Meat Science 239 (2026) 110120

Contents lists available at ScienceDirect

Meat Science

journal homepage: www.elsevier.com/locate/meatsci

Lactic-fermented tomato ingredient as a multifunctional strategy to improve microbial stability and sensory attributes in KCl-reduced-sodium pork burgers

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ARTICLE INFO

Keywords:
Reduced sodium
KCl replacement
Shelf-life
Biopreservation
Lipid oxidation

ABSTRACT

Sodium reduction in meat products poses significant technological, sensory, and microbiological challenges. This study evaluated the effectiveness of a lactic-fermented tomato ingredient (LFT) as a multifunctional strategy to mitigate the drawbacks of sodium reduction in pork burgers formulated with partial NaCl replacement by KCl. Burgers were assessed for cooking properties, instrumental color and texture, sensory attributes, lipid oxidation, and microbial stability during refrigerated storage. Sodium reduction decreased hardness, gumminess, and cooking yield, whereas partial replacement with KCl partially restored textural properties but introduced bitterness-related sensory deviations. The incorporation of LFT enhanced perceived saltiness under reduced-sodium conditions, attenuated the sensory association with bitterness in KCl-containing formulations, and improved redness perception immediately after processing. During storage, all formulations showed progressive lipid oxidation; however, LFT-containing burgers exhibited up to 10% reduction in TBARS values at peak oxidation stages and reduced sensory perception of oxidation-related defects. LFT consistently reduced and slowed mesophilic aerobic growth by approximately 1.5–2 log units throughout storage, regardless of the salt strategy, without affecting lactic acid bacteria populations. Overall, the combined use of KCl and LFT represents a viable strategy for producing reduced-sodium meat products by simultaneously mitigating key technological, sensory, and microbiological limitations associated with sodium reduction.

1. Introduction

Excessive sodium intake is widely recognized as a major public health concern due to its strong association with hypertension and cardiovascular diseases (Egan et al., 2025). Processed meat products are among the primary dietary sources of sodium, largely because sodium chloride (NaCl) plays a central technological role in these systems. Beyond its flavor contribution, NaCl is essential for protein solubilization, water binding, texture development, microbial stability, and overall product quality (Wang et al., 2023). Consequently, reducing sodium in meat products remains a major challenge, as simple salt reduction often leads to undesirable technological, microbiological, and sensory consequences (Campagnol, Lorenzo, Dos Santos, & Cichoski, 2022).

To mitigate these limitations, potassium chloride (KCl) has been extensively studied as one of the most common substitutes for NaCl (Pateiro, Munekata, Cittadini, Domínguez, & Lorenzo, 2021). KCl can partially restore ionic strength and maintain protein functionality, thereby improving water-holding capacity and texture in reduced-sodium formulations. However, KCl does not fully replicate the technological role of NaCl and frequently introduces sensory drawbacks, particularly bitterness and metallic aftertaste (Correa et al., 2025; da Rosa et al., 2023; da Silva et al., 2020). Therefore, successful sodium-reduction strategies often require complementary ingredients that

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https://doi.org/10.1016/j.meatsci.2026.110120
Received 25 February 2026; Received in revised form 20 April 2026; Accepted 11 May 2026

compensate for both technological and sensory deficiencies associated with salt replacement.

In this context, fermented plant-derived ingredients have been explored as functional components in food products due to the biochemical transformations promoted by microbial metabolism, which enhance the formation and bioavailability of bioactive compounds and modify sensory attributes. During fermentation, microorganisms catalyze enzymatic reactions that lead to the release and synthesis of compounds such as organic acids, phenolics, bioactive peptides, and other metabolites, which are associated with improved functional and nutritional properties of food products (Peng, Nie, & Xu, 2025). In parallel, the accumulation of organic acids, particularly lactic acid, contributes to improving the microbial stability. At the same time, fermentation also promotes changes in physicochemical properties and antioxidant activity. Additionally, fermentation increases the diversity and concentration of volatile compounds, including alcohols, esters, and acids, which are directly related to aroma formation and sensory perception (Yuan et al., 2023). These changes are particularly relevant in reduced-sodium formulations, where both microbial stability and flavor balance are compromised.

Tomato-based ingredients represent a suitable matrix in this context due to their natural composition, which includes organic acids, carotenoids such as lycopene, and a wide range of metabolites, including amino acids, carbohydrates, and lipids, that are directly involved in taste and aroma perception. During lactic fermentation, microbial metabolism modifies the concentration and profile of these compounds, generating organic acids and volatile molecules and altering the balance of taste-active components, thereby influencing flavor and palatability (Sawant, Park, Sim, Kim, & Choi, 2025; Zhao et al., 2024). These fermentation-driven biochemical transformations and the resulting metabolite profile may enhance flavor perception and can help mask off-flavors associated with KCl, particularly bitterness and metallic notes. Therefore, fermented tomato-based ingredients may contribute to sodium-reduction strategies by combining acidification effects with sensory modulation derived from changes in metabolite composition.

Despite these reported effects, the application of fermented plant ingredients as multifunctional ingredients in reduced-sodium meat products remains poorly explored. In particular, limited information is available on their combined effects on technological properties, oxidative stability, microbial growth, and sensory quality during storage, especially when used alongside traditional sodium-replacement strategies such as KCl. Understanding these interactions is essential to determine whether such ingredients can effectively address the multiple quality challenges associated with sodium reduction in meat products.

Therefore, this study aimed to evaluate the impact of sodium reduction and partial replacement with KCl, alone or combined with a lactic-fermented tomato ingredient (LFT), on the cooking properties, physicochemical parameters, microbial stability, and sensory quality of pork burgers during refrigerated storage. Special emphasis was placed on assessing whether LFT could mitigate key limitations of sodium reduction, including texture weakening, sensory deviations, oxidative deterioration, and increased microbial growth.

2. Material and methods

2.1. Lactic-fermented tomato ingredient (LFT)

The lactic-fermented tomato ingredient (LFT) used in this study was a commercially available liquid product (MasterMix Biocor®, BRC Ingredientes, Brazil). According to the manufacturer, tomato flour (Fuchs Gewürze do Brasil Ltda., São Paulo, Brazil) was used as the substrate for lactic fermentation. The upstream process consisted of dispersing tomato flour at 2% (*w*/*v*) in distilled water under continuous mechanical agitation in a 3000 L stainless-steel bioreactor constructed from food-grade AISI 304 stainless steel. The suspension was supplemented with a pectinolytic enzyme preparation (EC 3.2.1.15) at 1000 U/L. Enzymatic hydrolysis was conducted at 42 °C for 60 min under gentle agitation to promote the degradation of cell wall polysaccharides and matrix disintegration. Enzyme activity was subsequently terminated by thermal inactivation at 80 °C for 5 min, followed by rapid cooling to 36 °C. Two lactic acid bacteria strains, *Lacticaseibacillus paracasei* ATCC 25302 and *Pediococcus acidilactici* ATCC 8042, were used as starter cultures. The inoculum was prepared through a sequential 1:10 scale-up to 30 L and cultivated at 36 °C for 18 h to reach the logarithmic growth phase. It was added at 1% (*v*/*v*), resulting in an initial microbial load of approximately 7 log CFU/mL per strain. Co-culture fermentation was conducted at 36 °C for 15 h under controlled conditions. After fermentation, the product was heated to 80 °C for 5 min in a jacketed system to ensure uniform heat distribution. The product was then hot-filled into polypropylene containers under hygienic conditions and sealed while still at elevated temperature.

2.2. Characterization of the lactic-fermented tomato ingredient (LFT)

The LFT was characterized by pH, titratable acidity, instrumental color, sodium and potassium content, and organic acid profile. All analyses were performed in triplicate. The pH of LFT was measured using a calibrated digital pH meter (Model 130 MA, Mettler Toledo, Barueri, Brazil). The total titratable acidity of LFT was determined by titration with NaOH according to the AOAC official method 942.15 (AOAC, 2010), and the results were expressed in % citric acid. Instrumental color was measured using a colorimeter (CR-400, Konica Minolta Sensing Inc., Osaka, Japan) operating in the CIELAB system with illuminant D65 and a 10° standard observer. Approximately 30 mL of LFT was poured into a glass optical cell with a 10 mm light path. The parameters lightness (L^*), redness (a^*), and yellowness (b^*) were recorded. Sodium and potassium contents (g/100 g) of LFT were quantified according to AOAC official methods (AOAC, 2010), following acid digestion of samples and determination by inductively coupled plasma optical emission spectrometry (ICP-OES). Organic acids were determined by gas chromatography after derivatization, as described by de Lima Alves et al. (2020), with modifications. LFT was diluted in methanol (1:250), and a 100 μL aliquot was transferred to a 2 mL vial and dried under nitrogen at 50 °C. After the addition of 50 μL dichloromethane and a second evaporation step under the same conditions, the residue was derivatized with 50 μL acetonitrile and 50 μL N-*tert*-butyldimethylsilyl-*N*-methyltrifluoroacetamide at 100 °C for 120 min. For quantification, 1 μL of the derivatized extract was injected into a gas chromatograph (Varian Star 3400CX, Palo Alto, USA) equipped with a flame ionization detector (FID) and an RTX-5MS capillary column (30 m × 0.25 mm × 0.25 μm). Hydrogen was used as a carrier gas at 10 psi. The oven temperature program was 100 °C for 1 min, increased to 180 °C at 5 °C min^{-1}, then to 320 °C at 15 °C min^{-1}, and held for 5 min. Organic acids were quantified using external calibration curves, and the results were expressed as g/100 g of sample. Qualitative identification of organic acids was performed using gas chromatography–mass spectrometry (GC–MS; QP2010 Plus, Shimadzu, Tokyo, Japan) under the same chromatographic conditions. The mass spectrometer was operated in electron ionization (EI) mode with full-scan acquisition (m/z 50–500). Compounds were identified by comparing their mass spectra with those in the NIST library and by retention time consistency.

2.3. Experimental design and burger processing

Six pork burger formulations were developed to evaluate the effects of sodium reduction and the addition of LFT (Table 1). The treatments consisted of: full-salt formulation (FS: 1.5% NaCl), low-salt formulation (LS: 0.75% NaCl), low-salt with partial NaCl replacement by KCl (LS-K: 0.75% NaCl +0.75% KCl), full-salt with LFT (FS-LFT: 1.5% NaCl +2% LFT), low-salt with LFT (LS-LF: 0.75% NaCl +2% LFT), and low-salt with KCl and LFT (LS-K-LFT: 0.75% NaCl +0.75% KCl + 2% LFT). The inclusion level of LFT (2%) was defined based on the manufacturer's

Table 1
Formulation of low-sodium pork burgers produced with KCl and lactic-fermented tomato flour.

(%)	FS	LS	LS-K	FS-LFT	LS-LFT	LS-K-LFT
Pork meat	78.5	78.5	78.5	78.5	78.5	78.5
Pork back fat	15.0	15.0	15.0	15.0	15.0	15.0
NaCl	1.5	0.75	0.75	1.5	0.75	0.75
KCl	0.0	0.0	0.75	0.0	0.0	0.75
Lactic-fermented tomato flour (LFT)	0.0	0.0	0.0	2.0	2.0	2.0
Water	5.0	5.75	5.0	3.0	3.75	3.0
Total	100	100	100	100	100	100

recommendation for antimicrobial applications in meat products.

Pork ham and pork back fat were obtained from a local commercial supplier, trimmed of visible connective tissue, and stored frozen (−18 °C) until processing. The pork ham presented 74.63 ± 0.2% moisture, 20.95 ± 0.16% protein, and 0.92 ± 0.07% lipid content, whereas pork back fat contained 18.57 ± 0.24% moisture, 70.85 ± 0.53% lipids, and 2.96 ± 0.14% protein (mean ± standard error, $n = 3$). Before burger preparation, raw materials were thawed at 4 °C for 24 h. Meat and fat were ground separately using a meat grinder equipped with an 8-mm plate.

Ground pork was mixed with NaCl and KCl (when applicable) for 3 min to promote myofibrillar protein extraction. Subsequently, the remaining ingredients were added and mixed for an additional 2 min until a homogeneous batter was obtained. Burgers (30 g; approximately 5.5 cm diameter and 1 cm thickness) were formed using a manual aluminum mold, placed on polystyrene trays, wrapped with oxygen-permeable polyvinyl chloride (PVC) film, and stored in the dark at 4 °C for 16 days. The storage period was extended beyond the typical commercial shelf life to allow spoilage processes to progress and enable a clearer evaluation of treatment effects. Each treatment consisted of 35 burgers per processing batch. The entire processing experiment was performed in triplicate on different days using independent raw material batches.

2.4. *Proximate composition and sodium and potassium contents*

Proximate composition of raw pork burgers was determined in triplicate according to standard AOAC methods (AOAC, 2010). Moisture content was measured using oven drying (AOAC method 950.46), protein content by the Kjeldahl method (AOAC method 992.15; conversion factor 6.25), ash content by incineration in a muffle furnace (AOAC method 920.153), and lipid content using the Bligh and Dyer (1959) extraction method.

Sodium and potassium contents of raw pork burgers were quantified according to AOAC official methods (AOAC, 2010), following acid digestion of samples and determination by inductively coupled plasma optical emission spectrometry (ICP-OES). Results were expressed as g/100 g for proximate composition and mg/100 g for sodium and potassium content.

2.5. *Texture profile and cooking properties*

Texture profile analysis (TPA) of raw pork burgers was performed using a texture analyzer (TA.XT2, Stable Micro Systems, Godalming, UK) equipped with a 40-mm diameter cylindrical probe (P/40). Samples were subjected to two consecutive compression cycles to 50% of their original height at a test speed of 1 mm/s. Six cylindrical samples (approximately 2 cm in diameter and 1 cm in thickness) were analyzed per treatment. The parameters recorded included hardness (N), springiness (dimensionless), cohesiveness (dimensionless), gumminess (N), and chewiness (N).

Cooking yield and dimensional shrinkage were determined using five burgers per treatment. Burgers were cooked on an electric grill until the internal temperature reached 72 °C, monitored with a calibrated thermocouple inserted into the geometric center of each sample. Cooking yield was calculated as the percentage difference between cooked and raw weights, while dimensional shrinkage was determined from the diameter reduction before and after cooking, measured with a digital caliper.

2.6. *Instrumental color*

Instrumental color was measured using a colorimeter (CR-400, Konica Minolta Sensing Inc., Osaka, Japan) operating in the CIELAB color space system. Measurements were performed using illuminant D65 and a 10° standard observer angle. Color parameters lightness (L^*), redness (a^*), and yellowness (b^*) were determined on the surface of raw pork burgers at storage days 1, 4, 8, 12, and 16. Three burgers per treatment were analyzed at each sampling time, and three readings were taken at different locations on each sample surface.

2.7. *Lipid oxidation*

Lipid oxidation in raw pork burgers was evaluated by measuring thiobarbituric acid-reactive substances (TBARS) on days 1, 4, 8, 12, and 16 of storage, as described by Bruna, Ordóñez, Fernández, Herranz, and de la Hoz (2001), with modifications. Approximately 5 g of sample was weighed and homogenized with 1 mL of 0.15% butylated hydroxytoluene (BHT) and 20 mL of 5% trichloroacetic acid (TCA). The mixture was maintained in an ice bath for 10 min and homogenized using an Ultra-Turrax. Subsequently, samples were centrifuged at 3000 rpm for 10 min at 4 °C, and the supernatant was filtered. For the colorimetric reaction, 2 mL of the filtrate was mixed with 2 mL of 0.08 M thiobarbituric acid (TBA) solution and incubated at 95 °C for 5 min. After cooling to room temperature, absorbance was measured at 532 nm. Quantification was performed using a standard curve prepared with 1,1,3,3-tetraethoxypropane (TEP), and results were expressed as mg malondialdehyde (MDA) per kg of sample. Analyses were performed using three burgers per treatment at each sampling time.

2.8. *pH*

The pH of raw pork burgers was measured on days 1, 4, 8, 12, and 16 of storage using a calibrated digital pH meter (Model 130 MA, Mettler Toledo, Barueri, Brazil). For each determination, 5 g of sample was homogenized with 50 mL of distilled water, and measurements were performed in triplicate per treatment and sampling time.

2.9. *Microbiological analysis*

Microbiological analyses were performed on days 1, 4, 8, 12, and 16 of storage to determine the counts of total aerobic mesophilic bacteria and lactic acid bacteria in raw pork burgers. For each determination, 10 g of sample was aseptically collected and homogenized with 90 mL of sterile peptone water using a stomacher, and serial decimal dilutions were prepared in sterile peptone water. Total aerobic mesophilic bacteria were enumerated on Plate Count Agar (PCA, Merck, Darmstadt, Germany), after incubation at 30 °C for 72 h. Lactic acid bacteria were enumerated on de Man, Rogosa and Sharpe (MRS) agar (Merck, Darmstadt, Germany), after incubation at 30 °C for 72 h under anaerobic conditions. Analyses were performed using three burgers per treatment at each sampling time, and results were expressed as log CFU/g (International Standard Organization, 2007).

2.10. *Sensory evaluation*

Sensory evaluations were conducted by a trained panel of 15 assessors, all regular consumers of pork burgers. Assessors were selected and trained in accordance with ISO 8586:2023 guidelines (ISO, 2023). Before the evaluations, assessors participated in three training sessions, each approximately 60 min, to familiarize them with the sensory attributes, reference standards, and evaluation procedures. During training, consensus was reached regarding attribute definitions and scoring criteria.

A descriptive sensory analysis of cooked burgers was performed on storage day 1. Burgers were cooked on an electric griddle until the internal temperature reached 72 °C, monitored with a thermocouple inserted into the geometric center of the sample. Cooked samples were wrapped in aluminum foil and maintained at 60 °C until serving. Attributes evaluated included appearance (characteristic color and reddish color), aroma (characteristic and acidic), flavor (characteristic, salty, acidic, and bitter aftertaste), and juiciness. Samples were coded with random three-digit numbers and presented monadically in a randomized and balanced serving order (Macfie, Bratchell, Greenhoff, & Vallis, 1989). Assessors evaluated samples individually in sensory booths under controlled lighting conditions using a 9-cm unstructured line scale anchored at “low intensity” and “high intensity” ends. Between samples, panelists cleansed their palate with water and unsalted crackers (Stone & Sidel, 2004).

During refrigerated storage, additional sensory evaluations were conducted on raw burgers at storage days 1 and 16 to assess color and aroma changes. The same trained panel evaluated the attributes of characteristic color, oxidized color, characteristic aroma, reddish color, acidic aroma, and rancid aroma using the same evaluation scale and experimental conditions.

All assessors provided written informed consent before participation, and the study protocol was approved by the Ethics Committee of the Federal University of Santa Maria (UFSM, Brazil) under CAAE number 92580725.9.0000.5346.

2.11. Statistical analysis

Proximate composition, sodium and potassium contents, texture profile parameters, cooking properties, instrumental color, lipid oxidation (TBARS), pH, and microbiological data were analyzed using a generalized linear model (GLM) considering treatment and storage time as fixed effects and processing batch ($n = 3$ independent batches) as a random factor. The interaction between treatment and storage time was also included in the model. When significant effects were detected ($P < 0.05$), means were compared using Tukey's multiple comparison test.

Sensory data were analyzed using Generalized Procrustes Analysis (GPA). Separate GPA models were performed for the two sensory evaluations. For the characterization of cooked burgers on storage day 1, GPA was applied to the data matrix composed of treatments and the intensity scores assigned by the 15 trained assessors for each sensory descriptor. To evaluate sensory changes during refrigerated storage, GPA was applied to matrices obtained from raw burgers evaluated at storage days 1 and 16.

All statistical analyses were performed using XLSTAT software (version 2019.2.2, Addinsoft, Paris, France).

3. Results and discussion

3.1. Physicochemical properties, mineral composition, and organic acid profile of the lactic-fermented tomato ingredient (LFT)

The physicochemical properties, mineral composition, and organic acid profile of the LFT are presented in Table 2. The ingredient exhibited an acidic profile, with a pH of 5.28 and a high titratable acidity of 2.96% (expressed as citric acid equivalents). Organic acid analysis showed that lactic acid was the only compound detected, at a concentration of 3.82 g/100 g. This result is consistent with the metabolic characteristics of the starter cultures used (*Lacticaseibacillus paracasei* and *Pediococcus acidilactici*), which are predominantly homofermentative lactic acid bacteria that convert fermentable substrates mainly into lactic acid as the primary end product (Holzapfel & Wood, 2014). This value accounts for nearly all the titratable acidity when considering the different equivalent weights of lactic and citric acids. LFT presented low L^* (27.8) and b^* (3.98) values, and a high a^* value (8.18), indicating a dark reddish appearance. In addition, LFT contained 2.19% sodium and 1.48% potassium.

Table 2
Physicochemical properties, mineral composition, and organic acid profile of the lactic-fermented tomato ingredient (LFT).

Parameter	LFT (mean ± SEM)
Physicochemical properties	
pH	5.28 ± 0.01
Titratable acidity (%, as citric acid)	2.96 ± 0.02
Color (CIE L^*, a^*, b^*)	
L^*	27.80 ± 0.1
a^*	8.18 ± 0.01
b^*	3.98 ± 0.01
Mineral composition (g/100 g)	
Sodium	2.19 ± 0.02
Potassium	1.48 ± 0.02
Organic acids (g/100 g)	
Lactic acid	3.82 ± 0.05

SEM: standard error of the mean.

3.2. Proximate composition and sodium and potassium content

Moisture content was significantly affected by salt reformulation ($P < 0.001$; Table 3). However, only the LS-LFT treatment showed higher moisture values than full-salt control (FS), whereas the other treatments did not differ significantly from the FS. Protein and lipid contents were not affected by treatment ($P > 0.05$). Ash content was significantly affected by salt reformulation ($P < 0.05$), with LS and LS-LFT showing lower values than the other formulations, reflecting the lower total mineral addition resulting from partial NaCl removal without compensation by KCl (Table 1).

Sodium and potassium contents were influenced by salt reformulation ($P < 0.05$; Table 3). All LS treatments exhibited substantially lower sodium contents than the full-salt samples (FS and FS-LFT). Specifically, sodium levels decreased by approximately 43.6–46.8% in LS formulations without LFT (LS and LS-K) and by about 37% in LS treatments containing LFT (LS-LFT and LS-K-LFT) relative to FS. Potassium content was strongly influenced by KCl addition ($P < 0.05$), with KCl-containing treatments showing pronounced increases compared with FS, reaching approximately 95% higher values in LS-K. The incorporation of LFT also significantly influenced the sodium and potassium contents. Samples containing LFT showed increases of up to 18% in sodium and 16% in potassium contents relative to their respective controls, reflecting the sodium (2.19%) and potassium (1.48%) contents of the LFT ingredient (Table 2).

These modifications resulted in a marked reduction in the sodium-to-potassium ratio (Na/K), decreasing from approximately 1.8–2.0 in full-salt formulations to ~1.0 in LS and to ~0.5 in KCl-containing treatments. This latter value is consistent with WHO recommendations for sodium and potassium intake, which correspond to an approximate molar Na/K ratio of 1:1 (≈0.6 on a mass basis) (WHO 2012a). Although LFT slightly increased sodium levels, it did not compromise this trend, as LS-K-LFT maintained a low Na/K ratio (~0.5).

Table 3
Chemical composition, sodium and potassium content, and texture profile of low-sodium pork burgers formulated with KCl and lactic-fermented tomato ingredient.

	FS	LS	LS-K	FS-LFT	LS-LFT	LS-K-LFT	SEM	SIG
Chemical composition (g/100 g)								
Moisture	65.2^{bc}	64.6^{c}	64.6^{c}	65.0^{bc}	66.7^{a}	65.8^{ab}	0.2	***
Fat	13.2^{a}	10.8^{a}	13.3^{a}	13.9^{a}	11.7^{a}	13.1^{a}	0.3	n.s.
Protein	18.5^{a}	19.1^{a}	19.5^{a}	19.7^{a}	19.2^{a}	19.1^{a}	0.1	n.s.
Ash	2.5^{a}	1.7^{b}	2.4^{a}	2.7^{a}	1.9^{b}	2.7^{a}	0.1	***
Minerals (mg/100 g)								
Na	545.9^{b}	307.9^{d}	290.4^{d}	635.4^{a}	344.2^{c}	342.6^{c}	27.9	***
K	305.6^{b}	306.8^{b}	596.0^{a}	325.6^{b}	300.1^{b}	693.3^{a}	36.7	***
Texture profile								
Hardness (N)	37.1^{a}	25.0^{c}	30.4^{b}	31.9^{b}	27.3^{bc}	31.7^{b}	0.8	***
Springiness	0.8^{a}	0.8^{a}	0.8^{a}	0.8^{a}	0.8^{a}	0.8^{a}	0.01	n.s.
Cohesiveness	0.4^{a}	0.4^{a}	0.4^{a}	0.4^{a}	0.4^{a}	0.4^{a}	0.01	n.s.
Gumminess (N)	13.5^{a}	8.9^{c}	11.6^{ab}	12.5^{a}	9.7^{bc}	11.7^{ab}	0.3	***
Chewiness (N)	11.0^{a}	7.4^{c}	9.5^{abc}	9.3^{abc}	8.0^{bc}	9.6^{ab}	0.2	***

Values are presented as mean. Different superscript letters in the same row indicate significant differences ($P < 0.05$).
Treatments: FS = full-salt formulation (1.5% NaCl); LS = low-salt formulation (0.75% NaCl); LS-K = low-salt formulation with KCl addition (0.75% NaCl and 0.75% KCl); FS-LFT = full-salt formulation with lactic-fermented tomato ingredient (LFT) addition (2% LFT); LS- LFT = low-salt formulation with LFT addition (2% LFT); LS-K- LFT = low-salt formulation with KCl (0.75%) and LFT addition (2% LFT).
SEM: standard error of the mean
SIG (level of significance): n.s. (not significant); *** $P < 0.001$

3.3. *Texture profile and cooking properties*

Salt reformulation significantly influenced texture profile parameters (Table 3) and cooking yield (Fig. 1) ($P < 0.05$), while dimensional shrinkage remained unchanged (Fig. 1; $P > 0.05$).

Texture profile analysis of raw burgers showed that hardness, gumminess, and chewiness were significantly reduced by sodium reduction, whereas springiness and cohesiveness were unaffected across treatments. The absence of differences in these latter parameters suggests that the basic internal integrity and elastic recovery of the meat matrix were preserved, while reformulation primarily affected force-related attributes associated with matrix compactness and binding strength (Inguglia, Zhang, Tiwari, Kerry, & Burgess, 2017). These changes reflect the well-established role of NaCl in increasing ionic strength and promoting myofibrillar protein solubilization and extraction, which enhance protein–protein interactions and binding capacity in comminuted meat systems (Wang et al., 2023; Yotsuyanagi et al., 2016).

Partial replacement of NaCl with KCl mitigated these negative effects. LS-K formulation exhibited higher hardness and gumminess values than LS ($P < 0.05$), reflecting improved matrix compactness and binding capacity. This behavior is associated with potassium ions' ability to promote protein–protein interactions and structural rearrangements, thereby enhancing aggregation and gel network formation in myofibrillar proteins (Yu et al., 2024). Nevertheless, hardness remained lower than that of FS, confirming that KCl does not fully replicate the technological role of NaCl, a trend widely reported in low-sodium meat systems (Horita, Messias, Morgano, Hayakawa, & Pollonio, 2014).

The incorporation of LFT exerted a salt-dependent effect on texture.

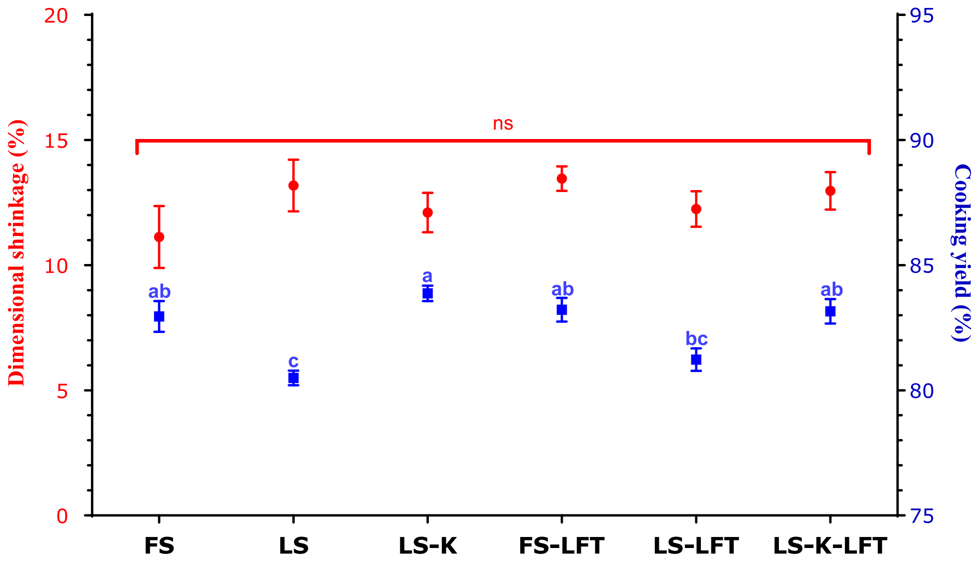


Fig. 1. Cooking yield and dimensional shrinkage of low-sodium pork burgers formulated with KCl and lactic-fermented tomato ingredient during refrigerated storage.
Different letters indicate significant differences based on Tukey's test ($P < 0.05$). Error bars depict the standard error of the mean. Batches: FS = full-salt formulation (1.5% NaCl); LS = low-salt formulation (0.75% NaCl); LS-K = low-salt formulation with KCl addition (0.75% NaCl and 0.75% KCl); FS-LFT = full-salt formulation with lactic-fermented tomato ingredient (LFT) addition (2% LFT); LS- LFT = low-salt formulation with LFT addition (2% LFT); LS-K-LFT = low-salt formulation with KCl (0.75%) and LFT addition (2% LFT).

FS-LFT samples had lower hardness than FS. This effect can be associated with the lower pH of FS-LFT relative to FS (Fig. 3), resulting from the high acidity of LFT (Table 2), which can be associated with a less compact raw matrix by reducing myofibrillar protein solubility and impairing protein network formation under lower pH conditions (Chen et al., 2024; Lee & Chin, 2020). In contrast, under low-sodium conditions, where protein extraction and binding were already limited by reduced ionic strength, LFT did not significantly affect texture parameters, suggesting that the dominant effects of sodium reduction masked its structural contribution.

Overall, these findings demonstrate that sodium reduction weakens the structural consistency of raw meat systems primarily by limiting protein extraction. In contrast, KCl acts as the main factor mitigating these effects, and LFT can be incorporated without compromising texture stability under reduced-salt conditions.

Dimensional shrinkage was not affected by reformulation ($P > 0.05$; Fig. 1), indicating that neither sodium reduction nor the incorporation of KCl or LFT altered the contraction behavior of the meat matrix during thermal processing. This result suggests that structural factors governing dimensional stability remained sufficient despite differences in protein functionality.

In contrast, cooking yield was significantly influenced by sodium reduction ($P < 0.05$; Fig. 1). The LS treatment exhibited lower yield than FS ($P < 0.05$), reflecting reduced water and fat retention due to limited protein extraction and binding capacity under low ionic strength conditions (Ruusunen & Puolanne, 2005). Importantly, all other reformulated treatments, including those containing KCl and/or LFT, did not differ ($P > 0.05$) from FS in cooking yield, indicating that ionic compensation by KCl and the incorporation of LFT were sufficient to preserve water-holding capacity and fat retention during cooking. The absence of yield differences despite variations in raw texture reflects the distinct mechanisms governing these properties. Texture profile analysis reflects structural consistency before heating, whereas cooking yield depends primarily on moisture and fat immobilization during thermal processing. Thus, reformulation strategies may maintain cooking yield even when differences in raw matrix consistency are present. Overall, preserving cooking yield across reformulated treatments represents a positive technological outcome, demonstrating that sodium reduction in combination with KCl and/or LFT can be achieved without compromising processing performance or product functionality.

3.4. Instrumental color

Instrumental color parameters were significantly affected by salt reformulation, storage time, and their interaction ($P < 0.05$; Fig. 2). Across all treatments, redness (a^*) decreased and yellowness (b^*) increased during refrigerated storage, reflecting the typical discoloration pattern of raw meat products.

Lightness (L^*) differed among treatments at specific time points; however, no consistent pattern attributable to salt reformulation was observed over storage. Sodium reduction alone (LS) resulted in higher L^* values at the beginning of storage than FS, indicating a lighter appearance, commonly associated with reduced myofibrillar protein solubilization and increased light scattering in low-salt meat matrices (Barretto, Pollonio, Telis-Romero, & da Silva Barretto, 2018). However, these differences diminished over time, suggesting that storage effects predominated over formulation effects in determining lightness.

Redness (a^*) was the parameter most affected by reformulation. Sodium reduction alone (LS) markedly decreased a^* values compared with FS, particularly during the early storage period, indicating reduced color intensity under low ionic strength conditions. Although NaCl is known to exert pro-oxidative effects in meat systems by promoting hemoglobin-mediated lipid oxidation (Wu, Park, & Richards, 2022), it also alters the structural organization and myofibrillar lattice spacing within the meat matrix, thereby increasing water-holding capacity and altering light-cattering properties (Feiner, 2006). Such salt-induced structural changes influence instrumental color parameters in raw meat (Hughes, Oiseth, Purslow, & Warner, 2014). In this context, the lower a^* observed in LS is likely associated with modifications in protein organization and light reflectance rather than solely with oxidative mechanisms.

The incorporation of LFT exerted a marked effect on redness. The LFT presented low lightness ($L^* = 27.80$) and relatively high redness ($a^* = 8.18$) (Table 2), indicating a dark reddish color profile. Accordingly, immediately after processing, LFT-containing formulations exhibited significantly higher a^* values than their corresponding controls without LFT, indicating an intrinsic contribution of the ingredient to the red appearance of the raw burgers. Throughout storage, LFT-containing treatments consistently maintained higher a^* values than non-LFT formulations, although all treatments exhibited a progressive decline in redness. The limited antioxidant effect of LFT (Fig. 3) indicates that the higher a^* values are mainly attributable to the ingredient's intrinsic color rather than to oxidative stabilization. Similar behavior has been reported by Luisa García, Calvo, and Dolores Selgas (2009), who demonstrated that increases in a^* values in burgers with tomato peel were primarily associated with pigment incorporation rather than antioxidant-driven mechanisms.

Yellowness (b^*) increased progressively during storage across all treatments, reflecting pigment oxidation typical of refrigerated burgers (Da Silva et al., 2025; de Lima Guterres et al., 2023). However, no consistent differences were observed between LFT-containing and non-LFT formulations, indicating that the ingredient did not exert a measurable influence on this parameter.

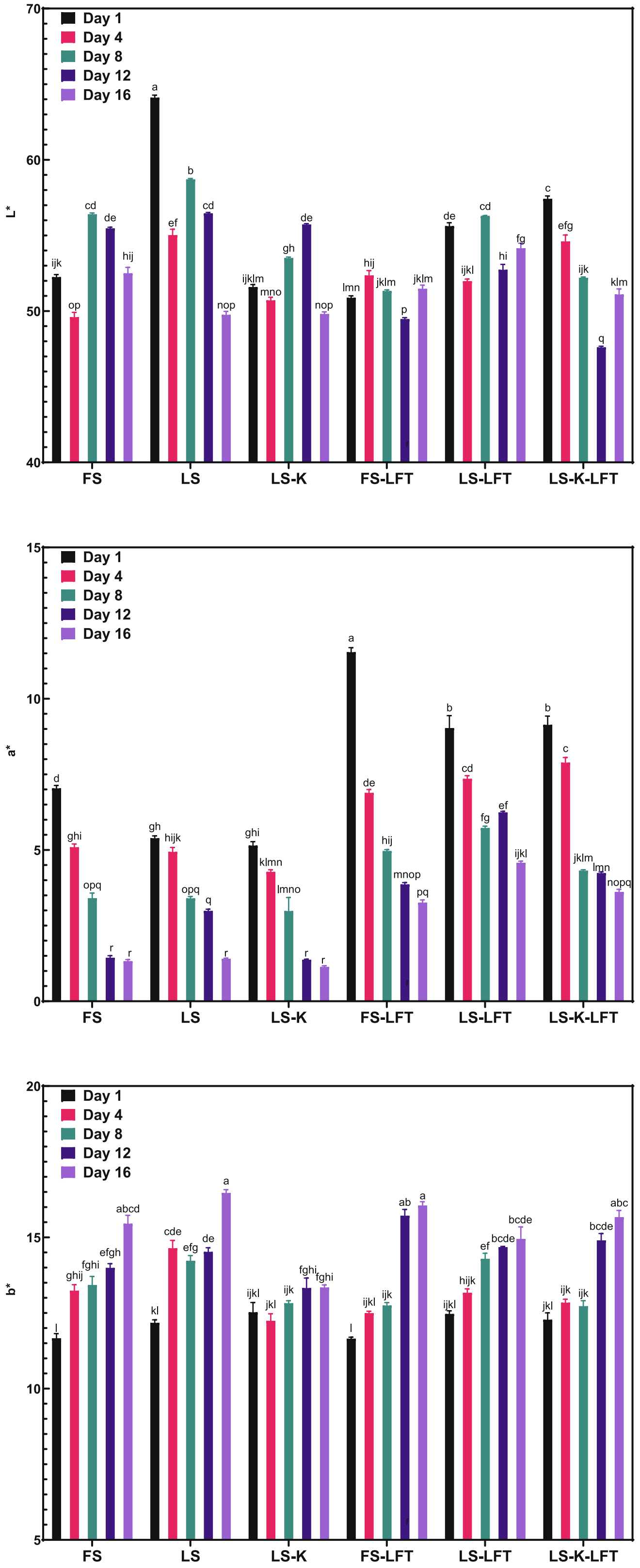
Overall, these results demonstrate that sodium reduction reduced redness, whereas LFT increased redness by enhancing initial color through pigment incorporation, resulting in higher a^* values throughout storage. This effect is technologically relevant, as maintaining a red color is a critical determinant of consumer acceptance and purchase intent for raw meat products (Mancini & Hunt, 2005).

3.5. TBARS and pH

TBARS and pH values were significantly affected by salt reformulation, storage time, and their interaction ($P < 0.05$; Fig. 3). TBARS increased markedly from day 1 to day 12 across all formulations, then decreased at day 16. This non-linear pattern reflects the typical behavior of lipid oxidation in meat, in which TBARS peak during intermediate storage and may decline later due to further reactions or transformation of malondialdehyde into compounds not detected by the assay (de Lima Guterres et al., 2023; Domínguez et al., 2019). In the present study, peak TBARS values were higher than those previously reported for pork burgers produced and stored under similar conditions (Da Silva et al., 2025; de Oliveira et al., 2023), despite the low initial oxidation levels observed in the raw materials (approximately 0.05 mg MDA/kg). This outcome may be associated with intrinsic variability in the fatty acid composition of pork fat, which is known to vary substantially depending on animal diet and production conditions (Świątkiewicz, Oczkowicz, Ropka-Molik, & Hanczakowska, 2016).

Regarding formulation effects, sodium reduction alone (LS) and partial replacement with KCl (LS-K) exhibited TBARS values that were statistically different from FS at specific storage times, particularly at day 12; however, their overall oxidative evolution remained very similar to the full-salt control. These findings indicate that reducing NaCl or substituting it with KCl did not meaningfully alter lipid oxidation dynamics under the present conditions, as all formulations followed comparable oxidation profiles throughout storage. Differences among treatments were most evident at the intermediate storage stage, confirming the significant treatment × time interaction and highlighting that reformulation effects were primarily time-dependent.

The incorporation of LFT resulted in significantly lower TBARS values than the corresponding non-LFT treatments at the peak oxidation stage (day 12). However, the magnitude of this reduction was modest,



(caption on next column)

Fig. 2. Changes in instrumental color parameters (L^*, a^*, and b^*) of low-sodium pork burgers formulated with KCl and lactic-fermented tomato ingredient during refrigerated storage.

Values are expressed as mean ± standard error. A significant treatment × storage time interaction was observed ($P < 0.05$). Different letters indicate significant differences among treatment–storage time combinations, as determined by Tukey's test ($P < 0.05$). Batches: FS = full-salt formulation (1.5% NaCl); LS = low-salt formulation (0.75% NaCl); LS-K = low-salt formulation with KCl addition (0.75% NaCl and 0.75% KCl); FS-LFT = full-salt formulation with lactic-fermented tomato ingredient (LFT) addition (2% LFT); LS- LFT = low-salt formulation with LFT addition (2% LFT); LS-K-LFT = low-salt formulation with KCl (0.75%) and LFT addition (2% LFT).

and TBARS levels remained relatively high across formulations, indicating that LFT exerted only limited control over lipid oxidation under the conditions evaluated.

While TBARS primarily reflect lipid oxidation, pH changes provide complementary information on broader biochemical transformations during storage. pH values remained relatively stable during the early and intermediate storage periods but showed pronounced treatment-dependent differences at the end of storage, reflecting the significant treatment × time interaction ($P < 0.05$). In formulations without LFT, pH increased sharply at day 16, a behavior commonly associated with progressive storage-related biochemical reactions in refrigerated meat products (Nychas, Skandamis, Tassou, & Koutsoumanis, 2008). In contrast, LFT-containing treatments maintained significantly lower pH values at the same storage stage, demonstrating a clear divergence in temporal pH evolution among formulations. This time-dependent pattern suggests that LFT influenced the progression of storage-induced biochemical processes rather than merely causing an initial acidification effect. Given that pH in raw meat products reflects buffering capacity and the accumulation of basic compounds during storage, the observed stabilization in LFT-containing formulations indicates a delayed progression of these deterioration-related changes (Gram et al., 2002; Zhou, Xu, & Liu, 2010).

3.6. Microbiological quality

Mesophilic aerobic bacteria and lactic acid bacteria (LAB) counts increased progressively during refrigerated storage in all formulations, reflecting the expected microbial growth pattern of raw meat products ($P < 0.05$; Fig. 4). However, the magnitude of microbial development varied markedly among treatments, resulting in a significant treatment × time interaction ($P < 0.05$).

Salt reformulation influenced mesophilic growth at specific storage times. At day 8, the LS treatment showed significantly higher counts (approximately one log cycle) than FS and LS-K ($P < 0.05$), confirming the well-established antimicrobial effect of NaCl (Orsi et al., 2025). Partial replacement with KCl (LS-K) resulted in mesophilic aerobic counts comparable to FS across all storage times ($P > 0.05$), consistent with the findings of Bidlas and Lambert (2008), who demonstrated that KCl exerts antimicrobial effects similar to NaCl. In contrast, the incorporation of LFT resulted in a pronounced and consistent reduction in mesophilic counts throughout storage. This inhibitory effect became particularly evident from day 8 onward and intensified at later storage stages, when LFT-containing treatments exhibited approximately 1.5–2 log lower counts than their corresponding non-LFT counterparts. These results indicate that LFT progressively slowed microbial proliferation during storage and was the main factor associated with the observed differences in microbial stability. The antimicrobial activity of LFT can be associated with its organic acid composition, particularly the predominance of lactic acid, as well as its high acidity (Table 2). This organic acid inhibits microbial growth by diffusing across the cell membrane in its undissociated form, leading to intracellular acidification and disruption of metabolic functions (Alakomi et al., 2000). These findings are consistent with previous studies reporting that the

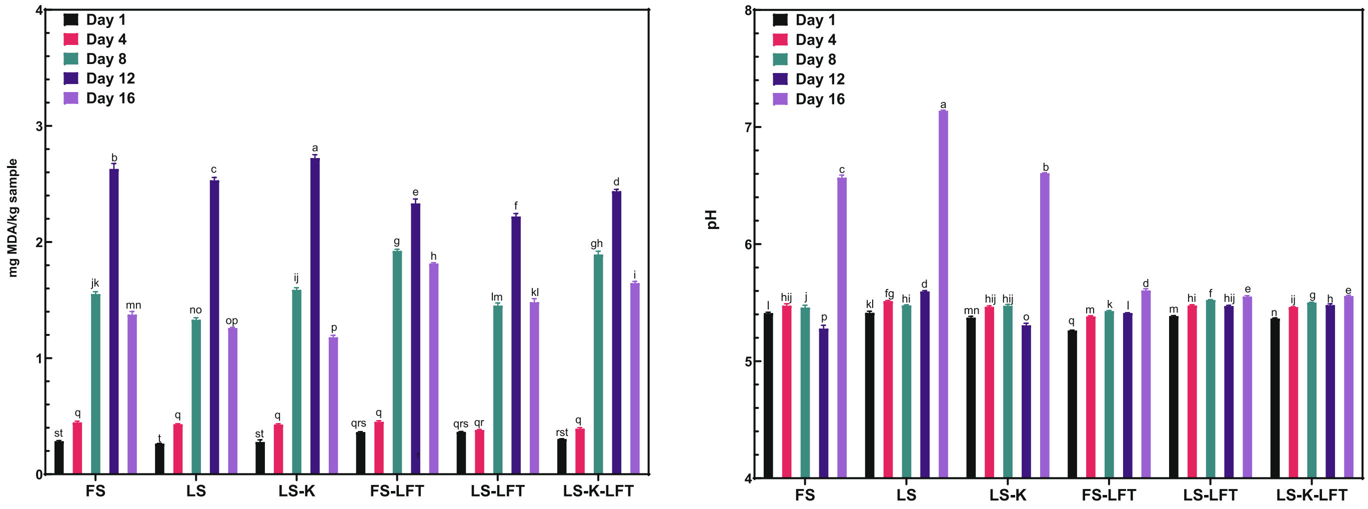


Fig. 3. Evolution of lipid oxidation (TBARS) and pH values of low-sodium pork burgers formulated with KCl and lactic-fermented tomato ingredient during refrigerated storage.
Values are expressed as mean ± standard error. A significant treatment × storage time interaction was observed ($P < 0.05$). Different letters indicate significant differences among treatment–storage time combinations, as determined by Tukey's test ($P < 0.05$). Batches: FS = full-salt formulation (1.5% NaCl); LS = low-salt formulation (0.75% NaCl); LS-K = low-salt formulation with KCl addition (0.75% NaCl and 0.75% KCl); FS-LFT = full-salt formulation with lactic-fermented tomato ingredient (LFT) addition (2% LFT); LS- LFT = low-salt formulation with LFT addition (2% LFT); LS-K-LFT = low-salt formulation with KCl (0.75%) and LFT addition (2% LFT).

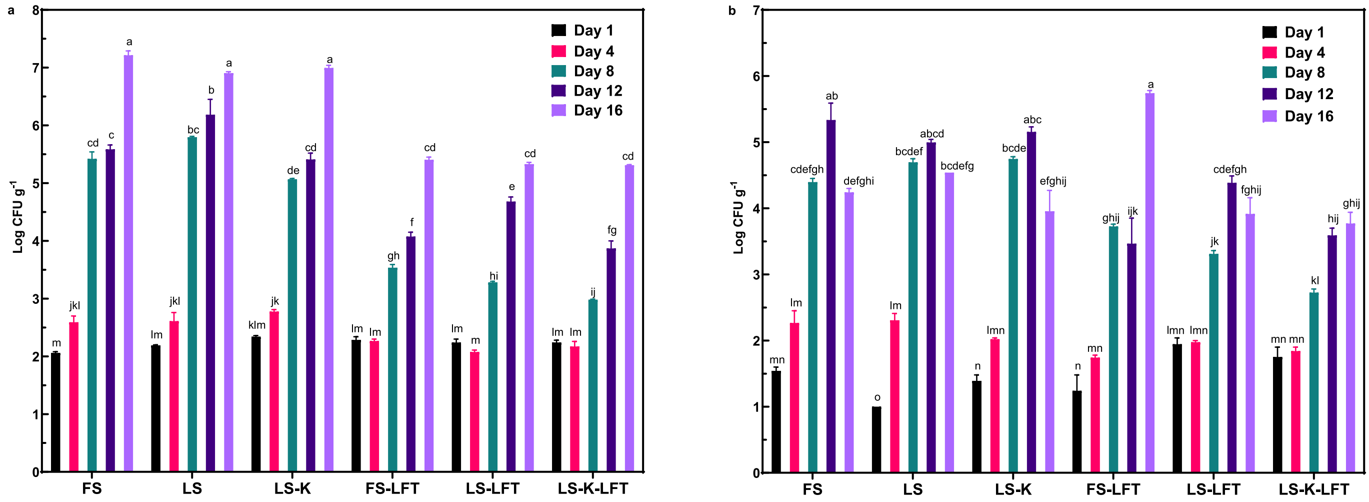


Fig. 4. Growth of mesophilic aerobic bacteria (a) and lactic acid bacteria (b) in low-sodium pork burgers formulated with KCl and lactic-fermented tomato ingredient during refrigerated storage.
Values are expressed as mean ± standard error. A significant treatment × storage time interaction was observed ($P < 0.05$). Different letters indicate significant differences among treatment–storage time combinations, as determined by Tukey's test ($P < 0.05$). Batches: FS = full-salt formulation (1.5% NaCl); LS = low-salt formulation (0.75% NaCl); LS-K = low-salt formulation with KCl addition (0.75% NaCl and 0.75% KCl); FS-LFT = full-salt formulation with lactic-fermented tomato ingredient (LFT) addition (2% LFT); LS- LFT = low-salt formulation with LFT addition (2% LFT); LS-K-LFT = low-salt formulation with KCl (0.75%) and LFT addition (2% LFT).

application of lactic acid in meat products results in significant reductions in microbial load (de Ávila, Marques, Piccolli, & Schwan, 2013; Rey, Cap, Favre, Vaudagna, & Mozgovoj, 2025).

LAB counts increased during storage in all treatments, and no consistent differences were observed between LFT-containing formulations and their respective controls. This indicates that LFT did not exert a measurable inhibitory effect on LAB under the conditions evaluated. This behavior is consistent with the physiological characteristics of LAB, which are inherently adapted to acidic environments and possess mechanisms to maintain intracellular pH homeostasis, allowing them to better tolerate organic acids and fermentation-derived compounds than the broader mesophilic microbiota (Papadimitriou et al., 2016). Therefore, the antimicrobial effect of LFT appears to be primarily directed toward more sensitive spoilage-associated microorganisms rather than acid-tolerant LAB populations.

3.7. *Sensory quality*

The sensory profile of cooked burgers evaluated immediately after processing revealed clear differences among formulations, as illustrated by the generalized Procrustes analysis (GPA) map (Fig. 5). The first two dimensions explained 61.6% of the total variability, indicating that the multivariate configuration adequately captured the main sensory relationships among treatments. All descriptors were located on the

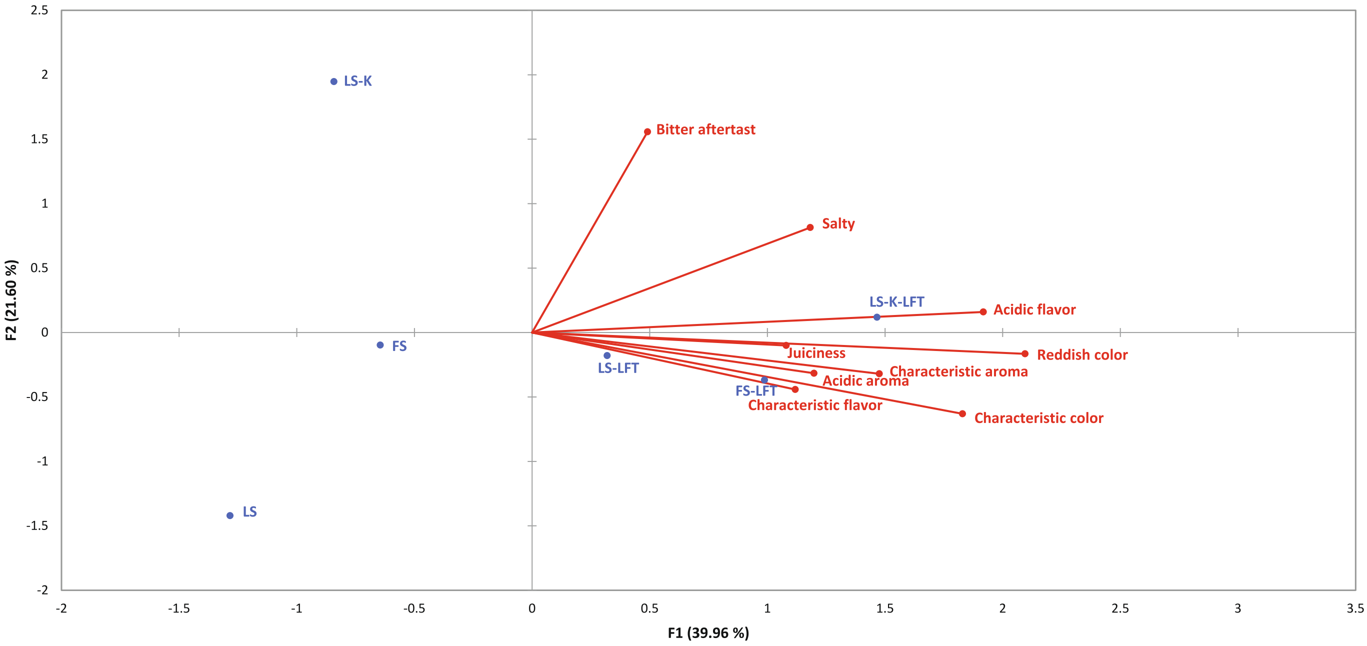


Fig. 5. Generalized Procrustes analysis (GPA) of descriptive sensory attributes of cooked pork burgers immediately after processing under different salt reformulation strategies.

Batches: FS = full-salt formulation (1.5% NaCl); LS = low-salt formulation (0.75% NaCl); LS-K = low-salt formulation with KCl addition (0.75% NaCl and 0.75% KCl); FS-LFT = full-salt formulation with lactic-fermented tomato ingredient (LFT) addition (2% LFT); LS- LFT = low-salt formulation with LFT addition (2% LFT); LS-K-LFT = low-salt formulation with KCl (0.75%) and LFT addition (2% LFT).

positive side of the first dimension (F1), indicating that sample discrimination occurred primarily through spatial proximity to attribute vectors and separation across quadrants rather than through opposing attribute polarities.

The LS formulation was positioned in the opposite direction to the "salty" vector, reflecting reduced perception of saltiness. This positioning is consistent with the well-established sensory consequence of sodium reduction in meat products, in which decreased NaCl levels typically lead to a diminished salty taste intensity (Dos Santos et al., 2015; Pedro et al., 2021). Notably, the LS-LFT formulation shifted toward the "salty" direction relative to LS, suggesting that incorporating LFT enhanced the perception of saltiness despite the reduced sodium content. This finding is particularly relevant from a reformulation standpoint, as loss of salty perception represents one of the main sensory limitations of reduced-sodium meat products (Inguglia et al., 2017).

Partial replacement of NaCl with KCl (LS-K) resulted in a distinct sensory displacement toward the "bitter aftertaste" vector, confirming the classical sensory drawback associated with potassium-based salt substitutes (Correa et al., 2025; da Silva et al., 2020). Although the combined formulation LS-K-LFT was located within the same general quadrant, it was positioned farther from the "bitter aftertaste" vector than LS-K, indicating a reduced association with bitterness. This spatial relationship suggests that LFT may have attenuated the bitterness-related sensory impact of KCl, thereby mitigating one of the principal limitations of sodium reduction strategies in meat systems.

Formulations containing LFT (FS-LFT, LS-LFT, and LS-K-LFT) were generally positioned closer to positive quality-related attributes, including reddish color, characteristic color, characteristic aroma, characteristic flavor, and juiciness. This configuration indicates that LFT contributed to enhancing visual appearance and preserving the typical sensory characteristics of cooked burgers. The strong association with reddish color suggests that LFT enhanced the retention of red color tones after cooking, indicating reduced pigment denaturation or oxidation.

To complement the instrumental color and lipid oxidation analyses, descriptive sensory evaluation was performed on raw burgers at days 1 and 16 of refrigerated storage to assess perceptible changes in color and aroma associated with oxidative deterioration. The resulting GPA map is presented in Fig. 6.

The first principal dimension (F1, 65.02% of explained variance) clearly represented the primary sensory gradient during storage, separating samples according to the development of oxidation-related attributes. Positive F1 scores were strongly associated with oxidized color, rancid aroma, and acidic aroma, whereas negative F1 scores were associated with fresh appearance descriptors, including characteristic color, reddish color, and characteristic aroma. This distribution indicates that F1 essentially reflects the progression of oxidative sensory deterioration during storage.

At day 1, all formulations were positioned on the negative side of F1, confirming their association with fresh sensory characteristics. Among them, LFT-containing samples (FS-LFT, LS-LFT, and LS-K-LFT) were located closer to the vectors representing reddish color and characteristic color than their respective controls. This spatial proximity indicates a stronger perceptual association with desirable fresh color attributes, consistent with instrumental color results showing higher a^* values immediately after processing in LFT-containing burgers (Fig. 2).

During storage, all samples shifted toward the positive F1 region, reflecting the expected development of oxidative sensory changes. However, the magnitude of this displacement varied among treatments. At day 16, formulations without LFT (FS, LS, and LS-K) were located closer to oxidation-related descriptors, particularly rancid aroma and oxidized color, indicating a stronger perception of deterioration. In contrast, LFT-containing formulations remained farther from these vectors, suggesting reduced sensory association with oxidation-related defects. This pattern is consistent with the instrumental TBARS results, which showed a marked increase in lipid oxidation during storage across all treatments, followed by a modest but statistically significant reduction in TBARS values in LFT-containing burgers at the peak oxidation stage (Fig. 3). Although TBARS levels remained relatively high in all formulations, the GPA results suggest that even small differences in lipid oxidation intensity were perceptible at the sensory level, particularly in attributes directly associated with oxidative deterioration, such as rancid aroma and oxidized color.

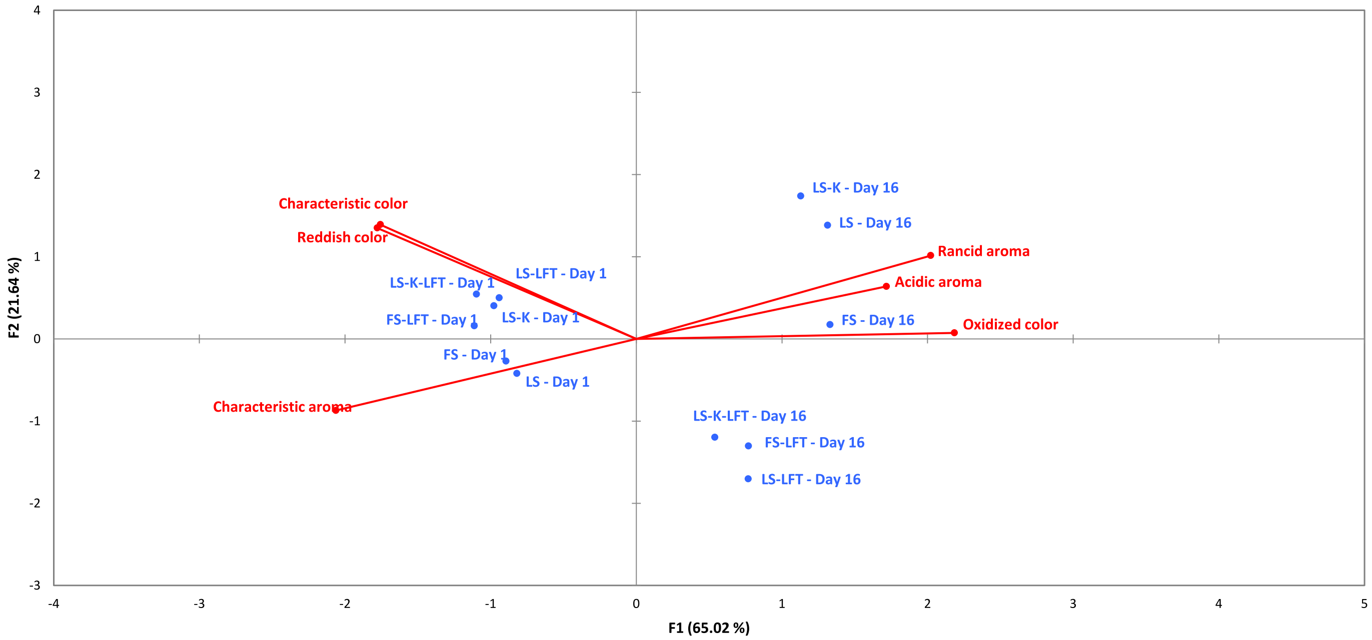


Fig. 6. Generalized procrustes analysis (GPA) of sensory changes in color and aroma of raw pork burgers at days 1 and 16 of refrigerated storage.
Batches: FS = full-salt formulation (1.5% NaCl); LS = low-salt formulation (0.75% NaCl); LS-K = low-salt formulation with KCl addition (0.75% NaCl and 0.75% KCl); FS-LFT = full-salt formulation with lactic-fermented tomato ingredient (LFT) addition (2% LFT); LS- LFT = low-salt formulation with LFT addition (2% LFT); LS-K-LFT = low-salt formulation with KCl (0.75%) and LFT addition (2% LFT).

4. Conclusion

Salt reformulation significantly affected the technological, microbiological, and sensory stability of pork burgers, highlighting the multifaceted challenges associated with sodium reduction. Partial replacement of NaCl with KCl mitigated some technological limitations but did not fully compensate for sodium functionality and introduced sensory deviations.

The incorporation of LFT improved multiple quality attributes, particularly under reduced-sodium conditions. From a sensory perspective, LFT enhanced saltiness perception in low-sodium formulations and attenuated bitterness associated with KCl. In addition, LFT enhanced redness perception, attenuated oxidation-related sensory deterioration, preserved cooking yield and texture under reduced-salt conditions, and, most importantly, reduced and slowed mesophilic microbial growth throughout storage, demonstrating a clear preservative effect independent of the salt strategy. Notably, this antimicrobial effect was selective, as LFT did not affect lactic acid bacteria populations.

These findings demonstrate that LFT represents a promising multifunctional strategy to overcome key technological, sensory, and microbiological challenges associated with sodium reduction. Its compatibility with KCl-based reformulation supports its application in reduced-sodium meat products. Future studies should investigate the bioactive composition of LFT and strategies to improve the stability of these compounds in meat products.

Consent form

Sensory evaluation procedures were approved by the Ethics Committee of the Federal University of Santa Maria (protocol no. 92580725.9.0000.5346). All participants provided written informed consent before participation.

CRediT authorship contribution statement

Andressa Inês Schú: Writing – original draft, Methodology, Investigation, Formal analysis. **Géssica Hollweg:** Visualization, Validation, Methodology, Investigation. **Bibiana Alves dos Santos:** Visualization, Validation, Methodology, Investigation, Formal analysis. **Jaqueline Graziela de Oliveira Zucheto:** Visualization, Validation, Investigation. **Luis Eduardo Lobo e Silva:** Formal analysis, Investigation, Methodology. **Milena Padilha:** Visualization, Validation, Investigation. **Milene Milbradt Moreira:** Visualization, Validation, Investigation. **Patricia Storch:** Visualization, Validation, Investigation. **Marcelo Antonio Morgano:** Visualization, Validation, Methodology, Investigation. **Roger Wagner:** Formal analysis, Investigation, Methodology. **Alexandre José Cichoski:** Writing – review & editing, Visualization, Validation, Methodology, Investigation. **Paulo Cezar Bastianello Campagnol:** Writing – original draft, Supervision, Project administration, Funding acquisition, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The author has no conflicts of interest in disclosing to the paper entitled "Lactic-fermented tomato ingredient as a multifunctional strategy to improve microbial stability and sensory attributes in KCl-reduced-sodium pork burgers".

Acknowledgments

This research received partial funding from the Coordination for the Improvement of Higher Education Personnel - Brazil (CAPES) - Finance Code 001.

Data availability

Data will be made available on request.

References

Alakomi, H.-L., Skyttä, E., Skyttä, S., Saarela, M., Mattila-Sandholm, T., Latva-Kala, K., & Helander, I. M. (2000). Lactic acid Permeabilizes Gram-negative Bacteria by disrupting the outer membrane. *Applied and Environmental Microbiology, 66*(5), 2001–2005. https://doi.org/10.1128/AEM.66.5.2001-2005.2000

AOAC. (2010). *Association of official analytical chemists – Official methods of analysis* (18th ed.). Gaithersburg, MD: AOAC.

de Ávila, A. R. A., Marques, S. C., Piccolli, R. H., & Schwan, R. F. (2013). Sensitivity to organic acids in vitro and in situ of salmonella spp. and escherichia coli isolated from fresh pork sausages. *Journal of Food Quality, 36*(3), 155–163. https://doi.org/10.1111/jfq.12026

Barretto, T. L., Pollonio, M. A. R., Telis-Romero, J., & da Silva Barretto, A. C. (2018). Improving sensory acceptance and physicochemical properties by ultrasound application to restructured cooked ham with salt (NaCl) reduction. *Meat Science, 145*, 55–62. https://doi.org/10.1016/j.meatsci.2018.05.023

Bidlas, E., & Lambert, R. J. W. (2008). Comparing the antimicrobial effectiveness of NaCl and KCl with a view to salt/sodium replacement. *International Journal of Food Microbiology, 124*(1), 98–102. https://doi.org/10.1016/J.IJFOODMICRO.2008.02.031

Bligh, E. G., & Dyer, W. J. (1959). A rapid method of total lipid extraction and purification. *Canadian Journal of Biochemistry and Physiology, 37*(8), 911–917. https://doi.org/10.1139/o59-099

Bruna, J. M., Ordóñez, J. A., Fernández, M., Herranz, B., & de la Hoz, L. (2001). Microbial and physico-chemical changes during the ripening of dry fermented sausages superficially inoculated with or having added an intracellular cell-free extract of Penicillium aurantiogriseum. *Meat Science, 59*(1). https://doi.org/10.1016/S0309-1740(01)00057-2

Campagnol, P. C. B., Lorenzo, J. M., Dos Santos, B. A., & Cichoski, A. J. (2022). Recent advances in the development of healthier meat products. *Advances in Food and Nutrition Research, 102*, 123–179. https://doi.org/10.1016/BS.AFNR.2022.04.009

Chen, B., Du, G., Li, K., Wang, Y., Shi, P., Li, J., & Bai, Y. (2024). Properties of myofibrillar protein in frozen pork improved through pH-shifting treatments: The impact of magnetic field. *Foods (Basel, Switzerland), 13*(13), Article 1988. https://doi.org/10.3390/foods13131988

Correa, L. P., Pinton, M. B., dos Santos, B. A., Morgano, M. A., Vargas-Ramella, M., Cichoski, A. J., … Campagnol, P. C. B. (2025). Hydrolyzed collagen, KCl, and arginine: A successful strategy to reduce fat and sodium while maintaining the physicochemical, sensory, and shelf life quality of mortadella. *Meat Science, 223*, Article 109775. https://doi.org/10.1016/j.meatsci.2025.109775

Da Silva, R. D. C. S., Camponogara, J. A., Farias, C. A. A., Dos Reis, A. R., dos Santos, B. A., Pinton, M. B., … Barcia, M. T. (2025). Synergistic effects evaluation of jabuticaba and strawberry extracts on oxidative stability of pork burgers. *Meat Science, 219*, Article 109685. https://doi.org/10.1016/j.meatsci.2024.109685

Domínguez, R., Pateiro, M., Gagaoua, M., Barba, F. J., Zhang, W., & Lorenzo, J. M. (2019). A comprehensive review on lipid oxidation in meat and meat products. *Antioxidants, 8*(10), 429. https://doi.org/10.3390/ANTIOX8100429

Dos Santos, B. A., Bastianello Campagnol, P. C., da Cruz, A. G., Galvão, M. T. E. L., Monteiro, R. A., Wagner, R., & Pollonio, M. A. R. (2015). Check all that apply and free listing to describe the sensory characteristics of low sodium dry fermented sausages: Comparison with trained panel. *Food Research International, 76*, 725–734. https://doi.org/10.1016/j.foodres.2015.06.035

Egan, B. M., Lackland, D. T., Sutherland, S. E., Rakotz, M. K., Williams, J., Commodore-Mensah, Y., … Whelton, P. K. (2025). PERSPECTIVE – The growing global benefits of limiting salt intake: An urgent call from the world hypertension league for more effective policy and public health initiatives. *Journal of Human Hypertension, 39*(4), 241–245. https://doi.org/10.1038/s41371-025-00990-1

Feiner, G. (2006). *Meat Products Handbook: Practical Science and Technology*.

Gram, L., Ravn, L., Rasch, M., Bruhn, J. B., Christensen, A. B., & Givskov, M. (2002). Food spoilage—Interactions between food spoilage bacteria. *International Journal of Food Microbiology, 78*(1–2), 79–97. https://doi.org/10.1016/S0168-1605(02)00233-7

Holzapfel, W. H., & Wood, B. J. B. (2014). *Lactic Acid Bacteria: Biodiversity and Taxonomy* (Vol. 9781444333831). https://doi.org/10.1002/9781118655252.

Horita, C. N., Messias, V. C., Morgano, M. A., Hayakawa, F. M., & Pollonio, M. A. R. (2014). Textural, microstructural and sensory properties of reduced sodium frankfurter sausages containing mechanically deboned poultry meat and blends of chloride salts. *Food Research International, 66*, 29–35. https://doi.org/10.1016/j.foodres.2014.09.002

Hughes, J. M., Oiseth, S. K., Purslow, P. P., & Warner, R. D. (2014). A structural approach to understanding the interactions between colour, water-holding capacity and tenderness. *Meat Science, 98*(3), 520–532. https://doi.org/10.1016/j.meatsci.2014.05.022

Inguglia, E. S., Zhang, Z., Tiwari, B. K., Kerry, J. P., & Burgess, C. M. (2017). Salt reduction strategies in processed meat products – A review. *Trends in Food Science & Technology, 59*, 70–78. https://doi.org/10.1016/j.tifs.2016.10.016

International Standard Organization. (2007). *ISO 7218 microbiology of food and animal feeding stuffs - general requirements and guidance for microbiological examinations. Microbiologie Des Aliments - Exigences Générales et Recommendations*.

ISO. (2023). *ISO 8586:2023(E) Sensory analysis-Selection and training of sensory assessors*. International Standard Organization for Standardization.

Lee, C. H., & Chin, K. B. (2020). Influence of the pH and salt concentrations on physicochemical properties of pork Myofibrillar protein gels added with cornstarch. *Food Science of Animal Resources, 40*(2), 254–261. https://doi.org/10.5851/kosfa.2020.e10

de Lima Alves, L., Donadel, J. Z., Athayde, D. R., da Silva, M. S., Klein, B., Fagundes, M. B., … Cichoski, A. J. (2020). Effect of ultrasound on proteolysis and the formation of volatile compounds in dry fermented sausages. *Ultrasonics Sonochemistry, 67*, Article 105161. https://doi.org/10.1016/j.ultsonch.2020.105161

de Lima Guterres, L., Pinton, M. B., dos Santos, B. A., Correa, L. P., Cordeiro, M. W. S., Wagner, R., … Campagnol, P. C. B. (2023). Hydrogelled emulsion from linseed oil and pea protein as a strategy to produce healthier pork burgers with high technological and sensory quality. *Meat Science, 195*, Article 109028. https://doi.org/10.1016/J.MEATSCI.2022.109028

Luisa García, M., Calvo, M. M., & Dolores Selgas, M. (2009). Beef hamburgers enriched in lycopene using dry tomato peel as an ingredient. *Meat Science, 83*(1), 45–49. https://doi.org/10.1016/j.meatsci.2009.03.009

Macfie, H. J., Bratchell, N., Greenhoff, K., & Vallis, L. V. (1989). Designs to balance the effect of order of presentation and first-order carry-over effects in hall tests. *Journal of Sensory Studies, 4*(2), 129–148. https://doi.org/10.1111/J.1745-459X.1989.TB00463.X

Mancini, R. A., & Hunt, M. C. (2005). Current research in meat color. *Meat Science, 71*(1), 100–121. https://doi.org/10.1016/j.meatsci.2005.03.003

Nychas, G.-J. E., Skandamis, P. N., Tassou, C. C., & Koutsoumanis, K. P. (2008). Meat spoilage during distribution. *Meat Science, 78*(1–2), 77–89. https://doi.org/10.1016/j.meatsci.2007.06.020

de Oliveira, A. S., dos Santos, B. A., Farias, C. A. A., Correa, L. P., Cordeiro, M. W. S., Pinton, M. B., … Campagnol, P. C. B. (2023). Raspberry extract as a strategy to improve the oxidative stability of pork burgers enriched with Omega-3 fatty acids. *Foods, 12*(8), 1631. https://doi.org/10.3390/foods12081631

Orsi, A. S., Lemos, W. J. F., Junior, Alegbeleye, O. O., Muniz, D. C., Horita, C. N., & Sant'Ana, A. S. (2025). Sodium chloride reduction in meat processing: Microbial shifts, spoilage risks, and metagenomic insights. *Meat Science, 226*, Article 109848. https://doi.org/10.1016/j.meatsci.2025.109848

Papadimitriou, K., Alegría, Á., Bron, P. A., de Angelis, M., Gobbetti, M., Kleerebezem, M., … Kok, J. (2016). Stress physiology of lactic acid Bacteria. *Microbiology and Molecular Biology Reviews, 80*(3), 837–890. https://doi.org/10.1128/MMBR.00076-15

Pateiro, M., Munekata, P. E., Cittadini, A., Domínguez, R., & Lorenzo, J. M. (2021). Metallic-based salt substitutes to reduce sodium content in meat products. *Current Opinion in Food Science, 38*, 21–31. https://doi.org/10.1016/j.cofs.2020.10.029

Pedro, D., Lorenzo, J. M., Saldaña, E., Heck, R. T., Dos Santos, B. A., Cichoski, A. J., & Campagnol, P. C. B. (2021). Sodium reformulation and its impact on oxidative stability and sensory quality of dry-cured rabbit legs. *Meat Science, 177*, Article 108485. https://doi.org/10.1016/j.meatsci.2021.108485

Peng, B., Nie, P., & Xu, H. (2025). Plant-based fermented foods: Classification, biochemical transformations, and health benefits. *Fermentation, 11*(7), 364. https://doi.org/10.3390/fermentation11070364

Rey, M.d.l. A., Cap, M., Favre, L. C., Vaudagna, S. R., & Mozgovoj, M. V. (2025). Use of propidium monoazide coupled with real-time PCR methodology to evaluate *Escherichia coli* O157 lethality in beef burgers after organic acid addition. *Journal of Food Science, 90*(3). https://doi.org/10.1111/1750-3841.70109

da Rosa, J. L., Rios-Mera, J. D., Castillo, C. J. C., Lorenzo, J. M., Pinton, M. B., dos Santos, B. A., … Campagnol, P. C. B. (2023). High-power ultrasound, micronized salt, and low KCl level: An effective strategy to reduce the NaCl content of Bologna-type sausages by 50%. *Meat Science, 195*. https://doi.org/10.1016/J.MEATSCI.2022.109012

Ruusunen, M., & Puolanne, E. (2005). Reducing sodium intake from meat products. *Meat Science, 70*(3), 531–541. https://doi.org/10.1016/j.meatsci.2004.07.016

Sawant, S. S., Park, H.-Y., Sim, E.-Y., Kim, H.-S., & Choi, H.-S. (2025). Microbial fermentation in food: Impact on functional properties and nutritional enhancement—A review of recent developments. *Fermentation, 11*(1), 15. https://doi.org/10.3390/fermentation11010015

da Silva, S. L., Lorenzo, J. M., Machado, J. M., Manfio, M., Cichoski, A. J., Fries, L. L. M., … Campagnol, P. C. B. (2020). Application of arginine and histidine to improve the technological and sensory properties of low-fat and low-sodium bologna-type sausages produced with high levels of KCl. *Meat Science, 159*. https://doi.org/10.1016/j.meatsci.2019.107939

Stone, H., & Sidel, J. L. (2004). *Sensory Evaluation Practices: Third Edition* (pp. 1–374). https://doi.org/10.1016/B978-0-12-672690-9.X5000-8

Świątkiewicz, M., Oczkowicz, M., Ropka-Molik, K., & Hanczakowska, E. (2016). The effect of dietary fatty acid composition on adipose tissue quality and expression of genes related to lipid metabolism in porcine livers. *Animal Feed Science and Technology, 216*, 204–215. https://doi.org/10.1016/j.anifeedsci.2016.03.020

Wang, J., Huang, X.-H., Zhang, Y.-Y., Li, S., Dong, X., & Qin, L. (2023). Effect of sodium salt on meat products and reduction sodium strategies — A review. *Meat Science, 205*, Article 109296. https://doi.org/10.1016/j.meatsci.2023.109296

WHO. (2012). *World Health Organization - sodium intake for adults and children*. Geneva, Switzerland: World Health Organization (WHO).

Wu, H., Park, S. Y., & Richards, M. P. (2022). Effects of sodium chloride and sodium tripolyphosphate on the prooxidant properties of hemoglobin in washed Turkey muscle system. *Food Chemistry: X, 16*, Article 100480. https://doi.org/10.1016/j.fochx.2022.100480

Yotsuyanagi, S. E., Contreras-Castillo, C. J., Haguiwara, M. M. H., Cipolli, K. M. V. A. B., Lemos, A. L. S. C., Morgano, M. A., & Yamada, E. A. (2016). Technological, sensory and microbiological impacts of sodium reduction in frankfurters. *Meat Science, 115*, 50–59. https://doi.org/10.1016/j.meatsci.2015.12.016

Yu, C., Chen, L., Ouyang, K., Chen, H., Xu, M., Lin, S., & Wang, W. (2024). Effect of partial substitution of NaCl by KCl on aggregation behavior and gel properties of beef myosin. *Food Chemistry, 458*, Article 140178. https://doi.org/10.1016/j.foodchem.2024.140178

Yuan, J., Zhang, H., Zeng, C., Song, J., Mu, Y., & Kang, S. (2023). Impact of fermentation conditions on physicochemical properties, antioxidant activity, and sensory properties of apple–tomato pulp. *Molecules (Basel, Switzerland), 28*(11), Article 4363. https://doi.org/10.3390/molecules28114363

Zhao, L., Maimaitiyiming, R., Hong, J., Wang, L., Mu, Y., Liu, B., … Aihaiti, A. (2024). Optimization of tomato (*Solanum lycopersicum* L.) juice fermentation process and analysis of its metabolites during fermentation. *Frontiers in Nutrition, 11*. https://doi.org/10.3389/fnut.2024.1344117

Zhou, G. H., Xu, X. L., & Liu, Y. (2010). Preservation technologies for fresh meat – A review. *Meat Science, 86*(1), 119–128. https://doi.org/10.1016/j.meatsci.2010.04.033