Use of ultrasound as a pre-treatment for vacuum cooling process of cooked broiler breasts

Hande Özge Güler Dal, Oguz Gursoy, Yusuf Yilmaz
Department of Food Engineering, Faculty of Engineering and Architecture, Burdur Mehmet Akif Ersoy University, İstiklal Campus, 15030 Burdur, Turkey

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ABSTRACT
In this study, ultrasound application at two different frequencies (37 or 80 kHz) and durations (15 or 30 min) was used as a pre-treatment for raw broiler breasts, and its effect on cooling, color, textural and sensory characteristics of cooked broiler breasts during vacuum cooling process was determined. The anterior and posterior parts of broiler breast halves were carefully removed, and these parts with a 20 mm width were named as the regions A and B, respectively. Both regions were vacuum-packed and pre-treated by ultrasound, followed by oven-cooking in aluminum foils, and cooling time, weight loss and temperature distribution characteristics were determined. Besides sensory and textural properties, the effect of the ultrasound pre-treatment on the pH, dry matter and ash contents and color (CIELAB) values of cooked breasts was determined. During vacuum cooling, ultrasound pre-treatment significantly reduced cooling time required to cool cooked broiler breasts from 85 °C to 12.5 °C, and the lowest values for the regions A and B were obtained for the 30 min ultrasound pre-treatment at 37 kHz as 12.72 and 14.61 min, respectively (p < 0.05). The cooling losses of breasts from the regions A and B were 12.64 and 11.61%, respectively. In comparison to immersion pre-treatment, increasing the frequency and duration of ultrasound pre-treatment generally decreased cooking loss values for both A and B regions while cooling loss increased. Instrumental hardness values of breast samples for the 15 min ultrasound pre-treatment decreased while they increased with the 30 min pre-treatment (p < 0.05) at both frequencies. The redness values (a*) increased by ultrasound pre-treatment while the highest value was found for a 30 min pre-treatment at 80 kHz for both regions. Sensory hardness (on a 14.5 cm scale) results indicated that the highest value (9.33) was determined for a 30 min ultrasound pre-treatment at 37 kHz while the ultrasound pre-treatment at 37 kHz for 15 min had no negative effect on hardness compared to control samples (p > 0.05). In conclusion, ultrasound pre-treatment can be successfully used for the vacuum cooling process of broiler breasts for the reduction of cooling time, and a 30 min ultrasound pre-treatment at 37 kHz can provide relatively superior cooling characteristics.

1. Introduction
Meat has a special place in many communities for a variety of reasons including its preferability, traditional use, availability and nutritional content [1]. The importance of meat in diet is not only related to its high biological value, but also its amino acid composition, which is capable of complementing plant proteins. Moreover, meat is a good source of iron, zinc and vitamin B. Meat and meat products are highly sensitive to microbial growth and quality losses. Therefore, there is a continuous need to develop suitable preservation methods for meat and meat products. Chicken meat is one of the most preferred types of meat for consumers in all over the world, and its consumption has been increasing steadily in recent years due to its low cost compared to red meat, its nutritional content rich in vitamins and minerals, its ease of preparation and consumption with various dishes. In addition to its low caloric value, it is easily digestible and chewable due to the short meat fibers in its structure [2,3]. Chicken meat contains almost all amino acids in sufficient amounts that are essential for human nutrition. It can be consumed directly after cooking, or after processing into numerous meat products such as salami, ham, sausage, hamburger, doner and meatballs [4]. pH values of meat vary depending on the type, quantity and quality of the protein and affect the functional properties of meat as color and emulsion properties, water holding capacity and cooking loss [5,6].

The temperature range between 10 and 72 °C is very critical for food safety because surviving microorganisms after heat treatment can easily...
multiply in foods in this range. In addition, poultry meat and meat products can be contaminated with various pathogenic bacteria such as *E.coli*, *Campylobacter* spp. and *Salmonella* spp. during processing. Novel preservation methods besides traditional ones are needed to be developed for this group of foods [7]. The most common method for prolonging the shelf life of meat and meat products is an efficient cooling process. Meat is first cooled after slaughter to avoid undesirable spoilage and losses. The lack of refrigeration and other preservation methods in meat industry can result in significant losses and lead to public health problems [8]. While there is no decrease in the nutrient content of meat products during cold storage, positive changes in flavor can be achieved by ripening, and fast and homogeneous cooling techniques are very important for cooked meat and meat products due to their poor thermal conductivity [9]. For this purpose, vacuum cooling is widely used in the production of high-quality products by providing high cooling rate and short process times, low energy consumption and homogeneous temperature distribution [10,11]. Vacuum cooling has been used for a long time to cool various food products with high free water content that will not be damaged by the removal of water [11]. This technique involves the removal of heat from the food product by reducing the ambient pressure in a vacuum chamber and consequent water evaporation [12,13]. Vacuum cooling has several advantages over conventional cooling methods. The biggest advantage is to achieve high cooling rates and thus very short cooling times. In addition, it is a safe working technique with high energy efficiencies and long shelf lives [14]. On the other hand, since the cooling effect is achieved by evaporation, it causes high cooling loss, which means low efficiency and may adversely affect the meat quality [11].

In a number of studies, vacuum cooling was used in meat products to improve feasibility and quality characteristics, to save energy and processing time, also to reduce weight losses during cooling (i.e. to increase system efficiency) [5,9–11]. In these studies, different cooking methods were applied in combination with vacuum cooling processing. Moreover, some procedures were also tested in the literature to increase the practical uses of vacuum cooling in meat and meat products such as immersion vacuum cooling, ripening in brine, pulsed immersed vacuum cooling, vacuum impregnation and bubbling vacuum cooling [9,15–19].

High-power ultrasound applications, ultrasonic waves about 20 kHz, are usually used for the vibration effects, which make cavitations in liquids or biological media. High-power ultrasound has been studied by various researchers in meat industry since it provides homogeneous temperature distribution, short processing time, increased product quality and efficiency of traditional methods, also improved heat and mass transfer [20–23]. Acoustic parameters, especially for the frequency level, determine the magnitude of the desired results of ultrasonication. The physical, chemical or mechanical effects of ultrasonic waves can change the product properties, especially the tenderness; however, mechanical cavitation and disruption in meat muscle structure may be limited at high frequencies where poor caviation may occur [22,23]. Li et al. [24] found that high-power ultrasound treatment significantly improves the textural properties of chicken meat and creates significant differences in cooking loss. Ultrasound technology may increase the tenderness and also decrease the shear force and cooking loss in chicken breast [25].

Although the improvement of the vacuum cooling application in food industry has been studied widely, no study is available on the use of ultrasound as a pre-treatment in combination with vacuum cooling technology and its effects on cooked broiler breasts in the literature. In this study, it was aimed to shorten the cooling time and to improve the textural properties of broiler breasts by vacuum cooling process combined with ultrasound pre-treatment. Therefore, the effect of ultrasound pre-treatment at 37 or 80 kHz for either 15 or 30 min on the cooling time and temperature distribution, weight losses, physicochemical, textural and sensory properties of the broiler breasts was determined and compared with immersion pre-treatment as a control.

## 2. Materials and methods

### 2.1. Materials

In this study, a total of 120 random samples of broiler breasts (each weighting about 170 g) from the same hen were obtained from a local meat market (Gelikoglu Food Co., Burdur, Turkey) a day after slaughter and were used as a raw material. All samples were immediately transferred to the laboratory in an insulated ice box and then subjected to the following treatments. Textural properties of broiler breast halves, especially their hardness values, were previously reported to vary laterally in the literature [26]. Therefore, the skin, fat and nerve tissues of broiler breasts were carefully removed (Fig. 1). The anterior and posterior parts were separated by a sharp knife, and the samples were sized to have a width of ca. 20 mm (± 2 mm) and a weight of 46 ± 5 g so that two parts were obtained from each broiler breast halves. The parts marked as A and B in Fig. 1 show the regions A (anterior part) and B (posterior part) used in the study, and the parts indicated as X were discarded [26]. After completing the size and weight measurements of the A and B regions with a digital caliper (Wert W2325, China) and an analytical balance (Weightlab WL-3002L, Turkey), samples were vacuum-packed in 250x750 mm and 80 μm thick polyethylene bags (Vishakha, Poly Fab Pvt. Ltd., Ahmadabad, India). Samples in vacuum-packages were then stored under refrigerated conditions (4 ± 1 °C) until analyses. Since texture analyses, thermal camera imaging, cooking, cooling and sensory analyses were destructive, batches of random samples were used.

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**Fig. 1.** Trimming of broiler breasts (Parts marked as A and B regions were used in experiments while parts marked as X were discarded.)

### Nomenclature

| Symbol | Description |
|--------|-------------|
| a*     | Redness in CIELAB color scale |
| b*     | Yellowness in CIELAB color scale |
| L*     | Lightness in CIELAB color scale |
| ΔC     | Chroma difference |
| ΔE     | Total color difference |

### Abbreviations

| Abbreviation | Description |
|--------------|-------------|
| US           | Ultrasound |
| I-15         | Immersion for 15 min as a pre-treatment |
| I-30         | Immersion for 30 min as a pre-treatment |
| US37-15      | Ultrasound pre-treatment for 15 min at 37 kHz |
| US37-30      | Ultrasound pre-treatment for 30 min at 37 kHz |
2.2. Ultrasound as a Pre-treatment

For the ultrasound pre-treatment, the temperature of an ultrasonic water bath (Apple Schmidbauer GmbH, Elmasonic P180H, Germany) was kept at 10 °C by the circulation of ethylene glycol inside a copper coil (1 m). Since ultrasonication process generates heat, a circulated water bath (Daihan Scientific Co., Ltd. MaXircu CR-12, Gangwon-do, Korea) was used to maintain the temperature of the ultrasonic water bath at 10 °C, which was the lowest temperature obtained in preliminary experiments. Ultrasound pre-treatment was applied to broiler breasts in vacuum-packages at a frequency of 37 or 80 kHz for 15 or 30 min. During pre-treatment, the acoustic energy density was calculated as ~ 113 W/L based on the ultrasonic bath data supplied by the manufacturer, and the immersion ratio was ~ 2.4 g/100 mL. Vacuum-packed samples for immersion were not pre-treated by ultrasound, and they were used as control samples. Control samples were pre-treated by immersion in a water bath at 10 °C for either 15 or 30 min. After treatments, all samples were kept at 4 ± 1 °C for 2 h prior to cooking.

2.3. Cooking

Prior to cooking process, meat samples were carefully removed from vacuum packages and then wrapped in aluminum foils. A forced convection oven (Arçelik MF 44, Istanbul, Turkey) was used, and samples were cooked for 30 min on the middle shelf of the oven at 200 °C (until the core temperature was about 85 ± 1 °C). During cooking, the central temperature of the product was controlled by a thermocouple connected to the digital oven thermometer (Cheerman DT1004A, China).

2.4. Vacuum cooling

Vacuum cooling process was conducted in a vacuum chamber (Memmert 30–750 Vacuum Oven, Schwabach, Germany) integrated by a vacuum pump (MVP 24, Woosung Vacuum Co. Ltd, Jeju, Korea) with 20–24 m³/h pumping speed. During experiments, the heating feature of the vacuum chamber (i.e. vacuum oven) was disabled. The vacuum cooling was conducted under constant vacuum pressure (15 mbar) at room temperature until the central temperature of the samples reached 12.5 °C. This was selected as the target cooling temperature since the vacuum cooling process of broiler breasts very slow below 12.5 °C temperature. Schematic representation of the system is presented in Fig. 2. The vacuum-cooled samples were kept in a refrigerator (4 ± 1 °C) until further analyses.

2.5. Methods

2.5.1. Temperature measurements and determination of its distribution

During vacuum cooling, central and surface temperatures of the samples were determined by T-type and K-type thermocouples connected to a data logger (Testo 176 T3, Lenzkirch, Germany) at 10 s intervals, respectively. The temperature profiles of surface and cross-section areas were monitored by a thermal camera (FLIR Systems OU, FLIR C2, Wilsonville, Oregon, USA) immediately after vacuum cooling process, and the temperature distribution (profile) was evaluated by means of the image processing program of the device. Temperature profiles were only reported for the broiler breasts of the region A, which had a shorter cooling time than the region B.

2.5.2. Determination of cooking loss

Cooking loss values for broiler breasts were determined by subtracting the weight of cooked samples (Wcooked) from the initial weight of raw breasts (Wraw) by using a digital balance, and they were expressed as percentages on raw material using the Equation (1).

\[ \text{Cooking Loss(\%) } = \frac{(W_{\text{raw}}) - (W_{\text{cooked}})}{(W_{\text{raw}})} \times 100 \]  

2.5.3. Determination of cooling time and cooling loss

The time required to reduce the central temperature of samples from 85 °C to 12.5 °C was determined as cooling time. For cooling loss values, the weights of broiler breasts before (Wcooked) and after vacuum cooling (Wcooled) were monitored with a digital balance, and they were expressed as the percentage of cooling loss on cooked material using the Equation (2). Cooling time was pre-determined for each pre-treatment, and the same time was applied to broiler breasts. Finally, temperature data was used to calculate cooling loss values.

\[ \text{Cooling Loss(\%) } = \frac{(W_{\text{cooked}}) - (W_{\text{cooled}})}{(W_{\text{cooked}})} \times 100 \]  

2.5.4. Determination of overall color properties

Color measurements were performed using a colorimeter (Konica-Minolta CR400, Osaka, Japan). During overall color measurements, raw and cooked samples were carefully ground and homogenized by a porcelain mortar and pestle, and three measurements were obtained for each replication. Prior to measurements, the tristimulus values of CIE L*a*b* readings were calibrated against a standard white plate (Y = 84.8000; x = 0.3199; y = 0.3377) supplied by the manufacturer.
and then the color of samples were determined using a D65 light source and the observer angle of 10°. Total color difference (ΔE), total chroma difference (ΔC) and hue angle values were calculated by the Equations (3) to (5), respectively. Color values of raw samples were used as the initial color values in these equations.

\[
\Delta E = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}
\]

(3)

\[
\Delta C = \sqrt{\left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}
\]

(4)

\[
\text{Hue angle } = \tan^{-1}\left(\frac{b^*}{a^*}\right)
\]

(5)

### 2.5.5. Determination of pH values

A digital pH-meter with a penetration probe (Testo 205, Lenzkirch, Germany) was used to determine the pH values of broiler breast samples.

### 2.5.6. Determination of dry matter content

The dry matter contents of sample (5 g) were determined by drying samples at 105 °C in a convective oven (Nüve EN500, Ankara, Turkey) until reaching a constant weight (about 18 h) [27].

### 2.5.7. Determination of ash content

The ash contents of the dried samples were determined by weighing samples into porcelain crucibles and subjecting them to a temperature of 550 °C in a furnace until the color turned gray-white (for 18–24 h) [28]. Ash contents of samples were expressed on dry basis.

### 2.5.8. Texture analyses

Vacuum cooled samples were wrapped by stretch foil and stored at 4 ± 1 °C for a maximum of 24 h until texture analyses were carried out. Prior to analyses, samples from the regions A and B were carefully trimmed by a sharp knife to obtain meat blocks similar in size (15x20x40mm ± 2mm). A digital caliper was used to obtain breast parts at the center of the regions A and B. The shear force values (N) were determined by using a texture analyzer (Shimadzu Corporation EZ-X, Kyoto, Japan) with a cutting apparatus (Warner-Bratzler 60°V-cut flat end face). Muscle fibers of the breast cuts were aligned perpendicular to the cutting apparatus. During the analyses, 5 mm/s test speed was used.

### 2.5.9. Sensory analyses

Sensory analyses were performed by ten semi-trained panelists (22–25 years old), and the method of Muñoz [29] was used with a slight adaptation. Foods were mostly adapted to obtain hardness scales based on their availability in the national market. During analyses, samples were coded with three-digit numerical numbers and served to panelists on the same day with treatments. During training, the interaction and calibration of panelists were facilitated; however, special cabinets were used to prevent their interaction during the sensory analyses of the treated-samples of cooked broiler breasts. Panelists were trained by informing about the configuration of the hardness test and the evaluation of the hardness scores of 14.5 cm long standard hardness scale (1: low (cream cheese), 7: medium (chicken sausage), 14.5: high (hard candy)) [29]. Cream cheese (Aknaz, Bahçivan Food Inc., Kirkkareli, Turkey), chicken sausage (Tombik, Abalıoğlu Food Inc., İzmir, Turkey) and hard sugar (Olipol, Kent Foods, Kocaeli, Turkey) used as standard samples and obtained from local markets in Burdur, Turkey. During the analyses, panelists evaluated four different intact samples for which the shortest cooling times were obtained (ultrasound pre-treated samples at 37 kHz frequency for 15 and 30 min and their immersion counterparts as control) in region A. Between samples, panelists were instructed to consume some unsalted breads and to drink water (Nazlı, Aydın, Turkey). After the panel, the average hardness scores were calculated.

### 2.5.10. Statistical analysis

Data were analyzed by General Linear Model ANOVA procedures of the Statistical Analysis System (The SAS System for Windows 9.0, Chicago, IL, USA). For this purpose, ANOVA and the Duncan multiple comparison test were used at a 95% confidence level to test significant differences among means. A 2x3 full factorial design with two pre-treatment time (15 and 30 min) and three pre-treatments (immersion, ultrasonication at 37 and 80 kHz) was used in experiments. All experiments were performed in triplicates, and analyses were conducted in two or three parallels while the results were expressed as mean ± standard deviation.

### 3. Results and discussion

#### 3.1. Effect of ultrasonic Pre-treatment on cooling Time, cooking and cooling losses

In vacuum cooling trials, the dry matter content (on dry basis) of vacuum cooled broiler breasts was between 37.00 and 41.37% while their ash content ranged from 9.63 to 11.36%. The effect of immersion and ultrasound pre-treatments on cooling time, cooling loss and cooking loss values of A and B regions is presented in Table 1. Cooking loss for both regions decreased with ultrasound pre-treatment. Ultrasound assisted cooking process may increase cooked weight of meat by reducing cooking losses [23]. Similar to our results, ultrasound process was reported to increase the cooking yields of cured ham rolls [30]. Ultrasound pre-treatment for 30 min at both frequencies reduced the cooking loss values of the region A, which resulted in a significant difference from the control sample, which was pre-treated by the immersion method (p < 0.05). For the region B, the highest cooking loss (48.96%) was obtained for the immersion pre-treatment for 15 min

| Region | Treatment (Frequency) | Treatment time (Frequency) | Cooking loss (%) | Cooling time (s) | Cooking loss (%) |
|--------|----------------------|--------------------------|-----------------|-----------------|-----------------|
| A      | Immersion            | 15                       | 40.96 ± 1.24a   | 1093.33 ± 81.45a | 8.57 ± 1.88c    |
|        |                      | 30                       | 40.21 ± 2.62b   | 976.67 ± 5.77b  | 9.65 ± 0.96ac   |
|        | US (37 kHz)          | 15                       | 36.49 ± 0.43b   | 946.67 ± 20.82a | 9.58 ± 0.55ac   |
|        |                      | 30                       | 28.97 ± 7.24c   | 763.33 ± 15.28a | 12.64 ± 0.61a   |
|        | US (80 kHz)          | 15                       | 33.46 ± 1.63c   | 923.33 ± 11.55a | 11.84 ± 1.55ab  |
|        |                      | 30                       | 29.11 ± 1.41c   | 856.67 ± 11.55c | 11.18 ± 1.56ab  |
| B      | Immersion            | 15                       | 48.96 ± 2.18a   | 1203.33 ± 15.28a| 9.07 ± 0.93c    |
|        |                      | 30                       | 40.38 ± 2.26b   | 1176.67 ± 15.28a| 8.71 ± 0.65c    |
|        | US (37 kHz)          | 15                       | 36.16 ± 2.96b   | 1130.00 ± 10.00b| 9.22 ± 0.08ac   |
|        |                      | 30                       | 34.02 ± 6.57b   | 876.67 ± 32.15c | 11.61 ± 1.45a   |
|        | US (80 kHz)          | 15                       | 33.16 ± 1.98b   | 1126.67 ± 15.28c| 10.69 ± 0.69ac  |
|        |                      | 30                       | 29.59 ± 3.22b   | 940.00 ± 52.9c  | 11.96 ± 0.73a   |

A-E; Different letters in the same column indicate statistical differences (p < 0.05).
Fig. 3. Time-dependent changes in the temperature of the surface and center of broiler breasts pre-treated by immersion (A), ultrasound at 37 kHz (B) and at 80 kHz (C) pre-treatments during vacuum cooling.
(p < 0.05). While the effect of treatment type and time on cooking loss values in regions A and B was significant (p < 0.05), the effect of treatment-time interaction was insignificant (p > 0.05). Cooking method may influence cooking loss values of meat samples significantly. For example, Schmidt et al. [16] reported that cooking losses were 19.1 and 19.6% during the vapor and immersion cooking of chicken breasts, respectively. Dickens et al. [31] studied the effect of ultrasound pre-treatment on physical characteristics of broiler breasts and reported that cooking loss was 18.0% in ultrasound treated samples for 15 min while this value was 17.9% in control samples (p > 0.05). They concluded that the cooking loss of broiler breasts was significantly influenced by ultrasound pre-treatment. Differences in cooking and the cooling losses may be due to the nature of chicken breast used, cooking type and conditions and many other factors.

Weight loss during cooking process may arise mainly from a decrease in the water holding capacity of the muscle as a result of the shrinkage of meat fibers and connective tissue and also from protein denaturation [16,32]. Relatively low cooking loss values for broiler breasts was obtained by the application of ultrasound pre-treatment, which may be important in reducing economic losses.

Among cooling times for the region A, the longest cooling time was determined by the application of immersion for 15 min (1093.33 s), while the lowest value was obtained by the 37 kHz of ultrasound pre-treatment applied for 30 min (763.33 s) (p < 0.05) (Table 1). For cooling times in the region B, the lowest value was determined by the ultrasound pre-treatment at 37 kHz (876.67 s) for 30 min and the second lowest value was for the ultrasound pre-treatment at 80 kHz for 30 min (940.00 s) (p < 0.05). Leong et al. [33] reported that bubbles formed during ultrasound process could grow until they reached a critical size known as resonance size and that size might depend on the applied frequency, showing an inverse relationship between the frequency value and the bubble radius. They reported that the bubbles produced at the ultrasound frequency of 20 kHz are relatively large and result in strong shock waves, whereas the bubbles produced between 100 and 1000 kHz are much smaller. McDonald and Sun [34] reported that the efficiency of vacuum cooling process might depend on the development of higher porosity and larger pore size distributions during cooling that causes higher diffusion rates and more efficient cooling times of samples. In our study, low frequency ultrasound (37 kHz) seems more effective on creating larger bubbles, higher cavitation and porosity in broiler breasts, which resulted in a shorter cooling time, in comparison to high frequency ultrasound at 80 kHz.

The effect of ultrasound pre-treatment, time and their interaction on the cooling time of broiler breasts was statistically significant for both regions (p < 0.05). For the region A, while the individual effect of ultrasound pre-treatment on the cooling loss of breast samples was significant, the effect of time and treatment-time interaction was statistically insignificant (p > 0.05). For the region B, the effect of ultrasound pre-treatment, time and their interaction was statistically significant (p < 0.05). Similar results were also obtained in a study of Zhuang and Savage [35] where the broiler breast fillets were categorized by lightness as light, medium and dark. These authors reported significant differences among the cook yields of fillets from different lightness categories.

According to Table 1, cooling loss increased with the application of ultrasound pre-treatment, and it was 12.64% for the samples of the region A that were pre-treated by the 37 kHz ultrasound for 30 min. Similarly, cooling loss values increased by ultrasound pre-treatment for the region B in comparison to immersion samples. Evaporation of high amounts of water during cooling process can be related to high cooling losses by the ultrasound pre-treatment [36]. Evaluating the vacuum cooling of chicken breasts (1 kg), Schmidt and Laurindo [18] reported that the temperature in the center point of the samples reduced from 80 to 10 °C in 28 min while the cooling loss by the vacuum cooling combined with immersion cooking was determined as 11.6%. The shape and size of chicken breasts may have an influence on the cooling loss during vacuum cooling. For example, the cooling loss of cylindrical shaped chicken breasts was found between 9.72 and 10.83% by Huber and Laurindo [15] while the cooling loss of cooked chicken breasts was between 3 and 12% by vacuum and immersion vacuum cooling [16]. Self et al. [17] carried out the steam cooking and vacuum cooling processes of chicken breasts, and they reported the overall weight losses of chicken breasts between 26.4 and 37.7%. In the present study, vacuum cooling loss of broiler breasts pre-treated by ultrasonication for two different periods were in the range of 9.22–12.64%, which were compatible with results reported in previous studies.

![Graph](image_url)

**Fig. 4.** The effect of ultrasound pre-treatment on the shear force values of broiler breasts (A, B, C and D: different letters indicate the statistical differences for the regions A and B, respectively (p < 0.05)).
3.2. Effect of ultrasound Pre-treatment on surface and center temperatures during vacuum cooling

Changes in the temperatures of the surface and center points of cooked broiler breasts for the region A are given in Fig. 3 for immersion and ultrasound pre-treatments.

According to Fig. 3A, the surface temperatures of the samples pre-treated by immersion for 15 and 30 min ranged from 70.9 to 11.2 °C and 70.2 to 10.4 °C, respectively where the center temperatures decreased from 84.8 to 12.5 °C and 85.4 to 12.5 °C, respectively. The surface temperatures of the breast samples pre-treated at 37 kHz varied from 77.5 to 10.3 °C for the 15 min pre-treatment and 76.9 to 10.1 °C for the 30 min pre-treatment while the corresponding central temperatures of these two pre-treatments decreased from 84.4 to 12.5 °C and from 84.4 to 12.5 °C (Fig. 3B). The surface temperature of breast samples decreased from 71.6 to 9.9 °C for the 15 min pre-treatment and from 77.8 to 10.6 °C for the 30 min pre-treatment at 80 kHz while the corresponding central temperatures for these two pre-treatments decreased from 85.0 to 12.5 °C and from 84.6 to 12.6 °C (Fig. 3C).

Differences in cooling rates for different pre-treatments and times were found by the cooling curves. The ultrasound pre-treatment at 37 kHz for 30 min resulted in the highest cooling rate, and approximately 22% reduction (213 s) was calculated for their processing time in comparison to the samples pre-treated by immersion. Similarly, Schmidt et al. [16] reported the vacuum cooling time of 800 s required to reduce the central temperature of chicken meat from about 80 to 14 °C. The cooling rate generally slowed down when the center temperature dropped below 20 °C as shown in the cooling curves (Fig. 3). Likewise, Sun and Wang [37] found that the vacuum cooling rate of pork decreased after reaching an intermediate temperature of 25 °C. Studying the vacuum cooling of chicken breasts from 90 to 20 °C, Huber and Laurindo [15] reported that the highest temperature drop occurred in the first 300 s of the process when most of the free water evaporated. Evaporation significantly reduces when there is no free water remained in the cooled material. Main weight loss in the cooling process takes place in the first stages where evaporation plays a significant role [37]. Since vacuum cooling time is strongly dependent on meat porosity and other factors, it is possible to obtain different cooling times in literature studies [37].

3.3. Effect of ultrasonic Pre-treatment on shear force

Effects of immersion and ultrasound pre-treatments on the shear force values of broiler breasts from the regions A and B are presented in Fig. 4. Initial shear force value of cooked breast samples was 67.17 N, which reduced to 48.38 N after ultrasound pre-treatment at 37 kHz for 15 min for the samples from the region A. For the shear force values of breasts pre-treated by ultrasound, a statistically insignificant difference was observed between different frequency values within the same pre-treatment time (p > 0.05). The shear force values of breasts pre-treated by ultrasound for 30 min was higher than that for 15 min (p < 0.05) (Fig. 4).

In general, the shear force values of the breast samples were reduced by the ultrasound pre-treatment for 15 min in comparison to the immersion group while increasing by the pre-treatment for 30 min (p < 0.05). Ultrasound pre-treatment at 80 kHz for 15 min decreased the shear force values of breasts significantly when compared with the immersion group (p < 0.05). The effect of treatment, time and their interaction on the shear force values of the breasts from the regions A and B was statistically significant (p < 0.05). McDonald et al. [40] stated that an increase in the hardness of beef muscles might be caused by high water loss during vacuum cooling and consequent compression of the muscle fibers. Schmidt et al. [16] reported the hardness values of vacuum cooled broiler breasts from 24.7 to 40.8 N. In the present study, the hardness values of vacuum cooled breasts pre-treated by ultrasound at 37 kHz for 15 and 30 min were 48.38 and 65.91 N for region A and 50.29 and 62.28 N for region B, respectively.

Sudden pressure changes during vacuum cooling process can lead to an increase in the gaps between muscle fibers and fiber bundles by the expansion of the gas in the sample pores. Evaporation of water in high amounts during vacuum cooling process is more likely to be the reason for the increased shear force values in the process. This condition results in drying the surface of a product at the end of the process. Another possible explanation for increased shear force values by ultrasound pre-treatment may be associated with the high protein content resulting from excessive water loss [18].

3.4. Effect of ultrasound Pre-treatment on color parameters

Changes in color parameters for ultrasound and immersion pre-treated broiler breasts before vacuum cooling are given in Table 2. The lowest brightness value (L*) of the breasts from the region A (71.95) was determined for 30 min of 80 kHz ultrasound pre-treatment among ultrasound pre-treated samples, and this value was similar to that of the breasts pre-treated by immersion for 15 min (p > 0.05) (Table 2). In a study by Omama et al. [38], the L* values of high pressure processed chicken breast meats without any additives were reported between 70 and 90, which were in good agreement with the present study. The redness value (a*) of breasts pre-treated by ultrasound at 80 kHz for 30 min (4.05) was significantly the highest (p < 0.05). Redness values for the ultrasound pre-treated samples were generally higher than those of the immersion pre-treated samples.

| Region | Treatment | Treatment time (min) | L*  | a*  | b*  | ΔE  | ΔC  | Hue angle |
|--------|-----------|----------------------|-----|-----|-----|-----|-----|-----------|
| A      | Immersion | 15                   | 73.71 ± 1.84 | 2.04 ± 0.76 | 14.38 ± 0.56 | 26.68 ± 2.62 | 6.93 ± 1.68 | 1.43 ± 0.05 |
|        | US (37 kHz) | 15                   | 75.83 ± 1.53 | 1.75 ± 0.71 | 15.37 ± 1.10 | 29.04 ± 1.76 | 7.97 ± 2.46 | 1.46 ± 0.04 |
|        | US (80 kHz) | 15                   | 75.93 ± 2.79 | 2.09 ± 0.79 | 14.87 ± 0.62 | 28.96 ± 3.49 | 7.37 ± 2.30 | 1.43 ± 0.01 |
| B      | Immersion | 15                   | 71.95 ± 4.78 | 4.05 ± 1.40 | 13.74 ± 0.85 | 24.88 ± 4.56 | 6.43 ± 1.94 | 1.29 ± 0.09 |
|        | US (37 kHz) | 15                   | 73.39 ± 2.66 | 1.34 ± 0.97 | 14.43 ± 1.31 | 23.45 ± 3.14 | 6.92 ± 1.26 | 1.48 ± 0.06 |
|        | US (80 kHz) | 15                   | 77.24 ± 1.45 | 1.36 ± 0.49 | 14.81 ± 0.88 | 27.19 ± 1.80 | 7.17 ± 1.42 | 1.48 ± 0.02 |

A-D: Different letters in the same column for each region indicate statistical differences (p < 0.05).
In terms of yellowness (b*) values of breast samples from the region A, 30 min of 80 kHz ultrasound pre-treatment resulted in the similar yellowness value (13.74) with 15 min of immersion pre-treatment (14.38) (p > 0.05).

For breast samples from the region B, the lightness value (L*) of samples pre-treated by 15 min of immersion was 73.39, which was similar to that pre-treated by ultrasound at 80 kHz for 30 min (74.98) (p > 0.05). Also, the redness values (a*) of the ultrasound pre-treated samples were higher than those of the immersion group, and the difference was statistically significant (p < 0.05). Insignificant differences were found among the \( b^* \) values of the samples from the region B (p > 0.05) (Table 2).

The total color difference (\( \Delta E \)) of the samples pre-treated by ultrasound at 80 kHz for 30 min was 24.88 for the region A, and it was significantly lower than others (p < 0.05) with the exception of the samples pre-treated by immersion for 15 min. Total chroma differences (\( \Delta C \)) in Table 2 indicated that differences among treatments and times for the samples from the regions A and B were insignificant (p > 0.05). For the samples of the region A, the effect of treatment and time on the L*, \( b^* \), \( \Delta E \) values was insignificant (p > 0.05) while their interaction was significant (p < 0.05). Moreover, the effect of treatment, time and their interaction on the hue angle values of breast samples was significant (p < 0.05), and their effects on the \( \Delta C \) values of breasts were insignificant (p > 0.05). For the samples from the region B, the effect of treatment, time and their interaction on L* and \( \Delta E \) values were significant (p < 0.05) while the effect of these factors on \( b^* \) and \( \Delta C \) values were insignificant (p > 0.05). The hue angle and a* color values of breast samples were significantly influenced by the type of treatment (p < 0.05).

Color is an important factor in the consumers’ evaluation of the quality of meat and meat products. Moisture removal may increase the separation between muscle fibers and also cause hypochromic effect due to migration of water-soluble substances to the surface including color pigments [10]. Dong et al. [9] reported that the lightness value of vacuum-cooled pork meat was lower and redness value was higher than that of other cooling methods, which was explained by an increase in pigment concentration on the surface due to high cooling losses.

### 3.5. Effect of ultrasound Pre-treatment on temperature distribution

Thermal camera images of broiler breasts can be used to determine the temperature distributions before and after the vacuum cooling process. For the region A, the temperature distributions of the samples pre-treated by immersion method and ultrasound at 37 kHz for 30 min are given in Figs. 5 and 6, respectively. Surface temperature distributions for both treatment methods after the cooking and cooling processes were similar (Fig. 5). The surface temperature of the broiler breasts after cooking ranged from 74.1 to 78.4 °C, while it was between 9.8 and 12.2 °C after vacuum cooling. Thermal camera images in Fig. 6 indicated that the post-cooking temperature distribution of the samples subjected to ultrasound pre-treatment was more uniform after than the samples pre-treated by immersion. The ranges of temperatures in the cross-section areas of breast samples was 82.1–84.5 °C after cooking and 12.2–13.2 °C after vacuum cooling (Fig. 6). Due to the heat conduction in the cooked meat, temperature differences may be observed between the cross section and surface areas after vacuum cooling. Similarly, Sun and Wang [37] reported uniform temperature distributions at 20 and 80 mm distances from the surface of vacuum cooled pork meat.

### 3.6. Effect of ultrasound Pre-treatment on pH

The effect of treatments on pH values of A and B regions is presented in Table 3. There were statistically insignificant differences among the pH values of breast samples from the regions A and B for different treatments and times (p > 0.05). Ultrasound pre-treatment, its duration and their interaction did not change the pH values of breasts from both regions significantly (p > 0.05). Although the range of pH values

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**Fig. 5.** Surface temperature distribution of broiler breasts from the region A before vacuum cooling (a) after vacuum cooling (b) (Within each thermal camera image, I and US37 indicate pre-treatments of immersion and ultrasound at 37 kHz, respectively while 30 is the durations of treatment in minutes.)
for normal broiler breasts was reported between 5.7 and 6.1 [39], the pH values in the current study were compatible with data reported previously in some studies. For example, the pH values of manually and mechanically deboned poultry meat were previously reported between 6.32 and 6.48 [6], and Castromán et al. [40] found the pH values of chicken meat in three muscles between 5.98 and 6.22. pH is an important parameter by its microbiological indicator property and effects on the physical properties of food products as color and water holding capacity [36].

3.7. Effect of ultrasonic Pre-treatment on sensorial hardness

The effect of ultrasound pre-treatment (US) on pH of cooked broiler breasts from the regions A and B (mean ± standard deviation).

| Region | Treatment (Frequency) | Treatment time (min) | pH     |
|--------|-----------------------|----------------------|--------|
| A      | Immersion             | 15                   | 6.24 ± 0.02A |
|        |                       | 30                   | 6.27 ± 0.06A |
|        | US (37 kHz)           | 15                   | 6.22 ± 0.05A |
|        |                       | 30                   | 6.24 ± 0.05A |
|        | US (80 kHz)           | 15                   | 6.24 ± 0.03A |
|        |                       | 30                   | 6.29 ± 0.06A |
| B      | Immersion             | 15                   | 6.25 ± 0.07A |
|        |                       | 30                   | 6.29 ± 0.08A |
|        | US (37 kHz)           | 15                   | 6.24 ± 0.04A |
|        |                       | 30                   | 6.24 ± 0.04A |
|        | US (80 kHz)           | 15                   | 6.28 ± 0.04A |
|        |                       | 30                   | 6.30 ± 0.06A |

A-D; Different letters in the same column for each region indicate statistical differences (p < 0.05).

4. Conclusions

The potential use of ultrasound pre-treatment in vacuum cooling of broiler breasts has been demonstrated by this study. Results showed that ultrasound pre-treatment of raw broiler breasts changed the physicochemical, textural and sensory properties significantly during vacuum cooling of cooked breasts. Ultrasound pre-treatment before vacuum cooling resulted in high cooling rates during the vacuum cooling of cooked breast samples. The shortest cooling time of 12.72 min was determined for breast samples from the region A that were pre-treated by ultrasound at 37 kHz for 30 min, and cooling time was reduced by 22% in comparison to immersion pre-treatment with the same treatment time (p < 0.05). While the cooling loss increased by ultrasound pre-treatment for the samples obtained from both regions, cooking loss values generally decreased by ultrasound pre-treatment in comparison to the samples pre-treated by immersion. Additionally, 15 min of US37 pre-treatment had no negative effects on sensorial hardness compared to control samples. Ultrasound can be considered as an effective pre-treatment in order to achieve significantly low cooling times in vacuum cooling technology. For vacuum cooling of cooked broiler breasts, ultrasound pre-treatment at 37 kHz can be recommended because this frequency level seems more efficient in terms of cooling rate. Since cooling rates are highly influenced by a variety of factors such as the size, shape and type of meat samples, more research is needed to investigate the effect of ultrasound pre-treatment on preserving and improving the quality characteristics of cooked meats in industrial applications.
Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

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