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Effect of chitosan coating with potato peel extract on physicochemical properties and oxidative stability of beef meat

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Abstract
Lipid oxidation contributes significantly to the deterioration of the physicochemical quality of beef during refrigerated storage. The incorporation of natural antioxidants through edible coatings has been proposed as an effective strategy to mitigate oxidative processes and preserve meat quality. This study evaluated four treatments with chitosan solutions mixed with potato peel extract to coat two commercially important beef cuts: top round (PNG) and chuck (DZM). The conditions were with and without 1% potato peel extract. pH, color, water-holding capacity, texture, and oxidative stability (lipid oxidation) were measured during refrigerated storage (16 days at 4 ± 1 °C). Potato peel extract (PPE), chitosan coating solution (CCS), and chitosan coating solution + potato peel extract (CCS-PPE) were used for the identification of polyphenols and antioxidants. The results indicate that the application of the three extracts PPE > CCS-PPE showed ($p<0.05$) the presence of polyphenols, phenols, flavonoids, and chlorogenic acid, but these were absent when applied only with CCS. Furthermore, PPE > CCS-PPE exhibited free radical scavenging properties and reduced cation radical scavenging capabilities. The parameters evaluated in the meat samples at the end of storage (day 16) showed no differences in pH and b* (yellowness) values between treatments ($p>0.05$). Conversely, PNG and DZM samples treated with CCS-PPE had lower oxidation levels (TBARS) and L* (luminosity) ($p<0.05$) compared to the PNG and DZM controls, as well as higher a* (redness) values ($p<0.05$). In the PNG group, the sample showed a lower water-holding capacity (WHC) and higher texture values ($p<0.05$) compared to the other treatments. In conclusion, CCS-PPE could be an antioxidant additive for beef.
Keywords: chitosan, natural extract, phenolic compounds, bioactivity, meat.

Efecto del recubrimiento de quitosano con extracto de cáscara de papa sobre las propiedades fisicoquímicas y estabilidad oxidativa de la carne de res

Resumen
La oxidación lipídica contribuye de manera significativa al deterioro de la calidad fisicoquímica de la carne de res durante el almacenamiento refrigerado. La incorporación de antioxidantes naturales mediante recubrimientos comestibles se ha propuesto como una estrategia eficaz para mitigar los procesos oxidativos y preservar la calidad de la carne. Este estudio evaluó cuatro tratamientos con soluciones de quitosano mezcladas con extracto de cáscara de papa para recubrir dos cortes cárnicos de res de importancia comercial, Pulpa negra (PNG) y Diezmillo (DZM). Las condiciones fueron sin y con 1% de extracto de cáscara de papa. Se midieron el pH, el color, la capacidad de retención de agua, la textura y la estabilidad oxidativa (oxidación lipídica) durante el almacenamiento refrigerado (16 días a 4 ± 1 °C). El extracto de cáscara de papa (PPE), la solución de recubrimiento de quitosano (CCS) y la solución de recubrimiento de quitosano + extracto de cáscara de papa (CCS-PPE) se utilizaron para la identificación de polifenoles y antioxidantes. Los resultados indican que la aplicación de los tres extractos PPE > CCS-PPE mostraron ($p<0.05$) la presencia de polifenoles, fenoles, flavonoides y ácido clorogénico, pero ausentes al hacerlo sólo con el CCS. Además, PPE > CCS-PPE ejercen propiedades de eliminación de radicales libres y de cationes radicales, con poder reductor. Los parámetros evaluados en las muestras de carne, al final del almacenamiento (día 16), sin diferencias en los valores de pH y b* (amarillez) entre los tratamientos ($p>0.05$). Por el contrario, las de PNG y DZM tratadas con CCS-PPE tuvieron niveles de oxidación (TBARS) y de L* (luminosidad) más bajos ($p<0,05$) en comparación con los controles de PNG y DZM, así como los valores a* (enrojecimiento) más altos ($p<0.05$). En la PNG con una menor capacidad de retención de agua (WHC) y valores de textura más altos ($p<0.05$) que los de otros tratamientos. En conclusión, el CCS-PPE podría ser un aditivo antioxidante para la carne de res.
Palabras clave: quitosano, extracto natural, compuestos fenólicos, bioactividad, carne.

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Introduction

In Latin America, beef production is one of the most important activities in the livestock sector and has recently become the third most popular meat in Mexico, with per capita consumption of 16 kg in 2023, totaling 2.1 million metric tons (COMECARNE, 2024). In addition, it is a valuable source of major components, including proteins, amino acids, lipids, and fatty acids. However, oxidative deterioration of these constituents is considered one of the principal causes of quality deterioration in raw meat during refrigerated storage, which may negatively affect nutritional and physicochemical properties (Cobos & Díaz, 2015; Trabelsi *et al.*, 2019).

Synthetic antioxidants have been used to control the oxidation of raw meat; however, their uncontrolled use in meat has been related to consumer health risks. Thus, consumer preferences and perceptions of the safety of these compounds have increased (Xu *et al.*, 2021). In this regard, the recovery of antioxidant compounds, such as polyphenols, from agro-industrial residues (pomace, seeds, and peels) and their incorporation into meat and meat products has been proposed as a promising strategy to mitigate oxidative processes (Calderón-Oliver & López-Hernández, 2020).

The potato (*Solanum tuberosum* L.) is one of the world's most cultivated and consumed food crops, and its industrial processing generates potato peel residues that are considered an important source of polyphenols, including phenolic acids (*p*-coumaric, chlorogenic, caffeic, ferulic, and gallic acids), as well as flavonoids like rutin and quercetin, among others (Rodríguez-Martínez, Gullón & Yáñez, 2021). In this context, potato peel extract has been proposed as a natural preservative to enhance the oxidation stability of lamb meat (Kanatt, Chander, Radhakrishna & Sharma, 2005).

Moreover, innovations in food packaging are ongoing and align with consumers' preferences for acquiring safe, healthy food with minimal synthetic inputs. Using an active packaging system supplemented with antioxidants, such as polyphenols, is considered a strategy that, in addition to protecting the food from the external environment, also reduces oxidative processes in the meat product (Ahmed *et al.*, 2017). Edible coatings are food-grade suspensions that can be applied by spraying, spreading, or dipping, forming a clear, thin layer over the food surface upon drying. These materials represent a specific form of film applied directly to the surface of the material and are considered part of the final product (Han, 2014). For example, incorporating natural antioxidants into chitosan coatings has been reported to confer several benefits (Muñoz-Tebar, Pérez-Álvarez, Fernández-López & Viuda-Martos, 2023). Furthermore, agro-industrial residues, such as banana peel extract, have been successfully used to enhance antioxidant capacity (Zhang, Li & Jiang, 2020). Therefore, the edible coatings enriched with bioactive compounds have been proposed to improve the oxidative stability of perishable food (Ahmed *et al.*, 2017; Zhang *et al.*, 2020).

Therefore, this study aimed to valorize potato peel, an agro-industrial by-product, as a source of phenolic antioxidants and to assess the effectiveness of a chitosan-based edible coating solution enriched with this extract in improving the physicochemical properties and oxidative stability of beef during refrigerated storage.

Materials and methods

Potato peel powder

A commercial supplier (La Costeña®) in Guasave, Mexico, donated potato peel. The plant material was disinfected by submersion in a hypochlorite solution (0.1%, *v*/*v*) for 15-20 min, rinsed three times with distilled water (soaking process) for 5 min each period, and subjected to a peeling process. After, the residue was dried (35 ± 5 °C/8 days) and pulverized at 0.5 mm (hammer mill Pulvex-200, Mexico City, Mexico). The obtained powder was packed under vacuum (Food Saver®, Boca Raton, FL, USA) and stored (25 ± 1 °C) until its use and analysis.

Extraction of polyphenols

Polyphenols from potato peel powder were extracted using a mixture of 1:1 water and ethanol (Fagalab®) as solvent (1:10, *w*/*v*) by maceration-assisted method in a magnetic stirring plate (PC-620D, Coring, NY, USA) at 200 ± 1 rpm for 48 h (25 ± 1 °C), in the dark. After that, the resultant mixture was centrifuged (J2-21, Beckman, CA, USA) at 2,500× *g* for 10 min (4 ± 1 °C). The solution was filtered (Whatman no. 1 filter paper), concentrated under reduced pressure at 120 ± 1 rpm and 60 ± 1 °C (RE301, Yamato, TYO, Japan), and dried (DC401, Yamato, TYO, Japan). The obtained potato peel extract (PPE) was packed under vacuum in the dark until further analysis (Montaño-Sánchez *et al*., 2020).

Preparation of chitosan-based coating solutions

The chitosan-based coating solutions (CCS) were prepared as previously described (Montaño-Sánchez *et al*., 2020). To obtain CCS, a chitosan (75% degree of deacetylation, Sigma®) 1% solution (1%, *w*/*v*) was prepared by dissolving 10 g of chitosan in 1,000 mL of distilled water (1%, *w*/*v*) with glacial acetic acid (1%, *v*/*v*; Baker®), under magnetic stirring at 200 ± 1 rpm for 24 h (40 ± 1 °C). While to obtain CCS-PPE, 1% of PPE was incorporated into the CCS (1% solution) and homogenized under magnetic stirring at 200 ± 1 rpm for 24 h (40 ± 1 °C). The obtained coating solutions were stored at 4 ± 1 °C until further use.

Polyphenols content

Total phenolic content (TPC) of samples (PPE, CCS, and CCS-PPE) was measured by the Folin–Ciocalteu method

(Matić & Jakobek, 2021). An aliquot of 20 µL of each sample (10 mg/mL) was homogenized with 20 µL of FC–reagent (2 M, Sigma®) and 30 µL of sodium carbonate (7%, *w*/*v*; Sigma®). Afterward, 80 µL of distilled water was added to the reaction mixture and incubated (25 ± 1 °C in the dark for 1 h). The absorbance was measured at 750 nm using a spectrophotometer (Multiskan FC UV-Vis, Thermo Scientific, TYO, Japan), and the results were expressed as mg of gallic acid (Sigma®) equivalents (GAE)/g.

The total flavonoid content (TFC) of the samples was determined using the aluminum chloride method (Matić & Jakobek, 2021), with slight modifications. An aliquot of 20 µL of each sample (10 mg/mL) was homogenized with 160 µL of methanol and 20 µL of aluminum chloride (10%, *w*/*v*; Sigma®). The reaction mixture was incubated (25 ±1 °C/in the dark/30 min). The absorbance was measured at 412 nm, and the results were expressed as mg of rutin (Sigma®) equivalents (RE)/g.

The total chlorogenic acid (CGA) content of the samples was determined using the sodium–nitrite method (Griffiths, Bain, & Dale, 1992), with slight modifications. An aliquot of 20 µL of each sample (10 mg/mL) was homogenized with 200 µL of urea (0.7 M, Fagalab®), 200 µL of glacial acetic acid (0.1 M, Sigma®), and 500 µL of distilled water. After, 500 µL of sodium nitrite (0.14 M, Fagalab®) and 500 µL of sodium hydroxide (0.5 M, Fermont®) were mixed with the reaction mixture, and subsequently centrifuged (2,250× *g*/4 ± 1 °C/in the dark/10 min), (ST18R, Thermo Fisher Scientific, USA). The absorbance was measured at 510 nm, and the results were expressed as mg of chlorogenic acid (Sigma®) equivalents (CAE)/g.

Antioxidant activity tests

The free-radical scavenging activity (FRSA) of the samples was determined by the DPPH method (Ozgen, Reese, Tulio, Scheerens & Miller, 2006), with slight modifications. An aliquot of 100 µL of each sample was homogenized with 100 µL of DPPH• ethanol solution (300 µM, Sigma-Aldrich®) and incubated (50 ± 1 °C/in the dark/30 min). The absorbance was measured at 517 nm, and the results were expressed as inhibition percentage:

$$Inhibition\,(\%)=\frac{(Abs\ DPPH\ at\ 0\ min)-(Abs\ DPPH+Sample\ at\ 30\ min)}{(Abs\ DPPH\ at\ 0\ min)}x100 \quad (1)$$

The radical cation scavenging activity (RCSA) of the samples was determined using the $ABTS^{\bullet+}$ method (Ozgen *et al*., 2006), with slight modifications. An aliquot of 20 µL of each sample was homogenized with 180 µL of $ABTS^{\bullet+}$ ethanol solution (0.8 abs, Sigma-Aldrich®) and incubated (25 ± 1 °C/in the dark/10 min). The absorbance was measured at 734 nm, and the results were expressed as inhibition percentage:

$$Inhibition\,(\%)=\frac{(Abs\ ABTS\ at\ 0\ min)-(Abs\ ABTS+Sample\ at\ 30\ min)}{(Abs\ ABTS\ at\ 0\ min)}x100 \quad (2)$$

The reducing power ability (RPA) was measured by the Prussian blue method (Işıl Berker, Güçlü, Tor, Demirata & Apak, 2010), with slight modifications. An aliquot of 100 µL of each sample was homogenized with 300 µL of phosphate buffer (0.2 M, pH 6.6), 300 µL of potassium ferricyanide (1%, *w*/*v*; Sigma-Aldrich®), and incubated in a water bath (50 ± 1 °C/in the dark/20 min). Afterward, 300 µL of trichloroacetic acid (10%, *w*/*v*; Baker®) was added to the reaction mixture, which was then centrifuged (4,200× *g*/4 ± 1 °C/in the dark/10 min). Then, 100 µL of the supernatant was mixed with 100 µL of distilled water and 250 µL of ferric chloride (0.1%, *w*/*v*; Sigma®). The absorbance was measured at 700 nm, and the results were expressed as absorbance (abs 700) at the same wavelength.

Beef meat preparation and storage

Beef meat (Pulpa negra - *Semimembranosus* m. and Diezmillo - *Triceps brachii* m., 24 h *postmortem*) was procured from a local processing plant (Pegson, Sonora, Mexico). Meat cuts were excised (1.5 cm thickness) to be subjected to the four treatments in three independent experimental trials as follows:

1. PNG, non-coated Pulpa negra.
2. DZM, non-coated Diezmillo.
3. PNG-C, coated Pulpa negra with CCS-PPE.
4. DZM-C, coated Diezmillo with CCS-PPE.

The meat cuts were submerged in each treatment solution for 5 min; the excess dispersion was drained off, and the cuts were subsequently air-dried at 2 ± 1 °C for 2 h. The thickness of the edible film ranged between 0.022 and 0.026 mm in both muscles. Afterward, the samples were placed on a Styrofoam tray, wrapped with polyvinyl chloride film (17,400 cm^3 O_2/m^2/24 h/23 ± 1 °C), and stored at 2 ± 1 °C/in the dark/16 days.

Physicochemical analysis of meat

Meat samples were homogenized with distilled water (1:10, *w*/*v*) in a homogenizer (Ultraturrax T25, IKA, Germany) at 9,500 ± 1 rpm/4 ± 1 °C/1 min. The pH was measured with a potentiometer (Hanna pH-211, Rhode Island, USA) according to method 981.12 (AOAC, 2005).

The packaging material from the meat samples was removed to allow color blooming, and the meat samples were exposed to atmospheric O_2 for 30 min (4 ± 1 °C), following the guidelines of the American Meat Science Association (AMSA, 2012). After blooming, instrumental color measurements were recorded on the bloomed surface of the samples using a spectrophotometer (CM-508d, Konica Minolta, TKY, Japan) with a D65 illuminant and 10° standard observer. Color

parameters were expressed as: lightness, L*; a*, redness; b*, yellowness (López-Marcos, Bailina, Viuda-Martos, Pérez-Alvarez & Fernández-López, 2015).

The water-holding capacity (WHC) of meat samples was determined (Sutton, Ellis, Lan, McKeith & Wilson, 1997). Meat samples (5 g) were placed on fine-mesh nylon, inserted into 50 mL tubes with screw caps, and centrifuged at 4,200× *g*/4 ± 1 °C/10 min. The WHC was calculated:

$$WHC\ (\%) = \frac{(Initial\ weight) - (Final\ weight)}{(Initial\ weight)}\ x\ 100 \qquad (3)$$

Meat samples were thawed at 4 ± 1 °C/24 h and grilled on a preheated plate at 160-180 ± 1 °C (George Foreman®, Salton Inc., MI, USA) until they reached an internal temperature of 71 ± 1 °C. A digital thermometer was inserted into the geometric center of each sample to monitor internal temperature. The cooked samples were cooled to room temperature for 2 h and stored at 4 ± 1 °C for 24 h. After that, the meat was cut into prims 1 x 1 x 3 cm and subjected to the Warner-Bratzler Shear Force (WBSF) protocol. The setting was pre-test speed = 100 mm/min, test speed = 200 mm/min, post-test speed = 600 mm/min, distance = 30 mm, and force = 5 g. The results were expressed as Kg-f (Silva, de Moura, Ramos & Ramos, 2017).

Oxidative stability of meat

Lipid oxidation was determined by the thiobarbituric acid reactive substances (TBARS) method (Pfalzgraf, Frigg & Steinhart, 1995). Meat samples were homogenized at 4,500 ± 1 rpm/4 ± 1 °C/1 min with trichloroacetic acid (10%, *w*/*v*), centrifuged at 2,500× *g*/4 ± 1 °C/20 min, and the supernatant was filtered (Whatman no. 1 filter paper). After that, 2 mL of TBA solution (20 mM, Baker®) was mixed with 2 mL of the filtered supernatant, and the mixture was incubated at 98 °C for 20 min. After cooling, the absorbance was measured at 531 nm. TBARS values were calculated from a 1,1,3,3–tetramethoxypropane (Sigma®) standard curve and expressed as mg of malondialdehyde per kg of meat (mg MDA/kg).

Statistical analysis

Mean ± standard deviation (SD) values were used as descriptive statistics. Data from polyphenol content and antioxidant activity were subjected to one-way ANOVA. In contrast, data from meat quality assays were subjected to a two-way ANOVA with treatments and storage period as main effects. Tukey-Kramer tests were carried out for multiple comparisons of means at $p<0.05$. Principal component analysis (PCA) was performed to evaluate relationships among the analyzed variables (SPSS, version 21).

Results and discussion

Polyphenol content and antioxidant activity

Table I reports the polyphenol content and antioxidant activity of PPE, CCS, and CCS-PPE. The results showed that PPE had higher ($p<0.05$) TPC, TFC, and CGA values compared to CCS + 1% PEE, as well as the highest FRSA, RCSA, and RPA values ($p<0.05$). Respect polyphenols and antioxidant activity CCS + 0% was absent. In this context, the addition of PPE to CSS decreased the polyphenol content and antioxidant activity.

TPC and TFC methods involve the formation of a complex when electrons are transferred to Mo(VI) from polyphenols, as well as the reaction of flavonoids-$AlCl_3$ complex formation, respectively (Matić & Jakobek, 2021). The CGA method

Table I. Polyphenol content and antioxidant activity of CCS, PPE, and CCS-PPE.

Item	Samples		
	Chitosan coating solution	Potato peel extract	CCS-PPE
Polyphenols			
TPC (mg GAE/g)	n.d.	80.17 ± 1.00	9.39 ± 1.08
TFC (mg RE/g)	n.d.	34.99 ± 0.77	n.d.
CGA (mg CAE/g)	n.d.	40.50 ± 1.11	3.07 ± 0.24
Antioxidant activity			
FRSA (% inhibition)	n.d.	75.92 ± 0.89	64.24 ± 0.80
RCSA (% inhibition)	n.d.	42.84 ± 1.19	17.17 ± 0.68
RPA (absorbance 700 nm)		0.09 ± 0.01	n.d.

TPC = total phenolic content; TFC = total flavonoids content; CGA, chlorogenic acid contents; FRSA = free-radical scavenging activity; RCSA = radical cation scavenging activity; RPA = reducing power ability; CCS = chitosan coating solution; PPE = potato peel extract; CCS-PPE = CCS with 1% of PPE. n.d. = no detected. Values expressed as mean ± SD (n = 6). Superscripts indicate significant treatment differences through storage time effects ($p<0.05$).

involves the formation of a stable complex between ortho-dihydroxyphenols and sodium nitrite (Griffiths *et al.*, 1992). In antiradical assays, the FRSA method involves the H-atom donation from polyphenols with hydrophobic properties to the DPPH• radical, forming DPPH-H. In contrast, the RCSA implies electron transfer from lipophilic and hydrophilic polyphenols to the ABTS•+ radical cation, yielding a stable radical (Echegaray *et al.*, 2021). In addition, the RPA method involves the ferricyanide oxidation of each polyphenol to form ferrocyanide as a reduction product, which is stabilized by ferric ions, resulting in Prussian blue-colored products (Işıl Berker *et al.*, 2010).

Potato peels are an important source of polyphenols, including phenolic acids (*p*-coumaric, chlorogenic, caffeic, ferulic, and gallic) and flavonoids (rutin and quercetin). These compounds are recovered using conventional extraction methods, such as the Soxhlet method, as well as non-conventional methods, including microwave-assisted, pressurized liquid, supercritical fluid, and ultrasound-assisted extractions. Additionally, these compounds exhibit antioxidant properties (Rodríguez-Martínez *et al.*, 2021). In agreement with our study, it has been reported that CCS incorporated with green tea extract improved phenolic composition and free-radical scavenging activity; however, if we compare with the crude extract, a reduction in the content of polyphenols and antioxidant activity can be observed due to the interaction between the matrix and the natural additive (Montaño-Sánchez *et al.*, 2020). Thus, the results of the present study indicate that CSC incorporated with PPE can be used as a natural additive to enhance the oxidative stability of meat.

Physicochemical changes in meat during storage

pH values of meat samples

pH is an important quality trait of meat that can affect color, WHC, and texture parameters (Andrés-Bello, Barreto-Palacios, García-Segovia, Mir-Bel & Martínez-Monzó, 2013). The pH values were not significantly affected by treatment ($p = 0.229$) but were significantly influenced by storage time and the interaction effect ($p = 0.001$) (**Figure 1**). On day 0 of storage, a reduction in pH ($p<0.05$) was observed in PNG-C and DZM-C compared with the controls (PNG and DZM). Although pH values increased ($p<0.05$) for all treatments during storage, no significant differences ($p>0.05$) were found between treatments on the last day of storage (day 16).

A previous study demonstrated that maintaining pH above 5.5 is important to avoid adverse effects on shelf life, color, WHC, and tenderness of meat (Carrasco-García *et al.*, 2020). A reduction in the initial pH values of meat samples treated with CCS could be attributed to the extract components (Cao, Song, Dong, Yu & Han, 2023). In agreement with our study, non-significant differences were found in beef patties containing CCS and CCS with 0.5% green tea extract after storage at 4 °C for 8 days

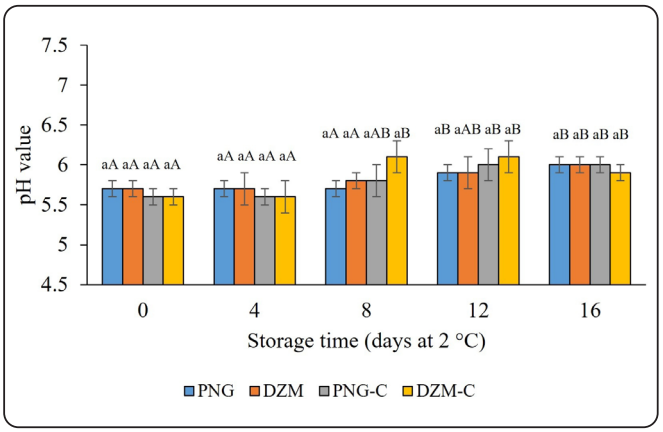

Figure 1. Effect of treatment and storage time on meat samples' pH values. Values expressed as mean ± SD (n = 6). PNG, non-coated Pulpa negra; DZM, non-coated Diezmillo; PNG-C, coated Pulpa negra with CCS-PPE; DZM-C, coated Diezmillo with CCS-PPE. Lowercase superscripts indicate significant treatment differences on each sampling day, while capital superscripts indicate significant differences on storage time ($p<0.05$).

(Özvural, Huang & Chikindas, 2016). In contrast, previous work reported that the inclusion of 2% CCS with *Satureja khuzestanica* Jamzad essential oil in lamb meat increased pH values (13.9%) after storage (4 °C/16) in comparison to control samples (Pabast, Shariatifar, Beikzadeh & Jahed, 2018). While the inclusion of 2% CCS with *Sataria multiflora* essential oil in beef meat (*Quadriceps femoris*) increased pH values (approx. 8%) after storage (4 °C/16 days) compared to control samples (Langroodi, Tajik, Mehdizadeh, Moradi, Kia & Mahmoudian, 2018). However, an increase in the pH values of meats could be associated with the utilization of amino acids by bacteria, and consequently, the undesirable production of ammonia and amines (Custódio, Vasconcelos-Neto, Theodoro, Chisté & Gloria, 2018).

Color values of meat samples

The surface color is a crucial quality trait of meat that significantly influences the initial impression when it is purchased (Calderón-Oliver & López-Hernández, 2020). The L*, a*, and b* values were significantly affected by treatment, storage time, and the interaction effect ($p = 0.001$), (**Figure 2**). In this study, the color surface of meat samples showed that initial L*, a*, and b* values were not affected ($p>0.05$). However, L* and a* parameters increased and decreased ($p<0.05$) for all treatments during storage time, while non-significant differences ($p>0.05$) were found in b* values through storage time for all samples. After 16 days of storage, PNG-C and DZM-C exhibited the lowest L* values and the highest a* values compared to the control samples ($p<0.05$).

It has been demonstrated that high L* values are associated with light scattering promoted by protein denaturation, while

low a* values are a result of myoglobin oxidation (Cao *et al.*, 2023). In agreement with our study, it has been demonstrated that beef patties incorporated with CCS with 0.5 % of green tea extract showed lower L* values and higher a* values than CSC without antioxidants after storage (4 °C/8 days). In contrast, the inclusion of CCS at 0.5% in beef patties reduces b* values (Özvural *et al.*, 2016).

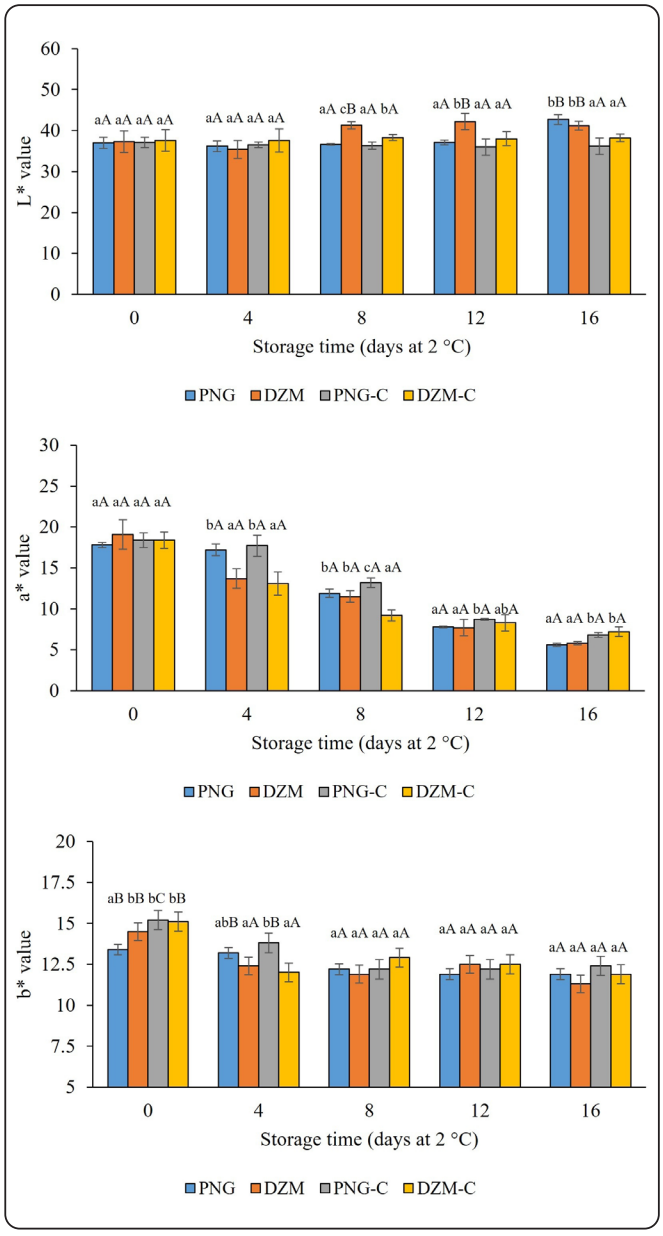

Figure 2. Effect of treatment and storage time on meat samples' color values. Values expressed as mean ± SD (n = 6). PNG, non-coated Pulpa negra; DZM, non-coated Diezmillo; PNG-C, coated Pulpa negra with CCS-PPE; DZM-C, coated Diezmillo with CCS-PPE. Lowercase superscripts indicate significant treatment differences on each sampling day, while capital superscripts indicate significant differences on storage time (p<0.05).

Water holding capacity and texture values of meat samples

Moreover, WHC and texture are two quality traits of meat related to meat juiciness and consumer acceptability (Andrés-Bello *et al.*, 2013). Both parameters are associated with tissue fiber integrity (Cao *et al.*, 2023). The WHC and texture values were significantly affected by treatment, storage time, and the interaction effect (p = 0.001), (**Figure 3**). On day 0 of storage, non-significant differences (p>0.05) were found in WHC values for all samples. However, a decrease (p<0.05) in texture values was observed for PNG-C and DZM-C samples. At the end of storage, no significant difference (p>0.05) was observed in these parameters between treatments. In agreement, it has been reported that the incorporation of 2% CCS with grape peel extract enhances the WHC of beef meat after freeze-thaw cycles, indicating that CCS can bind to biological tissues and polyphenols, which subsequently interact with proteins to prevent their degradation (Cao *et al.*, 2023). In addition, it has been reported that the incorporation of 1.5% CCS reduced texture values (9.7%) in pastirma dry product after storage

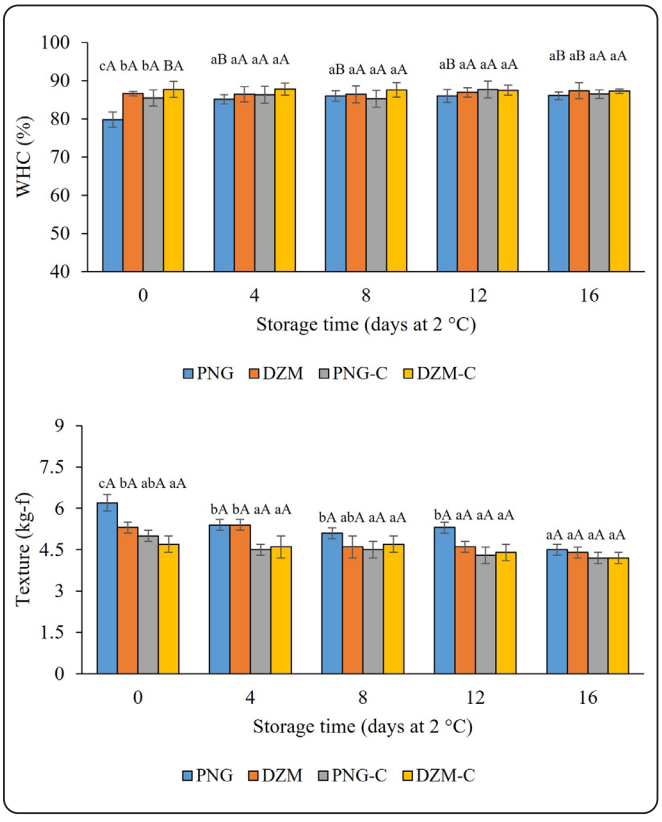

Figure 3. Effect of treatment and storage time on meat samples' WHC and Texture values. Values expressed as mean ± SD (n = 6). PNG, non-coated Pulpa negra; DZM, non-coated Diezmillo; PNG-C, coated Pulpa negra with CCS-PPE; DZM-C, coated Diezmillo with CCS-PPE. Lowercase superscripts indicate significant treatment differences on each sampling day, while capital superscripts indicate significant differences on storage time (p<0.05).

(4 °C/16 days) compared to control samples (Abdallah, Mohamed, Mohamed & Emara, 2017).

Oxidative stability changes in meat during storage

Lipid oxidation is the primary non-bacterial cause of quality loss in meat, contributing to reductions in nutritional value, sensory quality, and consumer acceptance (Domínguez, Pateiro, Gagaoua, Barba, Zhang & Lorenzo, 2019). The lipid oxidation values were significantly affected by treatment, storage time, and the interaction effect ($p = 0.001$), (**Figure 4**). At day 0 of storage, no significant differences ($p>0.05$) in TBARS values were observed between treatments. Although these values increased ($p<0.05$) during storage time for all treatments, on day 16, PNG-C and DZM-C showed the lowest TBARS values.

The TBARS values of the *T. brachii* muscle are higher than those of the Semimembranosus muscle, which could be attributed to their higher fat content, 6.36-7.7% and 5.06-6.4%, respectively (Brackebusch, McKeith, Carr & McLaren, 1999; Serra *et al.*, 2017). Similarly, it has been previously demonstrated that the *T. brachii* muscle (DMZ) exhibits higher TBARS values than the *Semimembranosus* muscle (PNG) after storage at 2 °C for 6 days (McKenna, Mies, Baird, Pfeiffer, Ellebracht & Savell, 2005). A similar trend has been observed in goat meat (24 h *post-mortem*); reported TBARS values were higher in T. brachii than in *Semimembranosus* muscle, and the authors indicated that these differences may be associated with differences in fat content and fatty acid composition (Kannan, Kousakou & Gelaye, 2001). In our study, the *T. brachii* muscle reached TBARS values higher than 1.2 mg MDA/kg; this value, according to the literature, exceeds the threshold of 1 mg MDA/kg of malondialdehyde, which is considered the limit for the perception of organoleptic

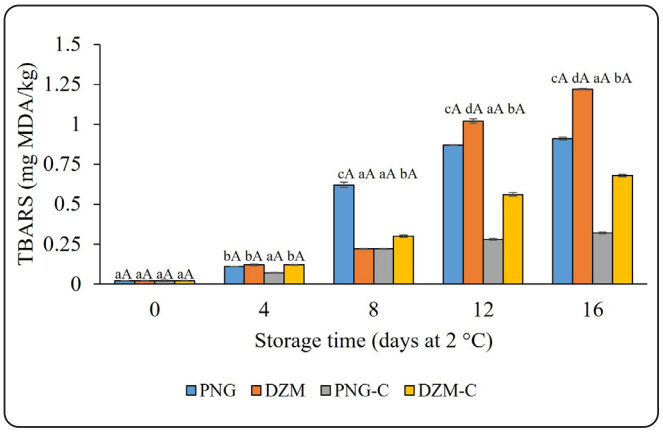

Figure 4. Effect of treatment and storage time on meat samples' lipid oxidation values. Values expressed as mean ± SD (n = 6). PNG, non-coated Pulpa negra; DZM, non-coated Diezmillo; PNG-C, coated Pulpa negra with CCS-PPE; DZM-C, coated Diezmillo with CCS-PPE. Lowercase superscripts indicate significant treatment differences on each sampling day, while capital superscripts indicate significant differences on storage time ($p<0.05$).

fat oxidation (Quevedo, Pedreschi, Valencia, Díaz, Bastías & Muñoz, 2018). It has been demonstrated that the incorporation of 2% CCS with grape peel extract decreased the TBARS values of beef meat after freeze-thaw cycles, indicating that the natural extract can scavenge free radicals and thereby prevent the initiation of the oxidative reaction chain (Cao *et al.*, 2023).

In agreement with our study, it has been reported that the inclusion of a combined 1% CCS + propolis extract reduced TBARS values (67.4%) in chicken breast meat after storage (4 °C/16 days), in comparison to control samples (Mehdizadeh & Langroodi, 2019). It has also been reported that 2% CCS incorporated with *Satureja khuzestanica* Jamzad essential oil reduced TBARS values (approximately 30%) in lamb meat after storage (4 °C/16 days), concerning control samples (Pabast *et al.*, 2018). Likewise, a reduction in TBARS values was reported in beef meat (*Quadripces femoris*) after storage (4 °C/16 days) when it was incorporated with 2% CCS and *Sataria multiflora* essential oil (Langroodi *et al.*, 2018). Furthermore, combining a 1.5% CCS reduced TBARS values (44.9%) in pastirma after storage at 4 °C/16 days (Abdallah *et al.*, 2017).

Principal component analysis

Figure 5 illustrates the PCA performed to investigate the relationship between treatment and meat quality parameters at the end of storage (day 16). The first and second components showed variances of 62.3% and 29.5%, respectively, i.e., the two components accounted for 91.8% of the total variation. The results demonstrated a separation between treatments and the evaluated parameters ($p<0.05$). For example, control samples (PNG and DZM) showed the highest lipid oxidation (TBARS) and L* values (in the right quadrant of the figure). At the same time, no differences were observed in pH, b*, WHC, and Texture parameters (near the center line of the figure). In addition, samples treated with CCS + 1% of PPE showed lower changes in a* values (left quadrant of the figure). In agreement, a high total variation (94%) was explained by the two components when comparing meat quality variables from beef patties treated with chitosan-cinnamon essential oil (Ghaderi-Ghahfarokhi, Barzegar, Sahari, Gavlighi & Gardini, 2017).

Beyond the statistical segregation observed in PCA, the spatial configuration of the variables suggests that lipid oxidation could be a major determinant of other quality attributes. The close clustering of TBARS and L* values in the control samples suggests a possible mechanistic relationship in which greater lipid peroxidation is associated with increased lightness (Domínguez *et al.*, 2019; Kannan *et al.*, 2001). This effect could be associated with oxidative modifications of myofibrillar proteins, leading to structural denaturation, altered water distribution, and increased light scattering on the meat surface (Domínguez *et al.*, 2019). Conversely, the samples treated with antioxidants were located closer to the a* vector, suggesting greater myoglobin stability and lower pigment oxidation

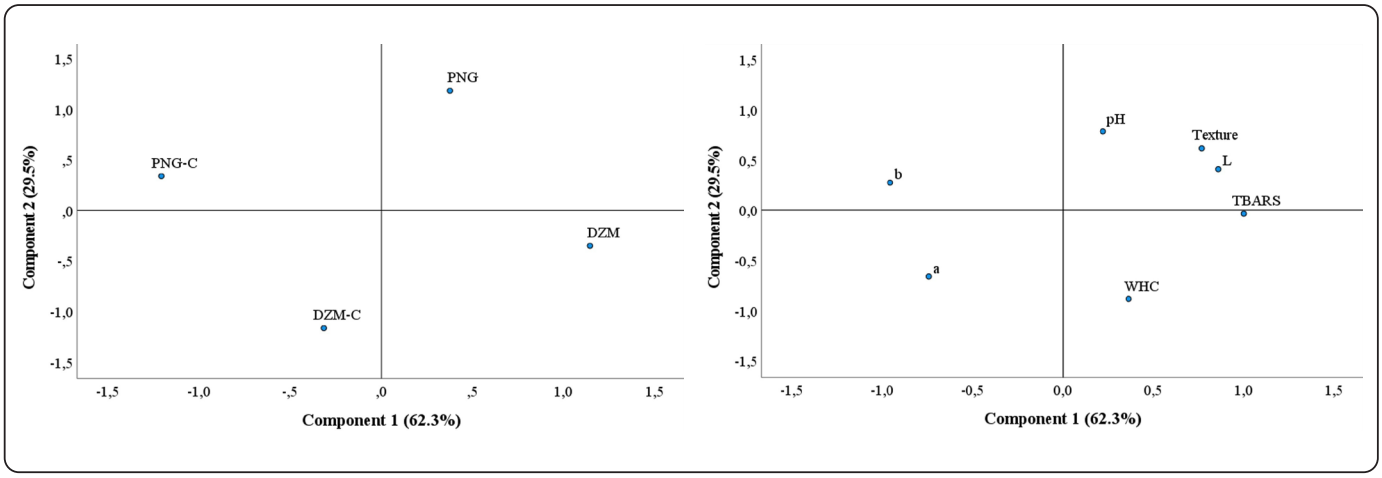

Figure 5. Principal component analysis of treatments and meat quality parameters at the end of storage.

(McKenna *et al.*, 2005). Although pH, water-holding capacity (WHC), and Warner-Bratzler shear strength were located near the centroid of the PCA plot, indicating limited discriminatory power between treatments at day 16, their relationships with oxidative processes remain physiologically relevant. Lipid peroxidation byproducts, such as reactive aldehydes, can interact with muscle proteins, promoting carbonyl formation, crosslinking, and conformational changes (Domínguez *et al.*, 2019; Trabelsi *et al.*, 2019). These oxidative modifications can impair protein functionality, ultimately affecting protein–water interactions and the mechanical properties of the muscle matrix (Sutton *et al.*, 1997). Therefore, the lower TBARS values observed in the antioxidant-treated samples may have indirectly contributed to preserving protein structural integrity, thereby stabilizing WHC and shear strength. Taken together, these findings support the concept that oxidative stability is a central regulatory mechanism that influences physicochemical and technological characteristics during refrigerated storage (Domínguez *et al.*, 2019). In this context, the proposed antioxidant strategy appears to act primarily by attenuating oxidative reactions, which, in turn, modulate pigment stability, protein functionality, and overall structural integrity in an interconnected manner.

Conclusions

The results of this study demonstrate that chitosan-coated solutions enriched with 1% potato peel extract (CCS-PPE) significantly enhance the oxidative stability and visual quality of Pulpa negra (PNG) and Diezmillo (DZM) beef cuts during 16 days of chilled storage at 4 ± 1 °C. Polyphenolic compounds, including phenols, flavonoids, and chlorogenic acid, were markedly higher ($p<0.05$) in PPE and CCS-PPE compared to CCS alone, conferring superior free-radical scavenging, radical cation inhibition, and reducing power. By day 16, CCS-PPE-treated samples exhibited the lowest lipid oxidation (TBARS, $p<0.05$), reduced luminosity (L*, $p<0.05$), and highest redness (a*, $p<0.05$) versus uncoated controls, while preserving overall physicochemical attributes despite PNG's inherent lower water-holding capacity and higher texture values. These findings position CCS-PPE as a powerful, natural antioxidant additive that extends beef shelf life and minimizes quality deterioration. Future research should explore its scalability in industrial meat processing—could this innovation transform sustainable waste valorization into a standard practice for global meat preservation?

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