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Accelerated brining kinetics and NaCl distribution of Chinese cabbage (*Brassica rapa ssp. pekinensis*) using pulsed electric field

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ABSTRACT

Brining is a representative processing method for the long-term preservation of food materials. We analyzed the effects of pulsed electric fields (PEF) at various strengths and brining solutions with two different NaCl concentrations (10 g/mL and 15 g/mL) at 25 °C for 12 h on Chinese cabbage. PEF had significant effects on mass transfer kinetics; k_1 and k_2 values were highest for PEF at 2.5 kV/cm, regardless of the brining solution concentration. Additionally, salinity and solid gain were highest for PEF at 2.5 kV/cm and gradually increased, depending on the strength of PEF. The hardness and cutting force were influenced by the PEF strength and NaCl concentration of the brining solution. The microstructure differed significantly between the PEF-pretreated and untreated samples. These results demonstrate that PEF can effectively reduce the brining time and NaCl concentration during brining process and may guide further research aimed at the practical application of PEF on food processing.

1. Introduction

Brining is a traditional preservation process and in many cases fermentation process go through then consumed as a product (Tang et al., 2022). Salt is a representative antimicrobial agent in the brining of vegetables because it can partially remove the water in the cytoplasm effectively and induce plasmolysis (Chiralt et al., 2001). Specifically, during the brining process, salt enters the tissues until osmotic pressure equilibrium is reached, which occurs through diffusion and capillary flow; water is then removed from the intracellular space via a concentration gradient (Rahman, 2007). This process is essential to reduce the risk of microorganism growth; however, owing to the osmotic pressure, pectin, the main component of the cell wall, is degrades, and soluble solids, such as vitamin C, sugars, free amino acids, and sulfur compounds, are drawn out from the cell membrane (Kim & Koh, 1989). Therefore, excessive brining process affect the appearance, texture, flavor, sensory properties, and fermentation quality of the final products (Kim, 1997).

Chinese cabbage (*Brassica rapa* L. subsp. *pekinensis*) is widely consumed as a salted vegetable in Eastern Asia (Lee, Choi, Chang, Song, & Chun, 2021). It is also the main ingredient of kimchi, a representative Korean traditional, fermented food (Kim, Dang, & Ha, 2022). Approximately 1.5 million tons of kimchi are consumed annually; however, the brining process requires 10–12 h using a 10–15 g/mL NaCl solution and depends on the type of Chinese cabbage and temperature owing to the complexity of cellular structure (Kim, 1997). Accordingly, productivity is low compared to consumption (Han & Seok, 1996; Zhao & Eun, 2018). Various methods have been evaluated to accelerate brining time for Chinese cabbage, including the use of high hydrostatic pressure (Choi, Lee, Son, Park, & Chun, 2020), ultrasound (Zhao & Eun, 2018), and vacuum brining; however, these methods are still under development in food industry (Park, 2022). Therefore, alternative technology with minor impact on the cellular structure and accelerate brining process of salted Chinese cabbage at the same time is still required.

Pulsed electric fields (PEF) are a type of cell hybridization and electrofusion technology (also known as the electropure process) that was developed in the 1920s; the process results in electroporation (Jeyamkondan, Jayas, & Holley, 1999). An additional electric field causes the irreversible destruction on the cell membrane (depending on the strength) and reduces the energy required for water molecules in the lipid layers to enter the cell membrane through aqueous pores (Prakash & Srimathveeravalli, 2021). Without PEF, water molecules can pass through the cell membrane during the brining process; however, the pores are unstable and easily collapse, inhibiting the distribution of NaCl (Prakash & Srimathveeravalli, 2021). The duration of the permeabilization response depends on the cell type, duration of electric pulse exposure, frequency, wave form, strength, and various conditions,

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Abbreviations

EDS	energy dispersive spectroscopy
FE-SEM	field emission scanning electron microscopy
PEF	pulsed electric field

such as osmotic pressure (Prakash & Srimathveeravalli, 2021). Due to these properties, PEF has been utilized to accelerate and improve food processing during drying, rehydration, freezing, brining, and extraction (Mohamed & Eissa, 2012). Many studies have investigated the effects of PEF on mass transfer in various vegetable tissues (Donsì, Ferrari, & Pataro, 2010) including beets (El Belghiti & Vorobiev, 2004), kiwifruit (Dermesonlouoglou, Zachariou, & Andreou, 2016), and mushrooms (Li, Li, et al., 2021). However, studies of the application of PEF to brining solids foods have been limited to seabass (Cropotova et al., 2021), pork (McDonnell, Allen, Chardonnereau, Arimi, & Lyng, 2014), and lotus root (Li, Li, et al., 2021), with the aim of accelerating the brining process and increasing salinity.

In the current study, the effects of PEF pretreatment on the Chinese cabbage brining process were evaluated by analyses of mass transport kinetics, texture, and quantitative NaCl profiles. Furthermore, the mechanism underlying NaCl diffusion during brining was investigated.

2. Materials and methods

2.1. Sample preparation

Chinese cabbage (*Brassica rapa* subsp. *pekinesis* L.) was purchased from a local market in Anseong, Korea in June 2022. The Chinese cabbages were stored at 4 °C for 12 h, cut into pieces (3 cm × 3 cm × 0.8 cm), washed three times, and drained for 30 min. The brining solutions (10 g/mL and 15 g/mL) were prepared in 2000 mL of water. To prepare the sample, Chinese cabbage was mixed with the brining solution at a ratio of 1:3 for a maximum of 10 h at 25 °C.

2.2. PEF pretreatment

Chinese cabbage was pretreated by PEF using a 5-kW pulse generator (HVP-5; DIL, Quakenbrück, Germany) and a parallel electrode gap of 80 mm for the batch treatment chamber. The electric switch of IGBT (Insulated Gate Biplar Transistor) and the condition of the electrical connection were the same as followed; power supply voltage: 400V, rated current: 25A, mains frequency: 50Hz and type of connection: 3-phases(3P + PE). The chamber was filled with 50 g of cabbage and 200 mL of tap water. The electric fields were applied using a 20 μs pulse width and 50 Hz pulse frequency at 25 °C and the electric field strengths were 1.0, 1.5, 2.0, and 2.5 kV/cm (referred to as PEF1.0, PEF1.5, PEF2.0, and PEF2.5, respectively). The surface moisture on the cabbage was removed by draining it for 30 min to obtain samples.

2.3. Electric conductivity and cell disintegration index

The electrical conductivity (S/m) of the sample was evaluated with a movable chamber using an LCR meter (LCR-8000G; GW Instek, New Taipei City, Taiwan) and measured at frequencies from 1 kHz to 1.9 MHz. The electrical conductivity was calculated using Eq. (l):

$$\sigma(\omega^s) = \frac{1}{A|Z(j\omega)^s|} \tag{1}$$

where l, A, and $Z(j\omega)^s$ are the length of sample, area horizontal to the electrical field, and system impedance, respectively. The degree of cell disintegration was estimated using the electrical conductivity cell disintegration index, Z. The Z-value for Chinese cabbage tissue was calculated using Eq. (2):

$$Z = (\sigma - \sigma_i) / (\sigma_d - \sigma_i) \tag{2}$$

where σ (S/m) is the electrical conductivity measured at 1 kHz. The subscripts, i, and d, refer to the conductivities of intact and completely destroyed tissue, respectively. The value of σ_i was determined from the values of electrical conductivity of the untreated sample, and σ_d indicated the values of electrical conductivity using thawed cabbage after freezing for 24 h.

2.4. Determination of changes in components and mass transfer parameters

The samples were weighed during the brining process at 1 h intervals and changes in total mass, water, and NaCl were investigated as described in Cropotova et al. (2021). To determine the dynamics of sorption during the brining process, the Peleg model (Peleg, 1988) was applied and NaCl uptake data were fitted using Eqs (3)–(5):

$$x_t = x_0 \pm \frac{t}{k_1 + k_2 \times t} \tag{3}$$

$$\frac{dx_t}{d_t} = \pm 1 \Big/ k_1 \tag{4}$$

$$x_{eq} = x_0 \pm 1/k_2 \tag{5}$$

where + indicates the gain of NaCl, - indicates the loss of water, and x_t and x_0 indicate NaCl or water content (dry matter basis) at each time point, t, and at the initial time point, respectively. The k_1 (min.g g^{-1}) indicates the mass transfer rate of the initial brining process and the change of water or NaCl contents at time t → ∞, determined by k_2 (g g^{-1}), where Xeq is the water or NaCl content at equilibrium (t → ∞). To evaluate the accuracy of the estimation and model fitting, the R^2 (determination coefficient) and RMSE (root mean square error) were determined, as indicated by Tomac, Mallo, Perez, Loredo, and Yeannes (2020).

2.5. Determination of pH, titratable acidity, salinity, and color

The pH was measured in all samples as described by Xiong et al. (2016) using a pH meter (TM S210; Mettler Toledo, Greifensee, Switzerland) and titratable acidity was calculated using the method of Sadler and Murphy (2010, pp. 219–238). To measure the salinity of sample, salinometer (SALT-FREE2500, Ohio, USA) was used. The color was measured using a colorimeter (CR-400; Konica Minolta, Tokyo, Japan) and the total color difference (ΔE) was calculated as described by Lee et al. (2021). All samples were measured three times.

2.6. Texture

To measure the texture of a sample, a texture analyzer (TA-XT; Stable Micro Systems Ltd., Surrey, UK) equipped with a cylindrical probe with a 5 mm diameter was used. The pre-test speed was set to 2.0 mm/s and test speed was 1.0 mm/s. The post speed was set to 5.0 mm/s, and a 40% compression two-bite test was applied. The cutting force was measured using a texture analyzer (TAHDi/500; TAHD, Godalming, UK) with a blade probe. The pre-test speed, test speed, distance, and trigger force were set to 5.0 mm/s, 10.0 mm/s, 10 mm, and 3.0 N, respectively.

2.6.1. Field emission scanning electron microscopy-energy dispersive spectroscopy (FESEM-EDS)

To measure the NaCl content and to obtain images of NaCl distributions in samples, FE-SEM (SIGMA, Zeiss Co Ltd., Jena, Germany) was used with EDS (Thermo NORAN System 7). Before use, all samples were freeze-dried for 5 days and put on carbon tabs on the aluminum SEM dish, as described by Wang, Wagner, Ghosal, Bedi, and Wall (2017), and were then coated with gold.

2.7. Statistical analysis

Data were analyzed using SPSS ver. 20.0 (IBM Corp., Armonk, NY, USA). Differences in means between groups were evaluated using Duncan's multiple-range comparison tests. The threshold for statistical significance was $p < 0.05$. The results are expressed as mean ± standard deviation.

3. Results and discussion

3.1. Effects of PEF pretreatment on cell membrane permeability

Electrical conductivity results are illustrated in Fig. 1 (a). As the strength of PEF increased, the release of ionic materials gradually increased, indicating that the cell membranes of Chinese cabbage were effectively disrupted by PEF. Intact cell membranes were observed in CON group, with less leaching of ionic materials than in the PEF-treated samples. These results were similar to those of Kim, Kwon, and Lee (2019), that ginseng cell membranes were substantially disrupted by PEF and a large number of ionic materials leached into the solution; they also demonstrated that conductivity was reliant on the electric field strength. In the current study, the leaching of ionic material indicated the extent of cell membrane damage and thus was indirectly related to cell membrane permeability.

The Z-values of samples are illustrated in Fig. 1 (b). Regarding electrical conductivity, a higher electric field strength was associated with a higher Z-value. PEF pretreatment increased Z-values gradually, with values for the CON, PEF1.0, PEF1.5, PEF2.0, and PEF2.5 groups of 0, 0.18, 0.44, 0.56, and 0.68, respectively. These findings were similar to those of Loginova, Lebovka, and Vorobiev (2011), that Z-values increased as the electric field strength increased in red beet. Additionally, Kim et al. (2019) reported that the Z-values for ginseng treated with 1.5 and 2.5 kV/cm were 0.22 and 0.42, respectively. Values closer to 1.0 indicate greater damage during the freeze–thaw process and a greater degree of tissue destruction. Therefore, as the strengths of PEF increased, the irreversible electroporation on the cell membrane induced then swelling and the rupture of the cell membrane occurred thus the portion of the damaged cell membrane increased.

3.2. Mass transfer parameters and kinetics

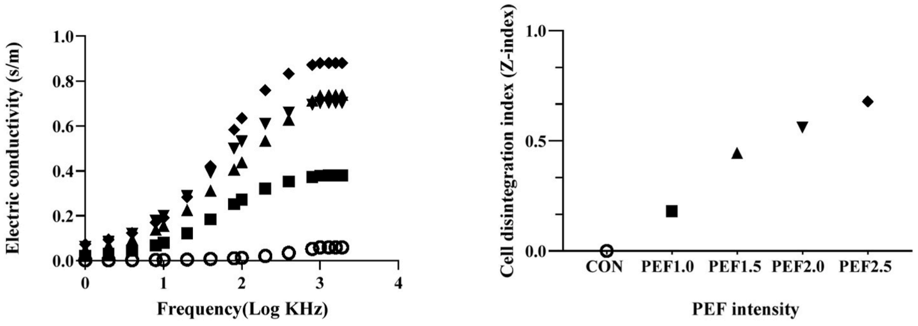
Fig. 2 illustrates the changes in total mass, water, and NaCl during the brining process at 10 g/mL (a–c) and 15 g/mL (d–f) NaCl concentrations. In CON group in 10 g/mL brining solution, total mass was reduced by almost 28% after 2 h and 43% after 10 h. The overall mass for 10 g/mL brining solution increased substantially between 28% and 41% during the first 2 h–8 h of the brining process. CON sample in 15 g/mL brining solutions showed a total mass change of approximately 37% during the brining process. However, samples subjected to PEF pretreatment showed slight changes of 3–9%, depending on the NaCl concentration of the brining solution and PEF strength. Moreover, only minor changes were observed after 5 h.

In all samples, NaCl uptake was observed over 12 h, and samples immersed in the 15 g/mL brining solution showed higher values compared to those of samples immersed in the 10 g/mL brining solution. NaCl uptake was higher in the PEF pretreatment group than in the CON group. During the brining process, water loss and NaCl uptake occur simultaneously; however, due to osmotic pressure and low NaCl transport, weight changes are greater for water than NaCl in cabbage tissues (Zhao & Eun, 2018).

Similarly, water loss was greater than NaCl uptake in this study. Water content tended to decrease, with slight differences between the CON and PEF pretreatment groups (Fig. 2). The water content in the CON group decreased to 37% at 2 h and then decreased to approximately 50% at the end of the brining process (12 h). In contrast, there were no marked differences in water content in the PEF pretreatment groups, regardless of the NaCl content of the brining solution.

Cropotova et al. (2021) reported that PEF pretreatment maintains the weight of seabass and even increases the weight slightly during the entire brining period due to electroporation, which increases the number of channels for NaCl diffusion, and this increases mass transfer and NaCl uptake during the brining process. The brining rate is the most important factor for improving the quality properties of salted Chinese cabbage, as a longer brining time increases soluble compound leakage out of cabbage, which causes the excessive modification of various properties, including color, texture, and fermentation quality (Shim et al., 2003). Similarly, Verma et al. (2014) found that an increase in cell permeability improved the mass transfer coefficient and decreased the brining rate and energy. Moreover, Gomez et al. (2019) reported that PEF pretreatment results in increased extra-cellular space and a large number of pores on the cell membrane, which promotes mass transfer during brining, drying, and rehydration. Thus, regarding the brining time and rate of NaCl uptake, PEF pretreatment is beneficial for the preservation of salted Chinese cabbage by avoiding the negative effects of a long brining process.

To evaluate the effects of PEF and the NaCl concentration of the brining solution on the NaCl uptake rate, the Peleg model was applied (Table 1). The Peleg model can be used to predict the mass transfer kinetics using short-term experimental data. The values of R^2 (the fitting correction factor) ranged from 0.99 to 1.0, suggesting that the linear



(a)

(b)

Fig. 1. Electric conductivity (a) and cell disintegration Z-index (b) with different strengths of pulsed electric field (PEF) pretreatment. CON (○): untreated; PEF1.0 (■): PEF treatment with intensity of 1.0 kV/cm; PEF1.5 (▲): PEF treatment with intensity of 1.5 kV/cm; PEF2.0 (▼): PEF treatment with intensity of 2.0 kV/cm; PEF2.5 (◆): PEF treatment with intensity of 2.5 kV/cm. Results are expressed as means ± standard deviations (error bars) of n = 3.

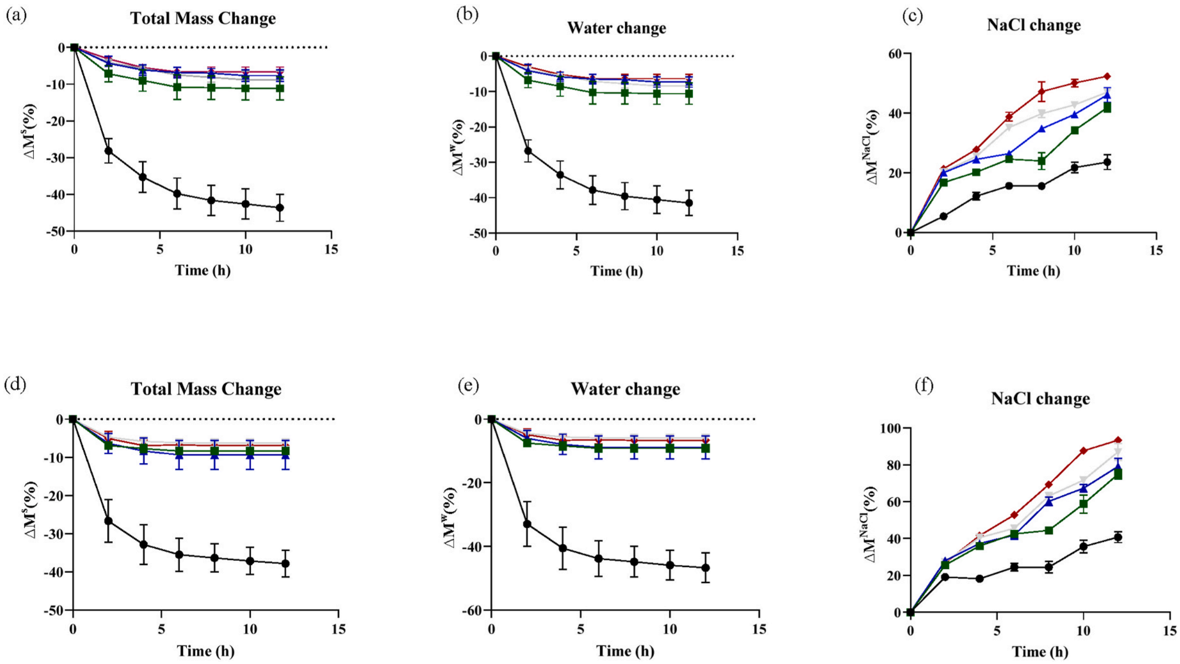


Fig. 2. Weight changes of total mass (a, d), water (b, e), NaCl (c, f) in Chinese cabbage brined at different NaCl concentrations (10 g/mL (a–c), 15 g/mL (d–f)) with different strengths of pulsed electric field (PEF) pretreatment. CON (●): untreated; PEF1.0 (■): PEF treatment with intensity of 1.0 kV/cm; PEF1.5 (▲): PEF treatment with intensity of 1.5 kV/cm; PEF2.0 (▼): PEF treatment with intensity of 2.0 kV/cm; PEF2.5 (◆): PEF treatment with intensity of 2.5 kV/cm. Results are expressed as means ± standard deviations (error bars) of n = 3.

Table 1
Peleg model constants, determination coefficient, and root mean square error (RMSE) values obtained for brined cabbage during the brining process with different strength of pulsed electric field (PEF) treatment and NaCl concentration of the brining solution.

Brining solution	Sample	k_1 (min.g g^{-1})	k_2 (g g^{-1})	R^2	RMSE
10 g/mL	CON[a]	0.0110	0.0559	1	0.04154
	PEF 1.0	0.0303	0.0736	0.9997	0.14037
	PEF 1.5	0.0125	0.0797	0.9999	0.10527
	PEF 2.0	0.0550	0.0796	0.9976	0.30144
	PEF 2.5	0.0492	0.0887	0.9977	0.39664
15 g/mL	CON	0.0095	0.0563	1	0.02580
	PEF 1.0	0.0166	0.0793	0.9998	0.12022
	PEF 1.5	0.0351	0.0793	0.9999	0.27903
	PEF 2.0	0.0359	0.0903	0.9991	0.18071
	PEF 2.5	0.0702	0.0951	0.9917	0.64225

[a] CON: untreated; PEF1.0: PEF treatment with intensity of 1.0 kV/cm; PEF1.5: PEF treatment with intensity of 1.5 kV/cm; PEF2.0: PEF treatment with intensity of 2.0 kV/cm; PEF2.5: PEF treatment with intensity of 2.5 kV/cm.

relationship was optimized. The k_1 and k_2 values gradually increased with increases in the PEF strength and concentration of the brining solution. The highest k_1 and k_2 values were observed for PEF2.5 (0.0792 and 0.0951, respectively) and immersion in a 15 g/mL brining solution. The lowest values were observed in the CON group for both k_1 and k_2. The values of k_1 and k_2 indicate the mass transfer rate at the beginning of the brining period and the time required to reach an equilibrium between the concentrations of NaCl and water, respectively. Higher values of k_1 and k_2 indicate effective mass transfer. Thus, in this study, PEF pretreatment improved mass transfer during the brining process over that of the CON group, regardless of the NaCl concentration of the brining solution.

In a previous study of the application of PEF to accelerate mass transfer during the brining process (Li, Li, et al., 2021), similar results were obtained for the lotus root, i.e., k_1 and k_2 increased from −2.27 to 1.85 and 1.79 to 2.38, respectively, depending on the strength of PEF.

The disruption of the cell membrane produces a new channel for a small molecule to pass through the cell membrane thus NaCl enters the cytosols which induce NaCl gain and a decrease in water loss due to the water-holding capacity of NaCl within the cytosols. Therefore, in the current study, pretreatment of PEF minimizes the water loss at the same time increases NaCl in the cytosols. These results further demonstrate that PEF pretreatment substantially increases mass transfer during the brining process.

3.3. *Physico-chemical properties of salted Chinese cabbage*

The results for titratable acidity, pH, salinity, water loss, solid gain, and color are shown in Table 2. Acidity decreased in a PEF strength-dependent manner; however, there was no correlation between acidity and the NaCl concentration of the brining solution. The pH increased as the strength of PEF increased, and these results were found in both 10 g/mL (6.14–6.30) and 15 g/mL (6.16–6.31) brining solutions ($p < 0.05$). The pH values in the CON group were 6.14 ± 0.02 in 10 g/mL brining solution and 6.16 ± 0.03 in 15 g/mL brining solution. The highest pH value was observed in PEF2.5 and the values were 6.30 ± 0.02 and 6.31 ± 0.03 in 10 g/mL and 15 g/mL brining solutions, respectively. Woo & Koh (1989) reported that as the NaCl concentration of the brining solution increased, the salinity and pH of salted Chinese cabbage increased, and the acidity decreased in the initial period after the brining process. Similarly, Xiong et al. (2016) reported that the initial pH values of salted cabbage were 6.35–6.65, depending on the NaCl concentration of the brining solution. These results might be explained by the change in elemental composition due to osmotic pressure and electroporation caused by PEF pretreatment.

The salinity was highest in PEF2.5, with values of 1.47 ± 0.01% and 2.58 ± 0.02% in the 10 g/mL and 15 g/mL brining solutions, respectively. Consistent with this result, solid gain was influenced by the PEF strength, with values of 0.16 for the CON group and 0.78–0.86 and 0.71–0.86 in the PEF1.0–PEF2.5 groups in 10 g/mL and 15 g/mL brining solutions, respectively ($p < 0.05$). However, the loss of water decreased as the PEF strength increased; thus, PEF2.5 was lowest in both 10 g/mL and 15 g/mL brining solutions. The proper salinity and brining time of

Table 2

Physicochemical properties of Chinese cabbage after brining at different NaCl concentrations (10 g/mL, 15 g/mL) with different strengths of pulsed electric field (PEF) pretreatment.

Sample		Physico-chemical properties					Color			
Brining solution		Acidity (%)	pH	Salinity (%)	Water loss (g/g)	Solid gain (g/g)	*L**	*a**	*b**	ΔE
10 g/mL	CON1)	0.14 ± 0.01^{a}	6.14 ± 0.02^{d}	1.17 ± 0.05^{e}	1.17 ± 0.09^{a}	0.16 ± 0.09^{b}	79.81 ± 0.02^{e}	-2.73 ± 0.02^{f}	11.20 ± 0.07^{a}	–
	PEF1.0	0.06 ± 0.01^{b}	6.23 ± 0.04^{bc}	1.25 ± 0.03^{de}	0.36 ± 0.12^{b}	0.78 ± 0.07^{a}	80.12 ± 0.03^{e}	-2.62 ± 0.15^{f}	11.06 ± 0.06^{a}	0.38 ± 0.09
	PEF 1.5	0.06 ± 0.01^{b}	6.24 ± 0.06^{bc}	1.32 ± 0.55^{de}	0.29 ± 0.09^{b}	0.85 ± 0.04^{a}	82.50 ± 1.17^{d}	-2.24 ± 0.13^{e}	8.30 ± 0.07^{c}	4.04 ± 0.86
	PEF 2.0	0.05 ± 0.00^{ab}	6.29 ± 0.01^{abc}	1.36 ± 0.03^{de}	0.25 ± 0.06^{b}	0.82 ± 0.05^{a}	84.38 ± 0.11^{b}	-1.86 ± 0.03^{cd}	7.80 ± 0.14^{d}	5.77 ± 0.07
	PEF 2.5	0.04 ± 0.01^{c}	6.30 ± 0.02^{ab}	1.47 ± 0.01^{d}	0.22 ± 0.05^{b}	0.86 ± 0.03^{a}	85.29 ± 0.08^{a}	-1.50 ± 0.05^{ab}	6.13 ± 0.13^{e}	7.56 ± 0.14
15 g/mL	CON	0.10 ± 0.01^{a}	6.16 ± 0.03^{d}	1.88 ± 0.01^{c}	1.07 ± 0.07^{a}	0.26 ± 0.06^{b}	78.90 ± 0.02^{f}	-2.66 ± 0.10^{f}	11.01 ± 0.03^{a}	–
	PEF1.0	0.06 ± 0.01^{ab}	6.25 ± 0.04^{bc}	1.97 ± 0.31^{c}	0.45 ± 0.35^{b}	0.71 ± 0.24^{a}	80.43 ± 0.06^{e}	-1.97 ± 0.09^{c}	9.80 ± 0.43^{b}	2.19 ± 0.35
	PEF 1.5	0.05 ± 0.00^{ab}	6.24 ± 0.02^{bc}	2.26 ± 0.12^{b}	0.30 ± 0.14^{b}	0.81 ± 0.09^{a}	82.00 ± 0.46^{d}	-1.49 ± 0.20^{ab}	8.45 ± 0.37^{c}	4.32 ± 0.35
	PEF 2.0	0.04 ± 0.01^{c}	6.25 ± 0.03^{bc}	2.39 ± 0.15^{ab}	0.20 ± 0.04^{b}	0.87 ± 0.02^{a}	83.37 ± 0.22^{c}	-1.42 ± 0.31^{ab}	8.28 ± 0.02^{c}	5.44 ± 0.32
	PEF 2.5	0.03 ± 0.00^{d}	6.31 ± 0.03^{a}	2.58 ± 0.02^{a}	0.23 ± 0.06^{b}	0.86 ± 0.03^{a}	84.40 ± 0.11^{b}	-1.33 ± 0.12^{a}	6.63 ± 0.30^{e}	7.87 ± 0.25

1) CON: untreated; PEF1.0: PEF treatment with intensity of 1.0 kV/cm; PEF1.5: PEF treatment with intensity of 1.5 kV/cm; PEF2.0: PEF treatment with intensity of 2.0 kV/cm; PEF2.5: PEF treatment with intensity of 2.5 kV/cm.

2)Values are expressed as means ± standard deviation (n = 3). Different superscripts (a–f) indicate significant differences between values in the same row according to Duncan's multiple-range test $p < 0.05$.

salted Chinese cabbage are close to 3% and 12–15 h, respectively, whereas salinities exceeding 3% accelerate the deterioration of texture caused by the excessive degradation of pectin in the cell wall which induces irreversible damage on cellular structure (Kim, 1967). Furthermore, as the concentration of the brining solution increases, the rate of brining decreases and deterioration of the cell structure increases (Han, 1996). This may be attributed to the collapse of the cellular structure by PEF during the brining process.

The value of L^* (brightness) was higher in PEF-treated samples (80.12–85.29) than in the CON group (79.81 and 78.90 in 10 g/mL and 15 g/mL brining solutions, respectively). The a^* values were highest in PEF2.5 (-1.50 ± 0.05 and -1.33 ± 0.12 in 10 g/mL and 15 g/mL brining solutions, respectively) and lowest in the CON group (-2.73 ± 0.02 and -2.66 ± 0.10 in 10 g/mL and 15 g/mL brining solutions respectively; $p < 0.05$). The value of b^* decreased depending on the strength of PEF but was not significantly correlated with the concentration of the brining solution. PEF2.5 exhibited a higher ΔE than the CON group, regardless of the brining solution. Choi et al. (2020) reported that the color of salted Chinese cabbage is influenced by the NaCl concentration of the brining solution, rate of NaCl uptake, loss of water, and cellular structure. As the NaCl concentration of the brining solution increases, the brightness gradually decreases in Chinese cabbage due to the collapse of the cellular structure (Choi et al., 2020). The color changes in the current study indicated that the deterioration of cellular structure resulted from osmotic pressure, which decreased the lightness value due to cell wall accumulation, whereas the intact cell volume and cellular structure of samples pretreated by PEF preserve the lightness of salted Chinese cabbage, with similar values to those of the CON group at the same time point.

Overall, these results confirm the potential for the practical application of PEF in the production of salted Chinese cabbage. These technologies can reduce production costs by reducing the brining time, amount of brining solution, and NaCl concentration of the brining solution.

3.4. *Texture*

The results of the textural analysis, including hardness, adhesiveness, springiness, gumminess, chewiness, and cutting force, are shown in Table 3. Hardness, gumminess, and chewiness decreased gradually as the PEF strength increased. For samples immersed in 10 g/mL brining solution, hardness values in the CON, PEF1.0, PEF1.5, PEF2.0, and PEF2.5 groups were 24.68 ± 2.38, 38.75 ± 4.33, 40.08 ± 1.46, 42.40 ± 3.47, and 44.44 ± 6.89, respectively ($p < 0.05$). Similar results were observed in samples immersed in 15 g/mL brining solution. The hardness values decreased as the NaCl concentration increased in the brining solution. Gumminess was highest in PEF2.5 (i.e., 18.32 and 15.05 in 10 g/mL and 15 g/mL brining solutions, respectively). Chewiness increased with PEF and was higher in the PEF2.5 group than in other samples, regardless of the NaCl concentration in the brining solution ($p < 0.05$). As the NaCl concentration in the brining solution increased, the hardness, gumminess, and chewiness values decreased. However, there were no significant differences in adhesiveness, springiness, and cohesiveness among samples, and similar results were obtained in 10 g/mL and 15 g/mL brining solutions. During the brining process, incipient plasmolysis occurs due to osmotic pressure, at which point the cell membrane does not shrink further and the cell volume is minimized; turgor pressure is 0 and irreversible damage to the cell is observed (Han & Noh, 1996). Due to this phenomenon, water loss is accelerated from the cell, and thus the hardness and cutting force of Chinese cabbage increases substantially due to the increase in fibers on the cutting surface compared to that of fresh Chinese cabbage (Song et al., 2016). Moreover, Sila et al. (2004) reported that pectin methylesterase leaks out from the cell and is hydrolyzed into pectic acid and methanol, followed by pectin cross-linking with Ca^{2+}; thus, the hardness increases in carrots during the brining process. An increase in Na^{+} ions in Chinese cabbage disrupts hydrogen bonding and thus the ability of calcium to support cellulose is weakened, thereby decreasing the hardness and increasing the flexibility of salted Chinese cabbage (Kim et al., 1987). In the current study, PEF pretreatment prevented excessive water loss and soluble compounds leaked out of the cell membrane; thus, the cell volume was preserved, hardness was increased, and the cutting force was decreased. Similarly,

Table 3

Textural properties in Chinese cabbage after brining at different NaCl concentrations (10 g/mL, 15 g/mL) with different strengths of pulsed electric field (PEF) pretreatment.

Brining solution	Sample	Hardness (N)	Adhesiveness	Springiness	Cohesiveness	Gumminess	Chewiness	Cutting force (N)
10 g/mL	CON[a]	24.68 ± 2.38^{b}	-7.03 ± 3.38^{NS}[b]	0.42 ± 0.06^{NS}	0.44 ± 0.07^{NS}	11.00 ± 2.16^{cd}	4.67 ± 1.50^{c}	6.92 ± 0.61^{a}
	PEF1.0	38.75 ± 4.33^{a}	-19.82 ± 4.81	0.42 ± 0.06	0.33 ± 0.05	12.57 ± 1.79^{bcd}	5.30 ± 1.44^{bc}	6.00 ± 0.31^{bc}
	PEF 1.5	40.08 ± 1.46^{a}	-17.14 ± 6.07	0.42 ± 0.02	0.36 ± 0.04	14.54 ± 2.23^{abc}	6.16 ± 1.25^{abc}	5.82 ± 0.08^{bc}
	PEF 2.0	42.40 ± 3.47^{a}	$-16.78 \pm .82$	0.58 ± 0.16	0.40 ± 0.10	16.68 ± 2.68^{ab}	9.96 ± 4.31^{ab}	4.77 ± 0.26^{df}
	PEF 2.5	44.44 ± 6.89^{a}	-22.22 ± 2.55	0.58 ± 0.06	0.41 ± 0.04	18.32 ± 3.59^{a}	10.56 ± 1.85^{a}	3.15 ± 0.99^{e}
15 g/mL	CON	19.51 ± 2.09^{b}	-8.67 ± 6.94	0.61 ± 0.26	0.44 ± 0.13	8.33 ± 1.69^{e}	5.40 ± 3.24^{bc}	6.21 ± 0.44^{ab}
	PEF1.0	26.12 ± 3.93^{b}	-15.59 ± 1.48	0.58 ± 0.22	0.30 ± 0.04	10.51 ± 0.58^{cd}	5.45 ± 2.15^{bc}	5.47 ± 0.47^{bcd}
	PEF 1.5	40.13 ± 1.68^{a}	-14.44 ± 4.64	0.45 ± 0.04	0.32 ± 0.07	12.12 ± 2.27^{bcd}	6.10 ± 1.36^{abc}	5.20 ± 0.15^{cd}
	PEF 2.0	40.16 ± 2.89^{a}	-29.28 ± 4.26	0.56 ± 0.07	0.37 ± 0.09	13.02 ± 3.73^{bcd}	7.42 ± 2.78^{abc}	4.69 ± 0.39^{df}
	PEF 2.5	40.95 ± 4.97^{a}	-21.67 ± 3.23	0.47 ± 0.02	0.38 ± 0.08	15.05 ± 4.06^{abc}	7.14 ± 2.25^{abc}	4.00 ± 0.54^{f}

[3)] Values are expressed as means ± standard deviation (n = 3). Different superscripts (a–f) indicate significant differences between values in the same row according to Duncan's multiple-range test $p < 0.05$.

[a] CON: untreated; PEF1.0: PEF treatment with intensity of 1.0 kV/cm; PEF1.5: PEF treatment with intensity of 1.5 kV/cm; PEF2.0: PEF treatment with intensity of 2.0 kV/cm; PEF2.5: PEF treatment with intensity of 2.5 kV/cm.

[b] NS: not significant.

solid gain was found to be positively correlated with hardness and the cutting force was highly correlated with water loss; these results further demonstrate that textural properties are related to PEF during the brining process (Fig. 3).

3.5. SEM with combined EDS

SEM images of the cellular structure of cabbages after the brining process are shown in Fig. 4. NaCl was detected around the cell wall in PEF-pretreated samples. The results of elemental composition analysis using EDS are shown in Fig. 5. NaCl was more abundant and homogeneous in the PEF2.5 groups than in the CON and PEF1.0, regardless of the NaCl concentration in the brining solution. Quantitative analyses indicated that the Na^{+} and Cl^{-} contents increased as the strength of PEF increased and the NaCl content was highest in samples immersed in the 15 g/mL brining solution. Zhao and Eun (2018) reported that the rupture of the cell membrane was associated with higher NaCl levels in the cell membrane and a more homogeneous distribution of NaCl in the

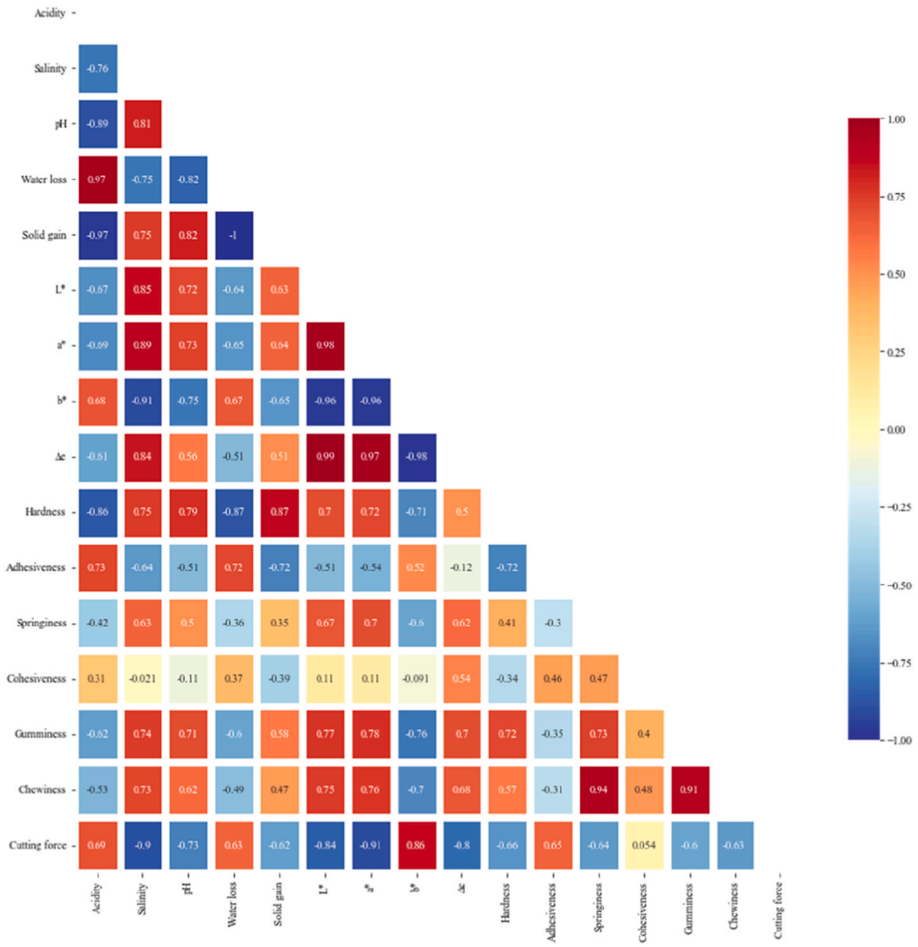


Fig. 3. Correlation of physicochemical properties and texture properties in Chinese cabbage brined at different NaCl concentrations (10 g/mL, 15 g/mL) with different strengths of pulsed electric field (PEF) pretreatment.

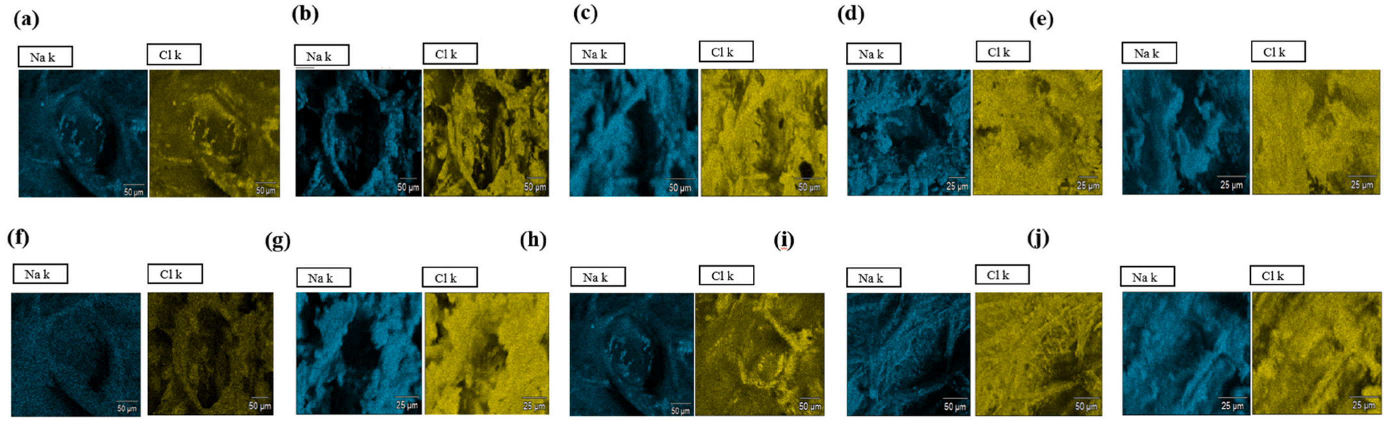


Fig. 4. NaCl distribution in Chinese cabbage observed by FESEM-EDS brined at different NaCl concentrations (10 g/mL, 15 g/mL) with different strengths of pulsed electric field (PEF) pretreatment. Magnification was × 200 and the scale bar indicated 25–50 μm. CON-PEF2.5 (a–e) at NaCl concentration (10 g/mL), CON-PEF2.5 (f–j) at NaCl concentration (15 g/mL). CON: untreated; PEF1.0: PEF treatment with intensity of 1.0 kV/cm; PEF1.5: PEF treatment with intensity of 1.5 kV/cm; PEF2.0: PEF treatment with intensity of 2.0 kV/cm; PEF2.5: PEF treatment with intensity of 2.5 kV/cm.

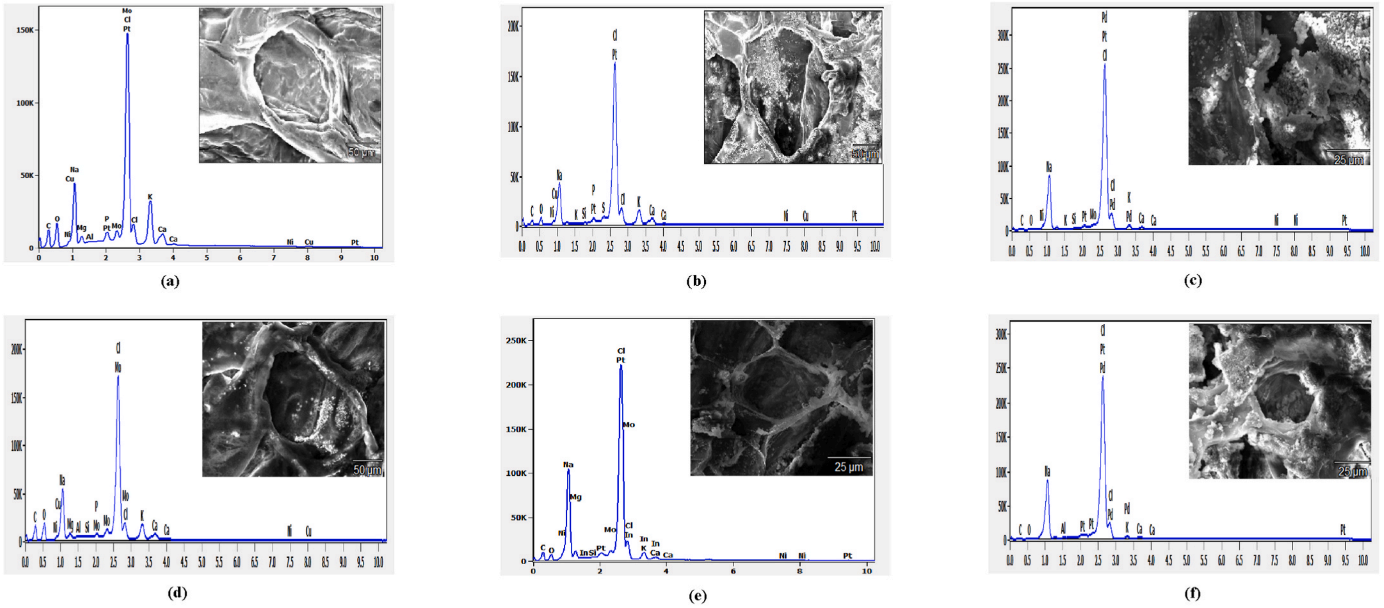


Fig. 5. Component of element in Chinese cabbage observed by FESEM-EDS brined at different NaCl concentrations (10 g/mL, 15 g/mL) with different strength of PEF pretreatment. Magnification was × 200 and the scale bar indicated 25–50 μm, x-axis: energy (keV), y-axis: counts. CON (a), PEF1.0 (b), PEF2.5 (c) at NaCl concentration (10 g/mL), CON(d), PEF1.0(e), PEF2.5(f) at NaCl concentration (15 g/mL). CON: untreated; PEF1.0: PEF treatment with intensity of 1.0 kV/cm; PEF2.5: PEF treatment with intensity of 2.5 kV/cm.

cell. In the current study, NaCl diffusion may be related to channels on the cell membrane and cell permeability caused by PEF; irreversible pore formation on the cell membrane may enable the NaCl solution to diffuse easily into the cell without incipient plasmolysis, which causes the severe disruption of the cellular structure. Thus, homogeneous NaCl in the cell membrane with an intact cell volume was confirmed by SEM and EDS results.

4. Conclusions

The NaCl concentration of the brining solution and PEF pretreatment affected water and NaCl exchange and transport during the production of salted Chinese cabbage. A higher NaCl concentration in the brining solution led to faster and greater NaCl uptake in salted Chinese cabbage. An increase in cell permeability maintained the cell volume and protected against incipient plasmolysis. Thus, PEF decreased the water loss and total mass change during the brining process and increased the solid gain and salinity over those of untreated samples. Furthermore, higher hardness improves salted Chinese cabbage texture and lowers the cutting force, thereby improving the freshness of the sample. In this investigation, PEF was an effective food technology for reducing the brining time and the concentration of NaCl in the brining solution, preventing a decrease in cell volume, and improving texture profiles, which can produce better-quality kimchi. Thus, further research is needed to investigate the application of PEF in the brining process and fermentation systems for kimchi production, including detailed analyses of sensory properties.

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CRediT authorship contribution statement

Siyoen Kim: Conceptualization, Visualization, Investigation, Writing – review & editing. **Se-Ho Jeong:** Methodology. **Hyun-Su Choi:** Validation. **Hyunho Yeo:** Formal analysis. **Dong-un Lee:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Declaration of competing interest

None

Data availability

The authors are unable or have chosen not to specify which data has been used.

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Further reading

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