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Biodegradable Films Incorporated With Peels of Jatobá (*Hymenaea courbaril* L.) and Pomegranate Fruit (*Punica granatum* L.) Extracts for Preserving Chicken Breast Fillets

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ABSTRACT

The use of biodegradable packaging for food preservation is a sustainable alternative for preserving perishable foods such as chicken fillet, which has a short shelf life even under refrigerated conditions. In this context, the present study aimed to develop biodegradable films incorporated with extracts from jatobá and pomegranate fruit peels for the preservation of chicken fillet at 4°C for 21 days. The chicken fillets were wrapped with films containing chitosan (CH) with or without jatobá extract (CHJE) or pomegranate extract (CHPE) and analyzed for weight loss, color, pH, lipid oxidation, and counts of total aerobic mesophilic bacteria and molds and yeasts. Weight losses were obtained in fillets with films (41%, 154%, and 181% for samples with CH, CHJE and CHPE films, respectively than without film) than without film (696%). The films promoted a significant reduction in lipid oxidation and microbial degradation on chicken. The counts of total aerobic mesophilic bacteria and molds and yeasts were reduced by up to 4.0 and 2.3 log CFU/g, respectively, in chicken with films containing extracts, especially the CHPE film; the shelf life was extended by 17 days compared to chicken without film (4 days). Considering the high perishability of chicken fillet, the results indicate that this environmentally friendly primary packaging can be applied to extend the product's shelf life under refrigerated storage conditions. Furthermore, these films only containing chitosan and low concentrations of jatobá or pomegranate peel extracts considerably extended the refrigerated storage of chicken fillets, when compared to other studies with films containing natural extracts (maximum of 12 days).

1 | Introduction

Chicken is one of the most consumed meats in the world due to its lower cost compared to beef and its versatility. In 2024, Brazil stood out as the second largest chicken fillet producer in the world, at around 15.3 million tonnes, with around 5 million tonnes exported (Embrapa 2024). The nutritional composition of chicken fillet, and consisting of free amino acids, fats, vitamins, minerals and moisture, provides a favorable environment for the growth of psychotrophic microorganisms in both fresh and processed meat during refrigerated storage. Despite storage at low temperatures, the shelf life of this product is short due to the action of microorganisms, which cause physicochemical and sensory changes that are not acceptable to consumers, such as color changes, unpleasant odors and sliminess (Katiyo et al. 2020).

In this context, new technologies have been developed to improve the preservation of perishable meats, such as the use of biodegradable films. These films are made with polymers,

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such as chitosan, which is biodegradable and non-toxic, has antifungal activity, and prevents weight and moisture loss in vegetables (Ribeiro et al. 2024; Nahar et al. 2025). These materials reduce the environmental impact caused by traditional petroleum-based packaging, which represents a major obstacle to sustainable development due to its slow degradation in the environment. The incorporation of fruit peel and seed extracts, which are generally rich in antioxidant and/or antimicrobial compounds, such as phenolic acids and flavonoids, has also improved the functionality of films in food preservation (Ribeiro et al. 2024; Nahar et al. 2025).

Some researchers have applied films of various materials to preserve chicken fillet such as: gelatine-based films containing chitosan nanofibres and ZnO nanoparticles (Amjadi et al. 2019), starch-based edible film incorporated with torch ginger inflorescence essential oil (Marzlan et al. 2022), mango peel-based film containing tea polyphenols, sodium carboxymethyl cellulose and sodium alginate (Chen et al. 2024), gelatine-based composite film incorporating lactoferrin-nisin nanoparticles (Liu et al. 2025), gelatine film containing turmeric extract (Huda et al. 2025), antibacterial hydrogel film prepared with chitosan, gelatin and lysine (Li et al. 2025), chitosan-based edible films incorporated with free, single, and double nanoemulsions of *Oliveria decumbens* essential oil and eggplant anthocyanins (Shiryanpour et al. 2025). In general, the films are incorporated with components that need to be previously synthesized, which can contribute to the high final cost of the material. Furthermore, in the reported studies, the authors evaluate the shelf life of chicken fillet for 6, 9, or a maximum of 12 days of storage.

One way to obtain functional and cost-effective films would be to incorporate fruit waste extracts that have antioxidant and/or antimicrobial properties. Fruit waste is commonly discarded as waste or fed to animals. In this context, Soares and Santana (2024a, 2024b) have shown excellent antioxidant and antimicrobial properties of chitosan-based films incorporating pomegranate or jatobá fruit peel extract, demonstrating potential for application in foods that can easily deteriorate due to oxidation or microbial processes, such as chicken fillet. Some studies have shown the antioxidant and antimicrobial potential of jatobá and pomegranate peel extracts. Pomegranate peel extract contains compounds rich in bioactive molecules, such as ascorbic acid, ellagic acid, ellagitannins, gallic acid, and punicalagin, responsible for bioactivity, particularly in preventing oxidative stress (Lavado and Cava 2024). Researchers have also shown that pomegranate peel extract incorporated in edible coatings or films can reduce respiration rates, oxidation and degradation of components related to the color and flavor of food products (Mohlamonyane et al. 2024). Jatobá peel possesses approximately 70% procyanidins (Veggi et al. 2014), compounds that have shown strong antimicrobial activity, especially against gram-positive bacteria (Gross et al. 1999). Scaramussa et al. (2022) have obtained high antioxidant activity of hydroalcoholic peel extracts (between 223.37 and 415.77 μmol Trolox/g dry residue by ABTS, DPPH and FRAP) and excellent antibacterial inhibition against *Pseudomonas aeruginosa*, *Staphylococcus aureus*, *Bacillus cereus*, *Bacillus subtilis*, *Escherichia coli*, *Salmonella Typhimurium*, *Enterococcus faecalis* and *Salmonella Enteritidis*. Choubaki et al. (2025) have developed a smart film containing chitosan, gelatin, nano zinc oxide and nanocapsules of pomegranate flower extract for evaluating the freshness of fish meat. In comparison to essential oils (EOs), substances widely used in film formulations, the extracts can be easily obtained from fruit peels by faster extraction methods than the hydrodistillation technique used to obtain EOs. Furthermore, the extracts from natural sources are a sustainable alternative to synthetic preservatives.

Few reports were found on films containing extract applied in the preservation of chicken fillet. Huda et al. (2025) showed DPPH radical scavenging activity of gelatin film containing 1% and 2% turmeric extract, of approximately 44% and 53%, respectively and Chen et al. (2024) evaluated only the antimicrobial potential of gelatin-based film containing mango peel pulp and tea polyphenols against *L. monocytogenes* and *E. coli*. On the other hand, chitosan films containing 0.1% and 0.3% jatobá peel extract have shown approximately 55% and 60% DPPH activity, respectively (Soares and Santana 2024b), and the film containing 0.3% pomegranate peel extract showed 52% of the same one (Soares and Santana 2024a). Furthermore, the antimicrobial activity of these films was evaluated against *B. subtilis*, *B. cereus*, *E. faecalis*, *E. coli*, *P. aeruginosa*, *S. marcescens*, *S. enteritidis*, *S. typhimurium* and *S. aureus* strains. Films containing jatobá peel extract inhibited 59% to 94% of *S. enteritidis* and 79% to 90% of *S. typhimurium*, while chitosan films with pomegranate peel extract were more effective in inhibiting *E. coli* (maximum 52% inhibition) (Soares and Santana 2024a and 2024b). These bacteria are quite relevant, since *Salmonella* spp. is commonly found in chicken fillet, and *E. coli* is directly related to the hygienic and sanitary conditions of manipulation and storage of this product. The chitosan film containing 0.3% pomegranate peel extract inhibited 21% of *P. aeruginosa* growth (Soares and Santana 2024a), a bacterium commonly found in refrigerated meat and well-known for its resistance to antimicrobial agents (Burt 2004).

Some researchers have used film with pomegranate extract to preserve meat but not chicken fillet. Mehdizadeh et al. (2020) investigated the effect of chitosan–starch film containing pomegranate peel extract and *Thymus kotschyanus* essential oil in beef preservation. Khalid et al. (2024) developed carboxymethyl cellulose nanocomposite films incorporated with nanoparticles of flavonoids derived from pomegranate extract to preserve poultry meat and Ahmad et al. (2024) used carboxymethyl cellulose/gelatine-based edible films with pomegranate peel extract for beef preservation. Considering the existing gap in the application of biodegradable films containing bioactive extracts from fruit residues, this study is the first to evaluate the effect of chitosan-based films incorporating pomegranate and jatobá fruit peel extract on the preservation of chicken fillet stored in a refrigerator for an extended period of 21 days.

2 | Materials and Methods

2.1 | Materials

Jatobá fruit was collected in the rural area of Campo Verde (latitude 15°33′73″ south and longitude 54°77′04″ west), Mato Grosso, Brazil. Pomegranate fruit of the 'Wonderful' variety was collected in the rural area of Caetité (latitude 14°10′16″ south and longitude 42°52′28″ west), Bahia, Brazil. Chicken fillets were purchased

from a butcher in the city of São Cristóvão (Sergipe, Brazil). Chitosan was purchased from Patense Agroecologia (Patos de Minas, Minas Gerais, Brazil) with a 100-mesh particle size, pH 7.4, viscosity of 24 cPs and deacetylation degree of 82.89%. Ethanol was purchased from Neon Analytical reagents (São Paulo, Brazil). Glycerine and acetic acid were purchased from Dinâmica Contemporânea LTDA. (São Paulo, Brazil). Plate count agar and potato dextrose agar were obtained from Kasvi (Paraná, Brazil).

2.2 | Preparation of Extracts

The peels, seeds and pulp of jatobá and pomegranate were separated manually. The pomegranate and jatobá peels were separately dried at 35°C for 48 h in a greenhouse with air circulation. Then, the peels were ground in an industrial blender and sieved through 32-mesh sieves to obtain flours. The flours were separately mixed with a 70% ethanol aqueous solution in a 1:5 ratio (flour: solvent) and shaken in an orbital shaker (model TE-420, Tecnal, BR) at 200 rpm for 1 h at 30°C. Samples were then filtered through quantitative filter paper, and the extracts (supernatants) were used in the films formulations (Scaramussa et al. 2022). The jatobá and pomegranate peel extracts were named JE and PE, respectively.

2.3 | HPLC Analysis of the Extracts

The extracts were injected into a high-performance liquid chromatography (HPLC) system (Series 1200, Agilent Technologies, Waldbronn-BW, Germany) coupled to a system consisting of a hybrid triple quadrupole/linear ion trap mass spectrometer (LC-ESI-MS/MS; Q Trap 3200 Applied Biosystems/MDS Sciex, Ontario, Canada) and a Synergi 4u Polar-RP column (4.0 μm, 150 × 2.0 mm i.d.; Phenomenex, Torrance, USA). The mass spectrometer was operated in negative electrospray ionization mode (Turbo Ion Spray Applied Biosystems/MDS Sciex, Ontario, Canada) under the following conditions: capillary needle maintained at 4500 V; curtain gas up to 10 psi; source temperature up to 400°C; gas 1 and gas 2 up to 45 psi; and CAD gas, medium psi. Aliquots of extracts (10 μL) were injected at a flow rate of 250 μL/min with gradient elution at 30°C. The mobile phases were comprised of 5% (v/v) water and 95% methanol (A) and 0.1% (v/v) formic acid (B). The gradient conditions were as follows: 0–5 min, 10% A; 5–7 min, 10%–90%, A; 7–10 min, 90% A; and 10–17 min, 10% A. Compounds were identified based on matching 2–3 mass transitions for each analyte at a specific chromatographic retention time; quantification was performed using calibration curves of 45 analytical standards (Soares et al. 2025).

2.4 | Preparation of the Films

Chitosan (2 g) was mixed with a 1% (v/v) acetic acid solution (100 mL) and left to stand for 1 h. The solutions were shaken for 1 h at 25°C in an orbital shaker at 200 rpm. Glycerine solution (1.5% w/v) was added, and samples were again shaken for 30 min. The solutions were filtered, and 0.3% (w/w) JE or 0.1% (w/w) PE was added, followed by shaking at 200 rpm for 15 min at 25°C. In our previous studies (Soares and Santana 2024a, 2024b), these extract concentrations (0.3% or 0.1%) were used in chitosan-based films and a greater inhibition against a typical pathogenic bacterium of chicken fillet (*Salmonella Typhimurium*) was obtained. The film-forming solutions were poured into plastic Petri dishes and dried at 30°C for 48 h. A film without extract was also prepared under the same conditions. The films were prepared with the following combinations: chitosan film (CH), chitosan film +0.3% EJ (CHJE-0.3) and chitosan film+0.1% EP (CHPE-0.1).

2.5 | Application of Films in Chicken Fillet Preservation

The chicken fillets were cut into pieces (50 g) under aseptic conditions in a laminar flow cabinet. The samples were wrapped with films and then placed in polyethylene trays covered with plastic film. All packaging materials were previously sterilized under UV light. Chicken fillets without films and placed in trays were named as "control". The samples were stored in BOD at 4°C with 56% relative humidity for 21 days. After 0, 4, 7, 10, 15 and 21 days, samples were analyzed for their physicochemical and microbiological characteristics. The experiments were performed in triplicate with 3 replicates at each analysis time.

2.6 | Physicochemical and Microbiological Analysis During the Shelf Life of Chicken Fillets

2.6.1 | Weight Loss

Mass loss was determined by weighing the chicken fillets at time 0 (Pi) and at each storage time (Pf) (Zhou et al. 2021). Weight loss was calculated using Equation (1):

$$Weight\ loss\ (\%) = \frac{Pi - Pf}{Pi} \times 100 \quad (1)$$

2.6.1.1 | pH. From each treatment, 10-g chicken fillet samples were collected at each storage time, mixed with 50 mL of distilled water, homogenized, and filtered. The pH was determined with a digital pH meter (Manzoor et al. 2022).

2.6.2 | Lipid Oxidation

Lipid oxidation was determined according to the methodology described by Manzoor et al. (2022). A 5-g sample was mixed with 25 mL of 7.5% trichloroacetic acid, homogenized and centrifuged at 3500 rpm for 10 min. An aliquot (5 mL) of the supernatant was mixed with 5 mL of 0.02 mol/L thiobarbituric acid and heated at 96°C for 40 min. The absorbance was read at 532 nm, and the results were expressed in mg malonaldehyde (MDA)/kg of meat.

2.6.3 | Color Analysis

The color of the chicken samples was determined using a digital colorimeter (Konica Minolta, CR-10, Tokyo, Japan). The color parameters L* (luminosity), a* (redness) and b* (yellowness) (CIE 1986) were recorded at 5 random points on the surface of the chicken fillets and the results were expressed as the average of the samples analyzed.

2.7 | Microbiological Analysis

A chicken fillet sample (25 g) was placed in a sterile bag with 225 mL of 0.85% saline solution for homogenization. After preparing serial dilutions, aliquots (1 mL) were placed in Petri dishes, and plate count agar was added. The plates were incubated at 35°C for 48 h, and the number of total aerobic mesophilic bacteria was expressed in colony forming units (CFUs) per gram (Sogut and Seydim 2018). To determine the number of molds and yeasts, aliquots (0.1 mL) were added to the surface of solidified potato dextrose agar culture medium. The plates were incubated at 25°C for 7 days, and the results were expressed in CFU/g.

2.8 | Statistical Analysis

Statistical analysis was performed using Statsoft Program version 13.5.0.17 (Copyright 1984–2018, TIBCO Software Inc.). Chicken samples (50 g) were evaluated (3 replicates × 4 treatments × 3 samples per time) at 0, 4, 7, 10, 15 and 21 days of storage. The results were expressed as the mean and standard deviation. All parameters obtained in triplicate were analyzed using a two-way analysis of variance (treatments and storage time) at a probability level of $p \leq 0.05$. If the interaction between the parameters was significant, the two-way analysis was maintained. Otherwise, the parameters were analyzed separately using one-way analysis. The homogeneity and normality of variances were analyzed before ANOVA using Bartlett's test and visual analysis by the P–P (probability-probability) plot. The $p > 0.05$ indicated homogeneity of variances and the normality of the data was indicated by the alignment of the graph points to the reference line. The comparison between means was analyzed by Tukey's post hoc test at $p \leq 0.05$.

3 | Results and Discussion

3.1 | Bioactive Compounds of Jatobá and Pomegranate Fruit Peel Extracts

JE contained 4 compounds, of which ellagic acid was the major compound (0.63 mg/L), followed by protocatechuic acid (0.29 mg/L), quercetin (0.24 mg/L) and methoxyphenylacetic acid (0.08 mg/L) (Table 1). In PE, 6 compounds were detected, of which ellagic acid was also the major compound (5.53 mg/L), followed by gallic acid (4.65 mg/L), isoquercetin (3.03 mg/L), protocatechuic acid (0.14 mg/L), p-coumaric acid (0.07 mg/L) and quercetin (0.02 mg/L). Ellagic acid, a polyphenolic biomolecule consisting of four aromatic rings, is a secondary metabolite found in plants, fruit and tree bark. In plants, this compound acts as a defense mechanism against attacks by animals and microorganisms due to its astringent capacity and ability to form complexes with proteins and polysaccharides (Evtyugin et al. 2020). The bioactivity of this compound includes antioxidant, anti-inflammatory, antidiarrheic and antimicrobial effects against *Escherichia coli*, *Salmonella typhi* and *Candida albicans* (Evtyugin et al. 2020; Vigbedor et al. 2022).

Protocatechuic acid (3,4-dihydroxybenzoic acid) is a phenolic compound that damages the cell membrane structure of microorganisms and has applications as an antimicrobial in the pharmaceutical, cosmetic and food areas (Krzysztoforska et al. 2019). Wu et al. (2022) found that protocatechuic acid reduced the abundance of *Yersinia enterocolitica* in pork during storage at 4°C for 7 days. p-Coumaric acid, also known as p-hydroxycinnamic acid, and its derivatives have bioactive activities, such as antioxidant, antibacterial and antimutagenic effects, and can be metabolized by plants, playing a protective role against pathogen infection and in response to high-intensity light and ultraviolet (UV) radiation (Qiu et al. 2024). Methoxyphenylacetic acid and its derivatives found in JE are derivatives of mandelic acid and inhibit fungi (Ichiba et al. 2002). In addition, the presence of the phenylacetic acid group present in this compound is found in several pharmaceutical drugs, such as atropine, camylofin and phenacemide (Singh et al. 2022). Gallic acid is a precursor for the enzymatic synthesis of propyl gallate used as an antioxidant in oils and beverages. This compound also has wide applications in the pharmaceutical industry as an intermediate in the production of the antibacterial drug trimethoprim (Banerjee et al. 2005; Sharma and Gupta 2003).

TABLE 1 | Bioactive compounds in the extracts of jatobá peel and pomegranate peel.

Compound	Jatobá peel (mg/L)	Pomegranate peel (mg/L)
Protocatechuic acid	0.29 ± 0.10	0.14 ± 0.04
p-Coumaric acid	< LQ	0.07 ± 0.01
Methoxyphenylacetic acid	0.01 ± 0.26	< LD
Gallic acid	< LD	4.65 ± 0.92
Ellagic acid	0.63 ± 0.19	5.53 ± 0.82
Quercetin	0.24 ± 0.27	0.02 ± 0.01
Isoquercetin	< LQ	3.03 ± 0.08

Note: Values expressed as mean and standard deviation. LQ: below the limit of quantification. LD: below the limit of detection.

Quercetin is a natural flavonoid found in plants that has antioxidant, anti-inflammatory, anti-cancer, anti-angiogenic, and antidepressive properties, among others (Rajesh and Dhanaraj 2023). However, isoquercetin is the glycoside form of quercetin, which is also known for its antioxidant potential (Kang et al. 2023). The presence of antioxidant and antimicrobial compounds in the extracts highlighted their potential to add bioactive properties to chitosan films.

3.2 | Effects of Films on Weight Loss, pH and Lipid Oxidation of Chicken Fillets

Chicken fillets without film and with CH, CHJE and CHPE film were stored at 4°C for 21 days and evaluated for weight loss, pH and lipid oxidation (Figure 1). Weight loss in meat products is an important quality factor and is related to the amount of evaporated water and release of the so-called "meat juice" due to hydrolysis and degradation

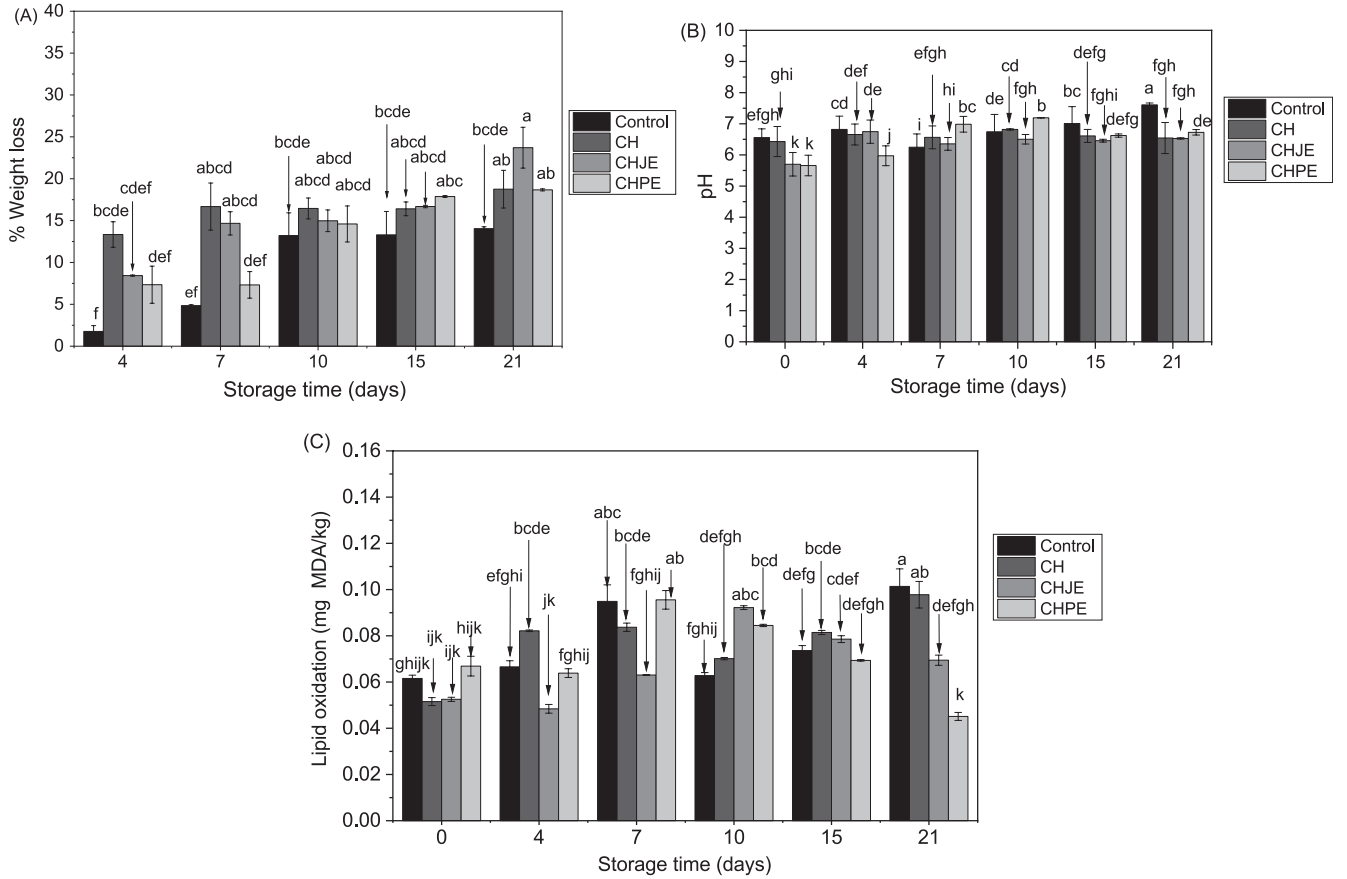

FIGURE 1 | Weight loss (A), pH (B) and lipid oxidation (C) of chicken breast fillets wrapped with and without chitosan films, stored at 4°C for 21 days. Control: chicken without film; CH: chicken with chitosan film; CHJE: chicken with chitosan film + jatobá peel extract; CHPE: chicken with chitosan film + pomegranate peel extract. [a-k]Different letters indicate that the samples differed statistically ($p \leq 0.05$), according to Tukey's test. Samples of 50 g of chicken fillet (three samples per day) were used in three replicates for each treatment.

processes by microorganisms during the storage period, resulting in changes in texture, color and flavor (Saricaoglu and Turhan 2019; Korany et al. 2024). For weight loss, the interaction between treatments and storage time was significant ($p \leq 0.05$) and, thus, was considered for comparison by Tukey's test. The data showed homogeneity ($p = 0.27$) and normality (most points aligned with the reference line).

The weight loss of the samples increased during storage ($p < 0.05$) for all treatments (Figure 1A). On the last day, the weight loss was 14.0%, 18.7%, 23.7%, and 18.7% for chicken without film (control) and with CH, CHJE and CHPE films, respectively. This result may be due to the greater affinity of the films for the water released from the chicken due to their hydrophilic nature. The greater weight loss of the chicken with the CHJE film may probably be due to the interaction of compounds of the extract with the polymer matrix, resulting in the presence of free spaces that facilitated the passage of water vapor molecules, indicating greater weight loss of this sample compared to the others. Another hypothesis is that the presence of the jatobá peel extract may have made the film more hydrophilic, absorbing water from the meat and consequently promoting greater weight loss. Comparatively Thakur et al. (2024) obtained weight losses between 18% and 22% in chicken fillet wrapped with gelatin or gelatin and chitosan-lactate or gelatin, chitosan and curcuma hydroethanolic extract films after 10 days of storage Meanwhile in the present study, weight losses were lower in chickens with films, as they did not exceed 15% on the 10th day of storage.

The pH is another parameter used to measure the freshness of chicken fillet (Zhao et al. 2022). In the present study, the interaction between treatment and storage time was significant ($p \leq 0.05$) and the data showed homogeneity ($p = 0.99$) and normality (most points aligned with the reference line). The pH of the samples from all treatments increased slightly over time, ranging from 5.7–7.6 ($p \leq 0.05$) (Figure 1B). The highest pH (7.6) was obtained by chicken without film on the last day of storage, differing significantly from the other samples ($p \leq 0.05$). The films were efficient in maintaining chicken with a pH around 6.5 and 6.7 on the 21st day. The lowest values were obtained in chicken with CH and CHJE films, which showed no differences ($p > 0.05$). Thakur et al. (2024) also obtained a higher pH in chicken without film during storage at 4°C for 10 days. Shiryanpour et al. (2025) also obtained increased pH with maximum values of 6.30 to 6.35 in chicken fillets wrapped with chitosan-based edible films incorporated with single and double nanoemulsions of *Oliveria decumbens* essential oil and eggplant anthocyanins during 12 days of storage at 4°C. The increase in pH in the control sample (chicken without film) may be due to the presence of amino compounds, such as ammonia, amines, dimethylamine and trimethylamine, resulting from amino acid degradation or

acidic metabolite formation due to the action of microorganisms (Zhao et al. 2022; Ranjbar et al. 2023).

The lipid oxidation of chicken was evaluated by quantifying MDA, a compound resulting from the oxidation of polyunsaturated fatty acids in hydroperoxides, which are the compounds responsible for the unpleasant flavor of meat (Ahmadi et al. 2019; Zhang et al. 2024). The interaction between treatments and time was significant ($p \leq 0.05$) and the data showed homogeneity ($p = 0.092$) and normality (most of the points aligned with the reference line). The lipid oxidation values ranged from 0.048–0.101 mg MDA/kg (Figure 1C). On the last day, samples with films containing jatobá or pomegranate extract (CHJE and CHPE) showed the lowest values of lipid oxidation, differing from the others ($p \leq 0.05$). This result may be related to the presence of antioxidant compounds in the extracts, such as ellagic acid, gallic acid, protocatechuic acid, quercetin and isoquercetin, which inhibit the initiation of free radical chain reactions by donating hydrogen atoms, resulting in a decrease in TBARS values (Thakur et al. 2024). Studies have shown that ellagic acid has greater antioxidant activity than low-molecular-molecule polyphenols. The mechanism of antioxidant action of these compound involves its ability to promote gene expression of molecules involved in antioxidant defense, as well as suppress oxidative stress by inhibiting the expression of proteins, enzymes, and transcription factors involved in this process (Evtyugin et al. 2020).

Sogut and Seydim (2018) and Thakur et al. (2024) obtained about 1.428% and 156% increase in lipid oxidation, respectively in chicken fillet wrapped with nanocellulose/chitosan/grape seed extract-based film and gelatin/chitosan-lactate/curcuma hydroethanolic extract-based film, respectively, after 15 and 10 days of storage. On the other hand, the chicken treated with CHJE and CHPE showed only increased lipid oxidation of 23% and 80%, respectively on the 10th day of storage (in relation to day 0). After 15 days, the CHJE-treated meat showed a 60% increase in lipid oxidation, and a 20% reduction (compared to the 10th day) for CHPE-treated meat was obtained. According to previous studies performed by Soares and Santana (2024a) and (2024b), the antioxidant potential of these films increased by 6 to 10 times when jatobá or pomegranate extracts were added.

3.3 | Effects of Films on the Color of Chicken Fillets

The visual appearance of chicken with and without films during storage indicated signs of deterioration from the 7th day onwards in the chicken without film, with liquid being released on the surface of the sample (Figure 2). In relation to color, the samples maintained the same visual appearance until the 10th day; however, the samples wrapped with CHJE and CHPE showed brownish spots at the ends of the meat from the 15th day onwards, which are characteristic of the color of the extracts.

For color parameters L*, a*, and b* evaluated during chicken storage, the interaction between treatment and time was not significant ($p > 0.05$); therefore, these factors were analyzed separately (Table 2). The L* values were normal and homogeneous ($p = 0.29$ and 0.71 in relation to treatment and time). The a* and b* values showed normality and homogeneity

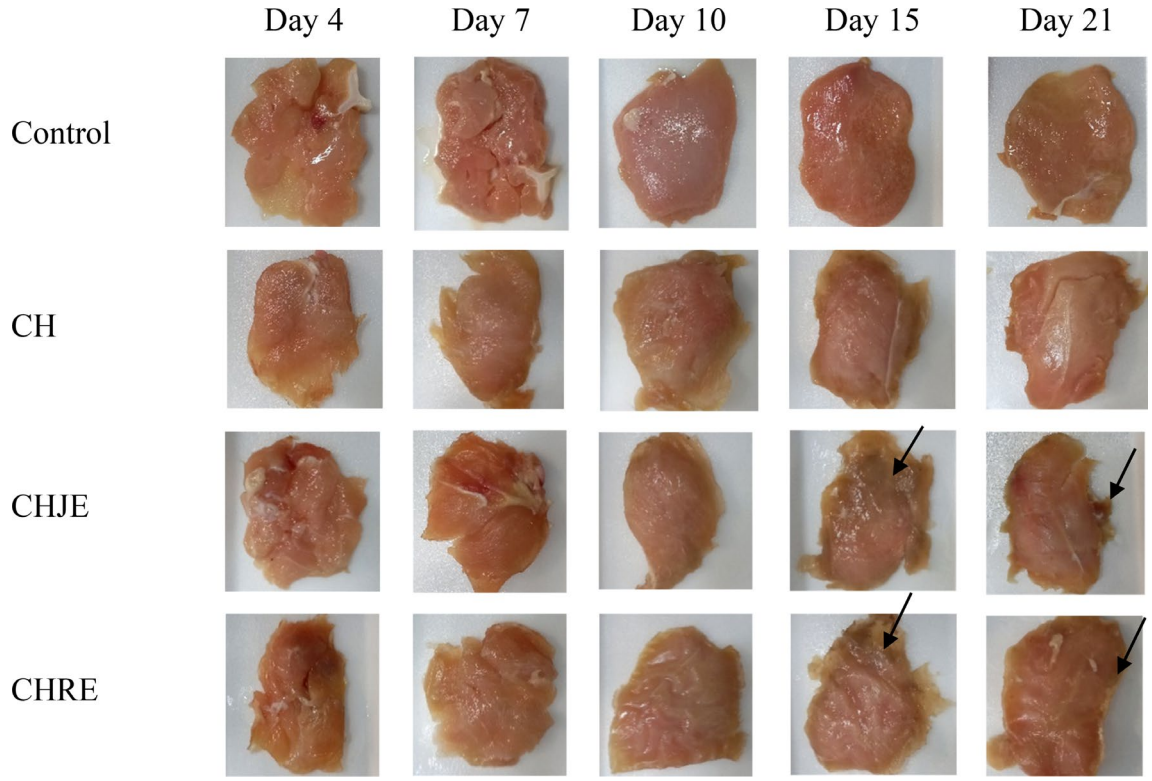

FIGURE 2 | Visual appearance of chicken breast fillets stored at 4°C for 21 days without film (control) and samples that were wrapped with chitosan film (CH), chitosan film incorporating jatobá peel extract (CHJE) and chitosan film incorporating pomegranate peel extract (CHPE). The arrows indicate the brownish spots on the meat.

TABLE 2 | Luminosity (L*), a* and b*parameters of chicken samples with and without chitosan films during 21 days of storage at 4°C.

		Storage time (days)					
Parameters	**Treatment**	**0**	**4**	**7**	**10**	**15**	**21**
L*	Control	36.30 ± 2.64 ^{aA}	39.80 ± 0.86 ^{abA}	34.58 ± 1.36 ^{bA}	35.20 ± 0.24 ^{bA}	37.19 ± 0.25^{bA}	35.89 ± 0.01 ^{abA}
	CH	40.23 ± 0.81 ^{aAB}	31.98 ± 0.44 ^{abAB}	37.42 ± 1.84 ^{bAB}	29.50 ± 3.46 ^{bAB}	34.14 ± 0.18 ^{bAB}	35.15 ± 0.47 ^{abAB}
	CHJE	36.86 ± 2.56 ^{aB}	31.41 ± 0.13 ^{abB}	28.37 ± 0.25 ^{bB}	35.19 ± 1.93 ^{bB}	31.37 ± 0.45 ^{bB}	34.98 ± 0.56 ^{abB}
	CHPE	35.68 ± 0.72 ^{aAB}	35.47 ± 0.01 ^{abAB}	32.98 ± 0.30 ^{bAB}	36.16 ± 0.48 ^{bAB}	30.97 ± 0.05 ^{bAB}	29.90 ± 0.30 ^{abAB}
a*	Control	9.59 ± 0.23 ^{A}	8.60 ± 0.04 ^{A}	9.47 ± 0.62 ^{A}	7.57 ± 0.48 ^{A}	9.74 ± 0.48 ^{A}	7.48 ± 0.36 ^{A}
	CH	10.77 ± 1.17 ^{A}	8.88 ± 0.04 ^{A}	7.47 ± 0.27 ^{A}	7.83 ± 0.23 ^{A}	8.51 ± 0.08 ^{A}	8.44 ± 0.88 ^{A}
	CHJE	11.77 ± 1.57 ^{A}	9.76 ± 0.42 ^{A}	10.09 ± 0.08 ^{A}	7.10 ± 0.16 ^{A}	8.41 ± 0.41 ^{A}	8.57 ± 0.79 ^{A}
	CHPE	10.51 ± 0.16 ^{A}	9.21 ± 0.15 ^{A}	7.54 ± 0.02 ^{A}	7.60 ± 0.08 ^{A}	9.26 ± 0.58 ^{A}	7.90 ± 0.02 ^{A}
b*	Control	25.90 ± 0.64 ^{A}	29.01 ± 0.62 ^{A}	26.78 ± 0.34 ^{A}	26.86 ± 0.10 ^{A}	27.51 ± 0.63 ^{A}	25.95 ± 0.09 ^{A}
	CH	27.18 ± 0.44 ^{A}	25.50 ± 0.56 ^{A}	24.60 ± 0.82 ^{A}	24.43 ± 0.25 ^{A}	27.01 ± 0.60 ^{A}	27.02 ± 0.66 ^{A}
	CHJE	29.98 ± 0.56 ^{A}	26.03 ± 0.01 ^{A}	25.44 ± 0.27 ^{A}	26.30 ± 0.42 ^{A}	26.78 ± 0.61 ^{A}	27.06 ± 0.18 ^{A}
	CHPE	30.27 ± 1.07 ^{A}	26.71 ± 0.33 ^{A}	24.96 ± 0.14 ^{A}	26.27 ± 1.03 ^{A}	26.93 ± 0.53 ^{A}	25.00 ± 0.46 ^{A}

Note: Control: chicken without film; CH: chicken with chitosan film; CHJE: chicken with chitosan film + jatobá peel extract; CHPE: chicken with chitosan film + pomegranate peel extract. For each parameter, $^{A\text{-}B}$uppercase letters in the same column refer to the comparison between treatments at the same time. $^{a\text{-}b}$Lowercase letters in the same row refer to the comparison of treatments during storage time. Different letters indicate that the samples differed statistically ($p \leq 0.05$), according to Tukey's test. The ANOVA was not used for a* and b* values in relation to storage time, since the data not showed normality and homogeneity.

only in relation to treatment ($p = 0.069$ and 0.77, respectively). Consequently, the ANOVA analysis was not applied to these parameters as a function of storage time. For each treatment, the a* and b* parameters did not vary significantly during storage ($p > 0.05$). Comparing the samples at each time, the chicken without film and with CH and CHPE films showed the highest luminosity values (L*), showing no differences ($p > 0.05$) on the 21st day. The lowest luminosity obtained in chicken with CHJE may be due to the transfer of extract components to the surface of the chicken. Sogut and Seydim (2018) obtained reduced luminosity in chicken samples after 6 days of storage at 4°C with chitosan films with or without grape seed extract. These authors attributed this fact to the probable transfer of moisture from the surface to the films. Serrano-León et al. (2018) also did not observe significant changes in the color of chicken wrapped in chitosan films with peanut shell or pink pepper residue extract. Conversely, Nandi and Guha (2024) obtained a significant reduction in a* values in chicken fillet packaged with starch films containing *Piper betle* L. leaf extract. Thakur et al. (2024) reported a significant increase in b* in chicken wrapped with film containing turmeric extract, which may have been related to the color of the extract that migrated to the surface of the samples.

3.4 | Effect of Films on the Microbiological Quality of Chicken Fillets

Chicken fillet is highly susceptible to microbial contamination due to its high moisture content (Yildiz et al. 2022). In the present study, the microorganism counts in the chicken samples with and without films were influenced by the interaction between treatment and storage time ($p \leq 0.05$). All results showed homogeneity ($p = 0.87$ and 0.078 for total bacteria and mold and yeast counts, respectively) and normality (most points aligned with the reference line). The counts increased over time for all samples but were significantly higher for chicken without film ($p \leq 0.05$) (Figure 3). The samples wrapped with CHJE and CHPE reached approximately 6.8 and 5.0 log CFU/g of bacterial counts against 8.4 and 9.0 for samples with CH and control (chicken without film), respectively in the last day of storage ($p \leq 0.05$). The CHPE was the film more effective to inhibit mold and yeast, maintaining counts of 6.9 log CFU/g in the 21st day ($p \leq 0.05$). According to the International Commission on Microbiological Specifications for Food, the maximum limit for total bacterial count in chicken fillet is 7.0 log CFU/g (Moradi et al. 2020). Based on this, chicken without film showed a shelf life of up to 4 days, and chicken with CH, CHJE and CHPE film maintained microbiological quality for up to 10, 21 and 21 days, respectively. Researchers have also reported the degradation of amino acids, such as cysteine, cystine and methionine, which contain sulfur, at bacterial counts above 8.0 log, resulting in the formation of volatile compounds, such as hydrogen sulphide, dimethyl sulphide and dimethyl disulphide, which generate off-flavors (Ellis et al. 2004). Regarding fungi, the presence of the genera *Aspergillus* and *Penicillium* is common in meat products, spreading from the air, equipment, raw materials, ingredients and handlers (Bernardi et al. 2021). If we also consider 7.0 log as the limit for fungal contamination, chicken without film would have a shelf life of up to 7 days, while

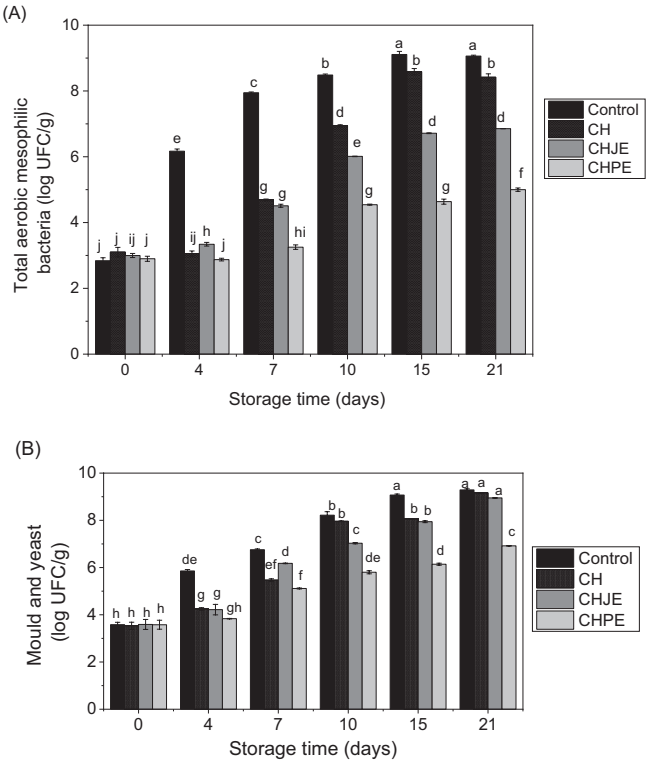

FIGURE 3 | Total aerobic mesophilic bacteria (A) mold and yeast (B) counts in chicken breast fillets wrapped with and without chitosan films stored at 4°C for 21 days. CH: Chicken with chitosan film; CHJE: Chicken with chitosan film + jatobá peel extract; CHPE: Chicken with chitosan film + pomegranate peel extract. [a-h]Different letters indicate that the samples differed statistically ($p \leq 0.05$), according to Tukey's test.

chicken with CH, CHJE and CHPE film would maintain quality for up to 7, 10 and 21 days, respectively.

Mirsharifi et al. (2023) reduced bacteria by up to 4.0 log in chicken stored with film containing almond gum, polyvinyl alcohol, and chitosan at 4°C for 21 days. Chen et al. (2024) showed a reduction of up to 1.5 log in bacterial counts in chicken wrapped with alginate and cellulose film containing mango peel extract stored at 4°C for 12 days and Farahani et al. (2025) obtained a reduction of 2.1 log of total bacteria counts on the 7th day of storage at 4°C in chicken fillet coated with 3% clove extract. In comparison, CHJE and CHPE films showed reductions of 2.2 and 4.0 log in total bacteria, respectively, on the 21st day of storage. Also, researchers such as Babolanimogadam et al. (2024) extended by 12 days the shelf life of beef patties by wrapping them with polylactic acid films incorporated with 1% ajwain essential oil and Salari and Yazdany (2025) extended by 15 days the shelf life of ostrich meat coated with 2% chitosan and 1.5% fennel extract, while in the present study the shelf life of chicken breast fillets wrapped with films was extended by 21 days.

The efficiency of CHJE and CHPE films on the microbiological quality of chicken was probably due to the presence of antimicrobial compounds (p-coumaric acid, gallic acid, ellagic acid, isoquercetin, 4-hydroxymethylbenzoic acid and protocatechuic acid) identified in JE and PE extracts. The presence of hydroxyl groups in the structure of phenolic compounds promotes the

interaction with membranes and active sites of bacterial cells, affecting microbial growth (Lima et al. 2019). For example, gallic acid can disrupt the cell membrane and block the absorption of substances such as iron, polysaccharides and amino acids (Zhou et al. 2025) and p-coumaric acid is a cinnamic acid that has the ability to bind to the double helix of bacterial DNA, preventing cellular processes and the expression of *Rec*A (Ojha and Patil 2019). These results demonstrate that the addition of low JE and PE concentrations in the film formulation can ensure the microbiological integrity of chicken fillet for prolonged storage times.

The CHJE and CHPE films have shown promise as primary packaging for preserving chicken fillet. A preliminary analysis of the production cost of films considered the prices of each component required to produce 100 L of film-forming solution, as follows: for CHJE, chitosan US$ 145; glycerol US$ 9.2; acetic acid US$ 10.0; ethanol US$ 0.47; and jatobá peel US$ 0.43; and for CHPE, chitosan US$ 145; glycerol US$ 9.2; acetic acid US$ 10.0; ethanol US$ 0.16; and pomegranate peel US$ 0.32. Therefore, the total cost would be approximately US$ 1.65 per liter of solution for each film. Considering that 1 L of film-forming solution yields approximately 900 g of film, the cost would be US$ 0.18 per 100 g of film. This analysis demonstrated a possible economic advantage of producing CHJE and CHPE films by packaging companies.

4 | Conclusions

Chitosan films containing pomegranate peel extract and jatobá peel extract were applied to preserve chicken fillet at 4°C for 21 days. The films were efficient in maintaining a constant pH and color parameters and reducing moisture loss in chicken fillets during storage. The addition of the extracts improved the antioxidant and antimicrobial activities of the films. Chicken fillets with CHJE or CHPE films showed the lowest lipid oxidation values on the last day of storage. Particularly, the CHPE film reduced 4.0 and 3.0 log of total bacteria and molds and yeasts, respectively, keeping within microbiological standards for up to 21 days. Considering the physicochemical, microbiological, and particularly visual results of chicken fillets wrapped with CHJE or CHPE films, a shelf life of 10 to 15 days under refrigerated storage is suggested. This means a minimum increase of 6 days in storage time compared to the control sample (without film). The use of films combined with refrigeration would be a desirable alternative to preserve chicken fillets in food service establishments, where rapid consumption of this product is required. Freezing can be an alternative method for long-term preservation and, when combined with the use of films, could minimize undesirable effects encountered during refrigeration, such as meat browning. Films with low concentrations of pomegranate or jatobá fruit peel extracts appear to be an "environmentally friendly" alternative for conservation, promoting an increase in the shelf life of chicken fillets without significantly altering the main physicochemical characteristics of the product. In addition to chicken fillet, these films containing natural extracts demonstrate potential for preserving various meat products. as also reported by Choubaki et al. (2025), which developed smart films incorporating zinc oxide nanoparticles and pomegranate flower extract nanocapsules for fish freshness monitoring. Furthermore, the low cost of preparing films would be an additional attraction for packaging companies. The limitation of these films would only be related to the availability of fruits to obtain the extracts for their preparation.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

The data that support the findings of this study are available from the corresponding author upon reasonable request.

References

Ahmad, H. N., Y. Yong, S. Wang, N. Munawar, and J. Zhu. 2024. "Development of Novel Carboxymethyl Cellulose/Gelatin-Based Edible Films With Pomegranate Peel Extract as Antibacterial/Antioxidant Agents for Beef Preservation." *Food Chemistry* 443: 138511. https://doi.org/10.1016/j.foodchem.2024.138511.

Ahmadi, A., A. Salehi, A. Dadmeher, et al. 2019. "The Effect of Banana Leaf Package on the Shelf Life of Rainbow Trout Fillet in Comparison With Plastic Bags." *Bioscience Journal* 35: 503–508. https://doi.org/10.14393/BJ-v35n2a2019-42730.

Amjadi, S., S. Emaminia, M. Nazari, S. H. Davudian, L. Roufegarinejad, and H. Hamishehkar. 2019. "Application of Reinforced ZnO Nanoparticle-Incorporated Gelatin Bionanocomposite Film With Chitosan Nanofiber for Packaging of Chicken Fillet and Cheese as Food Models." *Food and Bioprocess Technology* 12, no. 7: 1205–1219. https://doi.org/10.1007/s11947-019-02286-y.

Babolanimogadam, N., A. Akhondzadeh Basti, A. Khanjari, S. H. Sajjadi Alhashem, K. Babolani Moghadgam, and S. Ahadzadeh. 2024. "Shelf Life Extending of Probiotic Beef Patties With Polylactic Acid-Ajwain Essential Oil Films and Stress Effects on *Bacillus Coagulans*." *Journal of Food Science* 89, no. 2: 866–880. https://doi.org/10.1111/1750-3841.16864.

Banerjee, R., G. Mukherjee, and K. C. Patra. 2005. "Microbial Transformation of Tannin-Rich Substrate to Gallic Acid Through Co-Culture Method." *Bioresource Technology* 96, no. 8: 949–953. https://doi.org/10.1016/j.biortech.2004.08.004.

Bernardi, A. O., A. Stefanello, M. V. Garcia, and M. V. Copetti. 2021. "The Control of Cheese and Meat Product Spoilage Fungi by Sanitizers: In Vitro Testing and Food Industry Usage." *LWT Food Science and Technology* 144: 111204. https://doi.org/10.1016/j.lwt.2021.111204.

Burt, S. 2004. "Essential Oils: Their Antibacterial Properties and Potential Applications in Foods-a Review." *International Journal of Food Microbiology* 94: 223–253. https://doi.org/10.1016/j.ijfoodmicro.2004.03.022.

Chen, Z., R. Liu, Y. Wei, et al. 2024. "A Novel Strategy to Transform Mango Peel Waste Into Useful Product– Preparing Antibacterial Film Containing Tea Polyphenols for Chicken Breast Preservation." *LWT Food Science and Technology* 197: 115933. https://doi.org/10.1016/j.lwt.2024.115933.

Choubaki, S., H. Baghaei, and A. Mohammadi Nafchi. 2025. "Smart Indicator for Fish Freshness Monitoring: A Chitosan/Gelatin/Zinc Oxide Nanoparticle Composite Incorporating Pomegranate Flower Anthocyanin Extract Nanocapsules." *Food Science & Nutrition* 13, no. 9: e70944. https://doi.org/10.1002/fsn3.70944.

CIE. 1986. Colorimetrie, 2nd ed. Comission Internationale de L'Éclairage, Viena, Publication CIE 15.2.

Ellis, D. I., D. Broadhurst, and R. Goodacre. 2004. "Rapid and Quantitative Detection of the Microbial Spoilage of Beef by Fourier Transform Infrared Spectroscopy and Machine Learning." *Analytica Chimica Acta* 514, no. 2: 193–201. https://doi.org/10.1016/j.aca.2004.03.060.

Embrapa. 2024. Brazilian Enterprise for Agricultural Research [Empresa Brasileira de Pesquisa Agropecuaria]. https://www.embrapa.br/suinos-eaves/cias/estatisticas-frangos.

Evtyugin, D. D., S. Magina, and D. V. Evtuguin. 2020. "Recent Advances in the Production and Applications of Ellagic Acid and Its Derivatives. A Review." *Molecules* 25, no. 12: 2745. https://doi.org/10.3390/molecules25122745.

Farahani, Z. K., P. M. Shotorbani, A. A. Basti, H. Hamedi, B. Hassani, and A. M. Nafchi. 2025. "Assessing Coating With Clove Extract on Improving the Shelf Life of Chicken Fillet at Refrigeration Storage Temperature." *Food Science & Nutrition* 12, no. 8: e70786. https://doi.org/10.1002/fsn3.70786.

Gross, G. G., R. W. Hemingway, T. Yoshida, and S. J. Branham. 1999. *Plant Polyphenols 2*. Springer.

Huda, K. U., A. Ahmad, Z. Mushtaq, et al. 2025. "Development of Ultrasonic-Assisted Gelatin-Based Biodegradable Packaging Film Incorporated With Turmeric Extract for the Shelf-Life Extension of Chicken Minced Meat." *International Journal of Biological Macromolecules* 306: 141558. https://doi.org/10.1016/j.ijbiomac.2025.141558.

Ichiba, T., T. Murashi, S. Suzuki, T. Ohtsuka, and M. Masuko. 2002. "Fungicidal Activities of 2-Methoxy-2-[2-(Benzylideneaminooxym ethyl)phenyl]-N-Methylacetamide Derivatives." *Journal of Pesticide Science* 27: 223–228. https://doi.org/10.1584/jpestics.27.223.

Kang, M. J., D.-Y. Kim, Y. Baek, and H. G. Lee. 2023. "Enhancement of Antioxidant Activities and Stabilities of Quercetin and Isoquercetin Through the Combination of Nanoencapsulation and Hydrogel Incorporation." *Food Bioscience* 55: 102963. https://doi.org/10.1016/j.fbio.2023.102963.

Katiyo, W., H. L. de Kock, R. Coorey, and E. M. Buys. 2020. "Sensory Implications of Chicken Meat Spoilage in Relation to Microbial and Physicochemical Characteristics During Refrigerated Storage." *LWT-Food Science and Technology* 128: 109468. https://doi.org/10.1016/j.lwt.2020.109468.

Khalid, S. A., A. F. Ghanem, A. Abd-El-Malek, M. A. Ammar, T. El-khateib, and I. M. El-Sherbiny. 2024. "Free-Standing Carboxymethyl Cellulose Film Incorporating Nanoformulated Pomegranate Extract for Meat Packaging." *Carbohydrate Polymers* 332: 121915. https://doi.org/10.1016/j.carbpol.2024.121915.

Korany, A. M., N. S. Abdel-Atty, M. M. A. Zeinhom, and A. H. A. Hassan. 2024. "Application of Gelatin-Based Zinc Oxide Nanoparticles Bionanocomposite Coatings to Control *Listeria monocytogenes* in Talaga Cheese and Camel Meat During Refrigerated Storage." *Food Microbiology* 122: 104559. https://doi.org/10.1016/j.fm.2024.104559.

Krzysztoforska, K., D. Mirowska-Guzel, and E. Widy-Tyszkiewicz. 2019. "Pharmacological Effects of Protocatechuic Acid and Its Therapeutic Potential in Neurodegenerative Diseases: Review on the Basis of in Vitro and in Vivo Studies in Rodents and Humans." *Nutritional Neuroscience* 22, no. 2: 72–82. https://doi.org/10.1080/1028415x.2017.1354543.

Lavado, G., and R. Cava. 2024. "Antioxidant Potential of Pomegranate Peel and Acorn Cupule Extracts: A Comparative Analysis in Simulated in Vitro Digestion of Uncured Dry Sausages." *LWT-Food Science and Technology* 203: 116371. https://doi.org/10.1016/j.lwt.2024.116371.

Li, C., Y. Yang, R. Zhang, J. Wang, S. Zhong, and X. Cui. 2025. "Chitosan-Gelatin Composite Hydrogel Antibacterial Film for Food Packaging." *International Journal of Biological Macromolecules* 285: 138330. https://doi.org/10.1016/j.ijbiomac.2024.138330.

Lima, M. C., P. de Sousa, C. Fernandez-Prada, J. Harel, J. D. Dubreuil, and E. L. de Souza. 2019. "A Review of the Current Evidence of Fruit Phenolic Compounds as Potential Antimicrobials Against Pathogenic Bacteria." *Microbial Pathogenesis* 130: 259–270. https://doi.org/10.1016/j.micpath.2019.03.025.

Liu, R., J. Wang, Y. Zhang, Z. Xia, Y. Lu, and H. Hu. 2025. "Biodegradable and Gelatin-Based Composite Films Incorporating Lactoferrin-Nisin Active Nanoparticles: Preparation, Characterization, Antibacterial Applications of Cheese and Chicken." *Applied Food Research* 5, no. 1: 100883. https://doi.org/10.1016/j.afres.2025.100883.

Manzoor, A., S. Ahmad, and B. Yousuf. 2022. "Effect of Bioactive-Rich Mango Peel Extract on Physicochemical, Antioxidant and Functional Characteristics of Chicken Sausage." *Applied Food Research* 2, no. 2: 100183. https://doi.org/10.1016/j.afres.2022.100183.

Marzlan, A. A., B. J. Muhialdin, N. H. Zainal Abedin, et al. 2022. "Incorporating Torch Ginger (*Etlingera elatior* Jack) Inflorescence Essential Oil Onto Starch-Based Edible Film Towards Sustainable Active Packaging for Chicken Meat." *Industrial Crops and Products* 184: 115058. https://doi.org/10.1016/j.indcrop.2022.115058.

Mehdizadeh, T., H. Tajik, A. M. Langroodi, R. Molaei, and A. Mahmoudian. 2020. "Chitosan-Starch Film Containing Pomegranate Peel Extract and *Thymus Kotschyanus* Essential Oil Can Prolong the Shelf Life of Beef." *Meat Science* 163: 108073. https://doi.org/10.1016/j.meatsci.2020.108073.

Mirsharifi, S. M., M. Sami, M. Jazaeri, and A. Rezaei. 2023. "Production, Characterization, and Antimicrobial Activity of Almond Gum/Polyvinyl Alcohol/Chitosan Composite Films Containing Thyme Essential Oil Nanoemulsion for Extending the Shelf-Life of Chicken Breast Fillets." *International Journal of Biological Macromolecules* 227: 405–415. https://doi.org/10.1016/j.ijbiomac.2022.12.183.

Mohlamonyane, M. J., J. O. Adeyemi, and O. A. Fawole. 2024. "Pomegranate Fruit Peel: A Sustainable Bioresource in Food Preservation." *Food Bioscience* 62: 105532. https://doi.org/10.1016/j.fbio.2024.105532.

Moradi, E., M. H. Moosavi, S. M. Hosseini, et al. 2020. "Prolonging Shelf Life of Chicken Breast Fillets by Using Plasma-Improved Chitosan/Low Density Polyethylene Bilayer Film Containing Summer Savory Essential Oil." *International Journal of Biological Macromolecules* 156: 321–328. https://doi.org/10.1016/j.ijbiomac.2020.03.226.

Nahar, L., E. Habibi, G.-L. Gavril, et al. 2025. "Towards Sustainable Food Packaging Using Natural Compounds: A Review of Current Research Update." *Food and Bioproducts Processing* 150: 260–274. https://doi.org/10.1016/j.fbp.2025.01.015.

Nandi, S., and P. Guha. 2024. "Development, Characterization and Application of Starch-Based Film Containing Polyphenols of *Piper betle* L. Waste in Chicken Meat Storage." *Food Chemistry* 431: 137103. https://doi.org/10.1016/j.foodchem.2023.137103.

Ojha, D., and K. N. Patil. 2019. "P-Coumaric Acid Inhibits the *Listeria monocytogenes* RecA Protein Functions and Sos Response: An Antimicrobial Target." *Biochemical and Biophysical Research Communications* 517: 655–661. https://doi.org/10.1016/j.bbrc.2019.07.093.

Qiu, M., J. Jiang, W. Jiang, et al. 2024. "The Biosynthesis of L-Phenylalanine-Derived Compounds by Engineered Microbes." *Biotechnology Advances* 77: 108448. https://doi.org/10.1016/j.biotechadv.2024.108448.

Rajesh, R. U., and S. Dhanaraj. 2023. "A Critical Review on Quercetin Bioflavonoid and Its Derivatives: Scope, Synthesis, and Biological Applications With Future Prospects." *Arabian Journal of Chemistry* 16, no. 8: 104881. https://doi.org/10.1016/j.arabjc.2023.104881.

Ranjbar, M., M. H. Azizi Tabrizzad, G. Asadi, and H. Ahari. 2023. "Investigating the Microbial Properties of Sodium Alginate/Chitosan Edible Film Containing Red Beetroot Anthocyanin Extract for Smart Packaging in Chicken Fillet as a pH Indicator." *Heliyon* 9, no. 8: e18879. https://doi.org/10.1016/j.heliyon.2023.e18879.

Ribeiro, I. S., G. M. Maciel, D. G. Bortolini, et al. 2024. "Sustainable Innovations in Edible Films and Coatings: An Overview." *Trends in Food Science & Technology* 143: 104272. https://doi.org/10.1016/j.tifs.2023.104272.

Salari, M., and M. Yazdany. 2025. "Shelf Life Extension and Quality Improvement of Fresh Ostrich Meat by Active Chitosan Coating Enriched With Fennel Extract." *Food Science & Nutrition* 13, no. 5: e70262. https://doi.org/10.1002/fsn3.70262.

Saricaoglu, F. T., and S. Turhan. 2019. "Performance of Mechanically Deboned Chicken Meat Protein Coatings Containing Thyme or Clove Essential Oil for Storage Quality Improvement of Beef Sucuks." *Meat Science* 158: 107912. https://doi.org/10.1016/j.meatsci.2019.107912.

Scaramussa, S. A. L., L. A. Soares, and L. Santana. 2022. "Extracts From Jatobá (*Hymenaea Courbaril* L.) Peel and Seeds: Antioxidant and Antimicrobial Activities and Synergistic Effect of Extract Combinations." *Food Science and Technology International* 30, no. 2: 128–136. https://doi.org/10.1177/10820132221136589.

Serrano-León, J. S., K. B. Bergamaschi, C. M. P. Yoshida, et al. 2018. "Chitosan Active Films Containing Agro-Industrial Residue Extracts for Shelf Life Extension of Chicken Restructured Product." *Food Research International* 108: 93–100. https://doi.org/10.1016/j.foodres.2018.03.031.

Sharma, S., and M. N. Gupta. 2003. "Synthesis of Antioxidant Propyl Gallate Using Tannase From *Aspergillus Niger* Van Teighem in Nonaqueous Media." *Bioorganic & Medicinal Chemistry Letters* 13, no. 3: 395–397. https://doi.org/10.1016/S0960-894X(02)00977-0.

Shiryanpour, S., L. Nouri, M. Azizi, A. Najafi, and A. Mohammadi Nafchi. 2025. "Active Chitosan Film Containing Single and Double Nanoemulsions of Oliveira Decumbens Vent Essential Oil/Anthocyanin of Eggplant for Chicken Preservation." *Journal of Food Measurement and Characterization* 19: 7381–7403. https://doi.org/10.1007/s11694-025-03477-2.

Singh, H., P. Pinacho, M. M. Quesada-Moreno, and M. Schnell. 2022. "The Many Forms of Alpha-Methoxy Phenylacetic Acid in the Gas Phase: Flexibility, Internal Dynamics, and Their Intramolecular Interactions." *Physical Chemistry Chemical Physics* 24: 27312–27320. https://doi.org/10.1039/D2CP03962A.

Soares, L. A., A. T. Germano, L. Vitali, S. Mazzuti, and L. C. L. A. Santana. 2025. "Solid-State Fermentation as a Pre-Treatment Method for the Extraction of Bioactive Compounds From Pomegranate (*Punica Granatum* L.) and Jatobá Peel (*Hymenaea Courbaril* L.)." *Food Bioscience* 63: 105716. https://doi.org/10.1016/j.fbio.2024.105716.

Soares, L. A., and L. C. L. A. Santana. 2024a. "Physicochemical Characterization, Antioxidant and Antimicrobial Potential of Biodegradable Chitosan-Based Films Containing Pomegranate (*Punica Granatum* L.) Peel Extract." *Journal of Polymers and the Environment* 32, no. 4: 1729–1740. https://doi.org/10.1007/s10924-023-03063-x.

Soares, L. A., and L. C. L. A. Santana. 2024b. "Chitosan Films Incorporating Jatobá Fruit (*Hymenaea Courbaril* L.) Peel Extract: Physicochemical, Morphological, Thermal and Bioactive Properties." *Journal of Thermal Analysis and Calorimetry* 149, no. 10: 4479–4489. https://doi.org/10.1007/s10973-024-13011-z.

Sogut, E., and A. C. Seydim. 2018. "The Effects of Chitosan and Grape Seed Extract-Based Edible Films on the Quality of Vacuum Packaged Chicken Breast Fillets." *Food Packaging and Shelf Life* 18: 13–20. https://doi.org/10.1016/j.fpsl.2018.07.006.

Thakur, R., S. Wickramarachchi, K. Pal, and P. Sarkar. 2024. "Gelatin/Chitosan-Lactate/Curcuma Hydroethanolic Extract-Based Antimicrobial Films: Preparation, Characterization, and Application on Chicken Meat." *Food Hydrocolloids* 154: 110075. https://doi.org/10.1016/j.foodhyd.2024.110075.

Veggi, P., G. Anceski Bataglion, M. Eberlin, and M. A. Meireles. 2014. "Obtaining Phenolic Compounds From Jatoba (*Hymenaea Courbaril* L.) Bark by Supercritical -Fluid Extraction." *Journal of Supercritical Fluids* 89: 68–77. https://doi.org/10.1016/j.supflu.2014.02.016.

Vigbedor, B. Y., C. O. Akoto, and D. Neglo. 2022. "Isolation and Characterization of 3,3′-di-O-Methyl Ellagic Acid From the Root Bark of Afzelia Africana and Its Antimicrobial and Antioxidant Activities." *Scientific African* 17: e01332. https://doi.org/10.1016/j.sciaf.2022.e01332.

Wu, M., L. Tian, J. Fu, et al. 2022. "Antibacterial Mechanism of Protocatechuic Acid Against *Yersinia Enterocolitica* and Its Application in Pork." *Food Control* 133: 108573. https://doi.org/10.1016/j.foodcont.2021.108573.

Yildiz, E., A. A. Emir, G. Sumnu, and L. N. Kahyaoglu. 2022. "Citric Acid Cross-Linked Curcumin/Chitosan/Chickpea Flour Film: An Active Packaging for Chicken Breast Storage." *Food Bioscience* 50: 102121. https://doi.org/10.1016/j.fbio.2022.102121.

Zhang, A., X. Fan, X. Zeng, et al. 2024. "Enhancing Physicochemical, Antimicrobial, and Release Properties of Fish Skin Gelatin Films Using Dual-Layer Nanoparticles Loaded With Tea Polyphenols/Kojic Acid for Air-Dried Chicken Preservation." *Food Hydrocolloids* 149: 109580. https://doi.org/10.1016/j.foodhyd.2023.109580.

Zhao, Y., Z. Meng, L. Shao, R. Dai, X. Li, and F. Jia. 2022. "Employment of Cold Atmospheric Plasma in Chilled Chicken Breasts and the Analysis of Microbial Diversity After the Shelf-Life Storage." *Food Research International* 162: 111934. https://doi.org/10.1016/j.foodres.2022.111934.

Zhou, H., Z. Qi, H. Chen, X. Xue, L. Liu, and C. Wang. 2025. "Development of a Cationic Photodynamic Antibacterial Agent Based on Gallic Acid and Ethylene Glycol Diglycidyl Ether and Enriched With Hydroxyl Groups for Effective Antimicrobial Therapy." *Colloids and Surfaces B: Biointerfaces* 256: 114973. https://doi.org/10.1016/j.colsurfb.2025.114973.

Zhou, X., X. Zong, M. Zhang, et al. 2021. "Effect of Konjac Glucomannan/Carrageenan-Based Edible Emulsion Coatings With Camellia Oil on Quality and Shelf-Life of Chicken Meat." *International Journal of Biological Macromolecules* 183: 331–339. https://doi.org/10.1016/j.ijbiomac.2021.04.165.