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Edible coatings based on chitosan and zein improve shelf life and quality of vacuum-packaged lamb meat

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ABSTRACT: Traditional packaging is used to protect perishable products, such as meat, from deterioration. As an alternative for extending shelf life, edible coatings have been developed. This study examined the effects of chitosan- and zein-based edible coatings on physical-chemical characteristics, microbiological quality, sensory characteristics, and volatile compound profiles in lamb meat over 57 days at 1 °C. The results indicate that chitosan-coated samples exhibited lower yellowness (*b**) values and greater oxidative stability than zein-coated samples, despite the zein-coated samples containing pink pepper (*Schinus terebinthifolius*). However, zein coatings were less effective than chitosan coatings. Both types of coatings met the required microbiological quality. Notably, the zein-coated samples had a higher off-odor intensity (OFF) score (7.9) and presented specific volatile compounds, such as terpenes, which could negatively impact sensory quality. Therefore, chitosan-based coating emerged as the most suitable choice for vacuum-packaged lamb meat, as it effectively preserved oxidative stability, sensory characteristics, and microbiological quality.

Keywords: active packaging, flavor, oxidation, sensory analysis

Lamb consumption is on the rise, its quality – encompassing safety, convenience, and sensory attributes – is crucial for consumers. Traditional packaging methods typically result in a shorter shelf life for fresh meat because it is susceptible to oxidation, microbial spoilage, and changes in sensory quality. Small portions of refrigerated meat cuts are usually sold in plastic trays and wrapped in oxygen-permeable films, which provide a shelf life of only 2-3 days. Vacuum packaging is also commonly used for aged beef, extending their shelf life up to 60 days. Additionally, using edible coatings with vacuum packaging can further prolong the shelf life of meat. When incorporated into certain compounds, edible coatings can serve as active packaging by interacting with the product, absorbing undesirable substances, or releasing elements that enhance stability. They can also minimize water loss, preserve product structural integrity, and regulate microbial activity and gas permeability (Kapetanakou and Skandamis, 2016; Baschetti and Minelli, 2020). In the case of meat products, carbohydrate- and protein-based edible coatings act as effective alternatives to reduce microbial growth, maintain texture, color, and flavor, and prevent dehydration on the surfaces of both fresh and frozen meat (Antoniewski et al., 2007). Numerous studies have reported the use of chitosan and zein coatings in lamb and mutton meat (Pabast et al., 2018; Cordeiro et al., 2019; Economou et al., 2022; Song et al., 2022; Tsitsos et al., 2023), in addition to the extensive review of their application across various meat animal species Fernando et al. (2024). Several active coatings have been documented for use on lamb meat, including calcium alginate (Koushki et al., 2015; Behbahani and Shahidi, 2020; Guerrero et al., 2020; Vital et al., 2021). However, to our knowledge, there is a notable lack of studies comparing various edible coatings and their effects on lamb meat, particularly with regard to sensory attributes. This study aimed to examine changes in the physicochemical, microbiological, volatile compounds, and sensory properties of vacuum-packed lamb meat when applying chitosan- and zein-based edible coatings. Encouraging results related to the inhibition of lipid oxidation in lamb meat were observed with the addition of pink pepper (*Schinus terebinthifolius* Raddi) to zein coatings (Cordeiro et al., 2019), prompting its inclusion in this study.

The *Longissimus* muscle of male lambs, all sharing the same diet and genetic group, was sliced into 2.5-cm-thick steaks and assigned to one of three treatments: a control group (no coating), a chitosan-coated group, or a zein-coated group. The chitosan coating was formulated with 1 % w w^{-1} chitosan and 0.5 % w v^{-1} glycerol, which was solubilized in 1 % (v v^{-1}) lactic acid. Additionally, pink pepper oil from Mundo dos Óleos at 4 % w w^{-1} was incorporated into the zein filmogenic solution, which contained 0.5 % w w^{-1} zein and was solubilized in 70 % ethanol, as detailed by Cordeiro et al. (2019). The preparation of the mixtures followed the methodology outlined by Cardoso et al. (2016). The steaks were immersed in the filmogenic solution for 5 s, then placed on grids and kept in a low-oxygen-demand chamber at 4-6 °C for 30 min. They were subsequently vacuum-packaged (using a Selovac model 300B) and stored for 57 days at 1 ± 1 °C. Every 14 days, the steaks underwent a series of analyses, including physicochemical assessments (pH, instrumental color, shear force, and lipid oxidation), volatile compound evaluation, microbiological testing, and descriptive sensory analysis.

A pH measurement instrument (Testo AG, model 230) was used to measure pH at five locations on the steaks. Color parameters, including L^* (brightness on a scale 0-100, ranging from black to white) a* (with values from $-a^*$ to $+a^*$, indicating green to red), and b^* (from $-b^*$ to $+$b*, representing blue to yellow), were measured at three points using a Hunter Lab colorimeter (Hunter Lab MiniScan XE, Hunter Associates Laboratory, Inc.), employing Universal software (version 4.10), a D65 illuminant, and a 10° observer angle. Instrumental color data were applied to calculate ΔE between the initial and final days using the following formula: $\Delta E = [(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2]^{0.5}$ (King et al., 2023). Lipid oxidation was evaluated using the thiobarbituric acid reactive substances (TBARS) analysis, as described by Vyncke (1970) and later modified by Sørensen and Jørgensen (1996). The presence of thermotolerant coliforms at 45 °C, positive coagulase *Staphylococcus*, *Salmonella* spp., and sulfite-reducing *clostridia* was analyzed in accordance with the Bacteriological Analytical Manual/Food and Drug Administration (Andrews and Hammack, 2022). Sensory descriptive analysis was conducted following a series of steps: recruiting and selecting panelists, establishing terminology for sensory attributes, and defining reference materials for sensory appearance and aroma characteristics. The panelists evaluated appearance and aroma attributes using a 9-point structured scale, as follows: red color presence (RCP) (0 = none; 9 = much); red color intensity (RCI) (0 = clear; 9 = dark); brown color presence (BCP) (0 = none; 9 = much); brown color intensity (BCI) (0 = clear; 9 = dark); lamb meat characteristic aroma (LMCA) (1 = extremely bland; 9 = extremely intense) and off-odor intensity (OFF) (1 = none; 9 = extremely intense). Sensory evaluations were carried out every 14 days, resulting in two sessions for aroma assessment (one month) and four sessions for appearance evaluation (two months). Each set of attributes was evaluated in separate sessions by a panel of ten participants. For the appearance evaluations, the samples were kept in a refrigerated chamber with a glass door (Metalfrio, VN50R) maintained at 1.0 ± 1.0 °C, simulating grocery store conditions. Light intensity was measured with a digital lux meter (Minipa, model MLM1010), yielding an average of 853 lux throughout the study. Each sample was labeled with a tag featuring a three-digit number. To ensure a thorough assessment, the samples' positions were randomized on each day of analysis. The appearance attributes from the six treatments were evaluated using in individual ballots, and the panelists had access to defined references for each appearance attribute in their preferred order during all sessions. For aroma evaluation, the samples were thawed overnight in the refrigerator prior to analysis. They were then cooked on an electric grill (NKS, TSK 2933) until reaching an internal temperature of 70 °C. After cooking, the meat was cut into 2-cm cubes, wrapped in aluminum foil, and kept in a heated chamber at 60 °C. Panelists assessed the samples in a random order, one sample at a time, in individual booths. Data collection was facilitated using FIZZ software (version 2.41, Biosystèmes). The sensory analysis protocol was approved by the Ethics Committee for Research in Human Beings (protocol CAAE 95235318.5.0000.5504), with approval granted on 21st Aug, 2018. For the analysis of volatile compounds, lamb meat samples were prepared following the methods outlined by Madruga et al. (2009) and Bernardo et al. (2020). The solid-phase microextraction method using a CAR/PDMS (Carboxen/polydimethylsiloxane, Sigma-Aldrich) fiber was used to extract volatile compounds. A Gas Chromatograph coupled with Mass Spectrometry (MS) (QP-2010 model, Shimadzu®) featuring a DuraBond 5 Mass Spectrometry (DB-5 MS) column with 5 % phenyl, 95 % dimethylpolysiloxane with dimensions of 60 m × 0.25 mm internal diameter and 1 μm width of the stationary phase (J&W Scientific®) was employed to separate the volatile compounds. The identification of volatile compounds in lamb meat was documented by Bernardo et al. (2020). Additionally, the chitosan and zein filmogenic solutions (10 mL each) and pink pepper oil (2.5 mL) were analyzed separately, following the same extraction procedures and volatile compounds analysis as for the lamb meat samples. In the context of statistical analysis, physicochemical and lactic bacteria count data were assessed using analysis of variance (ANOVA), with packaging treatments (edible coatings) and time treated as fixed factors, along with their interactions. For descriptive sensory analysis data, panelists were added as a fixed factor. In the case of trained panels, the presence of a treatment × panelist interaction indicates consensus among the panelists regarding their responses; in such instances, the panelist was excluded. When a significant difference was identified ($p < 0.05$), the Tukey test was utilized. All data analyses were conducted using the XLSTAT software (version 2019.1.1, Addinsoft).

The b^* parameter showed a significant effect of coating ($p < 0.05$), with a difference ($p < 0.05$) between the coated and control treatments. No interaction between coating and time was observed, and time did not influence the color parameters ($p > 0.05$) (Table 1). Although the zein filmogenic solution typically exhibits a yellowish hue, its b^* parameter did not differ from that of chitosan. In a previous study on zein-coated lamb meat treated

Table 1 – Average values of color parameters of lamb meat coated with chitosan or zein for 57 days.

Source	Color parameter		
	*L**	*a**	*b**
Coating			
Control	38.00 ± 2.30	9.39 ± 1.40	9.63 ± 0.94b
Chitosan	40.13 ± 2.79	9.06 ± 0.74	10.29 ± 0.92a
Zein	38.63 ± 3.13	9.89 ± 0.62	10.67 ± 0.61a
p-value	0.156	0.078	0.010
Time			
1	39.13 ± 2.74	9.50 ± 1.42	9.67 ± 1.20
15	40.19 ± 1.98	9.59 ± 0.91	10.10 ± 0.57
29	37.78 ± 3.09	10.04 ± 0.75	10.51 ± 0.89
43	39.23 ± 2.89	9.14 ± 0.85	10.35 ± 0.78
57	38.28 ± 3.36	8.96 ± 0.90	10.36 ± 1.05
p-value	0.498	0.177	0.313

*L** = luminosity; *a** = redness; *b** = yellowness; Different letters at the same column for each variation source indicate difference by Tukey test ($p < 0.05$).

with pink pepper oil, a decrease in a^* values and an increase in b^* values were reported (Cordeiro et al., 2019); however, this trend was not observed in the present study. The impact of coatings and time on lamb meat color can be assessed using ΔE values. When comparing ΔE values from day 1 to subsequent measurements, all values were below 2, except for the control sample (ΔE = 2.7 between days 1 and 29) and the zein sample (ΔE = 2.6 between days 1 and 15) (data not shown). For ΔE values below 2.0, differences are generally undetectable to the human eye, although they may be apparent to a trained observer. Values ranging from 2.0 to 3.5 are categorized as medium differences, while only values exceeding 3.5 are considered obvious (Mokrzycki and Tatol, 2011; King et al., 2023), a distinction not observed in this study. Although a significant difference ($p < 0.05$) was noted for yellowness (b^*), which could influence the perceived intensity of red color in sensory analysis, the ΔE values remained below 3.5, indicating that no noticeable difference would be perceived by the average observer. In our study, both the control and chitosan-coated samples had lower values than the zein-coated samples. This finding aligns with a study on chitosan-coated ready-to-eat mutton products, which also reported no impact on sensory properties (Kannat et al., 2013).

An interaction between coating × time was observed for both pH and TBARS values (Figure 1A-B). Over 57 days, all treatments showed a significant decrease in pH ($p < 0.05$). The pH levels ranged from 4.94 to 5.49, with the lowest value of 4.94 recorded for the control treatment on day 57, in contrast to the values for the coated samples. Additionally, TBARS values significantly varied over time ($p < 0.05$), with the control treatment exhibiting the highest value of 0.305 mg malondialdehyde (MDA) kg^{-1}. In comparison, the chitosan-coated sample had the

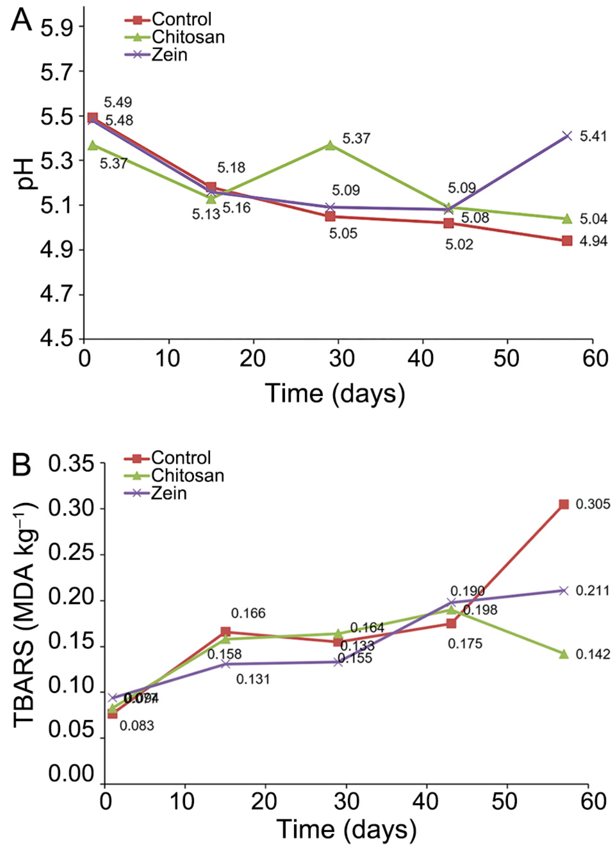

Figure 1 – A) pH × time and B) Thiobarbituric acid reactive substances (TBARS) time graphs of lamb meat coated with chitosan or zein for 57 days. MDA = malondialdehyde.

lowest TBARS value at 0.142 mg MDA kg^{-1}, followed by the zein sample with pink pepper coating at 0.211 mg MDA kg^{-1}. Meat oxidation occurs when TBARS values exceed 1.0 mg MDA kg^{-1} (Limbo et al., 2010). Chitosan has been shown to effectively retard lipid oxidation in meat and meat products (*Prashanth and Tharanathan, 2007;* Muthu et al., 2021). This includes applications of frozen beef (Darmadji and Izumimoto, 1994) and ready-to-eat meat products (Kanatt et al., 2013). The antioxidant activity of chitosan is attributed to its ability to scavenge hydroxyl radicals and chelate ferrous iron (Yen et al., 2009; Muthu et al., 2021). Additionally, pink pepper antioxidant properties in food systems, including meat products, were extensively reviewed by Vieira et al. (2023). Zein and pink pepper coatings applied to vacuum-packaged lamb meat have been shown to be effective in combating lipid oxidation (Cordeiro et al., 2019) and in artisanal smoked pork sausages (Santos et al., 2025). In the present study, the recorded TBARS values were relatively low, indicating that the samples were not oxidized; thus, any sensory differences should not be attributed to lipid oxidation. Although the zein coating, even with the addition of pink pepper, can inhibit lipid oxidation due to its phenolic compounds, it proved less effective than chitosan. Additionally, the sensory analysis revealed no interaction between coating × time for any evaluated attribute.

The RCI and OFF were influenced by the coating (Table 2). The coated samples exhibited the lowest RCI values. In the microbiological analysis, coliform counts at 45 °C were < 10 colony-forming units (CFU) g^{-1} for both the control and coated samples over time, in accordance with the established standards (ANVISA, 2024), which set the maximum limit for coliforms at 45 °C at 10^4 CFU for vacuum-packaged meat. For coagulase-negative *Staphylococcus*, all samples tested negative for the coagulase test, with counts < 10 CFU g^{-1}. *Salmonella* was not detected in any of the samples, indicating compliance with the established standards at the time of this study (ANVISA, 2024). Although, there is no specific standard for vacuum-packaged meat regarding sulfite-reducing *clostridia*, the standard for processed meat products was referenced. The results for this microorganism were also < 10 CFU g^{-1}.

In the analysis of volatile compounds across all treatments, 85 compounds were identified. These included alcohols (18 %), aldehydes (16 %), and carboxylic acids (15 %), followed by hydrocarbons (13 %), esters (12 %), ketones (9 %), and terpenes (8 %). Among the specific 26 compounds found were carboxylic acids (butanoic acid; pentanoic acid); hydrocarbons (decane; 1,3-octadiene); aldehydes (nonanal; octanal; heptanal; hexanal; pentanal; butanal, 3-methyl-; butanal, 2-methyl-; benzaldehyde); alcohols (1-butanol; 1-butanol, 3-methyl-; 1-hexanol; 1-hexanol, 2-ethyl-; 1-octen-3-ol; 1-pentanol; 2,3-butanediol); ketones (2,3-octanedione; 2-butanone, 3-hydroxy-; 2-heptanone); esters (decanoic acid, ethyl ester; octanoic acid, ethyl ester; hexanoic acid, ethyl ester; and lactone - butyrolactone). Notably, certain aldehydes, such as pentanal, hexanal, heptanal, nonenal, benzaldehyde, as well as ketones (2-heptanone, 2,3-octanedione), are associated with lipid oxidation. Additionally, compounds like 3-methylbutanal are classified as Strecker aldehydes, which are derived from the Maillard reaction and have been reported in previous studies on lamb meat (Elmore et al., 2005; Resconi et al., 2010; Bueno et al., 2011). Regarding coatings, the most significant finding is the presence of terpene compounds in the zein coating, including α-pinene, β-myrcene, β-phellandrene, 3-carene, and D-limonene (Table 3). Although zein, as a protein, is not expected to feature terpenes in its volatile compounds profile, maize (*Zea mays* L.) is known to produce volatile compounds, predominantly terpenes. Notably, β-myrcene has been identified as a compound produced in maize by terpene synthase 1 (Yactayo-Chang et al., 2024). Another possibility is that during ethanol extraction and zein solubilization, secondary compounds from maize, including terpenes derived from the pericarp and germ oil, were extracted and became associated with hydrophobic proteins such as zein (Shukla and Cheryan, 2001). Additionally, a unique terpene, 3,7,7-trimethyl- 1,3,5-cycloheptatriene, was identified in pink pepper oil.

For both the chitosan-coated and control samples, there was no observable qualitative difference in their volatile compounds (Table 3). The presence of pentanoic (dairy), hexanoic (goaty), and octanoic (cheesy) acids contributes significantly to the odor profile in meat. Additionally, alcohols such as 1-pentanol and 1-penten-3-ol, similar to those found in pink pepper oil, have previously been identified in meat and are formed from the degradation of homologous aldehydes during lipid oxidation, as well as from amino acids (Karabagias, 2018). For most of the compounds, no correlation was observed between those present in the coatings and those found in the meat; they were distinct and had notable odoriferous

Table 2 – Average values of sensory appearance and aroma attributes of lamb meat coated with chitosan or zein for 57 days.

Source	Sensory descriptive attribute					
	RCP	RCI	BCP	BCI	LMCA	OFF
Coating						
Control	7.7 ± 1.0	7.8 ± 1.1[a]	0.6 ± 1.0	0.3 ± 0.5	5.5 ± 2.1	3.2 ± 2.5[b]
Chitosan	7.4 ± 1.2	6.9 ± 1.2[b]	0.7 ± 1.0	0.7 ± 1.0	5.9 ± 1.4	3.2 ± 2.2[b]
Zein	7.5 ± 1.1	6.4 ± 1.4[c]	0.5 ± 0.8	0.5 ± 0.8	5.1 ± 2.5	7.9 ± 1.0[a]
p-value	0.497	< 0.001	0.423	0.210	0.370	< 0.001
Time (days)						
1	7.6 ± 1.1	7.0 ± 1.4	0.6 ± 1.1	0.3 ± 0.5	6.2 ± 1.9	3.4 ± 2.9[b]
15	8.0 ± 0.9	7.5 ± 1.2	0.9 ± 1.1	0.5 ± 0.6	5.0 ± 1.6	4.5 ± 3.1[ab]
29	7.4 ± 1.0	6.9 ± 1.3	0.5 ± 0.8	0.4 ± 0.8	5.2 ± 1.5	5.4 ± 2.7[a]
43	7.5 ± 1.2	7.0 ± 1.3	0.5 ± 0.8	0.6 ± 1.0	nd	nd
57	7.3 ± 1.2	6.9 ± 1.5	0.6 ± 0.9	0.5 ± 1.0	nd	nd
p-value	0.064	0.213	0.399	0.662	0.066	0.006

RCP = red color presence (0 = none; 9 = much); RCI = red color intensity (0 = clear; 9 = dark); BCP = brown color presence (0 = none; 9 = much); BCI = brown color intensity (0 = clear; 9 = dark); LMCA = lamb meat characteristic aroma (1 = extremely bland; 9 = extremely intense); OFF = off-odor intensity (1 = none; 9 = extremely intense); nd = not determined. Different letters in the same column for each source of variation indicate difference by Tukey test ($p < 0.05$).

Table 3 – Main volatile compounds found in the chitosan- and zein-coatings and pink pepper essential oil added to zein coating, and effects on the coated samples.

Volatile Compound	Coating material			Treatments		
	Chitosan	Zein	Pink pepper	Control	Chitosan	Zein
Carboxylic acid						
Butanoic acid, 3-methyl-	x			x	x	x
Hexanoic acid	x			x	x	x
Octanoic acid	x		x	x	x	x
Pentanoic acid			x	x	x	x
Propanoic acid			x	x	x	x
Hydrocarbons						
Decane	x			x	x	x
Dodecane		x	x	x	x	x
2-Octene, (Z)-			x	x	x	x
Alcohols						
1-Pentanol			x	x	x	x
1-Penten-3-ol			x	x	x	x
Aldehydes						
2-Hexenal			x			x
2-Nominal			x	x	x	x
2-Octenal, (E)-			x	x	x	x
Benzaldehyde	x		x	x	x	x
Decanal	x			x	x	x
Heptanal	x			x	x	x
Hexanal	x	x	x	x	x	x
Nonanal	x		x	x	x	x
Octanal	x			x	x	x
Pentanal	x		x	x	x	x
Ketones						
2-Heptanone	x		x	x	x	x
2-Pentanone	x		x	x	x	x
3-Pentanone	x			x	x	x
Terpenes						
α-Pinene		x				x
β-Myrcene		x	x			x
β-Phellandrene		x				x
1,3,5-Cycloheptatriene, 3,7,7-trimethyl-		x	x			x
3-Carene		x		x	x	x
D-Limonene		x		x	x	x

significance for the product. Terpenes were exclusively identified in the zein/pink pepper-coated samples, with D-limonene imparting citric notes, whereas myrcene and pinene were associated with "earthy, spicy" and "woody, green" aromas, respectively (Al-Khalili et al., 2025). The combination of lamb meat and a coating containing these terpenes has the potential to produce an off-odor, unlike chitosan-coated and control samples, which do not contain terpenes.

Although zein coatings exhibited promising oxidative stability in previous studies and demonstrated minor differences over time compared to control samples in the present study, sensory attributes such as appearance and aroma were problematic. These issues may lead to the rejection of zein-coated vacuum-packed lamb meat. In contrast, chitosan coatings effectively preserved oxidative stability, sensory qualities, including red color intensity, and microbiological quality, positioning them as the most suitable option for vacuum-packaged lamb meat in this storage context.

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Authors' Contributions

Conceptualization: Nassu RT, Forato LA. **Formal analysis**: Nassu RT, Francisco VC. **Investigation**: Cordeiro CS, Mauricio RA, Francisco VC, Okumura F. **Funding acquisition**: Nassu RT. **Project administration**: Nassu RT. **Resources**: Nassu RT. **Supervision:** Nassu RT. **Writing-original draft:** Nassu RT. **Writing-review & editing:** Nassu RT, Francisco VC, Forato LA.

Conflict of interests

The authors declare that there are no conflicts of interest.

Data availability statement

The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declaration of use of AI technologies

The author(s) used GRAMMARLY to perform a grammar review and identification of similarities. The content was reviewed and edited after using this tool/service and the authors take full responsibility for the publication content.

References

Agência Nacional de Vigilância Sanitária [ANVISA]. 2024. Instrução Normativa n° 313, de 4 de setembro de 2024. Ministério da Saúde. Available at: https://anvisalegis.datalegis.net/action/UrlPublicasAction.php?acao=abrirAtoPublico&num_ato=00000313&sgl_tipo=INM&sgl_orgao=DC/ANVISA/MS&vlr_ano=2024&seq_ato=000&cod_modulo=134&cod_menu=1696 [Accessed July 20, 2025] (in Portuguese).

Al-Khalili M, Pathare PB, Rahman S, Al-Habsi N. 2025. Aroma compounds in food: Analysis, characterization and flavor perception. Measurement: Food 18:100220. https://doi.org/10.1016/j.meafoo.2025.100220

Andrews WH, Hammack TS. 2022. Bacteriological analytical manual online. FDA U.S. food & drug. Available at: https://www.fda.gov/food/laboratory-methods-food/bam-chapter-1-food-samplingpreparation-sample-homogenate [Accessed July 20, 2025]

Antoniewski MN, Barringer SA, Knipe CL. Zerby HN. 2007. Effect of a gelatin coating on the shelf life of fresh meat. Journal of Food Science 72: E382-E387. https://doi.org/10.1111/j.1750-3841.2007.00430.x

Baschetti MG, Minelli M. 2020. Test methods for the characterization of gas and vapor permeability in polymers for food packaging application: A review. Polymer Testing 89: 106606. https://doi.org/10.1016/j.polymertesting.2020.106606

Behbahani BA, Shahidi F. 2020. Evaluation of microbial, chemical and sensory characteristics of coated lamb with Scutellaria lateriflora seed mucilage in combination with Carum copticum essential oil to shelf life extension at refrigerated storage. Iranian Journal of Food Science and Technology Research 16: 383-394 (in Iranian, with abstract in English). https://doi.org/10.22067/ifstrj.v16i4.82449

Bernardo APS, Silva ACM, Francisco VC, Ribeiro FA, Nassu RT, Calkins CR, et al. 2020. Effects of freezing and thawing on microbiological and physical-chemical properties of dry-aged beef. Meat Science 161: 108003. https://doi.org/10.1016/j.meatsci.2019.108003

Bueno M, Resconi VC, Campo MM, Cacho J, Ferreira V, Escudero A. 2011. Gas chromatographic-olfactometric characterization of headspace and mouthspace key aroma compounds in fresh and frozen lamb meat. Food Chemistry129: 1909-1918. https://doi.org/10.1016/j.foodchem.2011.06.001

Cardoso GP, Dutra MP, Fontes PR, Ramos ADLS, Gomide LAM, Ramos EM. 2016. Selection of a chitosan gelatin-based edible coating for color preservation of beef in retail display. Meat Science 114: 85-94. http://dx.doi.org/10.1016/j.meatsci.2015.12.012

Cordeiro CS, Forato LA, Bernardes Filho R, Nassu RT. 2019. Utilization of zein-based coatings containing vegetable oils on the physicochemical characteristics of vacuum-packaged lamb meat. Ciência Rural 49: e20190310. https://doi.org/10.1590/0103-8478cr20190310

Darmadji P, Izumimoto M. 1994. Effect of chitosan in meat preservation. Meat science 38: 243-254. https://doi.org/10.1016/0309-1740(94)90114-7

Economou V, Tsitsos A, Theodoridi A, Ambrosiadis I, Arsenos G. 2022. Effects of chitosan coatings on controlling Listeria monocytogenes and methicillin-resistant *Staphylococcus aureus* in beef and mutton cuts. Applied Sciences 12: 11345. https://doi.org/10.3390/app122211345

Elmore JS, Cooper SL, Enser M, Mottram DS, Sinclair LA, Wilkinson RG, et al. 2005. Dietary manipulation of fatty acid composition in lamb meat and its effect on the volatile aroma compounds of grilled lamb. Meat Science 69: 233-242. https://doi.org/10.1016/j.meatsci.2004.07.002

Fernando SS, Jo C, Mudannayake DC, Jayasena DD. 2024. An overview of the potential application of chitosan in meat and meat products. Carbohydrate Polymers 324: 121477. https://doi.org/10.1016/j.carbpol.2023.121477

Guerrero A, Ferrero S, Barahona M, Boito B, Lisbinski E, Maggi F, et al. 2020. Effects of active edible coating based on thyme and garlic essential oils on lamb meat shelf life after long-term frozen storage. Journal of the Science of Food and Agriculture 100: 656-664. https://doi.org/10.1002/jsfa.1006kjh

Kanatt SR, Rao MS, Chawla SP, Sharma A. 2013. Effects of chitosan coating on shelf-life of ready-to-cook meat products during chilled storage. LWT-Food Science and Technology 53: 321-326. https://doi.org/10.1016/j.lwt.2013.01.019

Kapetanakou AE, Skandamis PN. 2016. Applications of active packaging for increasing microbial stability in foods: Natural volatile antimicrobial compounds. Current Opinion in Food Science 12: 1-12. https://doi.org/10.1016/j.cofs.2016.06.001

Karabagias IK. 2018. Volatile profile of raw lamb meat stored at 4 ± 1 °C: The potential of specific aldehyde ratios as indicators of lamb meat quality. Foods 7: 40. https://doi.org/10.3390/foods7030040

King DA, Hunt MC, Barbut S, Claus JR, Cornforth DP, Joseph P, et al. 2023. American Meat Science Association guidelines for meat color measurement. Meat and Muscle Biology 6: 12473. https://doi.org/10.22175/mmb.12473

Koushki M, Azizi M, Koohy-Kamaly P, Amiri Z, Azizkhani M. 2015. Effect of calcium alginate coating on shelf life of frozen lamb muscle. Journal of Paramedical Sciences 6: 8115. https://doi.org/10.22037/jps.v6i1.8115

Limbo S, Torri L, Sinelli N, Franzetti L, Casiraghi E. 2010. Evaluation and predictive modeling of shelf life of minced beef stored in high-oxygen modified atmosphere packaging at different temperatures. Meat Science 84: 129-136. https://doi.org/10.1016/j.meatsci.2009.08.035

Madruga MS, Elmore JS, Dodson AT, Mottram DS. 2009. Volatile flavor profile of goat meat extracted by three widely used techniques. Food Chemistry 115: 1081-1087. https://doi.org/10.1016/j.foodchem.2008.12.065

Mokrzycki WS, Tatol M. 2011. Color difference ΔE - A survey. Machine Graphics and Vision International Journal 20: 383-411.

Muthu M, Gopal J, Chun S, Devadoss AJP, Hasan N, Sivanesan I. 2021. Crustacean Waste-Derived Chitosan: Antioxidant Properties and Future Perspective. Antioxidants 10: 228. https://doi.org/10.3390/antiox10020228

Pabast M, Shariatifar N, Beikzadeh S, Jahed G. 2018. Effects of chitosan coatings incorporating with free or nano-encapsulated *Satureja* plant essential oil on quality characteristics of lamb meat. Food Control 91: 185-192. https://doi.org/10.1016/j.foodcont.2018.03.047

Prashanth KVH, Tharanathan RN. 2007. Chitin/chitosan: modifications and their unlimited application potential-an overview. Trends in Food Science and Technology 18: 117-131. https://doi.org/10.1016/j.tifs.2006.10.022

Resconi VC, Campo MM, Montossi F, Ferreira V, Sañudo C, Escudero A. 2010. Relationship between odour-active compounds and flavour perception in meat from lambs fed different diets. Meat Science 85: 700-706. https://doi.org/10.1016/j.meatsci.2010.03.027

Santos PHD, Weis CMSC, Zanette CM, Bertan LC, Tormen L, Bainy EM. 2025. Pink pepper (*Schinus Terebinthifolius*) as a natural antioxidant in artisanal smoked pork sausages. Food and Humanity 4: 100576. https://doi.org/10.1016/j.foohum.2025.100576

Shukla R, Cheryan M. 2001. Zein: the industrial protein from corn. Industrial Crops and Products 13: 171-192. https://doi.org/10.1016/S0926-6690(00)00064-9

Song Z, Liu H, Huang A, Zhou C, Hong P, Deng C. 2022. Collagen/zein electrospun films incorporated with gallic acid for tilapia (*Oreochromis niloticus*) muscle preservation. Journal of Food Engineering 317: 110860. https://doi.org/10.1016/j.jfoodeng.2021.110860

Sørensen G, Jørgensen SS. 1996. A critical examination of some experimental variables in the 2-thiobarbituric acid (TBA) test for lipid oxidation in meat products. Zeitschrift für Lebensmittel-Untersuchung und Forschung 202: 205-210. https://doi.org/10.1007/BF01263541

Tsitsos A, Economou V, Chouliara E, Koutouzidou G, Arsenos G, Ambrosiadis I. 2023. Effect of chitosan and alginate-based edible membranes with oregano essential oil and olive oil in the microbiological, physicochemical and organoleptic characteristics of mutton. Microorganisms 11: 507. https://doi.org/10.3390/microorganisms11020507

Vieira JS, Oliveira VS, Carneiro MJ, Silva TL, Augusta IM, Carvalho MG, et al. 2023. Phenolic composition and insights into the use of pink pepper (*Schinus terebentifolius* Raddi) fruit against lipid oxidation in food systems. Food Bioscience 53: 102556. https://doi.org/10.1016/j.fbio.2023.102556

Vital ACP, Guerrero A, Guarnido P, Severino IC, Olleta JL, Blasco M, et al. 2021. Effect of Active-Edible Coating and Essential Oils on Lamb Patties Oxidation during Display. Foods 10: 263. https://doi.org/10.3390/foods10020263

Vyncke W. 1970. Direct determination of the thiobarbituric acid value in trichloracetic acid extracts of fish as a measure of oxidative rancidity. Fette, Seifen, Anstrichmittel 72: 1084-1087. https://doi.org/10.1002/lipi.19700721218

Yactayo-Chang JP, Broadhead GT, Housler RJ, Resende Jr MF, Verma K, Louis J, et al. 2024. Maize terpene synthase 1 impacts insect behavior via the production of monoterpene volatiles β-myrcene and linalool. Phytochemistry 218: 113957. https://doi.org/10.1016/j.phytochem.2023.113957

Yen M-T, Yang J-H, Mau J-L. 2009. Physicochemical characterization of chitin and chitosan from crab shells. Carbohydrate Polymers 75: 15-21. https://doi.org/10.1016/j.carbpol.2008.06.006