offered by CM-SEO coatings. In line with our results, other researchers have also reported lower TBARS or MDA values when essential oils and edible coating or active packaging applications were used on meat products (*Gautam et al.*, 2023; *Zimoch-Korzycka & Jarmoluk*, 2017; *Amiri et al.*, 2019; *Fiore et al.*, 2021). Throughout the 12-day storage period, TMAB counts gradually increased in all groups, reflecting normal microbial growth in chilled poultry. The control reached 5.70 log CFU/g by day 12, nearing the spoilage limit, whereas coatings with SEO significantly suppressed microbial proliferation. CMS3 (1.5% SEO) achieved the lowest TMAB count (4.60 log CFU/g), about 1 log lower than the control (Figure 2). The antimicrobial effect of sage essential oil compounds (*Speranza et al.*, 2013), aided by their slow release from the nanoemulsion and the protective chia mucilage matrix (*Barazandegan*, 2022) kept microbial levels in CMS2 and CMS3 below 5 log CFU/g during storage. Sensory evaluation results indicated that all parameters' scores remained similar across all treatments (Figure 2).

4. Conclusion

The application of chia mucilage-based coatings enriched with SEO nanoemulsions significantly improved the oxidative and microbial stability

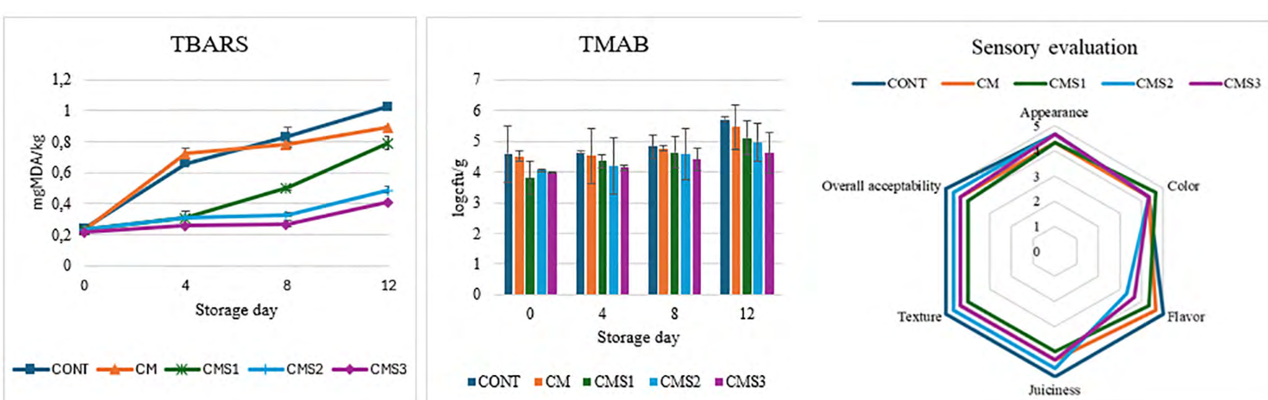

Figure 2. Changes in lipid oxidation (thiobarbituric acid reactive substances (TBARS), mg MDA/kg) and total mesophilic aerobic bacteria (TMAB, log CFU/g) and sensory evaluation of turkey breast strips coated with chia mucilage based nanoemulsions

of turkey breast meat during storage. CMS3 (1.5% SEO) exhibited the most effective performance, achieving the lowest TBARS values and a notable reduction in TMAB counts while preserving surface color and coating yield. These results indicate that the synergistic effects of chia mucilage and SEO provide strong antioxidant and antimicrobial protection, delaying quality deterioration. Therefore, such coatings hold potential as sustainable, clean-label solutions for extending the shelf life of poultry products. Further research should explore sensory evaluations and industrial-scale applications.

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