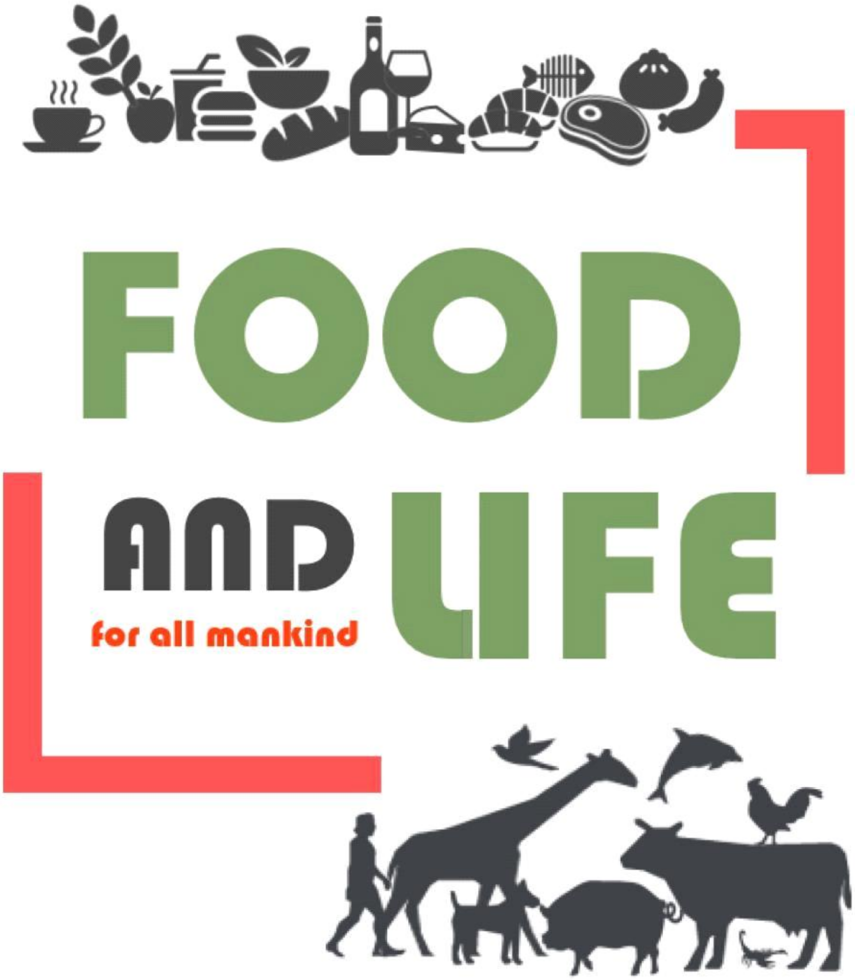

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Synergistic effect of Jeju lava sea water and high-intensity ultrasound on the quality characteristics of Jeju black pig during dry aging

AMM Nurul Alam[1,†], Eun-Yeong Lee[1,†], Jakir Hossain[1], Je-Bin Ryu[2], Deok-Hoon Ko[2], Young-Hwa Hwang[3], Seon-Tea Joo[1,3,*]

[1]*Division of Applied Life Science (BK 21 Four), Gyeongsang National University, Jinju 52828, Korea*
[2]*Tamrain Inc., Jeju 63034, Korea*
[3]*Institute of Agriculture & Life Science, Gyeongsang National University, Jinju 52828, Korea*

Abstract

A novel approach using 2,000 m deep lava seawater from Jeju island was used with high-intensity ultrasound (HIUS) to assess Jeju black pig ham's green salting efficiency and quality. Three concentrations of Jeju sea water (JSW), 3%, 6%, and 18% HIUS (22 W/cm2 and 37 kHz) for 120 min were applied to the treatment groups, and the control had no HIUS treatment. Following HIUS, treatments and controls (no HIUS) were aged for ten days, dipping in three concentrations of JSW. In the JSW18% group, lightness (42.74±0.91) was lower, and redness (16.47±1.15) was higher than the other treatments (JSW3% & JSW6%) and controls, respectively. Moisture (66.01±0.33) and drip loss (0.96±0.03) were lower (〈0.05) in JSW18%, and cooking loss was lower in control with 18% JSW. Salt concentrations in the muscle (5.60±0.11) were higher (〈0.05) in JSW18%, followed by JSW6% and JSW3%. JSW6% had significantly (〈0.05) lower pH (5.83±0.03) and warner bratzler shear force (3.29±0.19) than the other treatment and control groups. The saturated and monounsaturated fatty acid content increased, and polyunsaturated fatty acid content was reduced with increasing salt concentration combined with HIUS. The overall acceptance score of the raw meat sensory evaluation was higher in JSW18%. Electronic tongue revealed decreased sourness and increased umami and richness intensity with an increased concentration of JSW18% than other treatments and control. HIUS application with increasing concentration of JSW offered a clear advantage for efficient bringing of Jeju ham with positive effects on the technological properties to aid in further processing.

Keywords: Jeju seawater, green salting, high-intensity ultrasound, aging, Jeju black pork

Introduction

According to Jobst (2023), per capita pork meat consumption in South Korea was approximately 28.5 kg in 2022, which accounts for half of the meat consumption and shows an increasing trend with interest in cured, aged, and marinated products. Upon analyzing the pork price trend in Korea, it is evident that the average price of Jeju pig was approximately 2,600 KRW/kg higher than the national pork selling average till 2022 (Jeon et al., 2022). As a result, emphasis needs to be placed on developing diversified products from Jeju pigs through noble processing techniques. Meat aging is an age-old technology for preserving meat till the present day for the production of salami, ham, bacon, sausage, and smoked loin by enhancing both the structural and sensory qualities of pork meat products. Additionally, meat adding salt and spices continues to be a widespread technique in producing aged pork meat into specialty products of consumer choice. During dry aging, meat is soaked or mixed with different kinds of salts and seasoning ingredients, including organic acids, spices, and medicinal extracts (Gómez-Salazar et al., 2021; Latoch, 2020; Lopes et al., 2022; Ozturk and Sengun, 2019; Son et al., 2024). Sodium chloride salt is a frequently utilized chemical agent in marination and aging that plays a vital role in generating desirable meat texture, distinct flavors, and prolonged shelf life (Hu et al., 2020) by affecting biochemical events like proteolysis, lipolysis, and lipid oxidation that occur

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[†] These authors equally contributed to this study.

[*] **Corresponding author :** Seon-Tea Joo. Division of Applied Life Science (BK 21 Four), Gyeongsang National University, Jinju 52828, Korea. Tel: +82-55-772-1943, Fax: +82-55-772-1949, E-mail: stjoo@gnu.ac.kr

during the curing process (Armenteros et al., 2012; Kim et al., 2018; Vaskoska et al., 2021). Furthermore, NaCl can efficiently inhibit the growth of pathogens like *Clostridium botulinum, Listeria monocytogenes*, and *Staphylococcus aureus* by lowering water activity (Aw) to ensure the safety and stability of cured meat (Fraqueza et al., 2021). In dry-aged products, excessive sodium and other possible impurities from NaCl can be consumed. Nevertheless, as cured meat products are a significant component of consumers' daily food, reducing NaCl content during curing is feasible without sacrificing taste and safety (USDA, 2020). In response to concerns over health and nutrition-related sodium consumption, meat scientists and industry are working on techniques to decrease the amounts of sodium in cured products (Mariutti and Bragagnolo, 2017). This may be achieved through better management of the salting process to optimize and reduce salt content (Martuscelli et al., 2017). Efforts have been made to use sea salt instead of commercial salts as an alternative strategy in dry-cured ham (Škrlep et al., 2016).

Physical interventions such as ultrasound treatment, multi-needle injections, and tumbling are applied to aid the salting and marination process and reduce the required time before aging of meat (Dimakopoulou-Papazoglou and Katsanidis, 2020; Gao et al., 2015; Inguglia et al., 2019). To ensure the best quality meat during salting, there is a need to optimize the aging process by using novel techniques to tenderize meat. Such a cutting-edge technique is high-intensity ultrasound (HIUS), has shown an increased application in recent times to produce tendered meat and efficient aging (Alam et al., 2024b; Alarcon-Rojo et al., 2019; Al-Hilphy et al., 2020; Gonzalez-Gonzalez et al., 2020; Son et al., 2024). HIUS treatment efficiently provides distinct benefits in aging by enhancing technical qualities in pork, leaving an advantage for subsequent further processing (Garcia-Galicia et al., 2022). HIUS utilizes high-frequency sound energy above the human audible range (>20 kHz) to ensure meat tenderization, uniform transfer of salt, and extending shelf life (Alarcon-Rojo et al., 2019). The preferable HIUS technique is nonthermal, ensuring the meat's original taste and flavor with minimal treatment (Garcia-Galicia et al., 2022).

HIUS has been found to aid in greater uniformity of salt distribution after an application of 60 min (González-González et al., 2017), which is essential for efficient curing. The application of HIUS has drawn special consideration due to the increased demand for green-processed products as a viable option for enhancing the mass transfer of salt inside the meat, minimizing the use of chemical additives and preservatives (Delgado-Pando et al., 2021; Singla and Sit, 2021), and thus ensures lower potential environmental damage (Rosario et al., 2021).

Currently, no studies have been conducted on using natural seawater in HIUS applications for the salting or salting of meat before aging. This study aimed to evaluate the effect of Jeju seawater collected from 2,000 m deep sea in different concentrations in combination with HIUS to determine the effect on meat-keeping quality and to set up a novel approach to replace 100% use of commercial salt.

Material and Methods

Meat samples

Six hind legs of Jeju black pig (±14 kg), at 24 hours postmortem, were randomly selected from a commercial batch of Tamrain, Jeju, Korea. The Jeju seawater from 2,000 m depth in three concentrations (3%, 6%, and 18%) was supplied by Tamarin, Jeju, South Korea. The legs were trimmed off to remove hair from the skin and stored below 2℃ in an aging refrigerator before the start of the treatment. Legs were divided into control and treatment, where treatment samples were subjected to HIUS (MP-2 Air cooled type ultrasound chiller, Daehocooler, Namyangju, Korea) for 120 min with a parameter of (2,400 W, 36.5 kHz, 10 bar, 2℃) with Jeju sea water (JSW) having 3%, 6%, and 18% salt concentration. Right after the treatment, both the control and treatments were dipped in the three salt concentrations of JSW in polypropylene tubs, covered with polythene, and tied to keep them airtight. All the samples were kept in an aging chamber (Lassele, Ansan, Korea) below 2℃, with 60% relative humidity (RH), primary airflow of 6 LV, and sub-air flow of 3 LV. The whole meat sampling and treatment methodology process can be observed in the Fig. 1.

The meat color of Jeju pork ham

Three samples from each group underwent color assessments through a color measurement device (Konica Minolta CR-300, Osaka, Japan). The device was calibrated using a white plate with the standard values (Y=93.5, X=0.3132, y=0.3198). Measurements of CIE L*, a*, and b* were taken twice at the center and once at the edges of the samples.

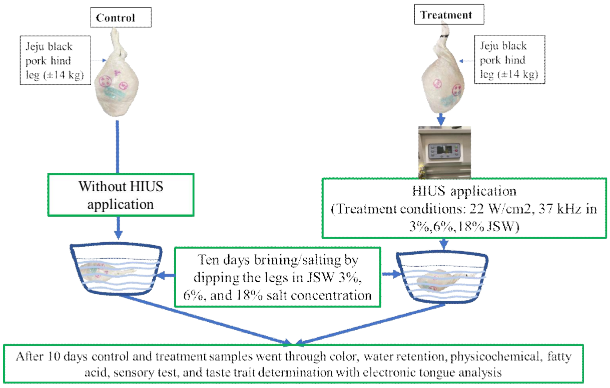

Fig. 1. Experimental methodology. HIUS, high intensity ultrasound; JSW, Jeju sea water.

Water retention characteristics of Jeju pork ham

The moisture content was evaluated by the AOAC (2002) standard. The samples weighed nearly 2±0.05 g and were dehydrated on an aluminum dish at 105℃ for 16 hours in a dry oven. The samples were after that desiccated. The moisture percentage was calculated using the Eq. (1) specified here.

$$\text{Moisture (\%)} = \frac{\text{Sample weight before drying} - \text{Sample weight after drying}}{\text{Sample weight before drying}} \times 100\% \tag{1}$$

The drip loss (DL) samples were weighted around 25±0.5 g. They were in the shape of a 2 cm thick disk. The samples were hung on a steel wire using a “S” shaped hook. All of this was done inside a plastic box measuring 18×15×10 cm. The extent of DL percentage was subsequently measured using the following formula:

$$\text{Drip loss (\%)} = \frac{\text{Initial weight} - \text{Final weight}}{\text{Initial weight}} \times 100\% \tag{2}$$

The samples’ cooking loss (CL) was determined threefold by measuring the weight loss percentage. Each sample, approximately 25±0.5 g in weight and 1.5 cm thick, was enclosed in a plastic zipper bag. The samples underwent heat treatment in 75℃ water for 30 min. The samples were then allowed to chill at ambient temperature and held for 30 min to exclude extra surface moisture. The CL percentage was determined using the following specified Eq. (3).

$$\text{Cooking loss (\%)} = \frac{\text{Weight of the sample before cooking} - \text{Weight of the sample after cooking}}{\text{Weight of the sample before cooking}} \times 100\% \tag{3}$$

Physicochemical characteristics of Jeju pork ham

The saltness of the meat was evaluated by applying a salinity measurement device (SB-2000PRO, HM digital, Seoul, Korea). Approximately 3±0.5 g of meat sample was mixed with 27 mL of deionized water and then homogenized (IKA T25 Ultra-Turax, IKA-Werke, Staufen, Germany) for 30 s.

For analyzing the pH, approximately 3±0.5 g of sample was mixed for 30 s with 27 mL of distilled water and subsequently using a homogenizer (IKA T25 Ultra-Turax, IKA, koenigswinter, Germany). Afterward, the pH of these samples was determined with a Benchtop pH m (Orion Star$^{\text{TM}}$ A21, Thermo Fisher Scientific Solutions, Waltham, MA, USA). Before data acquisition, the probe was calibrated at a specific temperature using calibration solutions with pH values of 7.00, 4.01, and 9.99.

The identical samples measuring CL were also used to determine the shear force value (WBSF, kg/cm^2). During this investigation, an Instron Universal Testing Machine (Model 3343, Instron, Norwood, MA, USA) was used, equipped with a V-shaped shear blade. Assessments were done for three samples to ensure accuracy. Before measuring the shear forces, each sample was cut correctly parallel to the muscle fibers into dimensions of 0.5 cm in width and 4.0 cm in length, resulting in an area of about 2.0 square cm. The speed of the crosshead was adapted to 100 mm/min. The load capacity attained a maximum of 50 kg.

Fatty acid composition analysis

The lipid extraction from samples was conducted following the procedure outlined by Folch et al. (1957). The lipid methyl esters were assessed by subjecting them to the treatment of a 1.0 N solution of methanolic NaOH and then methylated by boron trifluoride in a methanol solution. The determination of fatty acid methyl ester (FAME) was performed using a gas chromatography HP6890N (Hewlett-Packard, Palo Alto, CA, USA) equipped with an automatic sampler HP7683 (Hewlett-Packard). The extraction of FAME from the samples was performed under the specified conditions: the column oven temperature was raised from 50℃ to 180℃ at a rate of 10℃/min. It was then kept at 180℃ for 20 min. The injector and detector were both set at a temperature of 250℃. The volume of the sample injected was one μL. Finally, the concentration of each fatty acid was determined by comparing the retention durations to those of the FAME mixture standards (Supelco 37 Components FAME Mix, Sigma-Aldrich, St. Louis, MO, USA). The resulting data are presented as a percentage of the identified fatty acids, calculated using the total peak area.

Sensory evaluation

A trained group of ten researchers from the Department of Animal Sciences at Gyeongsang National University, South Korea, were sorted to assess the raw meat sensory attributes. The panelists were chosen following the guidelines set out by Lawless and Heymann (1999), adopted by Choi and Chung (2014). Samples were cut into 8×4×2 cm in length, width, and thickness, respectively. Coded samples were served in a white tray for sensory evaluation. The panel evaluated the samples under fluorescent illumination. The sensory characteristics of the samples were assessed using a 5–5-point hedonic scale (1=low score, 5=highest score).

Taste traits determination by electronic tongue

An electronic tongue system (ETS; INSERT SA402B Electric Sensing System, Insent, Tokyo, Japan) was used to examine the samples, implementing the technique exemplified by Ismail et al. (2020). The ETS system primarily comprises sensor arrays, electrodes, a data analysis program, and specialized artificial lipid membranes. The ETS was employed to ascertain the attributes of sourness, bitterness, umami, and richness. Each measured parameter was examined once all membranes were stabilized in a standard meat taste (SMT) solution. The SMT solution was comprised of 0.01% lactic acid (sourness), 0.25% monosodium glutamate (umami), and 0.0005% quinine hydrochloride (bitterness). Approximately 100±0.05 g of ground sample was mixed with 400 mL of hot double distilled water (95℃; 20 min). The blended solution was centrifuged for 15 min at 1,000×g, and the supernate was stored at −70℃ for further analysis.

Statistical analysis

The perceived data underwent statistical analysis using one-way analysis of variance (ANOVA) using SAS 9.4 (SAS Institute, Cary, NC, USA). A 2×2 factorial design was utilized for statistical analysis. Results are expressed as least square mean values of three independent replications, and SE is used for the error terms. Duncan's test was performed for multiple mean comparisons. A *p*-value less than or equal to 5% was considered statistically significant. For principle component analysis (PCA), R 4.4.1 software was used.

Results and Discussion

The meat color of pork ham

The consumer's initial assessment during meat purchase is primarily based on its color, which should be bright and vibrant red or pink, depending on the species (Hughes et al., 2014). The meat color might vary due to pH, oxygen availability, storage time (Olivera et al., 2013; Pastsart et al., 2013), and processing techniques like HIUS (Son et al., 2024). The meat color results during the present study are shown in Table 1. In the ultrasonic treatment, brightness, redness, and yellowness showed significant changes as concentration increased. Brightness tended to decrease as the concentration increased, while redness and yellowness tended to increase. In the case of the control group, only the brightness showed a significant difference, and as the concentration increased, the brightness tended to decrease. In the case of samples treated with 3% lava seawater, there was a significant difference in brightness, and the samples treated with ultrasonic waves were higher than the control. In the case of the sample treated with 6% lava seawater, only the brightness showed a significant difference. Unlike the 3% sample, the control group tended to be higher than the treatment group. In agreement with Diaz-Almanza et al. (2019), ultrasonic cavitation may cause meat water release by alteration of superficial structures, leading to an increase in lightness. Garcia-Galicia et al. (2020) showed similar results to the present study in fresh beef meat, where the brightness values (CIE L*) were increased due to the immediate application of HIUS and without aging. Reversely to the present study, an augmentation in brightness and a decrease in the intensity of red color in meat was observed due to HIUS treatment in a previous study (Diaz-Almanza et al., 2019). In a recent study, Gonzalez-Gonzalez et al. (2020) examined the quality of bovine muscles following HIUS at 40 KhZ and 11 W/cm^2 up to 80 min had no adverse effect on the color of beef meat.

Water holding capacity parameters

The results of water holding capacity parameters are shown

Table 1. Effect of the lava water concentration and high-intensity ultrasound (HIUS) application on meat color of pork ham

Measurement	Treatment	Concentration			SEM	p-value		
		JSW3%	JSW6%	JSW18%		Concentration	Ultrasound	C×U
CIE L*	Control	49.83^{ay}	46.70^{bx}	43.51^{c}	0.91	<.0001	0.0316	<.0001
	Ultrasound	50.28^{ax}	43.88^{by}	42.74^{b}				
CIE a*	Control	12.11	11.96	12.93^{y}	1.15	0.0009	0.1478	0.0126
	Ultrasound	12.04^{b}	11.01^{b}	16.47^{ax}				
CIE b*	Control	6.50	5.91	5.99^{y}	0.88	0.2390	0.3102	0.0324
	Ultrasound	5.16^{b}	7.24^{a}	7.33^{ax}				

$^{a-c}$ Different letters within a row of lava water concentration indicate statistically significant differences at $p<0.05$.
$^{x-y}$ Different letters within a column of high intensity ultrasound indicate statistically significant differences at $p<0.05$.
JSW, Jeju sea water; C, concentration; U, ultrasound.

in Table 2. Water present in muscle tissue is typically confined within the cellular structure, and HIUS can affect the water content by enhancing the rate of exudate and eater loss from muscle (Chang et al., 2015). In the present study the moisture content significantly decreased as the concentration of Jeju lava seawater increased. In the case of 3% lava seawater, the moisture and DL in the sonicated sample were higher than in the control group. However, the moisture content and DL of the ultrasonicated sample were significantly lower in the case of 18% lava seawater. This result was consistent with previous research showing that moisture content decreases when treated with ultrasonic waves (Valenzuela et al., 2021). Carrillo-Lopez et al. (2018) evaluate the effects of HIU on the quality of beef longissimus dorsi, finding that the water content increased significantly in the sonicated samples after 7 d of storage at 4℃. As a result of the meat juice reduction, the same trend as the moisture content result was observed, and it is believed that this was influenced by the moisture content lost due to ultrasonic treatment, and the amount of moisture held by the meat was small, so the amount of moisture exuded was also small. In addition, as reported in previous studies, the result seems consistent with the idea that water retention capacity increases as the salt content increases. As a result of heating loss and meat loss, the more the lava seawater concentration increases, the same as the meat loss. While it showed a decreasing trend, the ultrasonic treatment group of 6% and

Table 2. Effect of the lava water concentration and high-intensity ultrasound (HIUS) application on water-holding capacity of pork ham

Measurement	Treatment	Concentration			SEM	p-value		
		JSW3%	JSW6%	JSW18%		Concentration	Ultrasound	C×U
Moisture	Control	71.22^{aby}	71.71^{a}	70.86^{bx}	0.33	<.0001	<.0001	<.0001
	Ultrasound	73.28^{ax}	71.67^{b}	66.01^{cy}				
Drip loss	Control	1.40^{by}	1.60^{a}	1.02^{cx}	0.03	<.0001	0.0748	<.0001
	Ultrasound	1.60^{ax}	1.66^{a}	0.86^{by}				
Cooking loss	Control	23.29^{a}	22.59^{ay}	7.82^{by}	1.13	<.0001	0.0004	0.1364
	Ultrasound	24.53^{b}	26.67^{ax}	10.28^{cx}				

$^{a-c}$ Different letters within a row of lava water concentration indicate statistically significant differences at $p<0.05$.
$^{x-y}$ Different letters within a column of high intensity ultrasound indicate statistically significant differences at $p<0.05$.
JSW, Jeju sea water; C, centration; U, ultrasound.

18% lava seawater was significantly higher than the control group. This is thought to result from the formation of a microbubble in the meat due to the cavitation effect when ultrasonic waves are applied, making it easier to extract moisture during heating (Gallo et al., 2018). Amiri et al. (2018) state that myofibrillar proteins, especially actin and myosin, significantly impact meat characteristics. These proteins typically create a gel network, increasing water retention in muscle tissue due to enhanced moisture retention.

Physicochemical characteristics

The results of physicochemical characteristics are shown in Table 3. Salinity significantly increased as lava seawater concentration increased, and the treatment group tended to increase relatively rapidly compared to the control group. Both the control and treatment groups had the lowest pH level at 6% JSW, and the JSW3% had significantly higher pH in the treatment. However, the control group had significantly higher pH levels for JSW18% samples. The samples treated with 3% JSW and combined with HIUS were found to have significantly (<0.05) higher pH than the other concentrations in both the control and treatment groups. WBSF shear force was lower in the JSW 18 control and treatment groups than in the 6% and 3% groups. The pH level is a crucial determinant of meat softness, with ideal values within a range of 5.5–5.8. Various studies have examined meat pH followed by HIUS in different conditions. The increase in pH resulting from HIUS might be ascribed to the expulsion of ions from the cellular structure or alterations in the protein structure of the tissue, leading to modification in ion functioning within the muscle and subsequent elevation of pH (Alarcon-Rojo et al., 2019; Jayasooriya et al., 2007). HIUS followed by injection also resulted in a considerable increase in the pH of pork meat (Garcia-Galicia et al., 2022). The reduced pH due to HIUS represents a technological benefit of the contraction of the polypeptide chain network and a reduction in the water-holding capacity of meat (Huff-Lonergan and Lonergan, 2005). During the application of HIUS on meat, bubbles form with increasing size with each consecutive cycle of the sonication process, which affects the integrity of the cell structure, leading to an elevation of tenderness (Son et al., 2024). Under the aging conditions, lower shear force values were revealed (28.59 N to 31.29 N); on the contrary, aging combined with HIUS demonstrated increased shear force (43.98 N) (Garcia-Galicia et al., 2020). During assessing the proteolytic activity, Wang et al. (2018) experienced a decrease in shear force value in beef that was treated with HIUS and aged for seven days. The time of aging followed by HIUS significantly impacts the texture of meat, and according to Khan et al. (2016), the ideal duration for aging after HIUS should be 7–10 days, with a temperature of 0 to 1℃ (Bernardo et al., 2023), which was maintained in the present study.

Fatty acid content

The fatty acid composition of the control and treatment groups is given in Table 4. The content of saturated fatty acid

Table 3. Effect of the lava water concentration and high-intensity ultrasound (HIUS) application on physicochemical characteristics of pork ham

Measurement	Treatment	Concentration			SEM	*p*-value		
		JSW3%	JSW6%	JSW18%		Concentration	Ultrasound	C×U
Salinity	Control	1.35^{cx}	2.60^{b}	4.05^{ay}	0.11	<.0001	<.0001	<.0001
	Ultrasound	1.20^{cy}	2.55^{b}	5.60^{ax}				
pH	Control	6.15^{ay}	5.90^{c}	6.03^{bx}	0.03	<.0001	0.1007	0.0002
	Ultrasound	6.26^{ax}	5.83^{c}	5.98^{by}				
WBSF	Control	3.90^{a}	3.55^{b}	3.39^{b}	0.19	<.0001	0.4082	0.6756
	Ultrasound	3.93^{a}	3.45^{b}	3.29^{b}				

[a–c] Different letters within a row of lava water concentration indicate statistically significant differences at $p<0.05$.

[x–y] Different letters within a column of high intensity ultrasound indicate statistically significant differences at $p<0.05$.

JSW, Jeju sea water; C, concentration; U, ultrasound; WBSF, Warner-Bratzler shear force.

Table 4. Effect of the lava water concentration and high-intensity ultrasound (HIUS) application on fatty acid composition of pork ham

Fatty acid	Treatment	JSW3%	JSW6%	JSW18%	SEM	*p*-value
C12:0	Control	0.10	0.10^{y}	0.10^{y}	0.01	0.002
	Ultrasound	0.10	0.11	0.11		
C14:0	Control	1.49^{by}	1.51^{ax}	1.41^{cy}	0.03	0.0158
	Ultrasound	1.59^{bx}	1.47^{cy}	1.66^{ax}		
C14:1	Control	0.04	0.03	0.04	0.02	0.003
	Ultrasound	0.04	0.03	0.04		
C16:0	Control	25.67^{by}	25.58^{cy}	25.94^{ay}	0.31	0.2448
	Ultrasound	26.01^{bx}	27.61^{ax}	27.13^{ax}		
C16:1	Control	4.97^{a}	4.34^{b}	4.26^{c}	0.15	0.0418
	Ultrasound	4.84^{a}	4.38^{b}	4.29^{b}		
C18:0	Control	11.33^{cx}	12.63^{ay}	12.06^{b}	0.21	0.8267
	Ultrasound	11.12^{by}	14.03^{ax}	9.89^{b}		
C18:1n9c	Control	40.80^{cy}	41.00^{bx}	41.86^{ay}	0.42	0.3994
	Ultrasound	43.28^{bx}	39.49^{cy}	45.69^{ax}		
C18:2n6c	Control	12.59^{ax}	12.22^{bx}	12.13^{cx}	0.10	0.0984
	Ultrasound	10.89^{by}	11.17^{ay}	9.85^{cy}		
C18:3n3	Control	0.44	0.46	0.41	0.01	0.0094
	Ultrasound	0.44^{a}	0.31^{b}	0.44^{a}		
C20:0	Control	0.18	0.25	0.17	0.01	0.0179
	Ultrasound	0.15	0.20	0.21		
C20:4n6	Control	2.34^{ax}	1.82^{bx}	1.58^{cx}	0.08	0.0133
	Ultrasound	1.51^{ay}	1.13^{by}	0.64^{cy}		
C20:5n3	Control	0.02^{c}	0.03^{by}	0.02^{ax}	0.01	0.0066
	Ultrasound	0.02^{c}	0.03^{bx}	0.03^{ay}		
C22:6n3	Control	0.02^{ax}	0.02^{a}	0.01^{b}	0.01	0.0003
	Ultrasound	0.01^{by}	0.03^{a}	0.01^{b}		
SFA	Control	38.78^{cy}	40.08^{ay}	39.68^{b}	0.29	0.5644
	Ultrasound	38.98^{bx}	43.43^{ax}	39.01^{b}		
MUFA	Control	45.80^{by}	45.38^{cx}	46.17^{ay}	0.36	0.4404
	Ultrasound	48.16^{bx}	43.90^{cy}	50.02^{ax}		
PUFA	Control	15.41^{ax}	14.55^{bx}	14.16^{cx}	0.22	0.1254
	Ultrasound	12.87^{ay}	12.67^{ay}	10.98^{by}		

$^{a-c}$ Different letters within a row of lava water concentration indicate statistically significant differences at $p<0.05$.

$^{x-y}$ Different letters within a column of high intensity ultrasound indicate statistically significant differences at $p<0.05$.

JSW, Jeju sea water; C, concentration; U, ultrasound; SFA, saturated fatty acids; MUFA, monounsaturated fatty acids; PUFA, polyunsaturated fatty acids.

(SFA) and monounsaturated fatty acid (MUFA) showed a general trend with increasing JSW concentration. Furthermore, the polyunsaturated fatty acid (PUFA) content declined with increasing JSW concentration in the treatment groups. In Jeju Ham, the concentration of C 16:0, C18:1n9c, and C18:3n6c was relatively high, and the JSW18% treatment group was higher. In previous studies by Bao et al. (2022), ultrasound treatment significantly increased C18:0 content, but the levels of MUFA and PUFA declined, aligning with the present study. The elevated unsaturation level of the unsaturated fatty acid facilitated proton removal and the generation of free radicals, hence expediting lipid oxidation and diminishing the PUFA ratio (Gao et al., 2021). This illustrates that the cavitation action of ultrasound can oxidize unsaturated fatty acids, with the degree of oxidation escalating alongside increased ultrasonic power, leading to a reduction in unsaturated fatty acids in meat products.

Sensory characteristics

The sensory attributes of the control and treatment groups, encompassing marbling, color, texture, surface moisture, and overall acceptability, are illustrated in Fig. 2. All the sensory scores increased with increased concentration of salt combined with HIUS. The overall raw meat sensory examination acceptance score was superior in JSW18%. Stadnik and Dolatowski (2011) discovered that ultrasound could expedite overall color change, inhibiting oxymyoglobin development and decelerating metmyoglobin formation in their investigation of the effects of sonication on beef color. In a similar study, ultrasound-assisted processing enhanced the softness and quality of dry-cured yak meat Bao et al. (2022).

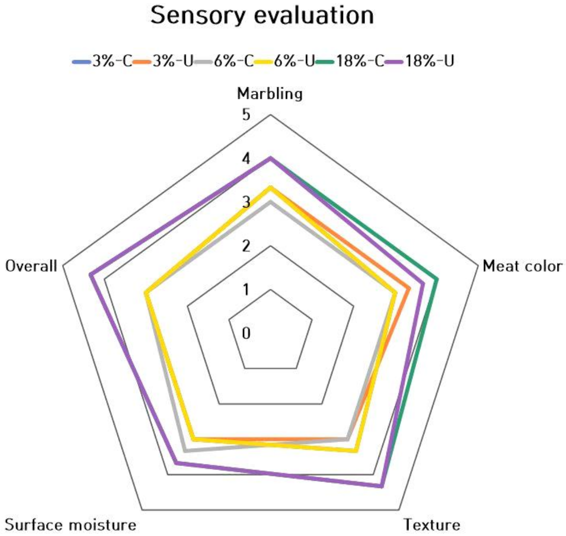

Fig. 2. Effect of the lava water concentration and high-intensity ultrasound (HIUS) application on sensory evaluation of pork ham. C, concentration; U, ultrasound.

An electronic tongue transforms electrical signals into taste signals to differentiate food flavors, eliminating sensory evaluation subjectivity due to its low sensory threshold (Alam et al., 2024a; Jiang et al., 2018). Fig. 3 illustrates the response values for sourness, bitterness, umami, and richness of Jeju pork meat subjected to different JSW concentrations and HIUS treatments. Similar results were reported by Bao et al. (2022), where the umami and richness in the HIUS treatment groups were considerably elevated compared to the control group. The elevated umami and richness values may be ascribed to muscle hydrolysate due to HIUS treatment of meat (Hossain et al., 2024; Wang et al., 2019). The electronic tongue indicated a reduction in sourness and an enhancement in umami and richness intensity with a higher concentration of JSW18% compared to other treatments and the control. This change is due to the natural phenomenon of meat during aging and the production of specific free amino acids glutamic acid, aspartic acid, and nucleotides from muscle breakdown, which are responsible for the umami taste and improvement in richness (Hossain et al., 2024).

Principle component analysis

PCA can reduce the complexity of intricate data and effectively summarize the overall information of any sample (Thampi et al., 2021). Fig. 4 explains the Principal PCA biplot, where PC1 (x-axis) explained 51.02% of the variance, and PC2 (y-axis) explained 77.15%, making these the most critical components to distinguish between the control and treatment groups using JSW and HIUS-assisted JSW respectively. The physicochemical parameters, ETS, and fatty acids data of the samples were analyzed to interpret the differences among the sample groups. The biplot indicates a clear separation between the control and ultrasound-treated groups across various percentages (3%, 6%, and 18%). The 18% groups show clear separation from the other concentrations along PC1, suggesting that the most significant differences in the data contributed to the changes in all parameters. This PCA indicates that both the treatment concentration and HIUS application substantially

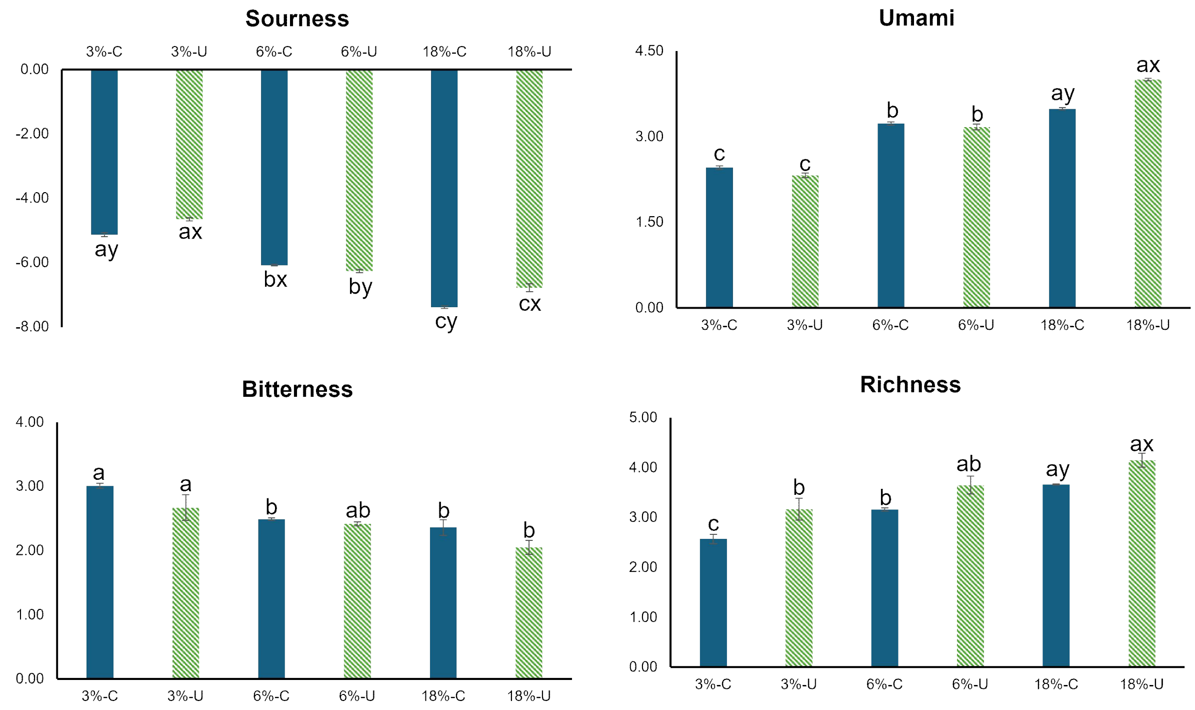

Fig. 3. Effect of the lava water concentration and high-intensity ultrasound (HIUS) application on electronic tongue sensory evaluation of pork ham. $^{a-c}$ Different letters within a row of lava water concentration indicate statistically significant differences at $p<0.05$. $^{x-y}$ Different letters within a row of high intensity ultrasound indicate statistically significant differences at $p<0.05$. C, concentration; U, ultrasound.

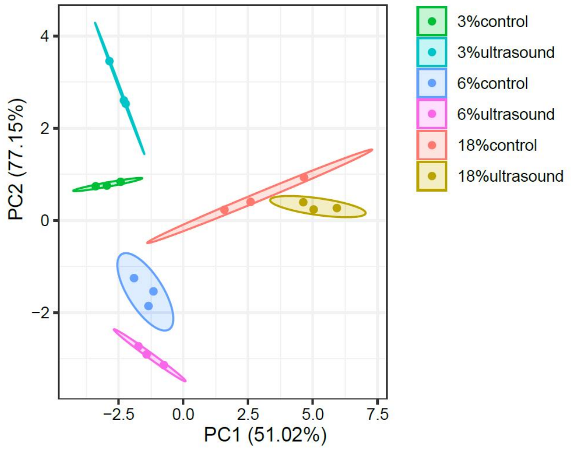

Fig. 4. Principal coordinates analysis (PCA) plot of meat quality and taste characteristics of pork ham. PC1, x-axis; PC2, y-axis.

affect the parameters during the present study.

Conclusion

In conclusion, the present findings demonstrate that using JSW combined with HIUS can markedly enhance black Jeju pork's color, salt penetration, water retention, and softness. Nonetheless, it adversely impacted the moisture and lightness of the meat. There was a reduction in PUFA levels and a rise in SFA and MUFA. The results from the electronic tongue indicated that JSW and HIUS combination markedly enhanced the taste and flavor profiles, including sourness, bitterness, umami, and richness of pork meat. The results suggest that using JSW in combination with HIUS effectively aids in the salting of meat before proceeding to dry aging. Moreover, it may serve as an effective solution for enhancing the quality of dry-cured Jeju pork meat.

Conflicts of Interest

The authors declare no potential conflict of interest.

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Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

Author Contributions

Conceptualization: Alam AMMN, Lee EY, Joo ST.
Data curation: Alam AMMN, Lee EY.
Formal analysis: Alam AMMN, Lee EY.
Methodology: Alam AMMN, Lee EY, Hossain J, Ryu JB, Ko DH, Joo ST.
Software: Alam AMMN, Lee EY, Hossain J, Ryu JB, Ko DH, Hwang YH, Joo ST.
Validation: Alam AMMN, Lee EY, Hossain J, Ryu JB, Ko DH, Hwang YH, Joo ST.
Investigation: Alam AMMN, Lee EY, Hossain J, Hwang YH, Joo ST.
Writing - original draft: Alam AMMN, Lee EY.
Writing - review & editing: Alam AMMN, Lee EY, Hossain J, Ryu JB, Ko DH, Hwang YH, Joo ST.

Author Information

AMM Nurul Alam (Ph.D. Researcher, Gyeongsang National University) https://orcid.org/0000-0003-3153-3718
Eun-Yeong Lee (Ph.D. Researcher, Gyeongsang National University) https://orcid.org/0000-0002-3467-7349)
Jakir Hossain (Ph.D. Researcher, Gyeongsang National University) https://orcid.org/0009-0008-7663-9202
Je-Bin Ryu (Manager, Tamrain Inc.) https://orcid.org/0009-0004-3585-7124
Deok-Hoon Ko (Manager, Tamrain Inc.) https://orcid.org/0009-0008-1902-288X
Young-Hwa Hwang (Research Professor, Gyeongsang National University) https://orcid.org/0000-0003-3687-3535
Seon-Tea Joo (Professor, Gyeongsang National University) https://orcid.org/0000-0002-5483-2828

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