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Thermal-assisted pressure processing: effects of marination, temperature, and pressure level on physicochemical, color and textural parameters of *Superficial pectoralis* beef muscle

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Abstract: This study aimed to evaluate the effects of salt addition and different thermal-assisted pressure processing (TAPP) conditions (temperature and pressure levels) on technological, chromatic, and textural parameters and lipid oxidation of *Superficial pectoralis* beef muscle. A factorial design with three factors was applied: KCl/NaCl marination (marinated samples MS; non-marinated samples, NMS), temperature during high-pressure processing (50, 70°C), and pressure level (0.1, 200, and 300 MPa). All factors affect the water-holding capacity of beef, which is important to ensure both high yields and optimal tenderness and juiciness in the final product. MS treated at 50°C had the highest yield values, regardless of applied pressure level. TAPP modified the color parameter values of raw samples, resulting in brighter and less reddish. After cooking, color differences remained, indicating that this process did not fully reverse the changes induced by TAPP treatments. MS had lower shear force values than NMS. The presence of salts slightly diminished shear force values. A similar texture profile was obtained for NMS treated at 70°C and 300 MPa and MS treated at 50°C and 200 MPa. NMS and MS treated at 70°C and 0.1 MPa had the highest thiobarbituric acid reactive substance values. Based on the results, marinated samples treated at 200 MPa and 50°C were selected for treatment. TAPP could be an innovative technology for the development of value-added beef products with assured texture.

KEYWORDS
beef, temperature, textural parameters, thermal-assisted pressure processing

Practical Application: Beef tenderness is an essential attribute in consumer satisfaction and purchase decisions. However, several factors affect tenderness, such as the amount of connective tissue, muscle contraction in rigor mortis, and proteolysis. The development of ready-to-cook products with guaranteed tenderness by applying thermally assisted pressure processing would benefit both the industry and consumers.

1 | INTRODUCTION

Juiciness, flavor, and tenderness are the main attributes that influence the sensory enjoyment of consuming meat, and among them tenderness has a significant role in consumer purchase decisions (Bhat et al., 2018). Meat tenderness is principally determined by the amount and solubility of connective tissue, sarcomere shortening during rigor development, and postmortem proteolysis of myofibrillar and myofibrillar-associated proteins (Koohmaraie & Geesink, 2006). Ensuring consistent tenderness through innovative processing, packaged as convenient ready-to-cook products with extended shelf-life, would greatly benefit the meat industry (Bolumar et al., 2021; Sikes & Tume, 2014).

High-pressure processing (HPP) is mainly applied to extend shelf-life and assure the safety of ready-to-eat meat products as a postprocessing method (Grossi et al., 2014). Those procedures are usually carried out at ambient or chilled temperatures. However, thermal-assisted pressure processing (TAPP) could have some advantages in fresh beef, mainly regarding texture. TAPP is an emerging technology that applies pressure levels between 100 and 600 MPa at moderate temperatures (30–80°C) for a short period. Its application aims to modify the structures of food and to improve its properties. It differs from pressure-assisted thermal processing which uses pressures from 600 to 800 MPa to achieve sterilization temperatures (121°C) for shelf-stable products (Al-Ghamdi et al., 2022). The effects of the application of TAPP on fresh beef texture have been well summarized in the reviews of Bolumar et al. (2021) and Sikes & Warner (2016). Different results were reported by applying TAPP to fresh beef since they depend on the nature of the muscle, the state of rigor when the treatment is applied, the pressure level, the temperature of the liquid medium, and the holding time (Sikes & Warner, 2016). To ensure a consistent tenderization of postrigor beef meat pressures of 100–200 MPa combined with temperatures of 60–80°C must be applied (Bolumar et al., 2021). Also, the holding times applied were longer than those used for high-pressure treatments at ambient temperature (20–30 min vs. 5 min) (Ma & Ledward, 2004; Sikes et al., 2010). So far, no previous studies have demonstrated the effect of salt addition before TAPP. NaCl and KCl are commonly used additives in meat products, impairing salty flavor and enhancing water retention and texture.

The objective of this study was to evaluate the effects of salt marination (KCl/NaCl) and different TAPP conditions (temperature and pressure levels) on technological, chromatic, and textural parameters and lipid oxidation of Superficial pectoralis beef muscle.

2 | Materials and methods

2.1 | Experimental design

A completely randomized 2 × 2 × 3 factorial design was applied (Table 1), and factors were marination (non-marinated samples—NMS, and marinated samples—MS), temperature during holding time (50 and 70°C), and pressure level (0.1, 200, and 300 MPa) with a total of 12 treatments (experimental unit eight samples per treatment). The complete design was carried out in duplicate.

2.2 | Samples preparation

Brisket cuts (*Superficial pectoralis*) from British breed steer carcasses 48 h postslaughter (pH 5.4–5.7, total weight 25 kg) were obtained from a local market (COTO CICSA, Buenos Aires, Argentina). The Brisket cut was selected since it is a popular cut from the forequarter, its geometry allows proper conditioning of the samples, and its firm texture requires special cooking conditions to achieve the desired tenderness. Cuts were trimmed of fat and vacuum-packed in Cryovac BB2800CB bags (Sealed Air Co., Buenos Aires, Argentina) and stored at 1.5 ± 0.5°C for 48 h. Cuts were cut into parallelepipeds (30 × 20 × 100 mm, approximately 70 g), with the direction of the fiber parallel to the longest side, and weighed (Vibra Model AJ-4200E, Japan). Then, meat samples assigned as NMS (48) were randomly separated into six groups, corresponding to TAPP treatments (Table 1). Samples were vacuum-packed in Cryovac BB2800CB bags and were kept at 1.5 ± 0.5°C until further processing. For MS preparation, 48 meat samples were divided into six plastic trays containing a brine formulated with a commercial mixture of KCl and NaCl (2:1, Dos Anclas, Buenos Aires, Argentina) at 4% (w/w), with a meat: brine ratio of 1:3. Then, trays were placed at 1.5 ± 0.5°C. After 1 h, meat samples were turned 180° and kept in brine for 1 h more. Then, MS was taken out of the brine, dried, weighed, vacuum-packed in Cryovac BB2800CB bags, and kept at 1.5 ± 0.5°C until further processing.

2.3 | Thermal-assisted high-pressure processing

Vacuum-packed NMS and MS were subjected to different TAPP treatments (Table 1). Before TAPP, samples were preheated in a water bath (Lindberg/Blue M, model RWB3220CY-1, NC, USA) to specific temperatures (44°C or 41°C for 200 MPa and 64°C or 61°C for 300 MPa) to achieve target temperatures (50°C or 70°C) after adiabatic heating.

TABLE 1 Description of the 2 × 2 × 3 factorial design.

Treatment	Marination	Temperature (°C)	Pressure (MPa)
1	NMS	50	0.1
2	NMS	50	200
3	NMS	50	300
4	NMS	70	0.1
5	NMS	70	200
6	NMS	70	300
7	MS	50	0.1
8	MS	50	200
9	MS	50	300
10	MS	70	0.1
11	MS	70	200
12	MS	70	300

Abbreviations: MS, marinated samples; NMS, non-marinated samples.

TAPP treatments were applied on a High-Pressure Iso-Lab System (model Iso-Lab FPG9400:922, Stansted Fluid Power Ltd., UK), with a vessel working volume of 2 L (maximum pressure: 900 MPa; temperature range: −20 to 120°C). A propylene glycol-distilled water mixture (70:30 v/v) was used as the compression fluid. Samples were pressurized at a rate of 300 MPa·min^{-1} and held at the target pressure for 5 min. Temperatures were measured using K-type rigid thermocouples, placed in two samples per treatment, using a plastic closure device during preheating and TAPP. Temperature recording during preheating was performed using a digital multimeter (Fluke Hydra 2625A, John Fluke Mfg. Co., Inc., Everett, USA) at 10 s intervals with an accuracy of ± 0.1°C and during that step TAPP was recorded and stored by SCADA software (Stansted, UK). Non-TAPP-treated samples (0.1 MPa) were heated to 50 or 70°C in a water bath and held for 5 min. Then, samples were cooled in an ice-water bath and were kept at 1.5 ± 1.0°C for 72 h. After storage, samples were removed from bags and weighed.

2.4 | Cooking

NMS and MS (TAPP-treated or not) were vacuum-packed in cook-in Cryovac CN640 bags (Sealed air, Buenos Aires, Argentina) and cooked in a water bath at 75°C (Lindberg/Blue M, model RWB3220CY-1, USA). A combination of 70°C and 2 min was applied at the slowest heating point, the recommended treatment to achieve a 6-D reduction of *Listeria monocytogenes*. The heat penetration curve was recorded using T-type flexible thermocouples placed by stuffing box devices (Ecklund Harrison Tech, USA). Data were recorded using a digital multimeter Fluke Hydra 2625A data logger (John Fluke Mfg. Co., Inc., Everett, USA). The temperature readings were taken at 10 s intervals with an accuracy of ± 0.1°C. After cooking, samples were immediately immersed in an ice-water bath and then stored at 1.5 ± 0.5°C until further study.

2.5 | pH measurement

The pH measurement was performed using a pH meter (Testo model 230, Argentina) equipped with a pH penetration electrode (Testo model 0650-0245) and an NTC food penetration probe (Testo model 0613-2411). The pH was measured in six meat samples after 0.1 MPa or TAPP (pH_T) and after cooking (pH_C).

2.6 | Weight losses and total yield

Weight losses were measured in samples after 0.1 MPa or TAPP (WL_1) and after cooking (WL_2). The weight loss at each stage was calculated using the following formula:

$$\mathrm{WL}\,(\%) = \frac{(m_i - m_f)}{m_{um}} \times 100,$$

where in WL_1, m_i, is the initial mass before TAPP and m_f is the mass after TAPP and in WL_2, m_i is the mass after TAPP and m_f is the mass after cooking. These percentages were calculated based on the mass of the untreated meat pieces, m_{um}.

Also, the total yield (TY) was calculated using the following formula:

$$\mathrm{TY}\,(\%) = \frac{m_c}{m_{um}} \times 100,$$

where m_{um} is the mass of the untreated meat pieces and m_c is the final mass of the cooked meat.

2.7 | Expressible moisture

Expressible moisture (EM) was measured on cooked meat samples (1.5 ± 0.2 g), according to Szerman et al. (2012). Measurements were carried out in two samples per treatment (per triplicate). EM was calculated as follows:

$$\text{EM}\,(\%) = \frac{(m_1 - m_2)}{m_1} \times 100,$$

where m_1 and m_2 are the mass of the sample before and after centrifugation, respectively.

2.8 | Color parameters

Color parameters were measured on meat samples after 0.1 MPa or TAPP and after cooking using a Chroma meter (Minolta model CR 400, Japan) with an illuminant D65 and 2° observer. Results are expressed as L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness) in the CIELab system. The average values of six samples per treatment, measured at three different points of each one, were used for statistical analysis.

2.9 | Warner–Bratzler shear force

Warner–Bratzler shear force (WBSF) values were determined on eight cylinders (diameter 12.7 mm, height 20 mm) obtained from cooked meat pieces equilibrated at room temperature (25°C). Each piece was sheared with a Warner–Bratzler shear blade attached to a texture analyzer TA.XT*plus2* (Stable Micro Systems Ltd., UK) with a 50-kg load cell and a crosshead speed of 5 mm·s^{-1}. The Texture Expert 32 software v5.1.1.0 (Stable Micro Systems) was used for data collection, and WBSF values were recorded as the maximum peak force of shearing (expressed in N).

2.10 | Texture profile analysis

Texture profile analysis was performed on eight cylindrical samples (diameter 12.7 mm, height 16 mm) obtained from cooked meat pieces equilibrated at 25°C. Texture parameters were determined with a double compression test using a cylindrical probe (35 mm diameter) attached to a texture analyzer (Stable Micro Systems model TA.XT*plus2*, UK) equipped with a 50-kg cell. Samples were compressed up to 70% of their original weight at 5 mm·s^{-1}. Hardness (N), springiness, cohesiveness, and chewiness (N) were calculated using Texture Exponent 32 software (v 5.1.1.0).

2.11 | Lipid oxidation measurement

Lipid oxidation was determined by measuring the content of thiobarbituric acid reactive substances (TBARS) as described by Pouzo et al. (2016). Briefly, triplicate 5 g chopped meat samples were put in bags containing 12.5 mL trichloroacetic acid (20% w/v) (Merck, Darmstadt, Germany) in metaphosphoric acid (1.6% w/v) and processed in a stomacher-type homogenizer for 180 s. The homogenates were filtered, and 2 mL of 2-thiobarbituric acid 0.02 M (Sigma-Aldrich, St. Louis, Mo. USA) was added. Samples were incubated at 25°C overnight. Absorbances were measured at 530 nm using a spectrophotometer (Lambda Bio 20, Perkin Elmer). TBARS concentrations were calculated using 1,1,3,3-tetra ethoxy-propane as standard (Sigma-Aldrich, St. Louis, MO, USA) as expressed as mg of malondialdehyde per kg of product.

2.12 | Statistical analysis

Data were analyzed as a balanced 2 × 2 × 3 factorial experiment in a completely random design. Analysis of variance (ANOVA) and Bonferroni's multiple comparisons test ($p = 0.05$) were performed to evaluate the effects of marination, temperature, and pressure level, and their interactions on each parameter. Replicates were considered as random effects. Data were expressed as mean ± standard error (SE) and were analyzed using the Infostat software version 2011 (Di Rienzo et al., 2011).

3 | RESULTS AND DISCUSSION

3.1 | pH measurements

Regardless of marination, pH_T values of NMS and MS treated at 50°C significantly ($p < 0.05$) increased as the pressure level increased (Figure 1a). Since myofibrillar proteins were not fully denatured at that temperature, pressure could induce structural modifications such as exposure of acidic groups or protein ionization, resulting in higher pH values (Ma & Ledward, 2004; Macfarlane et al., 1981; McArdle et al., 2011). However, pH_T values of NMS treated at 70°C were significantly ($p < 0.05$) lower at 200 MPa, whereas MS had no significant differences. This could be explained by the fact that most of

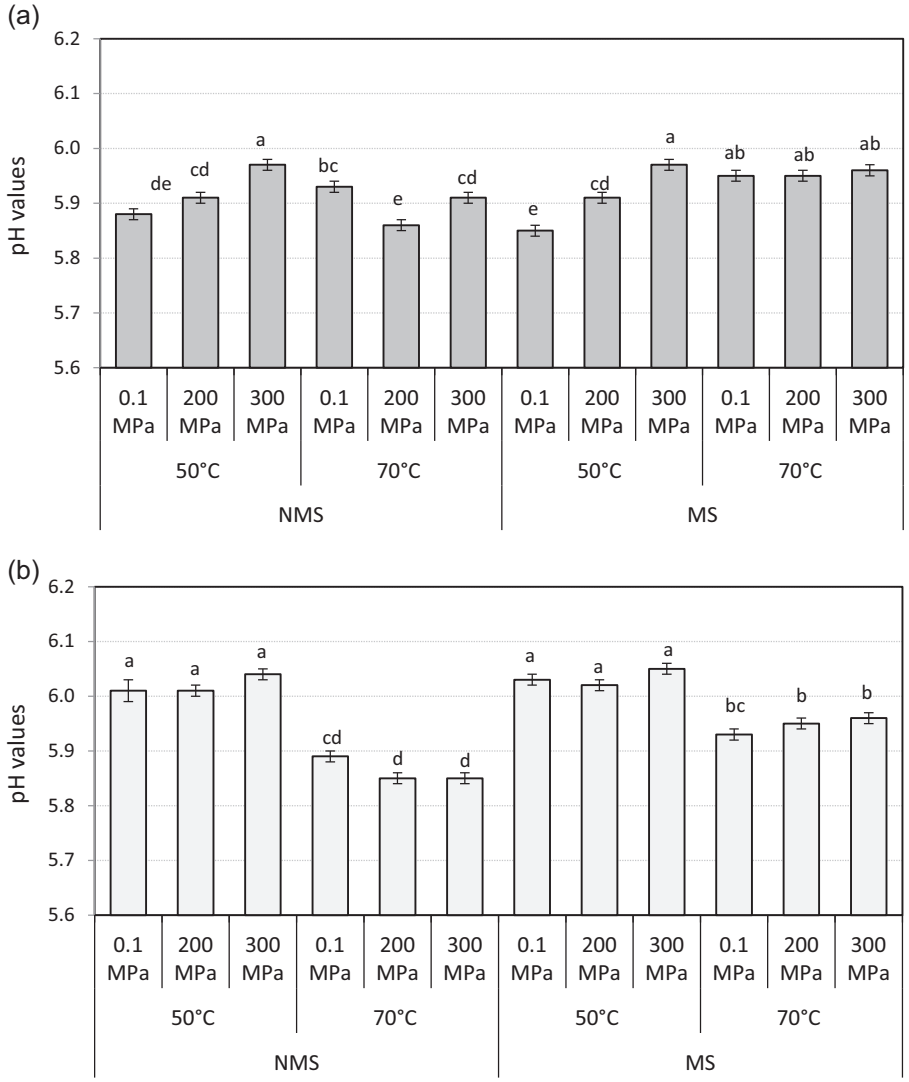

FIGURE 1 Effects of marination and TAPP treatments on pH values after 0.1 MPa or TAPP treatments (a) and after cooking (b). Data are presented as mean ± standard error of means. a–e: Means with different letters are significantly different ($p < 0.05$) corresponding to marination × temperature × pressure interaction. MS, marinated samples; NMS, non-marinated samples.

the myofibrillar proteins were completely denatured during the preheating at 70°C (Ma & Ledward, 2004), so no significant pH changes caused by pressurization were observed. Also, NaCl presence usually decreases the denaturation temperatures of myofibrillar proteins and alters their stability against heating (Speroni et al., 2014), which could explain differences between NMS and MS treated at 70°C.

The pH_C values of NMS and MS treated at 50°C were not significantly affected by pressure level ($p > 0.05$; Figure 1b). Similar behavior was observed in the pHc values measured in NMS and MS treated at 70°C; however, these were significantly lower compared to those measured in samples treated at 50°C. Cooking increases pH values, proportionally to the applied temperature. Since proteins were already denatured due to TAPP treatments at 70°C, they could not undergo further structural modifications during cooking. Consequently, the pH_C values were similar to the pH_T values. Sikes and Tume (2014) reported a similar behavior for temperature with high pressure on beef steaks.

3.2 | Weight losses and total yield

Concerning WL_1 values, the interaction among marination × temperature × pressure was significant ($p < 0.05$, Table 2). In general, WL_1 was higher for samples TAPP-treated at 70°C compared to 50°C. Besides, pressure improved water retention and, consequently, WL_1 values were lower, among MS and NMS subjected to the same temperature. MS treated at 50°C and 200 or 300 MPa

TABLE 2 Effects of marination and TAPP treatments on weight losses after 0.1 MPa or TAPP treatments (WL_1) and cooking (WL_2), total yield (TY), and expressible moisture (EM).

Marination	Temperature (°C)	Pressure (MPa)	WL_1(%)	WL_2(%)	TY(%)	EM(%)
NMS	50	0.1	10.5 ± 0.2^{d}	30.7 ± 0.4^{Ab}	58.8 ± 0.4^{f}	20.9 ± 0.2^{g}
		200	5.2 ± 0.2^{e}	31.8 ± 0.6^{Aab}	63.0 ± 0.7^{cd}	23.8 ± 0.3^{ef}
		300	4.6 ± 0.2^{e}	32.3 ± 0.4^{Aa}	63.1 ± 0.4^{cd}	26.8 ± 0.6^{cd}
	70	0.1	25.7 ± 0.4^{a}	14.2 ± 0.4^{Ce}	60.2 ± 0.6^{ef}	28.9 ± 0.4^{bc}
		200	16.5 ± 0.4^{c}	21.8 ± 0.6^{Cd}	61.7 ± 0.8^{de}	26.4 ± 0.4^{d}
		300	10.9 ± 0.3^{d}	23.7 ± 0.5^{Cc}	65.4 ± 0.6^{bc}	25.6 ± 0.3^{de}
MS	50	0.1	4.3 ± 0.2^{e}	24.5 ± 0.3^{Bb}	71.2 ± 0.3^{a}	33.6 ± 0.7^{a}
		200	2.0 ± 0.1^{f}	25.6 ± 0.3^{Bab}	72.3 ± 0.3^{a}	33.2 ± 0.6^{a}
		300	2.0 ± 0.2^{f}	25.9 ± 0.5^{Ba}	72.1 ± 0.5^{a}	29.2 ± 0.4^{b}
	70	0.1	19.9 ± 0.2^{b}	14.9 ± 0.5^{Ce}	65.2 ± 0.6^{bd}	23.1 ± 0.5^{fg}
		200	11.2 ± 0.2^{d}	22.9 ± 0.2^{Cd}	65.9 ± 0.3^{b}	22.9 ± 0.2^{fg}
		300	10.7 ± 0.2^{d}	24.7 ± 0.3^{Cc}	64.7 ± 0.4^{bc}	21.3 ± 0.5^{g}
R^2			0.99	0.95	0.89	0.89
p-value			≤0.05	≤0.05	≤0.05	≤0.05

Note: Data are presented as mean ± standard error of means. A–C: Means with different letters in the same column are significantly different ($p \leq 0.05$), corresponding to marination × temperature interaction. *a–e*: Means with different letters in the same column are significantly different ($p \leq 0.05$), corresponding to temperature × pressure interaction. a–g: Means with different letters in the same column are significantly different ($p \leq 0.05$) corresponding to marination × temperature × pressure interaction. Abbreviations: MS, marinated samples; NMS, non-marinated samples.

had the lowest WL_1 values. Regarding WL_2, marination × temperature and temperature × pressure interactions were significant ($p < 0.05$). NMS treated at 50°C had the highest values. WL_2 values were higher as the pressure level increased, and temperature decreased. NMS and MS treated at 70°C and 0.1 MPa had the lowest WL_2 values. The TY parameter allows us to evaluate the weight losses during the entire process. For TY, the interaction among marination × temperature × pressure was significant ($p < 0.05$, Table 2). The highest TY values were obtained in MS treated at 50°C.

The addition of salts, mainly NaCl, contributes to reducing water losses in meat products. Fiber swelling is the most accepted mechanism that explains this effect (Szerman et al., 2012). Also, myofibrillar protein solubilization caused by NaCl contributes to retaining water (Tamm et al., 2016); however, this phenomenon becomes important after cooking. KCl has a relatively limited hydration ability, compared to NaCl (Song et al., 2020). This is because the efficiency of ions in promoting the water-holding capacity of meat follows the Hofmeister series, and the different affinities of Na^+ and K^+ ions towards protein surfaces (Puolanne & Halonen, 2010). In this study, salt addition had a positive effect on water retention after TAPP treatments.

Also, pressure level and temperature during TAPP had important effects on the water-holding capacity of meat pieces. Speroni et al. (2014) concluded that the application of 200–300 MPa induced aggregate formation, which depended on whether the proteins were still forming myofibrils (insoluble aggregates) or whether they had already been extracted by NaCl (soluble aggregates). These aggregates retained water on their structure. Instead, the increase in processing temperatures caused higher weight losses, which can be attributed to the structural changes that occurred within the muscle tissue. Transverse shrinkage to the fiber axis (40–60°C) and cooperative longitudinal shrinkage of connective tissue network and muscle fibers (60–70°C) cause the highest water losses during heating (Tornberg, 2005). TAPP treatments at 70°C led to greater initial weight loss, but lower subsequent cooking losses compared to TAPP at 50°C. This indicated that most of the free water was lost during TAPP at 70°C, with a smaller amount of water to be lost during cooking. McArdle et al. (2011) reported that after cooking *Pectoralis profundus* muscles treated at 600 MPa exhibited higher cooking losses compared to those treated at 400 MPa, regardless of HPP treatment temperature. Likewise, McArdle et al. (2010) observed similar results for the same beef muscle in a lower pressure range (200–400 MPa) at moderate temperatures (20–40°C). Ma and Ledward (2004) found for beef that the increase in pressure level (200–800 MPa) at a constant temperature (40°C) produced lower losses with an increase in yield, compared to the application at 200 MPa and elevated temperatures (60 or 70°C).

The water-holding capacity of meat samples is important to ensure both high yield and optimal tenderness and juiciness in the final product. In this study, the three studied variables, marination, pressure level, and temperature, during TAPP, played an important role in this property. The mechanisms by which they exert their effect differ, as mentioned before; furthermore, they coexist. To sum up, the highest yields achieved were obtained in samples added with salts, treated at 50°C, with a small increase in those treated at 200 or 300 MPa.

3.3 | Expressible moisture

The EM parameter quantifies the amount of free or weakly bound water in a meat sample, which can be released by applying an external force. Also, EM is a parameter associated with TY and juiciness. The marination × temperature × pressure interaction was significant ($p < 0.05$, Table 2). MS treated at 50°C at 0.1 or 200 MPa had significantly ($p < 0.05$) higher EM values than the other samples. Conversely, MS treated at 70°C, regarding pressure level, and NMS treated at 50°C and 0.1 MPa presented significantly ($p < 0.05$) lower EM values.

The EM values in the different samples depended on the addition of salts and TAPP, which modified the water retention capacity of the muscle fibers, whose mechanisms were mentioned previously. Besides, both myofibrillar and sarcoplasmic proteins have a role in retaining water. In this sense, Marcos et al. (2010) found a negative correlation between sarcoplasmic protein solubility and EM in beef *longissimus dorsi* muscle, suggesting that pressure-induced denaturation of sarcoplasmic proteins could negatively influence to some extent water water-binding in pressurized meats. This fact could explain the effect observed in 300 MPa TAPP-treated samples, except for NMS treated at 50°C.

3.4 | Color parameters

One of the main disadvantages of applying high pressure to fresh meats is the drastic color change. This has a direct impact on their commercialization since they lack the typical color of fresh meat from the consumer's perspective. However, these changes are not relevant if the products are further processed, such as products that may be intended for food service (Bajovic et al., 2012). Regarding L^* parameter values in raw samples, the marination × temperature × pressure interaction was significant ($p < 0.05$). The highest values were obtained for NMS treated at 50 or 70°C and 300 MPa and the lowest for MS treated at 50°C and 0.1 MPa (Table 3). Regarding a^* parameter, NMS and MS treated at 50°C had significantly ($p < 0.05$) higher values than those treated at 70°C. NMS treated at 70°C and MS treated at 50 or 70°C had significantly ($p < 0.05$) lower values at 200 MPa or 300 MPa than at 0.1 MPa (Table 3). The b^* values were significantly ($p < 0.05$) higher in NMS and MS treated at 70°C than those treated at 50°C. The pressure level increase (300 MPa) significantly increased b^* values in NMS treated at 70°C and MS treated at 50°C.

In general, TAPP modified all color parameters, resulting in brighter and less red meat. These changes are mainly due to the denaturation of myoglobin and myofibrillar proteins and to the lower sarcoplasmic protein solubilization (Carlez et al., 1995; Marcos et al., 2010), which induces light scattering and lightness, oxidation of oxymyoglobin to metmyoglobin developing gray-brown color and structural modification of the porphyrin ring resulting in fading of red color (Bak et al., 2019). Also, it is interesting to highlight that temperature modified the samples treated at 0.1 or 200 MPa, increasing luminosity and reducing redness. This indicates that, at lower pressures, meat pigments were denatured due to heating, and modifying color (King & Whyte, 2006). At pressures above 200 MPa, the pressure effect became relevant. Also, salt addition affected the chromatic parameters. NaCl addition was associated with an increase in the denatured myoglobin percentage and a faster browning of meat (King & Whyte, 2006). Also, the presence of salts would be related to the enhanced water retention capacity because the degree of binding of the water at the surface of the meat has an important effect on the color since free water is responsible for its pale appearance (Baublits et al., 2006).

Cooking decreased the L^* and a^* values of all samples (Table 3). The marination × temperature × pressure interaction was significant for both parameter values. Cooked NMS and MS, treated at 50 or 70°C and 300 MPa, had the lowest L^* values. Also, the lowest L^* values were observed at 0.1 MPa. No significant differences ($p > 0.05$) were observed for a^* values of NMS and MS subjected to the same TAPP. For b^* parameter values, the marination × temperature interaction was significant. The lowest b^* values were obtained for MS treated at 50°C, and the highest for NMS treated at 70°C (Table 3). Adequate cooking of meat produces a color change to off-white, gray, or brown hues, mainly depending on the extent of ferrihemochrome formation, which in turn is a product of the initial proportionality of the myoglobins, and the final concentration of undenatured oxymyoglobin or deoxymyoglobin (King & Whyte, 2006). For this reason, the processes to which fresh meat is subjected, such as freezing, modified atmosphere packaging, etc. directly affect the color after cooking. However, there is not much information on the effects of the application of TAPP on meat color after cooking. In our study, modifications in color parameters were observed

TABLE 3 Effects of marination and TAPP treatments on *L**, *a**, and *b** parameter values measured on raw and cooked meat samples.

Marination	Temperature (°C)	Pressure (MPa)	Raw			Cooked		
			*L**	*a**	*b**	*L**	*a**	*b**
NMS	50	0.1	51.1 ± 0.4^{d}	25.0 ± 0.4^{b}	12.5 ± 0.1^{d}	40.2 ± 0.3^{e}	14.5 ± 0.3^{a}	13.6 ± 0.2^{B}
		200	52.7 ± 0.3^{c}	24.8 ± 0.4^{b}	12.8 ± 0.3^{d}	41.5 ± 0.4^{e}	14.3 ± 0.3^{ab}	14.8 ± 0.3^{B}
		300	58.0 ± 0.4^{a}	23.7 ± 0.4^{b}	13.3 ± 0.2^{cd}	48.3 ± 0.2^{abc}	13.6 ± 0.4^{abc}	14.9 ± 0.2^{B}
	70	0.1	53.6 ± 0.4^{c}	20.5 ± 0.4^{c}	14.5 ± 0.2^{b}	44.2 ± 0.3^{d}	13.0 ± 0.2^{bcd}	15.1 ± 0.2^{A}
		200	55.2 ± 0.2^{b}	16.5 ± 0.3^{e}	14.4 ± 0.2^{b}	48.7 ± 0.4^{ab}	12.0 ± 0.3^{def}	15.4 ± 0.2^{A}
		300	57.5 ± 0.2^{a}	15.0 ± 0.3^{ef}	16.1 ± 0.2^{a}	49.5 ± 0.3^{a}	12.0 ± 0.2^{def}	15.6 ± 0.2^{A}
MS	50	0.1	46.6 ± 0.3^{e}	27.4 ± 0.4^{a}	11.3 ± 0.2^{e}	44.6 ± 0.4^{d}	13.4 ± 0.3^{abc}	11.5 ± 0.2^{C}
		200	49.7 ± 0.4^{d}	24.6 ± 0.3^{b}	11.4 ± 0.2^{e}	46.5 ± 0.3^{bcd}	13.9 ± 0.2^{abc}	11.7 ± 0.1^{C}
		300	55.4 ± 0.2^{b}	24.0 ± 0.4^{b}	12.9 ± 0.2^{cd}	50.3 ± 1.4^{a}	13.4 ± 0.3^{abc}	12.0 ± 0.2^{C}
	70	0.1	51.1 ± 0.2^{d}	18.8 ± 0.2^{d}	13.7 ± 0.3^{bc}	44.8 ± 0.2^{d}	12.7 ± 0.2^{cde}	14.1 ± 0.2^{B}
		200	52.8 ± 0.2^{c}	14.4 ± 0.2^{f}	14.4 ± 0.2^{b}	46.2 ± 0.2^{cd}	11.7 ± 0.1^{ef}	14.2 ± 0.3^{B}
		300	56.0 ± 0.2^{b}	13.6 ± 0.2^{f}	14.5 ± 0.2^{b}	49.5 ± 0.3^{a}	10.8 ± 0.1^{f}	14.4 ± 0.2^{B}
R^2			0.94	0.97	0.88	0.85	0.72	0.88
p-Value			≤0.05	≤0.05	≤0.05	≤0.05	≤0.05	≤0.05

Note: Data are presented as mean ± standard error of means. A–C: Means with different letters in the same column are significantly different ($p \leq 0.05$), corresponding to marination × temperature interaction. a–f: Means with different letters in the same column are significantly different ($p \leq 0.05$) corresponding to marination × temperature × pressure interaction. Mean values of fresh meat color parameters: *L**, 41.2 ± 2.0; *a**, 28.9 ± 2.0; and *b**, 10.7 ± 1.8. Abbreviations: MS, marinated samples; NMS, non-marinated samples.

in raw meat but also in cooked meat. Further studies are needed to better understand the underlying mechanisms.

3.5 | WBSF and texture profile analysis

Regarding WBSF values, the marination × temperature × pressure interaction was significant. In general, MS presented lower WBSF values than NMS. MS treated at 50°C and 0.1 or 200 MPa presented the lowest WBSF values; similar to NMS treated at 50 or 70°C and 300 MPa and MS treated at 70°C and 300 MPa. Therefore, the application of 300 MPa on NMS had a positive impact on texture, regardless of the temperature applied. Instead, the salt presence slightly diminished shear force values. Also, the temperature of TAPP had an impact on WBSF. At 50°C, the application of pressures of 300 MPa to MS increased the shear force values.

For all the evaluated textural parameters, the marination × temperature × pressure interaction was significant. The lowest hardness values were observed in NMS treated at 50 or 70°C and 300 MPa, similar to those in MS treated at 50°C, regardless of the pressure level (Table 4). Springiness values were significantly ($p < 0.05$) lower in NMS treated at 70°C and 200 or 300 MPa or 50°C and 300 MPa. The rest of NMS and MS had similar values. Cohesiveness values were lower ($P < 0.05$) for MS treated at 70°C and 200 or 300 MPa; and higher for MS treated at 50°C and 300 MPa. Chewiness had significantly lower values in NMS treated at 50°C and 300 MPa or 70°C and 300 MPa. Instead, MS had the lowest chewiness values when treated at 50°C 0.1 or 200 MPa. It is noteworthy that for NMS treated at 70°C and 300 MPa and MS treated at 50°C and 200 MPa, the texture profile, in terms of hardness, elasticity, cohesiveness, and chewiness values, was similar.

In general, according to Warner et al. (2017), a tenderization of 30–80%, through measurements of hardness or WBSF, can be achieved by applying pressures in the range of 150 and 400 MPa and temperatures above 50–60°C. In our study, WBSF values were reduced by 20% in NMS treated at the highest pressure and increased up to 30% for MS treated at 200 MPa and 50°C or 0.1 MPa and 50°C. In terms of hardness, a similar behavior was observed. This effect on tenderness is attributed to several factors such as accelerated proteolysis (Ma & Ledward, 2004; Sikes et al., 2010), increased fracturing of myofibrillar proteins and protein solubilization, reduced water loss from the myofibrillar structure, or combinations of these, depending on the conditions applied (Buckow et al., 2013; Warner et al., 2017). The presence of salts favored the extraction and solubilization of myofibrillar proteins, increasing the water retention, as it was observed in EM values; and consequently, could create a softer texture. Modifications in the structure of the meat are also reflected in cohesiveness and springiness values. Both parameters are related to the strength of the internal fiber bonds. When fibers are more bonded, cooked meat has higher cohesiveness values, and lower springiness; thus, it is associated with a firmer texture. It is important to note that the presented results

TABLE 4 Effects of marination and TAPP treatments on WBSF and textural parameters values.

Marination	Temperature (°C)	Pressure (MPa)	WBSF(N)	Hardness(N)	Springiness	Cohesiveness	Chewiness(N)
NMS	50	0.1	30.3 ± 1.0^{bcd}	60.96 ± 1.80^{cd}	0.413 ± 0.006^{ab}	0.419 ± 0.007^{de}	26.69 ± 0.77^{cd}
		200	31.7 ± 1.3^{abc}	69.92 ± 1.38^{b}	0.423 ± 0.009^{ab}	0.474 ± 0.008^{a}	32.71 ± 0.62^{ab}
		300	29.6 ± 1.0^{bcde}	51.41 ± 1.34^{e}	0.395 ± 0.006^{bcd}	0.461 ± 0.008^{abc}	23.96 ± 0.74^{defg}
	70	0.1	35.6 ± 0.9^{a}	78.16 ± 1.30^{a}	0.415 ± 0.007^{ab}	0.466 ± 0.007^{ab}	35.70 ± 0.73^{a}
		200	32.1 ± 1.1^{abc}	60.09 ± 1.10^{cd}	0.380 ± 0.008^{d}	0.450 ± 0.008^{abcd}	27.319 ± 0.74^{c}
		300	29.3 ± 1.4^{bcde}	56.13 ± 1.21^{cde}	0.382 ± 0.006^{cd}	0.414 ± 0.006^{de}	22.83 ± 0.54^{efg}
MS	50	0.1	25.1 ± 1.0^{e}	54.71 ± 1.81^{de}	0.408 ± 0.004^{abcd}	0.425 ± 0.009^{cde}	22.39 ± 0.70^{fg}
		200	25.9 ± 0.7^{de}	52.50 ± 1.70^{e}	0.409 ± 0.004^{abcd}	0.429 ± 0.010^{bcde}	22.02 ± 0.59^{g}
		300	30.6 ± 1.0^{bcd}	54.12 ± 1.47^{de}	0.410 ± 0.006^{abcd}	0.470 ± 0.007^{a}	25.91 ± 0.49^{cde}
	70	0.1	32.1 ± 0.8^{ab}	71.46 ± 1.41^{ab}	0.428 ± 0.006^{a}	0.429 ± 0.008^{bcde}	31.95 ± 0.62^{b}
		200	30.7 ± 1.0^{bcd}	61.75 ± 1.23^{c}	0.398 ± 0.006^{abcd}	0.404 ± 0.008^{e}	25.24 ± 0.60^{cdef}
		300	27.2 ± 0.8^{cde}	60.25 ± 1.37^{cd}	$0.411@\#@ \pm 0.007^{abc}$	0.405 ± 0.008^{e}	24.85 ± 0.51^{cdefg}
R^2			0.34	0.67	0.25	0.39	0.74
p-Value			≤0.05	≤0.05	≤0.05	≤0.05	≤0.05

Note: Data are presented as mean ± standard error of means. a–g: Means with different letters in the same column are significantly different ($p < 0.05$) corresponding to marination × temperature × pressure interaction. Abbreviations: MS, marinated samples; NMS, non-marinated samples; WBSF, Warner–Bratzler shear forc

were obtained with 5 min treatments, and most of the reported studies applied more than 10 min.

3.6 | Lipid oxidation

The oxidation of beef lipids can be triggered by the application of high pressure, mediated by two mechanisms: increased iron accessibility of hemoproteins and alteration of membranes (Bajovic et al., 2012). Also, the effect of high pressure is mainly coupled with radical formation reactions, the presence of catalysts (enzymes, proteins, or metal ions), and the balance of antioxidant and pro-oxidant compounds (e.g., oxygen) in the product (Bolumar et al., 2021). The parameters applied during treatment (pressure, time, temperature) have a direct influence on those reactions (Bolumar et al., 2012).

For TBARS values, the marination × temperature × pressure interaction was significant (Figure 2). NMS and MS treated at 70°C and 0.1 MPa had the highest TBARS values. Besides, the TBARS values for MS treated at 50°C tended to increase with pressure. For MS, the increase in pressure level had different effects on lipid oxidation when samples were treated at 50°C or 70°C. At 50°C, lipid oxidation increased; but the opposite behavior was observed for MS treated at 70°C.

According to our results, the presence of salts increased TBARS values, which is consistent with the pro-oxidant capacity of NaCl (Mariutti & Bragagnolo, 2017). The possible mechanisms involved are related to the disruption of cell membrane integrity, liberation of iron, and inhibition of antioxidant enzyme activities.

In general, heating can promote lipid oxidation due to the disruption of muscle cell structure, inactivation of antioxidant enzymes, and release of oxygen and iron from myoglobin. Also, oxygen can readily access throughout the disrupted membranes causing rapid oxidation. Some authors suggested that the inactivation of catalase and glutathione peroxidase by heating could contribute to rapid lipid peroxidation in cooked meat (Min & Ahn, 2005). Bolumar et al. (2012) compared the formation of radicals in meat cooked at different temperatures or subjected to high pressure. They observed that heat treatment at 55°C had the lowest lipid oxidation reaction rate, followed by an order of magnitude increase at pressures of 500 or 600 MPa (25°C) or with heat treatment at 65°C; however, the highest rates were obtained at 700 MPa (25°C) or cooking at 75°C. In our studies, TAPP-treated samples at 200 MPa presented higher TBARS than those treated at 300 MPa. This can be explained by the fact that 200 MPa-treated samples underwent a pretreatment at a higher temperature. In conclusion, these results indicate that when TAPP is carried out close to 70°C, lipid oxidation is primarily attributed to heat treatment rather than pressure level.

4 | CONCLUSION

Thermal-assisted pressure processing significantly affected the physicochemical, technological, chromatic, and textural parameters of both marinated and non-marinated beef. Also, TAPP treatment had an impact on lipid oxidation, mainly in marinated beef. Salt addition, temperature, and pressure applied during treatments

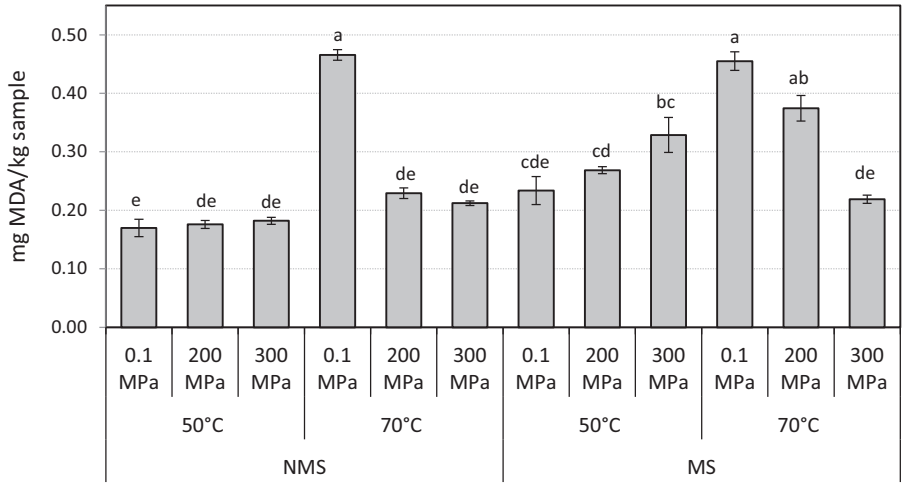

FIGURE 2 Effects of marination and TAPP treatments on TBARS values. Data are presented as mean ± standard error of means. a–e: Means with different letters are significantly different ($p < 0.05$) corresponding to marination × temperature × pressure interaction. MS, marinated samples; NMS, non-marinated samples.

modified myofibrillar protein structure by different mechanisms, and it had an impact on water-holding capacity. When meat pieces retained more water, they had higher yields and a softer texture. Further studies are needed to better understand the modifications of proteins, and pigments after TAPP processing and cooking. In conclusion, marinated samples treated at 200 MPa and 50°C achieved the best results concerning all the studied parameters. The development of innovative value-added beef products with assured texture, mainly oriented to food service, is a promising alternative for expanding the applications of high-pressure technology and driving the design of novel equipment.

AUTHOR CONTRIBUTIONS

Reynaldo Justino Silva Paz: Investigation; conceptualization; methodology. **Ana Maria Sancho**: Formal analysis; data curation. **Sergio Ramón Vaudagna**: Writing—review and editing. **Natalia Szerman**: Conceptualization; methodology; investigation; resources; writing—review and editing; writing—original draft; funding acquisition.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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