

ORIGINAL PAPER

OPTIMIZATION OF ULTRASOUND-ASSISTED BRINING FOR MEAT PRESERVATION USING A COMPOSITE PERFORMANCE INDEX

OLGA DRAGHICI¹, DARIUS DOCOLIN¹, MARIAN CRISTIAN CIOBOATA¹,
GABRIEL GEORGE RATIU¹, CATALIN VLAD FLOREA¹

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Abstract. This study evaluates the impact of ultrasound-assisted brining (37 kHz) on pork meat (*Longissimus dorsi*), analyzing the effects of brine concentration (15% – C1 and 25% – C2) and exposure time (30 and 60 min) compared to conventional immersion brining (T0). The results demonstrate that ultrasound significantly accelerates salt diffusion through acoustic cavitation, reaching a maximum NaCl content of 18.35% and reducing water activity to 0.942 under the C2T60 treatment. This dynamic is accompanied by a progressive decrease in pH and biphasic changes in free ammonia content. Optically, moderate exposure (30 min) enhances redness intensity (Δa^*), whereas prolonged treatment (60 min) intensifies pigment oxidation, increasing the metmyoglobin (MMb) fraction and promoting undesirable yellow-brown hues. Principal Component Analysis (PCA) confirmed that treatment duration is the dominant factor driving system variability. For an integrated evaluation, a Composite Performance Index (CPI) was developed to synthesize the physicochemical, oxidative, and color parameters into a single score.

Keywords: ultrasound-assisted brining; salt diffusion; water activity; myoglobin oxidation; meat quality.

1. INTRODUCTION

Brining is one of the oldest and most widely used methods of meat preservation, alongside refrigeration, smoking, and cooking, and plays an essential role in extending shelf life and developing the characteristic sensory properties of meat products [1,2]. In recent years, interest in emerging technologies has led to the exploration of ultrasound as a method for intensifying mass transfer in brining processes.

The application of ultrasound generates acoustic cavitation phenomena, which induce structural changes in the muscle matrix and enhance the diffusion of salt ions into the tissue. As a result, the brining process can be significantly accelerated, leading to reduced processing time and improved technological efficiency [3,4].

However, ultrasound may also induce undesirable changes in product properties, particularly pigment stability and color characteristics. Myoglobin transformations, including the formation of metmyoglobin, are closely linked to color changes and may affect consumer acceptability [5]. In this context, simultaneously evaluating technological parameters such as NaCl content, water activity, pH, myoglobin fractions, and color attributes is essential for optimizing the ultrasound-assisted brining process.

¹ "Lucian Blaga" University, Faculty of Agricultural Sciences, Food Industry and Environmental Protection, 550012 Sibiu, Romania. E-mail: olga.draghici@ulbsibiu.ro; mariancristian.cioboata@ulbsibiu.ro; georgegabriel.ratiu@ulbsibiu.ro; vladcatalin.florea@ulbsibiu.ro.

This study aimed to identify optimal ultrasound-assisted brining conditions using a quantitative multi-criteria decision-making approach based on a Composite Performance Index (CPI) [6]. This index integrates physicochemical, oxidative, and color stability parameters into a single descriptor, enabling the objective ranking of treatments. The CTPI was developed using six technologically relevant response variables: sodium chloride content (%NaCl), water activity (a_w), metmyoglobin content (MMb, %), ammonia content (NH_3 , $\mu\text{g/mL}$), redness variation (Δa), and lightness variation (ΔL).

2. MATERIALS AND METHODS

2.1. MATERIALS

Fresh meat samples (*Longissimus dorsi*) were obtained from a local processing facility and transported under refrigerated conditions ($4 \pm 1^\circ\text{C}$) to the laboratory within 2 h after purchase. Visible connective tissue and surface fat were carefully removed prior to experimentation.

The meat samples were cut into uniform 4 cm cubes to ensure comparable salt diffusion conditions during treatment. Before brining, the initial physicochemical characteristics of the raw material were determined, including water activity (a_w), pigment fractions, and free ammonia content, which served as reference values for evaluating the technological changes induced by ultrasound-assisted brining.

2.2. METHODS

2.2.1. Ultrasound-assisted brining treatment

Ultrasound-assisted brining was conducted using brine solutions at two concentrations, 15% and 25% (i.e., C1 and C2), to evaluate the influence of the osmotic gradient on salt diffusion and physicochemical changes. Meat samples were immersed in the corresponding brine solution and subjected to ultrasound treatment for different exposure times: 30 min (T30) and 60 min (T60). Control samples (T0) were immersed in brine for 30 min without ultrasound treatment. The ultrasound treatment was applied using an ultrasonic bath operating at a frequency of 37 kHz (Elmasonic EASY 60H, Belgium). During treatment, samples were fully submerged in the brine solution to ensure uniform exposure to acoustic cavitation effects. The temperature of the meat was maintained below 10°C . After treatment, samples were removed from the brine, gently drained to remove excess surface liquid, and immediately subjected to physicochemical analyses.

2.2.2. Determination of sodium chloride content

The sodium chloride content of the treated samples was determined by a titrimetric method based on chloride ion quantification, following the method described by Carnero-Hernandez et al. [7].

2.2.3. Water activity measurement

Water activity (a_w) was measured using LabMaster (Novasina, Lachen, Switzerland) at 25°C. Before analysis, samples were equilibrated at the measurement temperature to ensure stable readings.

2.2.4. pH measurement

The pH of the samples was determined using the Orion 3-Star pH Meter (Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA).

2.2.5. Free ammonia determination

Free ammonia (NH_3) concentration was determined spectrophotometrically (UV-1900, Shimadzu, Kyoto, Japan) according to the method described by Ketney et al. after extraction from homogenized meat samples [8]. The results were expressed as $\mu\text{g}\cdot\text{mL}^{-1}$ NH_3 in the extract and used as an indicator of protein degradation and proteolytic activity during processing.

2.2.6. Determination of myoglobin pigment fractions

Myoglobin fractions were determined using a UV-1900 spectrophotometer (Shimadzu, Kyoto, Japan) using the method described by Wang et al. [9] following pigment extraction from the meat matrix. The relative proportions of DMb, OMb, and MMb were calculated based on absorbance measurements at characteristic wavelengths.

2.2.7. Color measurement

Color parameters were determined using a colorimeter operating in the CIELab color space using an Agera Spectrophotometer (HunterLab, Reston, VA, USA). The following parameters were recorded: L^* (lightness), a^* (redness), and b^* (yellowness). Color differences were calculated relative to the reference untreated sample. Changes in Δa^* indicated red color stability, while ΔL^* variation was considered an important attribute affecting consumer perception.

2.2.8. Calculation of the composite performance index

To identify the optimal ultrasound-assisted brining condition, a quantitative multi-criteria decision-making (MCDM) approach was applied through the calculation of a Composite Technological Performance Index (CTPI). The index integrates physicochemical, oxidative, and color stability parameters into a single scalar descriptor, allowing objective ranking of treatments. The CTPI was constructed based on six technologically relevant response variables: sodium chloride content (%NaCl), water activity (a_w), percentage of MMb, ammonia content (NH_3 , $\mu\text{g}/\text{mL}$), redness variation (Δa^*), and lightness variation (ΔL^*).

Data normalization is necessary because the response variables are expressed in heterogeneous units and measured on different scales. Therefore, min–max normalization was applied to transform all variables into dimensionless values within the interval [0, 1].

For beneficial attributes requiring maximization (%NaCl and Δa^*), Equation (1) was applied, whereas Equation (2) was employed for non-beneficial parameters requiring minimization (a_w , MMb, NH_3 , and $|\Delta L^*|$). For ΔL^* , absolute deviation from the reference

state was considered as excessive darkening or lightning negatively affects product acceptability.

$$x_i^* = \frac{x_i - x_{min}}{x_{max} - x_{min}} \quad (1)$$

$$x_i^* = \frac{x_{max} - x_i}{x_{max} - x_{min}} \quad (2)$$

where x_i^* is the normalized value, x_i is the experimental value, x_{min} and x_{max} are the extreme values within the experimental design.

A weighted linear aggregation model was adopted:

$$\sum_{i=1}^n w_i = 1 \quad (3)$$

Weight coefficients (w_i) were assigned according to technological relevance and industrial priority, as follows: 0.25 for % NaCl, 0.20 for a_w , 0.20 for MMb, 0.15 for NH_3 , 0.10 for Δa^* , and 0.10 for ΔL^* . Higher weights were assigned to salt uptake and oxidative stability because they critically affect preservation efficiency and shelf-life extension.

The CTPI was calculated using a weighted sum model:

$$CPI = \sum_{i=1}^n w_i x_{ij}^* \quad (4)$$

where $CTPI_j$ represents the composite score corresponding to treatment j , w_i denotes the weight assigned to criterion i , and x_{ij}^* represents the normalized value of criterion i for treatment j .

The CTPI ranges between 0 (lowest performance) and 1 (optimal performance).

2.2.9. Statistical integration

For the Principal Component Analysis (PCA) calculations, the Statistics Kingdom platform was used. The CPI was interpreted alongside PCA to assess the dataset's multidimensional structure and identify the main factors influencing technological performance.

3. RESULTS AND DISCUSSION

3.1. EFFECT OF ULTRASOUND-ASSISTED BRINING ON SALT UPTAKE AND WATER ACTIVITY

Ultrasound-assisted brining produced substantial changes in sodium chloride incorporation and water activity of the meat samples. Introducing brine and ultrasound treatment resulted in progressive salt diffusion within the muscle structure. At the lower brine

concentration (C1), NaCl incorporation increased from 3.63% after immersion without ultrasound treatment (T0) to 4.32% after 30 min of ultrasound exposure and further to 12.39% after 60 min of treatment. A more pronounced increase was observed at the higher brine concentration (C2), where NaCl content reached 5.59% after immersion and increased to 13.79% and 18.35% after 30 and 60 min of ultrasound treatment, respectively. Fekete et al. reported similar results, showing that salt content increases more rapidly in meat samples under ultrasound-assisted wet brining than under conventional treatments [10]. Therefore, ultrasound-assisted brining effectively reduces brining time and enhances salt diffusion in pork meat [11].

This trend confirms the combined influence of osmotic pressure and ultrasonic cavitation on mass transfer phenomena. Acoustic cavitation induces microstreaming and structural disruptions within the muscle matrix, thereby facilitating the rapid penetration of salt ions into the tissue [12,13].

Changes in NaCl incorporation across treatment conditions were accompanied by variations in water activity. The progressive increase in salt uptake with increasing ultrasound exposure time suggests a corresponding modification of the water-binding environment within the muscle matrix. The higher brine concentration (C2) generally resulted in greater NaCl incorporation than C1 at comparable treatment times, indicating that brine concentration, together with ultrasound exposure time, influenced the extent of salt transfer into the meat.

Overall, the results indicate that ultrasound-assisted brining enhances salt uptake, with the effect becoming more pronounced as the treatment time and brine concentration increase. These findings support the potential of ultrasound as a processing aid for improving mass transfer during pork meat brining.

3.2. EFFECT OF ULTRASOUND-ASSISTED BRINING ON WATER ACTIVITY

The increase in salt uptake was accompanied by a gradual reduction in water activity. Samples treated with the lower brine concentration showed moderate decreases in a_w , reaching 0.966 after 30 min (C1T30) and 0.958 after 60 min (C1T60). A more pronounced reduction was observed at the higher brine concentration, with a_w values decreasing to 0.952 and 0.942 after 30 and 60 min of ultrasound exposure, respectively. The concurrent increase in salt uptake and decrease in a_w indicate that ultrasound-assisted brining promotes mass transfer and modifies the water availability within the meat matrix, which may contribute to the microbial stability of salted meat products. Galván-Navarro et al. reported similar trends, observing a decrease in water activity with increasing brining time under ultrasound-assisted conditions [14].

The observed reduction in a_w may be associated with the combined effects of salt diffusion, water migration, and acoustic cavitation. Ultrasound-induced cavitation can enhance mass transfer by generating microstreaming and increasing molecular mobility, thereby facilitating the transport of water and solutes within the meat matrix [15]. In addition, ultrasound may induce structural modifications in muscle proteins, potentially affecting their water-binding properties and consequently influencing water availability [16]. However, Fekete et al. reported no significant differences in a_w between ultrasound-treated and control samples, suggesting that the magnitude of the ultrasound effect may depend on the specific processing conditions, including brine concentration, treatment duration, and ultrasound parameters [10].

The results demonstrate a consistent decrease in a_w with increasing ultrasound exposure time, with the lowest a_w values observed at the higher brine concentration. This behavior, together with the increased salt uptake, indicates that ultrasound-assisted brining can enhance the mass transfer processes involved in salt incorporation and water availability during pork meat brining.

3.3. EFFECT OF ULTRASOUND-ASSISTED BRINING ON pH

pH values showed a progressive decrease with increasing ultrasound treatment time for both brine concentrations. For the C1 samples, pH decreased from 6.06 (T0) to 5.80 (T60). A similar but more pronounced trend was observed for C2, where pH values declined from 6.20 (T0) to 5.69 (T60). These results indicate that both treatment time and higher brine concentration contribute to pH reduction. Galván-Navarro et al. reported similar findings, while Da Rosa et al. attributed this phenomenon to interactions between protein side chains and free radicals generated by ultrasonic waves, leading to modifications in acidic groups [14, 16].

The observed decrease in pH with increasing ultrasound treatment time can be attributed to several concurrent mechanisms induced by acoustic cavitation. Ultrasound enhances mass transfer within the meat matrix through microstreaming and localized mechanical effects, facilitating ion diffusion between brine and tissue. This process may alter the ionic balance and buffering capacity of the muscle system, contributing to lower pH values [17]. In addition, ultrasound promotes structural modifications in muscle proteins, especially myofibrillar components, potentially exposing previously buried acidic groups such as carboxyl residues. This may increase the overall acidity and reduce the ability of the protein matrix to maintain acid–base equilibrium [18].

Furthermore, prolonged ultrasound exposure may reduce the meat's intrinsic buffering capacity through progressive protein denaturation. This may increase the sensitivity of pH to ongoing physicochemical changes and contribute to the observed decrease over time [19,20].

As observed, the reduction in pH during ultrasound-assisted brining may result from the combined effects of enhanced mass transfer, protein structural changes, and associated physicochemical reactions, with the observed changes becoming more pronounced as the treatment duration increases.

3.4. EFFECT OF ULTRASOUND-ASSISTED BRINING ON FREE AMMONIA

The decrease, followed by a slight increase, in NH_3 concentration can be explained by the combined effects of ultrasound on protein structure and biochemical reactions in meat. In the initial stage T0–T30, the significant reduction in NH_3 (e.g., from 23.831 $\mu\text{g/mL}$ to 15.429 $\mu\text{g/mL}$ for C1T30) can be attributed to diffusion and dilution effects induced by ultrasound. Acoustic cavitation enhances mass transfer, facilitating the migration of soluble nitrogen compounds, including ammonia, from the tissue into the brine. At the same time, salt penetration may inhibit enzymatic and microbial activity responsible for NH_3 formation, further reducing it [14,20].

At longer treatment times (T60), a slight increase in NH_3 concentration is observed (e.g., 16.548 $\mu\text{g/mL}$ for C1 and 18.671 $\mu\text{g/mL}$ for C2). This trend can be explained by the structural effects of ultrasound on proteins, including denaturation and fragmentation. These

changes may promote degradation reactions of nitrogenous compounds, such as deamination, leading to ammonia formation [18]. Additionally, the intensification of cavitation effects at higher salt concentrations C2 may further enhance these processes, explaining the higher NH_3 values observed for C2T30 and C2T60 compared to C1. The observed variation in NH_3 concentration with treatment time suggests that ultrasound influences both mass transfer and biochemical processes within the meat matrix. The initial decrease may be associated primarily with enhanced migration and redistribution of soluble nitrogen compounds, whereas the subsequent increase at longer treatment times may reflect the contribution of protein degradation and related reactions leading to ammonia formation.

This phenomenon can be explained by the cavitation effect specific to ultrasound, which generates microstructural disruptions in muscle tissue. These effects may increase the accessibility of enzymes and substrates, facilitating deamination and protein degradation reactions known to produce ammonia. At the same time, increased tissue permeability may enhance the migration and redistribution of these compounds within the meat. Overall, the changes in NH_3 concentration indicate a time-dependent response to ultrasound treatment, characterized by an initial decrease followed by a slight increase at longer treatment times. Brine concentration may further modulate this response, with the higher concentration (C2) generally showing greater NH_3 values at the later stages of treatment. These findings suggest that the balance between mass transfer, protein structural modifications, and biochemical reactions determines the evolution of ammonia concentration during ultrasound-assisted brining.

3.5. EVOLUTION OF MYOGLOBIN FRACTIONS DURING ULTRASOUND-ASSISTED BRINING

Ultrasound-assisted brining significantly altered the distribution of myoglobin fractions, indicating pronounced changes in the pigment system compared with the control sample. The untreated sample T0 had a relatively high proportion of OMb (42.85%) and a moderate level of MMb (46.44%), reflecting a balanced redox state of muscle pigments. Following treatment, all samples exhibited a marked increase in MMb content, with values ranging between approximately 56% and 63%. The highest level was observed in C1T60 (62.81%), followed by C2T60 (61.17%) and C2T30 (61.01%), indicating a greater degree of pigment oxidation under prolonged ultrasound exposure. In parallel, OMb decreased significantly across all treatments, reaching the lowest value in C1T60 (16.69%), suggesting a reduction in the oxygenated form responsible for the desirable bright red color. The proportion of DMb increased after processing, rising from 10.52% in the control to 14%-21% in treated samples, with the highest level in C1T60 (21.25%). This increase reflects a shift in the redox equilibrium of myoglobin forms and may indicate limited oxygen availability within the tissue.

These changes can be attributed to the combined effects of ultrasound and brining. Acoustic cavitation generates localized high-energy conditions and reactive species, which promote the oxidation of ferrous myoglobin (Fe^{2+}) to its ferric form (Fe^{3+}), resulting in MMb formation. At the same time, structural modifications induced by ultrasound may affect oxygen diffusion and pigment stability, further accelerating the conversion of OMb to MMb.

The influence of processing parameters suggests that treatment time plays a dominant role in pigment transformation. Prolonged exposure (T60 samples) led to higher MMb levels and lower OMb content, indicating enhanced oxidative processes. In contrast, the effect of

brine concentration was less pronounced, although MMb values were slightly higher at the higher concentration C2, likely due to increased ionic strength and protein destabilization.

Previous studies have mainly focused on meat color rather than on detailed pigment transformations. Araújo et al. reported no significant changes in DMb and MMb proportions, whereas Kononiuk et al. found that ultrasound application in beef decreased MMb and OMb proportions, accompanied by an increase in DMb content [21, 22].

The PCA shown in Fig. 1a explored changes in myoglobin fractions across varying ultrasound-assisted brining conditions. The first principal component (PC1) captured 99.1% of the total variance, with the second component (PC2) accounting for just 0.9%, suggesting that nearly all system variability aligns along one predominant axis. The distribution of variables along PC1 revealed a clear separation between oxidized and reduced pigment forms. MMb was strongly associated with the positive direction of PC1, while DMb and OMb were located on the negative side. This pattern reflects the progressive oxidation pathway of muscle pigments, where reduced and oxygenated forms are converted into MMb during processing. The spatial arrangement of treatments showed that all samples were distributed mainly along PC1, confirming that pigment oxidation is the dominant phenomenon influenced by ultrasound-assisted brining. Treatments corresponding to shorter processing times (T0 and T30) were positioned closer to the DMb and OMb regions, indicating higher proportions of reduced and oxygenated pigments and, consequently, better color stability. In contrast, prolonged ultrasound exposure (T60) led to a shift toward the positive region of PC1, particularly for C1T60, which showed the strongest association with pigment transformation. This suggests that extended ultrasound treatment promotes DMb oxidation to MMb, resulting in reduced color stability.

The influence of brine concentration appeared less pronounced compared to treatment time, as reflected by the minimal contribution of PC2 to total variance. Although slight differences between C1 and C2 treatments were observed along this secondary component, these variations were negligible compared to the dominant effect of ultrasound exposure time.

Overall, the PCA results demonstrate that ultrasound treatment duration is the key factor governing myoglobin oxidation, while brine concentration plays a secondary role in modulating pigment transformations. Shorter processing times favor preserving reduced and oxygenated pigment forms, whereas prolonged exposure accelerates oxidative changes associated with MMb formation.

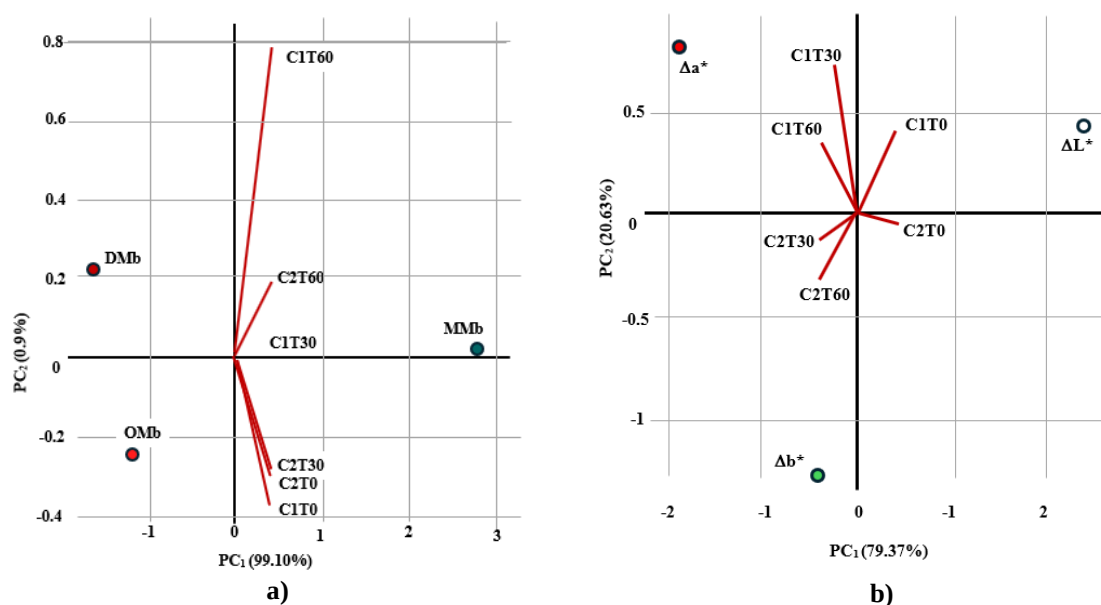


Figure 1. PCA applied to study the effect of ultrasound-assisted brining on meat pigments (a) and meat color (b).

3.6. EVOLUTION OF COLOR DURING ULTRASOUND-ASSISTED BRINING

Color differences determined in the CIE Lab* color space revealed distinct effects of ultrasound-assisted brining depending on treatment duration and brine concentration. Lightness (ΔL^*) increased for C1T30 (+2.4) and C2T60 (+2.1), whereas C1T60 showed a notable decrease (−2.6), indicating darkening under prolonged treatment at lower salt concentration.

The most pronounced increase in redness (Δa^*) was recorded for C1T30 (+5.5), followed by C2T30 (+4.9), suggesting a significant enhancement of red color under moderate treatment conditions. In contrast, longer ultrasound exposure resulted in lower Δa^* values (3.3 for C1T60 and 3.8 for C2T60), indicating attenuation of this effect.

For yellowness (Δb^*), the largest increases occurred at higher brine concentrations, particularly for C2T30 (+4.2) and C2T60 (+3.8), indicating a shift toward more yellowish tones. Conversely, C1T60 (−1.0) showed a slight reduction in this component.

Overall, the results suggest that moderate treatments (T30) enhance redness, while prolonged exposure (T60) reduces red intensity and may induce undesirable chromatic changes, particularly by increasing yellowness at higher brine concentrations.

Previous studies have reported inconsistent findings. Contreras-Lopez et al. observed no significant changes in L^* , a^* , or b^* after ultrasound treatment up to 90 min, whereas Guo et al. reported only a decrease in lightness [23, 24]. In contrast, Krasulya et al., using a 3% brine, reported a 22.2% increase in b^* at the surface, along with increases in L^* (3.45%) and a^* (33.3%) within the sample [25].

Principal Component Analysis (PCA) was performed to evaluate variations in color parameters (ΔL^* , Δa^* , Δb^*) considering all treatments, including the initial state (T0). As shown in Figure 1b, the first two principal components explained 99.99% of the total variance (PC1 = 79.37%, PC2 = 20.63%), indicating a robust representation of ultrasound-induced color changes.

The loading plot showed that PC1 was primarily associated with lightness (ΔL^* , positive direction), while redness (Δa^*) was oriented toward the negative side of PC1. PC2 mainly differentiated redness (positive direction) from yellowness (Δb^* , negative direction), indicating that this axis reflects chromatic transitions from red to yellow hues.

Treatment distributions showed distinct patterns depending on processing conditions. C1T0 was in the positive region of PC1, indicating a strong association with increased lightness, suggesting that initial brining already induced a noticeable brightening effect. C1T30 was positioned in the upper-left quadrant, showing a strong association with Δa^* , consistent with the highest increase in redness observed experimentally. This confirms that moderate ultrasound exposure enhances red color.

In contrast, C1T60 shifted toward the center, indicating a reduced contribution of redness and suggesting the onset of pigment oxidation. This trend was further supported by the positioning of C2T30 and C2T60 in the lower-left quadrant, where Δb^* was dominant, indicating increased yellowness and a transition toward less desirable yellow-brown tones.

The separation of C2T0 in the positive PC1 region suggests that higher brine concentration initially enhances lightness; however, subsequent ultrasound treatment promotes chromatic shifts rather than further brightening.

Overall, PCA demonstrates that moderate ultrasound treatment enhances redness, whereas prolonged exposure, particularly at higher brine concentrations, promotes yellowness and color degradation. These findings are consistent with the previously observed transformation of myoglobin fractions, where increased MMb formation is associated with reduced color stability and the development of undesirable hues.

3.7. COMPOSITE PERFORMANCE INDEX (CPI)

To provide an integrated, objective evaluation of the efficiency of ultrasound-assisted brining, a CPI was developed that combined physicochemical parameters, oxidative stability indicators, and color variables into a single quantitative descriptor. This multicriteria approach enabled a coherent comparative analysis of the investigated treatments from the perspective of overall technological performance.

The CPI included the following parameters: sodium chloride content (%NaCl), water activity (a_w), percentage of MMb, free ammonia concentration (NH_3), redness variation (Δa^*), and lightness variation (ΔL^*). Among these, %NaCl and Δa^* were defined as beneficial attributes to be maximized, while a_w , MMb, NH_3 , and the absolute value of ΔL^* were considered criteria to be minimized. The inclusion of $|\Delta L^*|$ was based on the assumption that both excessive darkening and lightening negatively affect perceived freshness and surface appearance stability.

To reflect the technological relevance of each parameter, namely salt diffusion, product safety, oxidative stability, and sensory quality, a weighted scoring scheme was applied (Table 1). Greater importance was assigned to preservation efficiency and oxidative stability, while color parameters contributed moderately to the overall evaluation.

Table 1. Weights assigned to CPI.

Parameter	Objective	Weighted scoring
NaCl	max	0.25
a_w	min	0.20
MMb	min	0.20
NH_3	min	0.15
Δa^*	max	0.10
ΔL^*	min	0.10
Total		1.0

After min–max normalization and weighted aggregation, Table 2 presents the CPI values for the analyzed treatments.

Table 2. CPI scores for ultrasound-assisted brining treatments.

Sample	CPI value
C1T30	0.59
C1T60	0.54
C2T30	0.64
C2T60	0.67

Based on these values, the ranking was established as follows: C2T60 > C2T30 > C1T30 > C1T60.

Within the C1 series, C1T30 exhibited superior overall performance compared to C1T60. This difference can be explained by higher Δa^* values (indicating greater redness), along with the lowest NH_3 level, moderate MMb content, and limited lightness deviation ($\Delta L^* = 2.4$). However, the relatively low salt uptake reduced its composite score, given the high weight assigned to this parameter. In contrast, C1T60 promoted greater NaCl diffusion but was penalized by negative ΔL^* values (indicating darkening), as well as increased MMb and NH_3 levels, suggesting intensified oxidative and proteolytic processes.

For the C2 series, both treatments demonstrated higher efficiency in salt diffusion, reflected in their superior CPI scores. C2T30 achieved substantial NaCl incorporation (13.79%) and a reduction in water activity ($a_w = 0.952$), accompanied by moderate MMb

levels and the smallest lightness variation among the samples ($\Delta L^* = 1.7$). This chromatic stability supported a better balance between technological performance and visual quality.

C2T60 showed the highest NaCl content (18.35%) and the lowest a_w value (0.942), indicating maximum efficiency in salt diffusion and dehydration, with favorable implications for preservation. Although MMb and NH_3 levels were higher, along with greater variation in ΔL^* (2.1) and Δb^* , the dominant contribution of preservation-related parameters yielded the highest composite index.

Including ΔL^* in the multicriteria model enabled more refined differentiation among treatments, highlighting the importance of maintaining surface appearance stability during ultrasound-assisted brining. Nevertheless, salt diffusion efficiency and water activity reduction primarily drove the overall optimization trend, confirming the major role of preservation-related parameters in determining global technological performance.

From an industrial perspective, C2T60 is the optimal treatment when the primary objective is to maximize preservation efficiency. However, when oxidative stability, visual quality, and processing time are jointly considered, C2T30 emerges as a more balanced and sustainable alternative, offering high technological performance with reduced processing time (30 min) and moderate oxidative impact.

3.8. LIMITATIONS AND CONSIDERATIONS FOR INDUSTRIAL SCALE-UP

Although ultrasound-assisted brining offers advantages in terms of enhanced mass transfer and reduced processing time, several limitations should be considered when comparing this technology with conventional brining. The use of ultrasound requires specialized equipment and additional energy input, while the distribution of acoustic energy may become less uniform as the treatment volume increases. Consequently, the process effectiveness may depend on the treatment vessel geometry, ultrasound intensity and frequency, transducer position and number, and the distance between the ultrasonic source and the meat. In addition, prolonged or excessive ultrasound exposure may result in localized heating and structural modifications of the muscle tissue, making precise control of processing conditions necessary.

The scale-up of the optimized technological conditions may also depend on the size and thickness of the meat pieces. Larger or thicker pieces increase the diffusion distance and may therefore require different treatment times or ultrasound intensities to achieve uniform salt incorporation and water activity throughout the product. At industrial scale, the distribution and circulation of the brine, product loading, treatment temperature, and spatial distribution of acoustic energy within the processing vessel should also be carefully controlled. Therefore, the optimized conditions identified in the present study should be considered as a basis for further pilot- and industrial-scale validation rather than as directly transferable operating conditions. Scale-up studies using industrial ultrasound-assisted equipment and representative meat-piece dimensions would be necessary to confirm treatment uniformity, process efficiency, and product quality under commercial processing conditions.

4. CONCLUSIONS

Ultrasound-assisted brining technology represents an effective alternative to conventional methods, substantially reducing processing time and optimizing preservation parameters. Exposure duration plays a critical role in quality control: while moderate 30-minute treatments preserve sensory properties and color stability, 60-minute treatments

maximize mass transfer efficiency at the expense of accelerated oxidative processes. Based on the multi-criteria decision-making model (CPI), the C2T60 treatment (25% brine, 60 min) was identified as optimal for industrial applications, as its superior salt uptake and water activity reduction outweigh the minor chromatic and structural degradations. Future studies should validate the optimized C2T60 treatment at pilot scales, considering meat size and thickness, ultrasound parameters, equipment configuration, brine circulation, and temperature control, while assessing treatment uniformity, oxidative stability, sensory quality, and storage performance. In addition, texture profile analysis could provide further information on the structural modifications induced by ultrasound treatment.

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