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Mass transport phenomenon during ultrasound-assisted osmotic dehydration of skipjack tuna (*Katsuwonus pelamis*)

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Ultrasound has emerged as a promising technique for enhancing mass transfer efficiency in meat processing, but the mechanisms of material movement must be thoroughly investigated prior to scaling for commercial applications. For this reason, the study assessed the influence of ultrasound on the mass transfer kinetics of skipjack tuna (*Katsuwonus pelamis*) chunks during osmotic dehydration (OD). Fresh tuna, with an initial moisture level of 73.9%, was soaked in a 20% NaCl solution through static OD and ultrasound-assisted osmotic dehydration (US-OD) at frequencies of 20, 28, and 40 kHz. The results indicated that ultrasound significantly improved moisture loss and solute gain when compared to static OD. Water loss was also more rapid than salt infusion due to the semi-permeable nature of cell membranes. Ultrasound reduces the formation of salt layers on the surface by promoting cavitation and the development of microchannels, enhancing internal diffusion. Mass transfer kinetics was modelled using a time-dependent power function, and statistical results (R^2 close to one; χ^2, RMSE, and MBE values close to zero) indicated a good fit of experimental and predicted data, implying that the models are acceptable representations of NaCl absorption. Depth profiling revealed a curvilinear pattern of diffusion under ultrasound, with more salt building up at both the surface and bottom layers of the tuna chunks, particularly at the 28 kHz frequency. The maximum diffusion coefficient (1.57×10^{-8} m^2 s^{-1}) was achieved at this frequency. Energy-dispersive X-ray (EDX) mapping confirmed a more uniform distribution of salt at 28 kHz. Conversely, 40 kHz encourages excessive microchannel development, leading to diminished salt retention. In summary, 28 kHz ultrasound was found to be the best frequency for boosting salt movement and enhancing osmotic dehydration effectiveness in tuna chunks.

Sustainability spotlight

This study supports the UN Sustainable Development Goals (SDGs) by promoting sustainable food processing through the use of ultrasound-assisted osmotic dehydration (US-OD) of skipjack tuna. The application of ultrasound in meat processing improves mass transfer efficiency, thereby reducing energy consumption and drying time (SDG 7: Affordable and Clean Energy), while also enhancing product quality and minimizing waste (SDG 12: Responsible Consumption and Production). This technology facilitates energy-efficient and environmentally friendly preservation, thereby reinforcing the sustainability of the seafood sector (SDG 14: Life Below Water) and contributing to resilient, resource-efficient food systems that are vital for long-term environmental and economic sustainability.

1. Introduction

The Philippines is an archipelago of more than 7100 islands with approximately 22 600 sq. km of coastal waters and 1.93 million sq. km of oceanic water.[1] Being agricultural in nature, one of the main industries in the country is fishing. The annual performance of the fisheries industry is attributed to the production of aquaculture, municipal capture fisheries, and commercial capture fisheries. In 2018, the Philippines ranked 8th among the top fish producing countries in the world with a total production of 4.35 million metric tons (MT) of fish, crustaceans, mollusks, and aquatic plants (including seaweed). The production constituted 2.06% of the total world production of 211.87 million MT.[2] In General Santos City, the $58-million industry employs around 120 000 people. Apart from the canneries and allied industries, the fishermen here also export fresh and frozen tuna to overseas markets.[3]

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The Philippines is a top global producer of tuna. Of the 21 species of tuna in Philippine waters, six are caught commercially: yellowfin, skipjack, eastern little, frigate, big eye, and bullet. Tuna remained the top export commodity with a collective volume of 134 412 metric tons for fresh/chilled/frozen, smoked/dried, and canned tuna products valued at USD 481 million. Canned tuna, though, constituted the bulk of tuna products being exported.[2]

In Japan, dried bonito or *katsuobushi* is an important culinary ingredient made from tuna that has undergone simmering, smoking, fermenting, and drying. The entire process is tedious, lasting from weeks to months.[4] It is rich in protein, containing niacin, selenium, vitamin B12, and inosinic acid that produces a strong umami flavor.[5] However, there are some food safety issues related to the product contents, particularly the mycotoxin beta-nitropropionic acid[6] and benzopyrene from tar and charcoal smoking, which once resulted in a temporary ban in the EU.[7] In Portugal and Spain, *muxama* or *mojama* is a traditional delicacy made from dry-cured tuna loins that are salted, brined, and dried using artisanal techniques.[8] The reduced water activity and lower pH improve the product stability.[9] The method of drying also affects color, flavor, and nutrition.[10]

Since 2017, provinces in North Sulawesi in Indonesia have been exporting katsuobushi to Japan. It has gained increasing high demand among Japanese buyers due to its high quality and taste, and because of this, the Indonesian government intends to widen the market to include US, Europe, Africa, and other countries in Asia.[11] As of 2023, the top global buyers of dried tuna include Cambodia, United States, Australia, South Korea, Singapore, and Sri Lanka, whereas the top global suppliers are Vietnam, Ecuador, Thailand, United States, and Indonesia. Dried tuna produced in the Philippines is exported to South Korea and Japan.[12]

The conventional methods of fish drying have several drawbacks including longer drying duration, poor sensory properties, and low rehydration abilities.[13] On the other hand, canning has its limitations including reduction of the nutrient value of food, significant investment in time and equipment, and possible deadly contamination due to inadequate processing or poor sanitation.[14] To address many issues related to current processing practices for fish products, several green technologies have emerged in recent years. Among the novel and non-thermal preservation technologies, high hydrostatic pressure (HHP), pulsed electric fields, cold plasma, pulsed light, irradiation, and ultrasound are the widely used techniques for processing various kinds of seafood.[15]

Ultrasound (US) is a non-thermal technology that enhances mass and energy transfer processes resulting in improved food quality.[16] It refers to sound waves exceeding the audible frequency range or greater than 20 kHz.[17] In the food industry, most research on the application of high power US (20–100 kHz, >1 W cm^{-2}) focuses on systems in which a liquid or a gaseous medium is used for the propagation of US waves.[18] These effects are caused specifically by the cavitation phenomenon, microcurrents, microjets, and the sponge effect.[16] US has a positive impact on meat processing procedures like marination, tenderization, and disinfection.[19] In tilapia, ultrasonication effectively lessened the drying time, reduced the water activity, and improved the rehydration characteristics.[20] In low-sodium salt curing of sea bass, the use of US enhanced the rate of NaCl uptake, decreased the hardness and chewiness of fish, and improved water retention.[21] Dried skipjack tuna, like other dried foods, has the drawbacks of being dark colored, hard, and less chewable. The main objective of this study was to investigate how ultrasound pretreatment can potentially enhance existing practices in processing tuna. With ultrasound pretreatment, it is expected to improve the marination process and flavor, particularly in terms of how salts are integrated into the meat.

Additionally, there is not much information available on the use of ultrasound in processing seafood, although numerous research studies are being conducted worldwide.[15] Also, before this method can be used in large-scale industries, the conditions for using ultrasound need to be studied thoroughly and set up properly.[19] In General Santos City, tuna is a major industry, and this research could help in providing better alternative in processing dried tuna products.

2. Materials and methods

2.1. Sample collection and preparation

Fresh skipjack tuna, measuring approximately 80 cm (2.62 ft), was procured from the General Santos City Fishport. It was then placed in iceboxes and transported to the MSU–General Santos City Postharvest Laboratory. The fish underwent washing, gutting (removal of the head, fins, tail, gills, and viscera), filleting lengthwise, and was subsequently cut into cubes measuring 10 × 20 × 20 mm. The preparation process was completed within a span of 5 minutes.[22] The samples were stored in the temperature range of 5–10 °C for less than 30 minutes prior to their use. Before the ultrasound-assisted osmotic dehydration (US-OD) process, any excess surface moisture on the tuna chunks was eliminated using absorbent paper.

2.2. Ultrasound-assisted osmotic dehydration (US-OD) pretreatment

The experiments utilized a fabricated ultrasonic water-bath system, which included a generator, transducers, and a 10-liter tank. The generator provided the necessary energy and facilitated the selection of frequencies (20, 28, or 40 kHz). The transducers, which were connected to the system, transformed electrical energy into ultrasound and propagated it through the brine solution.

For US-OD pretreatment, common food-grade table salt (NaCl) was used in preparing the 20% (20 g salt/100 g in water phase) brine solution. The ultrasound bath was filled with the brine solution, which was pre-warmed to the designated frequency, and chunks of tuna placed in mesh containers were immersed. A sample-to-solution ratio of no less than 1 : 20 was maintained since this was enough to reduce concentration variations in the solution.[23] To control the heat generated by ultrasound waves, ice cubes were added to the solution as necessary,[24] and the temperature of the brine was tracked using a thermocouple.

2.3. Mass transfer kinetics experiment

For mass transfer analysis, the tuna chunks were exposed to US-OD at frequencies of 20, 28, and 40 kHz. Samples were collected at intervals of 5, 10, 15, 30, 45, 60, 90, 150, 180, 210, 240, 300, and 360 minutes, subsequently rinsed with distilled water, and then blotted dry. Pressing the samples was also avoided. Weights of the samples were measured using an analytical balance. Additionally, a separate batch was maintained in brine until equilibrium was achieved. For comparison, static osmotic dehydration (OD) was conducted over the same time intervals.

The diffusion of NaCl into the food material was further investigated by determining the salt concentration at depths of 2, 4, 6, 8 and 10 mm from the surface at 10, 20, 30, 60, and 120 min. In this experiment, the chunks were cut into five layers using a #11 scalpel and the pieces were subjected to oven drying to determine the moisture content.

All experiments were performed in triplicate. The moisture content was evaluated through oven-drying (AOAC method 925.09), while brine salinity was measured using a refractometer.

2.4. Mathematical modelling of diffusion kinetics

Mass transfer during osmotic dehydration was analyzed using parameters on water loss (WL) and solute gain (SG):[25]

$$\text{Water loss }(\%) = \frac{(M_o x_{w,o}) - (M_t x_{w,t})}{M_o} \quad (1)$$

$$\text{Solute gain }(\%) = \frac{(M_t x_{s,t}) - (M_o x_{s,o})}{M_o} \quad (2)$$

where: M_o = initial weight (g) of tuna chunks before US-OD. M_t = weight (g) of tuna chunks at each US-OD time. $x_{w,o}$ and $x_{w,t}$ = water content of tuna chunks (g g^{-1} wet basis) at the initial and respective US-OD times, respectively. $x_{s,o}$ and $x_{s,t}$ = dry matter content of tuna chunks (g g^{-1} wet basis) at initial and respective US-OD times, respectively.

The kinetics of mass transfer in the aqueous phase of tuna was described using a power function of time-variant equation.[26] This model has been generally found to give the best fitted equations for studies on diffusion of cured meat.

The form of the power function time-variant equation is:

$$z_s = At^b \quad (3)$$

where: z_s = concentration of NaCl (g g^{-1}) in the tuna chunks, t = US-OD time (h), A and b = constants.

The concentration (g g^{-1}) was computed using weight fractions of NaCl as follows:

$$z_s = \frac{U_S}{U_T} \quad (4)$$

where: U_S = weight (g) of NaCl in the sample. U_T = total weight (g) of the sample.

The goodness of fit of the model was calculated using the coefficient of determination (R^2), reduced mean square of the deviation or chi-squared (χ^2), mean bias error (MBE), and root mean square error (RMSE). The parameters were calculated as follows:

$$\chi^2 = \frac{\sum (z_{exp} - z_{pred})^2}{N - m} \quad (5)$$

$$\text{MBE} = \frac{\sum (z_{exp} - z_{pred})}{N} \quad (6)$$

$$\text{RMSE} = \sqrt{\frac{\sum (z_{exp} - z_{pred})^2}{N}} \quad (7)$$

where z_{exp} = experimental $z_{w \text{ or } s}$, z_{pred} = predicted $z_{w \text{ or } s}$, N = number of observations, m = number of constants.

The mean R^2 of the model was computed using Fisher transformation while appropriate mathematical techniques were applied for averaging χ^2, MBE, and RMSE.

2.5. Determination of diffusion coefficients

The diffusion coefficient (D) can be computed based on Fick's second law of diffusion.[27] For one-dimensional slab geometry, the equation[28] is described as:

$$\frac{\partial M}{\partial t} = D\left(\frac{\partial^2 M}{\partial r^2} + \frac{\eta}{r}\frac{\partial M}{\partial r}\right) \quad (8)$$

The initial and boundary conditions are defined as $M(r,0) = M$ at $t = 0$, and r denotes the spatial coordinate, ranging from 0 to L, where L denotes the half-thickness (m). For planar geometry, the constant η is equal to 0.[28]

In this study, the tuna chunks were assumed to be an isothermal semi-infinite geometry slab with unidirectional mass transfer. It was also assumed that changes in temperature, sample volume, and external resistance are negligible during the US-OD process. Moreover, the effective diffusivities of NaCl (D_s) were treated as constant, as were the NaCl and moisture contents at the beginning of the process. With these assumptions, the equation was evaluated[29] as:

$$\text{MR} = \frac{M_t}{M_\infty} = \frac{8}{\pi^2}\sum_{n=0}^{\infty}\frac{1}{(2n+1)^2}\exp\left[-\frac{(2n+1)^2\pi^2}{4L^2}Dt\right] \quad (9)$$

In the case of long processing times, the first term of the series becomes dominant. Thus, the equation can be simplified to

$$\text{MR} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 Dt}{4L^2}\right) \quad (10)$$

In terms of diffusion, the coefficients can be expressed from the concentration *versus* time data using the equations for slab geometry:[30]

$$\frac{z_{s,t} - z_{s,eq}}{z_{s,0} - z_{s,eq}} = \frac{8}{\pi^2}\exp\left(-\frac{\pi^2 D_s t}{4L^2}\right) \quad (11)$$

where: $z_{s,t}$ = concentration of NaCl in the tuna chunks (g g^{-1}) at a given US-OD time, $z_{s,0}$ = initial concentration of NaCl in the tuna chunks (g g^{-1}), $z_{s,eq}$ = concentration of NaCl in the tuna chunks (g g^{-1}) at equilibrium. L = thickness of the tuna chunks (m).

Lastly, the exact values of the diffusion coefficients can be found using MS Excel Solver.

2.6. Salt mapping

A representative sample from each treatment was cut into half. The bottom part was used for the test with the broken surface facing upward. The laboratory analysis was conducted at Mindanao State University – Iligan Institute of Technology Center for Sustainable Polymers (MSU-IIT CSP) using a JEOL JSM-IT200 SEM. The resulting data on salt content were mapped using energy-dispersive X-ray (EDX) analysis.

3. Results and discussion

3.1. Mass transfer kinetics

The fresh tuna chunks had an initial mean moisture content (MC) of 73.9%. When subjected to osmotic dehydration (OD) in a 20% brine solution, there was a marked decrease in the moisture content of the samples at each time interval until equilibrium moisture content was reached. Whether or not ultrasound was introduced during brining, the plot of moisture content against time (Fig. 1) followed similar curves under all conditions.

In the case of OD with no ultrasound (0 kHz or control), there was only a small reduction in the moisture content of the samples. The equilibrium moisture content (EMC) was 69.43% after 360 min of OD which was longer than that for the treated samples. Among the samples subjected to US-OD, those treated at 28 kHz had the lowest EMC value at 65.01%, followed by 40 kHz at 65.52% and then 20 kHz at 66.02%. It can also be observed that the lowest curve in Fig. 1 corresponds to 28 kHz, which means that the lowest MC values were determined at this frequency. This implies that the highest reduction in MC during US-OD occurred when 28 kHz ultrasound was applied. Additionally, the differences in MC began to be significant at 30 min, indicating that the ultrasound frequency indeed influenced mass transfer during osmotic dehydration.

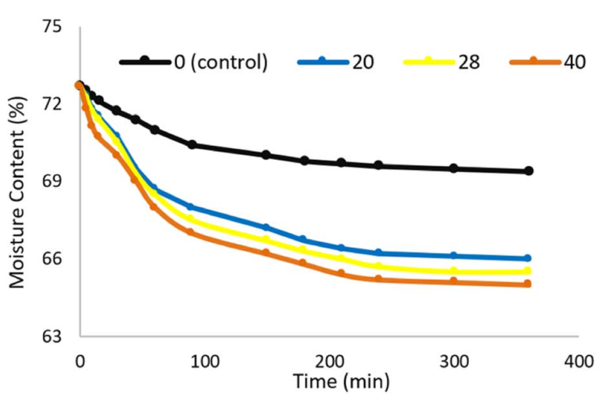

Fig. 1 Moisture content of untreated and ultrasonicated brined tuna.

In terms of solute gain and water loss, the plots of the percentage change with time (Fig. 2) for the two properties showed similar curves typical of any osmotic dehydration process. As observed in the curves, there was rapid water removal and salt gain at the beginning, followed by slower loss and gain in the later stages. This phenomenon can be attributed to the large osmotic gradient between the dilute content of the fresh tuna samples and the surrounding hypertonic solution. As the process progressed, more water was incorporated into the solution while salt was lost at the same time. This led to a slight reduction in the osmotic pressure on the surface of the sample, thereby slowing down both moisture loss and solute gain in the tuna chunks. The equilibrium condition was reached when

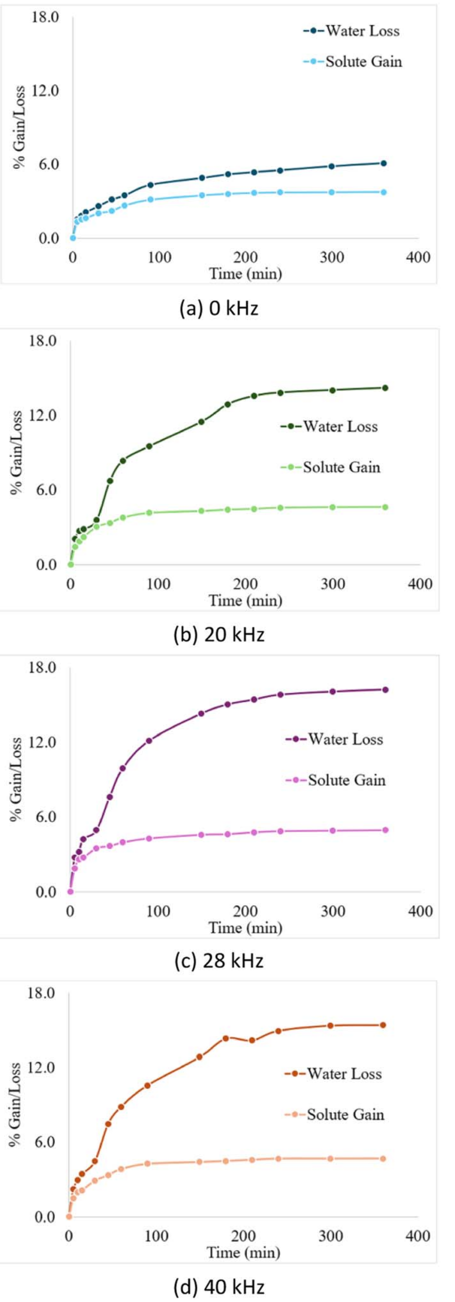

Fig. 2 Solute gain and water loss in brined tuna.

there was no more change in both solute gain and moisture loss.

Although both happened simultaneously, the curves for water loss were situated higher than the curves for solute gain. This implies that the uptake of salts occurred at a much slower rate than moisture loss. It can be attributed to the semi-permeability of the cellular membrane which regulates the passage of solids but not water.[31]

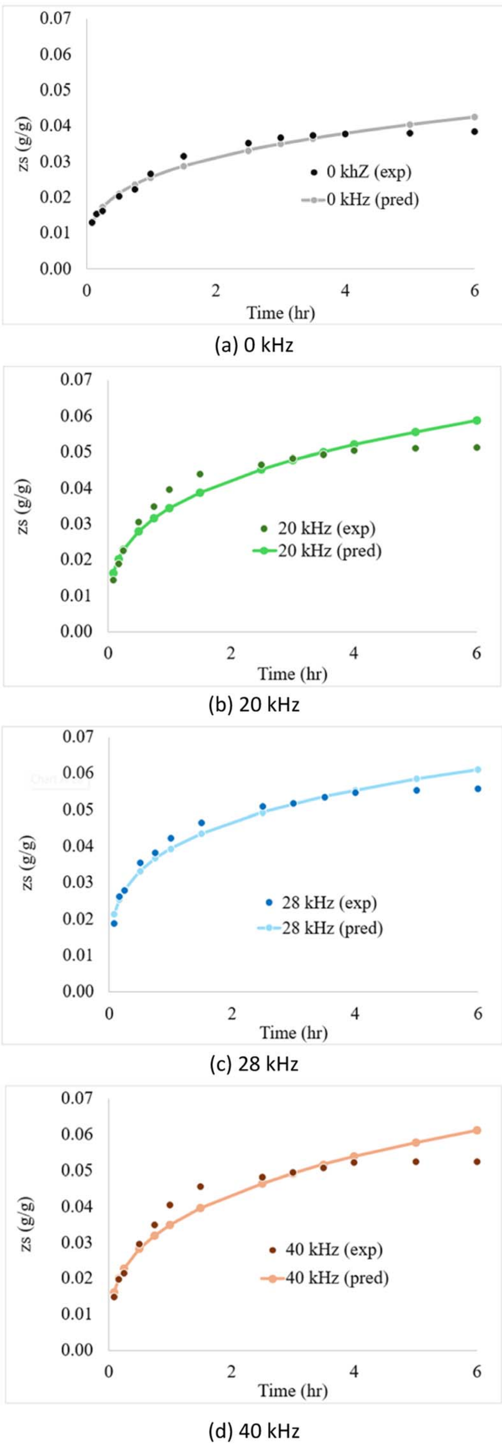

Fig. 3 Model fitting on NaCl concentration *vs.* time.

During OD, a dense deposit of solute eventually forms on the surface of the food. This layer disturbs the concentration gradients at the boundary between the product and the surrounding medium, producing a barrier that increases resistance to both solute infusion and moisture removal.[32] It can further cause structural changes, such as surface shrinkage and cell collapse, which lead to compaction of the surface layer, thereby hindering mass transfer of both water and solutes.[33]

3.2. Mass transfer modelling

The curves in Fig. 3 indicate that the concentration of salt in the tuna chunks increases as the brining process progresses. This is logical since longer immersion time in the brine solution will promote greater integration of NaCl into the product. From the raw data, the mean NaCl concentration in the tuna chunks ranges from 0.0131 to 0.0187 g g^{-1} at 5 min osmotic dehydration.

After 6 h, when equilibrium was observed, the concentration reached 0.0384 to 0.0611 g g^{-1}. Static osmotic dehydration (0 kHz) also showed the lowest salt concentrations in the tuna chunks from beginning to end of the process, while the 28 kHz exhibited the highest salt concentrations.

It can also be observed from the graphs in Fig. 3 that the models generated had a good fit to the experimental data. All the R^2 values or coefficients of determination are close to 1.0000, signifying that the models sufficiently describe the actual data (Table 1). As to the χ^2, RMSE, and MBE parameters, their values were almost zero, indicating that the predicted values of the models are close to the experimental data. Hence, the time-variant power function as a mass transfer model (Table 2) is a good representation of NaCl diffusion in tuna chunks during static and ultrasound-assisted osmotic dehydration.

The diffusion of NaCl into the food material was further investigated by determining the salt concentration at depths of 2, 4, 6, 8 and 10 mm from the surface at 10, 20, 30, 60, and 120 min, and the concentration curves over time are plotted in Fig. 4.

The curve for static brining (0 kHz) shows a different behavior compared to the ultrasonicated samples. It shows that NaCl concentration decreases along the depth of the food mass. The highest concentrations are always at the top, at 2 mm from the surface, because this part of the meat is most exposed to the brine solution, which serves as the entry point of the salt. On the other hand, the lowest concentrations are always at the bottom because it had the least exposure to the brine since the tuna samples almost touched the tank floor. The results imply that

Table 1 Equation constants and statistical measures for model fitting

US FREQ (kHz)	Model constants		R^2	χ^2	MBE	RMSE
	A	b				
0	0.0256	0.2826	0.9636	0.000004	0.000018	0.0017
20	0.0344	0.2984	0.9318	0.000015	−0.000038	0.0036
28	0.0394	0.2458	0.9548	0.000019	−0.000014	0.0027
40	0.0350	0.3110	0.9557	0.000017	−0.000023	0.0037

Table 2 NaCl diffusion models in tuna

US FREQ (kHz)	Equation
0	$z_s = 0.0256\ t^{0.2826}$
20	$z_s = 0.0344\ t^{0.2984}$
28	$z_s = 0.0340\ t^{0.2458}$
40	$z_s = 0.0350\ t^{0.3110}$

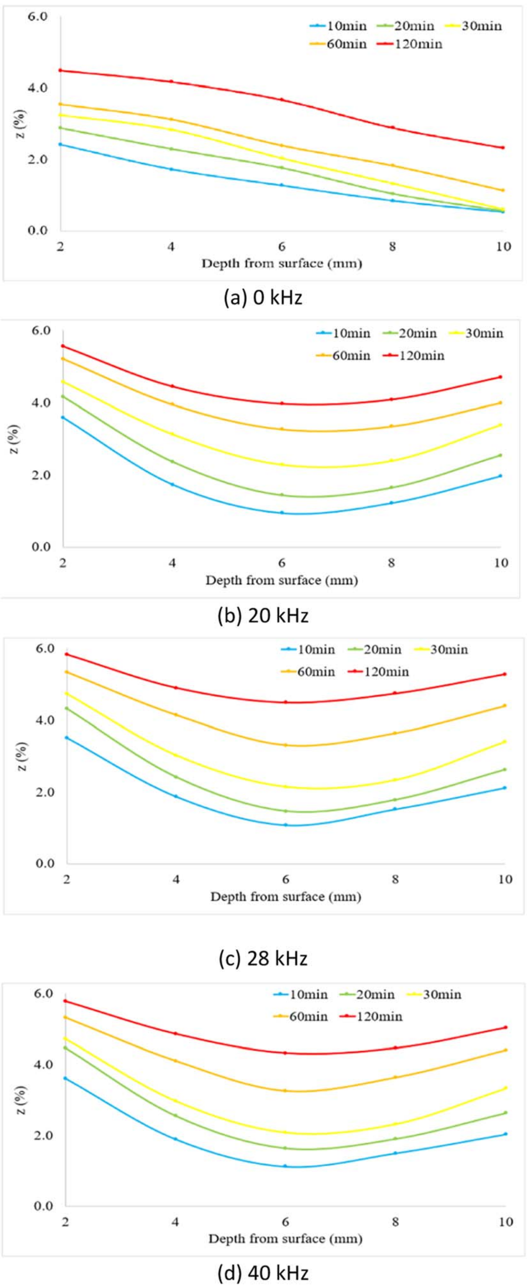

Fig. 4 Salt concentration at different depths in tuna meat.

during static brining, most of the added NaCl remained in the tuna superficial layer, and the salt concentrations gradually decreased with increasing depth in the meat. Moreover, the salt concentration also increased with processing time since the curve for 10 min is situated lowest in the plot when compared to the other curves.

Instead of a linear pattern similar to static brining, the curves for the US-OD treatments are curvilinear with the highest points at depths of 2 and 10 mm, and the lowest at 6 mm. Between the 2 and 10 mm depths, the former has the highest concentrations since by virtue of osmosis and gravitational effects, salt infusion would be highest at the surface. However, there is also rapid salt accumulation at the bottom of the meat which is the part exposed to the tank floor. This portion of the tank is where the transducers are fitted, and hence, ultrasound aided in the incorporation of salts through this part of the meat. It can be said that the effects of ultrasound such as cavitation and surface erosion are most manifested on the surfaces exposed to ultrasound. The lowest NaCl concentration in the tuna chunks is at its central potion since salt diffusion through the muscle fiber would take longer time to occur.

Additionally, the curves at 10 min for all three ultrasound frequencies show a more dramatic turn or "kink" than those for the other processing times. At this point, only a few salt molecules had reached the core of the meat. As US-OD progressed, more salts diffused to the center of the tuna samples, and the curves started to relax, and the "kink" began to flatten. At 120 min, the curves began to look more linear, although the salt concentration at the center remained lowest.

3.3. Diffusion coefficient of NaCl

From Table 3, the values of diffusion coefficients (D) computed for tuna are apparently greater than those for beef, duck, and chicken. This can be expected since tuna has more tender muscle fibers than the other meats, and thus, the diffusivity of salt into the fibers will be faster. The brining solutions in the other studies are also dilute, and thus, the osmotic gradient will be lower, resulting in slower diffusion of salts. The tumbling process of pork[34] resulted in large values of D due to the mechanical nature of the process itself that enables more efficient brining operation. Thus, the diffusion coefficients may vary greatly among different meat products due to the type of meat and the relevant operating conditions.

The results of ANOVA revealed that there is a significant difference in the diffusion coefficient as affected by ultrasound frequency. Specifically, the D value for 28 kHz is the highest at $1.5709 \times 10^{-8}\ m^2\ s^{-1}$ which is statistically different from the other three. On the other hand, the diffusion coefficients for 0 kHz (static brining), 20 kHz, and 40 kHz are not significantly different from each other. These findings imply that among the ultrasound frequencies, 28 kHz provides the most efficient infusion of salt into the tuna chunks, mainly due to the combined cavitation and sponge effects of the ultrasound treatment.

3.4. Salt map

Salt mapping was performed through energy-dispersive X-ray (EDX) mapping to visualize the spatial distribution of elements, in this case, NaCl. The salt is represented by blue dots in Fig. 5.

Table 3 Diffusion coefficients (D) of NaCl in some ultrasonicated meats

Meat	Processing conditions	Ultrasound parameters	D ($m^2 s^{-1}$)
Present study			
Skipjack tuna	Brining in 20% brine solution at 1 : 20 meat-brine ratio	0 kHz (untreated)	$1.17 \times 10^{-8(a)}$
		20 kHz	$1.27 \times 10^{-8(a)}$
		28 kHz	$1.57 \times 10^{-8(b)}$
		40 kHz	$1.25 \times 10^{-8(a)}$, note: means with different letters are significantly different
References			
Pork[34]	Tumbling in 8.6% brine solution at a 35 : 100 meat–brine ratio; ultrasound frequency of 20 kHz	Single stumbling	2.23×10^{-8}
		100 W	2.69×10^{-8}
		300 W	3.66×10^{-8}
		500 W	4.98×10^{-8}
		700 W	7.54×10^{-8}
Beef[30]	Brining in 3–6% brine solution at a 1 : 20 meat–brine ratio	Static brining	0.62×10^{-9}
		2.39 W cm^{-2}	0.76×10^{-9}
		6.23 W cm^{-2}	0.90×10^{-9}
		11.32 W cm^{-2}	1.14×10^{-9}
		20.96 W cm^{-2}	1.60×10^{-9}
Duck breast[35]	Marination in 2.5% brine solution at 20 kHz	Static marination	0.95×10^{-9}
		150 W	1.22×10^{-9}
		300 W	1.23×10^{-9}
		450 W	1.27×10^{-9}
Chicken breast[36]	Marination in 2.5% brine solution at 20 kHz	Static brining	1.19×10^{-9}
		150 W	1.25×10^{-9}
		300 W	1.27×10^{-9}
		450 W	1.38×10^{-9}

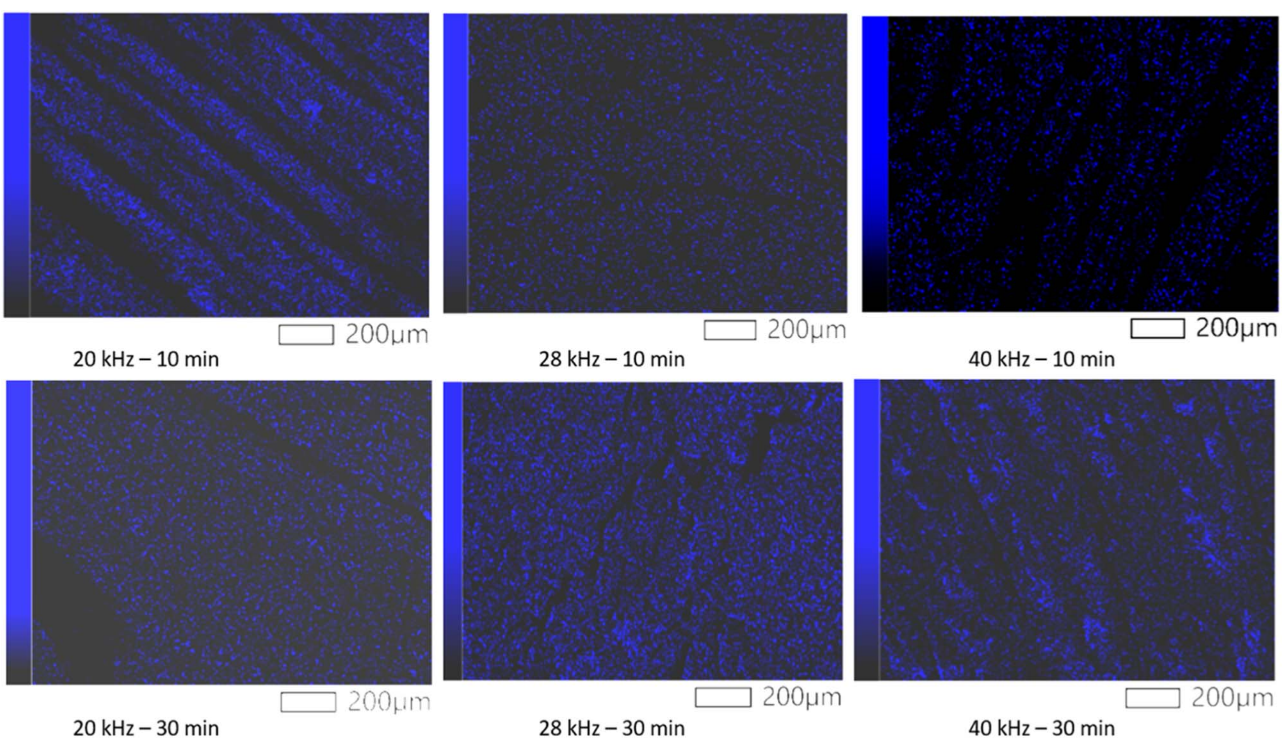

Fig. 5 Salt distribution (depicted as blue dots) in the tuna muscle fibers during US-OD.

Between the two application times, the higher salt deposition in the tuna muscle is at 30 min, indicated by the presence of more blue dots in the salt map. This supports the earlier claim that longer US-OD time enables greater accumulation of NaCl in the food product.

At 20 kHz, it can be observed that there is a systematic distribution of salt, as seen by the lines of blue dots in the images. It can be surmised that these "lines" correspond to the gaps between myofibers where NaCl accumulated during US-OD. The most scattered distribution of salt is at 28 kHz as observed in the image where the blue dots are irregularly distributed across the map. This demonstrates the ability of ultrasound to transport materials deep within the food material, not only into the spaces between cells but even at the intracellular level. Specifically, the formation of microchannels, as well as micro-injections on the meat surface, leads to a more uniform distribution of salt in the meat muscle.[37]

The drawback of the presence of more microchannels can be observed at 40 kHz where there is less distribution of NaCl based on the salt map. Since these microchannels carry both solutes and moisture during US-OD, there may be less retention of salt as they can also be carried out of the food materials. At higher US frequencies, the "sponge effect" becomes more dominant as the repeated decompression and compression of the meat in the brine solution can squeeze out different materials.

In this context, there may be an optimum ultrasound frequency for processing different meat products to achieve the best desired effects, such as the most uniform salt distribution with the least food material degradation. While salts aid in food preservation, excessive salt in food poses health risks. The World Health Organization has advocated lowering sodium intake, and one of their suggestions is to "reformulate food products to contain less sodium and set target levels for the amount of sodium in foods and meals.[38]" Meanwhile, the USFDA states the following guideline: a sodium content of 5% DV (daily value) or lower per serving is deemed low, while a sodium content of 20% DV or higher per serving is regarded as high.[39] Taking these factors into account, ultrasound may effectively tackle the health concerns in salted foods by controlling salt levels and processing parameters.

4. Conclusion

This study demonstrated that ultrasound can be an effective pretreatment for drying skipjack tuna (*Katsuwonus pelamis*) because of its ability to improve internal mass transport. During osmotic dehydration of fresh tuna chunks in 20% NaCl, ultrasound treatment significantly accelerated both moisture loss and solute gain compared to static brining. The 28 kHz frequency consistently produced the best results in terms of the lowest equilibrium moisture content and the highest salt absorption. This indicates that ultrasound, particularly under optimal conditions, can disturb inherent barriers to mass transfer.

Cavitation and microbubble implosions induced surface erosion, disrupted salt layer formation, and generated microchannels that facilitated the bidirectional transfer of water and solutes. These findings were further validated by modelling results, and the time-variant power function accurately fitted the NaCl absorption data. Energy-dispersive X-ray (EDX) mapping supported these results by visualizing deeper and more uniform salt distribution in ultrasonicated samples. Both the salt maps and the calculated diffusion coefficients showed that ultrasound effectively increased the integration of salts into the tuna chunks, with the maximum diffusivity occurring at 28 kHz. However, higher frequency ultrasound (40 kHz) was found to produce too many microchannels, which, although increasing permeability, may result in decreased salt retention because of the dominant sponge effect. Lastly, the results highlight the importance of optimizing ultrasound parameters to achieve a balance between enhanced diffusion and product integrity.

Author contributions

Guillermo P. Pantuhan: conceptualization, investigation, data curation, formal analysis, writing of the paper. Arnold R. Elepaño: conceptualization, supervision, investigation. Kevin F. Yaptenco: formal analysis, validation. Omar F. Zubia: validation. Katherine Ann T. Castillo-Israel: formal analysis.

Conflicts of interest

The authors have no conflicts of interest.

Data availability

All data generated or analyzed during this study are included in this published article.

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