



Pulsed electric field pretreatment to enhance sodium chloride and moisture diffusion in radish tissues while maintaining microstructural integrity

Se-Ho Jeong¹, Yang-An Kang¹, Jiyun Jung¹, Ki-Min Lee¹, Hafiz Muhammad Shahbaz², and Dong-Un Lee^{1,*}

¹Department of Food Science and Biotechnology, Chung-Ang University, Anseong, Republic of Korea

²Department of Nutrition and Health, College of Medicine and Health Sciences, United Arab Emirates University, Al Ain, United Arab Emirates

*Corresponding author: Department of Food Science and Biotechnology, Chung-Ang University, Anseong, 17546, Republic of Korea. Email: dong-un.lee@cau.ac.kr

Abstract

This study examined the influence of pulsed electric field (PEF) pretreatment on sodium chloride (NaCl) and moisture mass transfer in radish (*Raphanus sativus* L.) tissues, aiming to improve salting efficiency while preserving microstructural integrity. PEF was applied with 50, 75, and 150 pulses at a constant field strength (1.0 kV/cm), pulse width (20 μ s), and frequency (50 Hz). Cell membrane disintegration index (Z-index) increased from 0.00 to 0.85 with pulse number, indicating progressive electroporation of radish tissue. NaCl and moisture diffusion were modelled using Peleg, Azuara, and Crank equations, with Azuara's model providing the best fit ($R^2 = 0.713$ – 0.997 ; RMSE = 0.000–0.011), especially under isotonic and hypertonic conditions. Diffusion rate constants (s^1 and D^e) correlated positively with pulse number, confirming that higher PEF intensities accelerated solute transfer. PEF-pretreated samples exhibited greater NaCl uptake and moisture retention under hypertonic conditions, while maintaining mechanical stability. PEF-pretreated samples retained their cutting force after salting ($p > .05$), whereas controls exhibited significant softening ($p < .05$). They also showed reduced volume shrinkage ($p < .01$), reflecting preservation of microstructural integrity. These results demonstrate the potential of PEF as a nonthermal technique to enhance salting performance and maintain quality in plant-based food products.

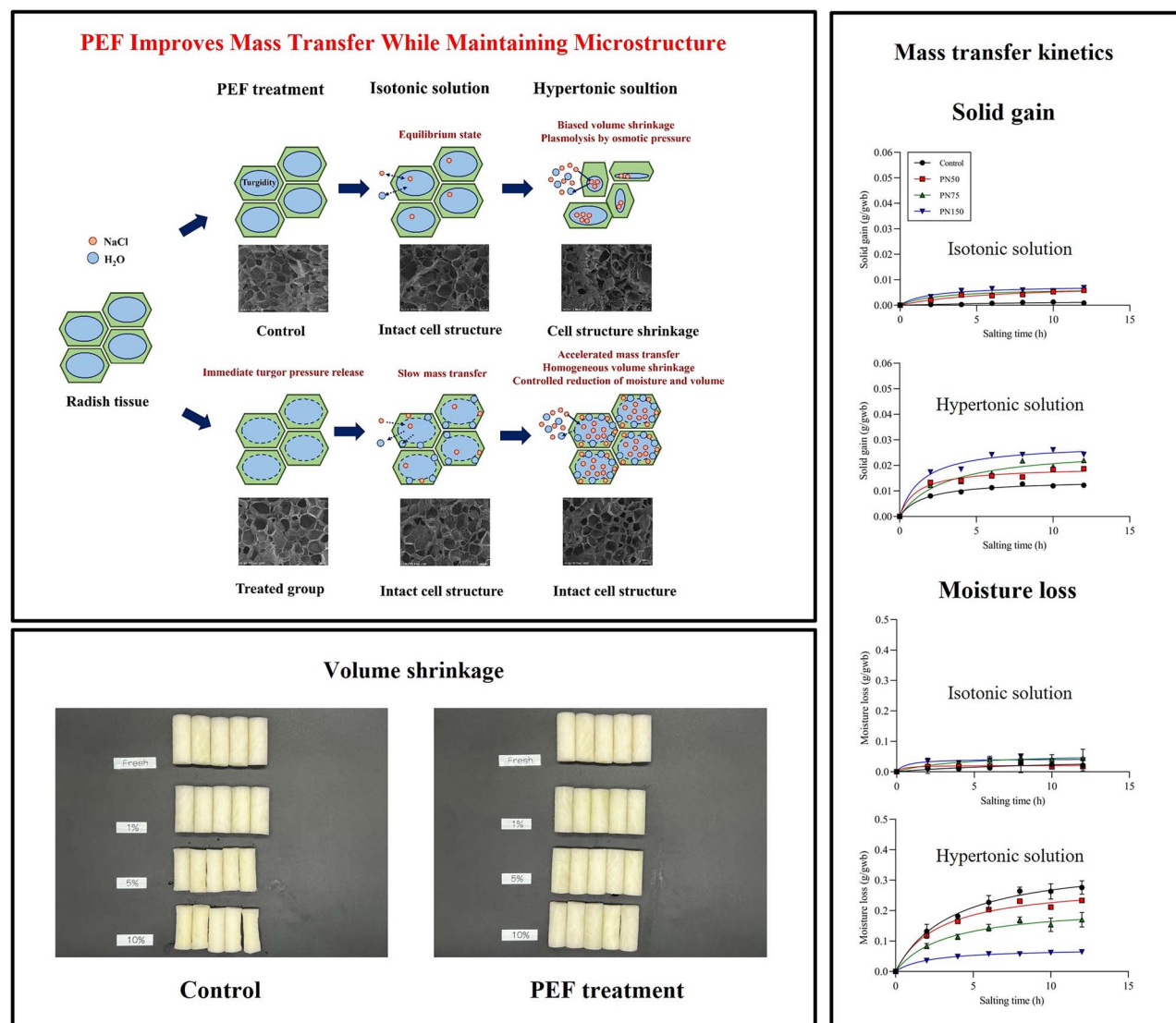
Keywords: pulsed electric fields (PEFs), NaCl diffusion, mass transfer kinetics, Z-index, radish tissue

Received: 21 August 2025. Accepted: 16 October 2025

© The Author(s) 2025. Published by Oxford University Press on behalf of the Institute of Food Science and Technology.

This is an Open Access article distributed under the terms of the Creative Commons Attribution License (<https://creativecommons.org/licenses/by/4.0/>), which permits unrestricted reuse, distribution, and reproduction in any medium, provided the original work is properly cited.

Graphical abstract



Introduction

Pulse electric field (PEF) has emerged as a promising nonthermal food processing technology because of its energy efficiency, low thermal degradation, and fast treatment time in comparison to conventional thermal methods (Morales-De La Peña et al., 2021). The process consists of applying high-voltage electric pulses for short durations, creating selective permeability in cell membranes within the range of a few microseconds (Gao et al., 2025). The pulse enhances cell permeability due to the formation of temporary or permanent nanopores within the cell membrane, thereby permitting the transfer of mass and retention of fresh-like quality attributes in plant tissues. The short duration of each pulse prevents excessive heat generation and retains the thermal integrity of the food materials. Most importantly, PEF maintains the sensory properties of the food products, unlike the established thermal techniques such as ohmic heating or autoclaving, which cause alterations in food material properties (Gavahian & Farahnaky, 2018). Therefore, PEF has shown benefits as a potential alternative for various

processing techniques, including pasteurisation, tenderisation, extraction, and enhancement of mass transfer (Bhat et al., 2019).

Electroporation is one of the primary mechanisms underlying PEF, which involves the disruption of the transmembrane potential by the application of an electric field, leading to pore formation in both plasma and tonoplast membranes. Irreversible electroporation is possible when the field strength exceeds a certain value, thereby creating changes in permeability that aid diffusion and ionic conductivity (Demir et al., 2023). This method has found applications in microbial destruction, extraction of bioactive compounds, drying, and osmotic dehydration (Gavahian & Farahnaky, 2018; Kumari et al., 2018).

Pulsed electric field-enhanced mass transfer has been reported in many food systems. Pulsed electric field has been utilised to enhance mass transfer during the drying of fruits and vegetables (Ostermeier et al., 2018; Parniakov et al., 2016) and in osmotic treatments like salting or sugaring (Tylewicz et al., 2020; Yu et al., 2017). In these aforementioned food systems, cell membrane permeabilisation can be regarded as the mechanism through

which the cytoplasmic constituents (often regarded as secondary metabolites) can be released from inside the plant tissue into the external solution. This effect has been used in osmotic dehydration and drying applications, which observed enhanced water loss and solid gain corresponding to increased porosity and disruption of vacuoles (Kumari et al., 2018). However, PEF applications in low-sugar or brine-based systems, typically encountered in fermentation or traditional food preservation, have not received much attention (Kim et al., 2024).

Radish (*Raphanus sativus* L.) is a cruciferous vegetable conventionally utilised in the preparation of fermented foods such as kimchi and tsukemono. Its firm texture and homogeneous tissue architecture are strong arguments for its utility for the study of the mass transfer induced by PEF (Kim et al., 2024). Additionally, its high-water content and response to structural change enable the estimation of electroporation effects on diffusion kinetics and texture preservation.

The structural characteristics of radish tissues, including thick cell walls and low intercellular air space, offer a unique system for understanding how electric field intensity affects internal solute migration. Moreover, radish tissues provide a reproducible matrix for imaging techniques such as scanning electron microscopy (SEM) and dye-staining that visualise permeability changes and cell damage (Kim et al., 2024). These features make it a model crop for testing mild preservation interventions such as low-temperature salting, especially where excessive dehydration or shrinkage may negatively impact final product quality.

Three representative approaches, specifically Peleg's, Azuara's, and Crank's models, were employed to model NaCl and moisture diffusion in plant tissues. The Peleg model provides a straightforward empirical description of the initial diffusion rate and equilibrium conditions. The Azuara model provides a semi-empirical framework for estimating equilibrium parameters under concurrent water loss and solid gain. In contrast, the Crank model, based on Fick's second law of diffusion, enables mechanistic calculation of effective diffusion coefficients. These models have been successfully applied to mass transfer studies involving various fruits and vegetables, including apples (Derossi et al., 2008), kiwifruits (Prithani & Dash, 2020), carrots (Deshmukh et al., 2021), and potatoes (Mokhtar et al., 2019). Together, these empirical, semi-empirical, and mechanistic frameworks provide a comprehensive basis for evaluating bidirectional mass transfer in radish tissues.

This study aimed to evaluate how PEF-induced changes in radish tissue permeability influence the kinetics of NaCl and moisture mass transfer under isotonic and hypertonic salting conditions. By modelling diffusion behaviour using Peleg, Azuara, and Crank equations, and by analysing tissue permeability, shrinkage, and mechanical integrity, this research aims to explore the relationship between electroporation intensity and salting efficiency. The goal is to validate PEF as a scalable, nonthermal approach for enhancing brining performance in plant-based food systems without compromising structural quality.

Materials and methods

Sample preparation and PEF treatment

Fresh radish (*R. sativus* L.) was purchased from a local market and stored at 5 °C until use. Only the lower white portion of each radish was selected for uniformity, with the central xylem core removed to minimise variability in texture and structure. The selected sections were cut into cylindrical shapes (20 mm diameter × 50 mm length) with an average weight of 17.76 ± 0.22 g.

The PEF processing was carried out using a 5-kW power pulse generator-HVP-5 (DIL, Germany). The batch-type experiment was then conducted, keeping the parameters constant: field strength of 1.0 kV/cm, pulse width of 20 µs, and frequency of 50 Hz. The intensity of the treatment was varied by changing the number of pulses delivered: 50, 75, and 150 (designated as PN50, PN75, and PN150, respectively). Each sample was positioned vertically and centrally between parallel stainless-steel electrodes in the treatment chamber. The selected pulse numbers (50, 75, and 150) were based on preliminary experiments in which the Z-index was used to evaluate tissue permeability, providing distinguishable treatment intensities without inducing excessive structural damage. To minimise thermal effects and ensure consistency across treatments, the field strength (1.0 kV/cm), pulse width (20 µs), and frequency (50 Hz) were held constant.

Determination of cell membrane permeability

Electrical conductivity measurement

Cell membrane permeability was assessed by measuring the electric conductivity (σ) of each sample. Conductivity was calculated from admittance values obtained using an LCR meter (LCR-8000G; Instek, Taiwan) after PEF treatment. The term "LCR" denotes inductance (L), capacitance (C), and resistance (R). The LCR meter was connected to a batch chamber, following the protocol described by Jeong et al. (2023). Each sample's admittance was measured at a frequency range of 1.0 kHz–1.9 MHz and reported on a logarithmic scale. The electrical conductivity was calculated using Equation 1 (Angersbach et al., 1999):

$$\text{Electrical conductivity } \sigma \text{ (S/m)} = L \times Y \times \frac{1}{A} \quad (1)$$

where σ is conductivity (S/m), L is the sample length (mm), Y is admittance (mS), and A is the cross-sectional area (mm²) of the radish cylinder.

Specific energy input calculation

Specific energy input (kJ/kg) was calculated as:

$$W_{\text{spec}} = \frac{U \times I \times t_{\text{pulse}} \times n}{m} \quad (2)$$

where U is the applied peak voltage (V), I is the average current determined from tissue conductivity ($\sigma = 0.02$ S/m at 1 kHz) and effective electrode area (20 mm diameter, 3.14×10^{-4} m²), t_{pulse} is pulse width (20 µs), n is the pulse number, and m is the mass of sample (g).

Ion leaching measurement

Ion leaching was used as an indirect measure of membrane disintegration. Five radish cylinders were immersed in 500 ml of deionised water at room temperature. Conductivity of the surrounding solution was recorded at 30-min intervals over a 2-hr period using a conductivity meter (CM-21P; TOA-DKK, Tokyo, Japan).

Conductivity disintegration index (Z-index)

The Z-index quantifies the degree of cell membrane rupture. It was calculated using Equation 2 based on conductivity values at 1 kHz (Lebovka et al., 2002):

$$Z - \text{index} = (\sigma_t - \sigma_i) / (\sigma_f - \sigma_i) \quad (3)$$

where σ_t , σ_i , and σ_f are the conductivities of the PEF-treated sample, intact (control) sample, and fully disrupted (frozen-thawed) sample, respectively. Full disruption was achieved by freezing samples at -20°C for 24 hr and thawing at 5°C for another 24 hr.

Neutral red staining

Cell viability and membrane integrity were visualised using neutral red (NR) staining (Ersus & Barrett, 2010). In each radish sample, the peripheral and central regions were cut into 500 μm -thick sections with 8 mm diameter on a hand microtome (FB1262; Finn Science, Inc., USA). The dye solution was prepared from 0.5% aqueous neutral red (Atom Scientific, Ltd., UK) and 0.2 M mannitol–0.01 M HEPES buffer (Thermo Fisher Scientific, MA, USA) at pH 7.8, making up 0.04% dye solution. The slices were placed in the prepared dye and stained for 2 hr, then rinsed with the same buffer for 10 min. Micrographs were obtained from both outer and central regions of the radish tissue using a compound light microscope (CX22LED, Olympus, Japan).

Salting procedure and NaCl determination

Salting was performed by immersing individual radish cylinders in NaCl solutions at 1%, 5%, and 10% (w/v) concentrations in deionised water. The ratio of solid to liquid was maintained at 1 cylinder per 100 ml. Samples were kept at 5°C under static conditions for 12 hr, and brined samples were collected at 2-hr intervals. The NaCl content was determined using the Mohr titration method with AgNO_3 as the titrant.

Determination of mass transfer

Solid gain and moisture loss

Mass transfer was evaluated by calculating solid gain (SG) and moisture loss (ML) on a wet basis, as defined in Equations 3 and 4:

$$\text{SG}_{(g/gwb)} = \frac{W_{st} - W_{s0}}{W_0} \quad (4)$$

$$\text{ML}_{(g/gwb)} = \frac{W_{mt} - W_{m0}}{W_0} \quad (5)$$

where W_0 is the initial weight of radish, W_{st} represents the NaCl weight at time t , W_{s0} denotes the initial NaCl weight, W_{mt} signifies the moisture weight at time t , and W_{m0} symbolises the initial moisture weight.

Peleg's model

Peleg's model describes mass transfer kinetics on a dry basis (Peleg, 1988):

$$X_t = X_0 \pm \frac{t}{k_1 + k_2 \cdot t} \quad (6)$$

$$\frac{dX_t}{dt} = \frac{1}{k_1} \quad (7)$$

$$X_e = X_0 \pm \frac{1}{k_2} \quad (8)$$

where X_t represents the NaCl or moisture content (g/gdb) at time t , and X_0 denotes the initial NaCl or moisture content of fresh radish. For NaCl uptake, k_1 and k_2 are used as the Peleg rate ($\text{s} \cdot [\text{g/gdb}]^{-1}$) and capacity ($[\text{g/gdb}]^{-1}$) constants, respectively; for moisture loss, k_3 and k_4 serve as the corresponding constants. Specifically, k_1 and k_3 describe the initial rate of NaCl gain and moisture loss at $t=0$, respectively. X_e is the equilibrium NaCl and moisture content.

Azuara's model

Azuara's model, applied on a wet basis, was used to estimate equilibrium values and rate constants (Azuara et al., 1992):

$$\text{SG}_t = \frac{s_1 \cdot t \cdot \text{SG}_\infty \text{ or } \text{ML}_\infty}{1 + s_1 \cdot t} \quad (9)$$

$$\frac{t}{\text{SG}} = \frac{t}{\text{SG}_\infty} + \frac{1}{s_1 \cdot \text{SG}_\infty} \quad (10)$$

where SG_t and SG_∞ represent the solid gain at time t and at equilibrium, respectively. s_1 is the Azuara diffusion rate constant for solid gain. For moisture loss, the same equations apply by replacing SG with ML, and s_1 with s_2 , the corresponding diffusion rate constant.

Crank's model

Effective diffusivity (D^1) was determined using Crank's model based on Fick's second law for cylindrical geometry (Crank, 1979):

$$\frac{\text{SG or ML}}{\text{SG}_\infty \text{ or } \text{ML}_\infty} = 1 - \sum_{n=1}^{\infty} \frac{4}{(r^2 \alpha_n^2)} \exp(-D_e \alpha_n^2 t) \quad (11)$$

where r is the sample radius, and α_n represents the roots of the equation $J_0(r\alpha_n) = 0$, and $J_0(x)$ denotes the Bessel function of the first kind of order zero.

Kinetics analysis

Kinetic models were fitted using GraphPad Prism ver. 9.3 (GraphPad software, Boston, MA, USA). All models were fitted using time in seconds. Model performance was assessed using the coefficient of determination (R^2) and root mean square error (RMSE), calculated as:

$$R^2 = 1 - \frac{\sum_{i=1}^n (X_{\text{exp},i} - X_{\text{pre},i})^2}{\sum_{i=1}^n (X_{\text{exp},i} - \bar{X}_{\text{exp}})^2} \quad (12)$$

$$\text{RMSE} = \left[\frac{1}{Z} \sum_{i=1}^n (X_{\text{exp},i} - X_{\text{pre}})^2 \right]^{1/2} \quad (13)$$

Radish microstructure

Radish microstructure was analysed using SEM (S-3400 N; Hitachi, Japan). Freeze-dried samples were affixed to carbon tape, coated with Pt-Pb, and imaged at 100 $\times$ magnification.

Textural properties

A texture analyser (TAHDI/500; Stable Micro Systems, UK) with a blade probe was used to determine cutting force (N), measured as the maximum resistance during a 30 mm cut at 4 mm/s. Measurements were taken following PEF treatment and after 12 hr of brining to assess the impact of both processes on texture.

Measurement of volume shrinkage

Volume was calculated using the sample radius and length before and after salting. Volume shrinkage (%) was calculated using:

$$\begin{aligned} \text{Volume shrinkage (\%)} \\ = \frac{\text{initial volume (mm}^3\text{)} - \text{final volume (mm}^3\text{)}}{\text{initial volume (mm}^3\text{)}} \times 100 \end{aligned} \quad (14)$$

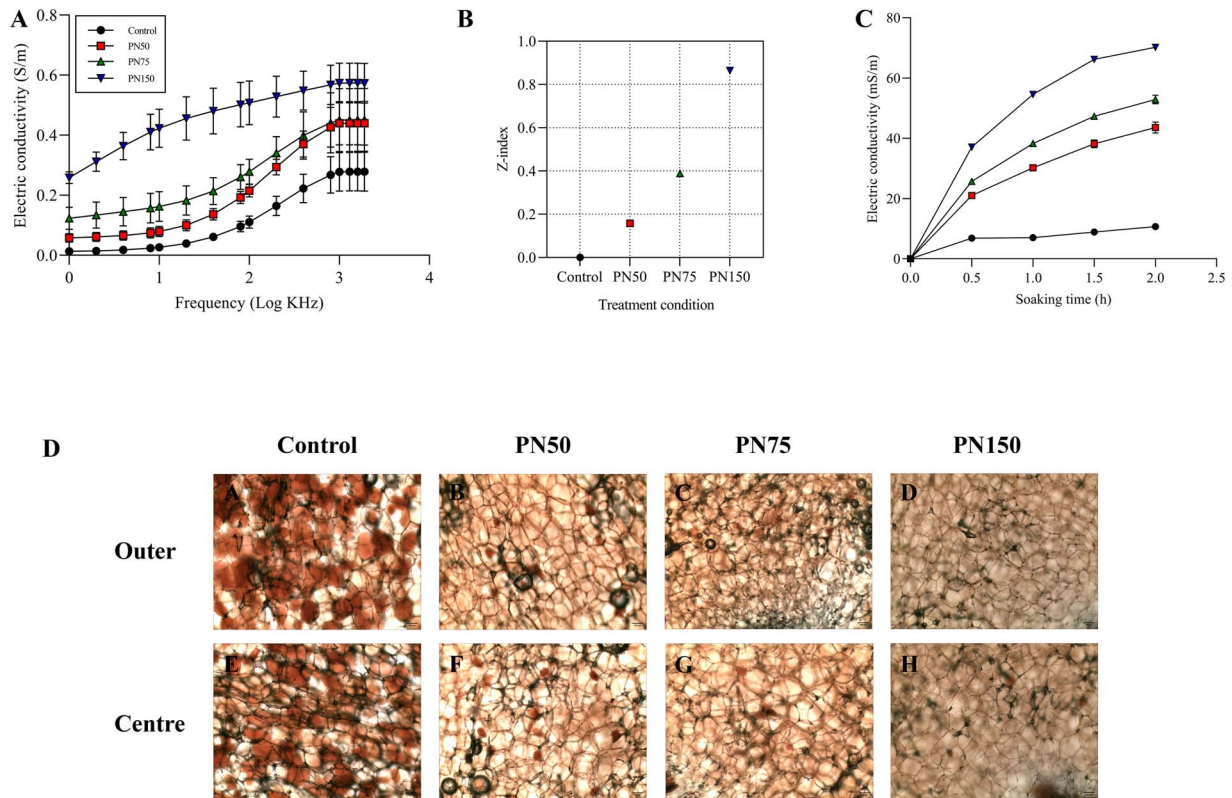


Figure 1. Cell membrane permeability of the control and PEF-treated radish. (A) Electric conductivity ($n=5$); (B) conductivity disintegration index (Z-index); (C) ion leaching ($n=3$); and (D) neutral red (NR) staining ($40\times$ magnification). The scale bar in the micrograph is $100\ \mu\text{m}$. Plots in (A) and (C) represent experimental data expressed as mean $\pm$ standard deviation. Plot (B) is based on Z-index calculations from data in (A).

Statistical analysis

All data were expressed as the mean $\pm$ standard deviation. Each experiment was performed in triplicate. One-way analysis of variance (ANOVA) and t-tests (SPSS v20, IBM, Armonk, NY, USA) were used to compare means; significance was set at $p < .05$, with Duncan's post hoc test applied where appropriate.

Results and discussion

Radish tissue permeability

Electrochemical properties

Radish tissue permeability was assessed using electrochemical properties (Figure 1). Electrical conductivity increased with PEF pulse number across the frequency range, indicating enhanced ion mobility due to membrane permeabilisation. The specific energy inputs for treatments PN50, PN75, and PN150 were calculated as 0.18, 0.27, and 0.53 kJ/kg, respectively, confirming that the treatments were applied within a low-energy, nonthermal range. As previously reported by Angersbach et al. (1999) and Dean et al. (2008), conductivity values are dependent on frequencies, with higher values at MHz frequencies for both intact and disrupted cells. The Z-index, calculated from conductivity values at 1 kHz, showed trends similar to conductivity, increasing with pulse intensity (Figure 1B), which indicates a proportional rise in cell disintegration.

This increased permeability reflects structural damage at the vacuolar and plasma membrane levels. In a previous study, ginseng tissues have been shown to undergo tonoplast and plasma membrane degradation (Kim et al., 2019). An increase in conductivity in ginseng tissue was reported following PEF application

at 3 kV/cm, indicating significant membrane disruption. The tonoplast disintegration initiates the degradation of the other organelles. Further breaking down of the membrane would allow moisture to undergo homogenisation, facilitating ion release. This was supported by increased ion leaching in PEF-treated samples (Figure 1C), confirming enhanced diffusion of ions into the extracellular space in contrast to the control samples, as reported by Genovese et al. (2023).

Microscopy of cell membrane permeability

Pulsed electric field affects membrane integrity, as indicated by NR staining (Figure 1D). The cells in the central and peripheral regions of the control tissues stained red because the dye was unable to remove the intact cells. There were no stained cells in PEF-treated samples (PN50 sample excluded). In contrast to the peripheral area, intact cells in the PN50 tissue were easier to see in the middle of the tissue. This outcome is explained by the fact that the PEF treatment (1.0 kV/cm, 50 pulses) does not generate enough energy to evenly destroy inner cells from the outer layer.

The heterogeneous cellular damage pattern is consistent with earlier findings that PEF sensitivity varies by cell size (Faridnia et al., 2015; López-Gómez et al., 2020). The NR-staining results, while indicative of membrane disruption, did not linearly reflect Z-index values, likely due to post-treatment staining artefacts and the progressive damage cascade during dye penetration. The NR-staining outcomes reflect the variability of PEF effects on heterogeneous tissue structures, influenced by cellular geometry and dielectric properties (Kotnik et al., 2015). While the Z-index and staining do not correlate perfectly due to post-treatment diffusion artefacts, both reveal progressive membrane degradation patterns.

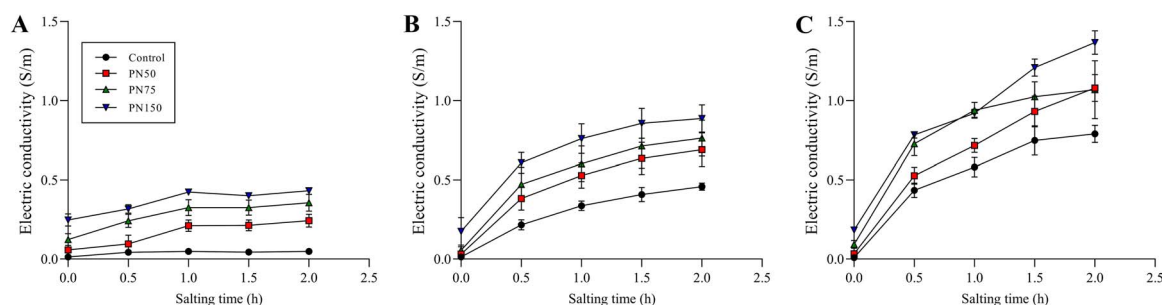


Figure 2. Change in electric conductivity of control and PEF-treated radish during the first 2 hr of brining across different NaCl concentrations. (A) 1% NaCl; (B) 5% NaCl; (C) 10% NaCl. Values are expressed as mean $\pm$ standard deviation ($n = 5$).

Mass transfer in radish tissue

Conductivity changes during salting

During early salting (0–2 hr), conductivity at 1 kHz increased with time and brine concentration, especially in PEF-treated samples (Figure 2). The 1% brine-treated control showed minimal conductivity change, suggesting limited ion diffusion due to isotonicity. In contrast, PEF-treated tissues exhibited continuous conductivity increase, signifying improved NaCl uptake. This effect has been previously documented by Kim et al. (2019), who showed that PEF-induced membrane damage resulted in the loss of cytoplasmic integrity and facilitates ionic exchange with the external medium. Parniakov et al. (2016) reinforced this by demonstrating conductivity increases in apple tissues under PEF, attributed to accelerated ion migration. The study reported a Z-index of ~ 0.98 , which indicated significant electroporation and showed that conductivity is a reliable quantitative marker of membrane disintegration.

At isotonic levels, the conductivity-based inference of NaCl diffusion is ambiguous due to comparable ionic strength between tissue and medium. Therefore, direct quantification of NaCl and moisture transfer was pursued.

Solid gain kinetics

The solid gain mass transfer kinetics were modelled by Peleg, Azuara, and Crank (Tables 1–3). Fresh radish in the 1% solution showed minimal mass transfer in Azuara's and Peleg's models, while mass transfer in the PEF-treated treatments demonstrated a linear connection. According to the facilitated rate at the isotonic level, the rate of NaCl absorption during initial salting was connected with k_1 . The k_1 values for PN150 and 1% control were 0.391×10^5 and 9.610×10^5 , respectively, suggesting that lower values indicate faster absorption.

Similarly, the diffusion rate-related s_1 values of 1% solution (1.681×10^5 – 14.42×10^5) showed a linear connection with PEF intensity. The concentration of the NaCl solution showed a similar upward trend. The action of PEF diminished as the concentration gradient widened. Following PEF treatment, the NaCl equilibrium concentration increased at each solution concentration and is associated with values of k_2 and SG_∞ . Under hypertonic conditions, the PEF-treated samples in Crank's model achieved their maximum $D_{e(SG)}$ values. Consistent with other models, the variations in solid gain kinetics decreased as the concentration gradient increased.

This observation is consistent with studies by Rahaman et al. (2019), who applied PEF to plum, and Li et al. (2021), who explored similar effects during the pickling of lotus roots. Both studies demonstrated improved solute diffusion as a result of electroporation-induced pore formation. Li et al. (2021)

reported that PEF pretreatment (10,000 pulses over 20 s at 0.5–1.5 kV/cm) increased the NaCl effective diffusion coefficient from 9.51×10^{-7} m²/s (control) to 17.42×10^{-7} m²/s in pickled lotus root. This, in turn, facilitated salt diffusion and water loss by disrupting cell structures and increasing membrane permeability.

Interestingly, the increase in solution concentration reduced the marginal benefit of PEF. This is due to the dominance of the osmotic gradient at higher NaCl levels, which tends to saturate transport mechanisms. As also reported by Wiktor and Witrowa-Rajchert (2020), mass transfer efficiency can plateau beyond a threshold, where osmotic forces override the mechanical enhancements from electroporation.

Even at low intensities, PEF treatment enhanced mass transfer in the current study. Mass transfer kinetics are increased by PEF intensity; however, under hypertonic conditions, the differences between the PEF-treated groups did not rise considerably. Changes in electrical conductivity throughout the early salting stages were followed by the results of $D_{e(SG)}$ (Figure 2). The permeability of the cell membrane controlled the mass transport during salting. According to its intensity, the PEF treatment increased the permeability. The strength of the PEF treatment allowed for the regulation of mass transfer with permeability level during the initial salting stage.

However, even with low-intensity PEF treatment, permeability increased gradually, which may have reduced the variance in the diffusion rate during salting (Suchanek & Olejniczak, 2018). R^2 and RMSE were used to assess the adequacy of Peleg's, Azuara's, and Crank's models. The best model was Azuara's (RMSE range: 0.000–0.002, R^2 range: 0.806–0.997). Since there is virtually no change in NaCl mass transfer at the isotonic level, the control sample's R^2 of 1% brine was the lowest of all the models.

Moisture loss kinetics

Among the three models tested, Azuara's model showed the best performance in describing moisture loss kinetics (RMSE range: 0.003–0.011, R^2 range: 0.713–0.995), validating its utility in dynamic salting conditions. Contrary to NaCl uptake, PEF-treated samples exhibited moderate moisture loss, particularly under hypertonic conditions. PN150 showed lower equilibrium moisture levels and higher mass transfer rates, reflecting its high Z-index and homogenous internal porosity. Moisture loss suppression in PEF-treated samples likely results from controlled pore formation, which maintains cellular hydration despite salt influx (Genovese et al., 2023). Notably, control samples in 1% brine showed the lowest Azuara s_2 values (2.586×10^{-5}), implying the greatest resistance to mass transfer and a slower approach to equilibrium

Table 1. Parameters of Peleg's model for solid gain and moisture loss with different PEF treatment and brine concentrations.

Brine conc.	Sample	Solid gain				Moisture loss			
		k_1 (s·(g/gdb) ⁻¹)	k_2 (g/gdb) ⁻¹	R^2	RMSE	k_3 (s·(g/gdb) ⁻¹)	k_4 (g/gdb) ⁻¹	R^2	RMSE
1%	Control	9.610×10^5	16.14	0.806	0.005	5.161×10^4	0.471	0.709	0.138
	PN50	1.165×10^5	5.255	0.955	0.010	0.259×10^4	1.250	0.885	0.099
	PN75	0.582×10^5	6.417	0.965	0.009	0.596×10^4	0.599	0.983	0.009
	PN150	0.391×10^5	5.653	0.948	0.013	0.438×10^4	0.658	0.927	0.131
5%	Control	2.017×10^4	3.026	0.990	0.011	1.429×10^3	0.118	0.994	0.184
	PN50	0.930×10^4	2.279	0.974	0.023	1.165×10^3	0.138	0.991	0.202
	PN75	1.766×10^4	1.656	0.966	0.032	1.684×10^3	0.174	0.985	0.203
	PN150	0.825×10^4	1.580	0.978	0.030	1.198×10^3	0.448	0.965	0.145
10%	Control	5.032×10^3	1.113	0.996	0.018	9.359×10^2	0.133	0.993	0.199
	PN50	4.148×10^3	1.014	0.984	0.041	8.474×10^2	0.123	0.992	0.226
	PN75	4.153×10^3	1.022	0.997	0.017	9.098×10^2	0.116	0.993	0.214
	PN150	4.924×10^3	0.767	0.995	0.028	9.458×10^2	0.308	0.961	0.220

Table 2. Parameters of Azuara's model for solid gain and moisture loss with different PEF treatment and brine concentrations.

Brine conc.	Sample	Solid gain				Moisture loss			
		s_1	SG_∞ (g/gwb)	R^2	RMSE	s_2	ML_∞ (g/gwb)	R^2	RMSE
1%	Control	1.681×10^{-5}	0.003	0.806	0.000	2.586×10^{-5}	0.046	0.814	0.004
	PN50	4.508×10^{-5}	0.008	0.955	0.000	64.08×10^{-5}	0.021	0.713	0.005
	PN75	11.02×10^{-5}	0.007	0.965	0.000	6.873×10^{-5}	0.061	0.966	0.003
	PN150	14.42×10^{-5}	0.008	0.948	0.001	44.86×10^{-5}	0.042	0.857	0.006
5%	Control	14.99×10^{-5}	0.015	0.990	0.000	7.565×10^{-5}	0.367	0.995	0.007
	PN50	24.54×10^{-5}	0.019	0.974	0.001	9.847×10^{-5}	0.290	0.987	0.010
	PN75	9.382×10^{-5}	0.027	0.966	0.001	8.567×10^{-5}	0.217	0.984	0.008
	PN150	19.17×10^{-5}	0.029	0.978	0.001	35.29×10^{-5}	0.056	0.903	0.006
10%	Control	2.214×10^{-4}	0.040	0.996	0.001	1.333×10^{-4}	0.294	0.989	0.009
	PN50	2.446×10^{-4}	0.044	0.984	0.002	1.280×10^{-4}	0.309	0.989	0.010
	PN75	2.463×10^{-4}	0.044	0.997	0.001	1.103×10^{-4}	0.337	0.990	0.010
	PN150	1.558×10^{-4}	0.058	0.995	0.001	4.564×10^{-4}	0.080	0.865	0.011

Table 3. Parameters of Crank's model for solid gain and moisture loss with different PEF treatment and brine concentrations.

Brine conc.	Sample	Solid gain			Moisture loss		
		$D_{e(SG)}$ (m ² /s)	R^2	RMSE	$D_{e(ML)}$ (m ² /s)	R^2	RMSE
1%	Control	3.304×10^{-10}	0.599	0.136	7.748×10^{-10}	0.312	0.775
	PN50	4.069×10^{-10}	0.653	0.126	11.64×10^{-10}	0.945	0.075
	PN75	6.330×10^{-10}	0.948	0.061	7.907×10^{-10}	0.748	0.130
	PN150	81.24×10^{-10}	0.927	0.081	11.63×10^{-10}	0.876	0.113
5%	Control	8.224×10^{-10}	0.839	0.122	5.979×10^{-10}	0.958	0.053
	PN50	6.930×10^{-10}	0.982	0.036	7.051×10^{-10}	0.961	0.054
	PN75	5.582×10^{-10}	0.961	0.077	6.292×10^{-10}	0.944	0.062
	PN150	11.81×10^{-10}	0.970	0.056	34.47×10^{-10}	0.943	0.086
10%	Control	7.295×10^{-10}	0.994	0.021	7.797×10^{-10}	0.982	0.039
	PN50	7.445×10^{-10}	0.977	0.043	8.169×10^{-10}	0.981	0.040
	PN75	7.580×10^{-10}	0.983	0.038	7.323×10^{-10}	0.981	0.039
	PN150	7.481×10^{-10}	0.992	0.025	20.27×10^{-10}	0.953	0.077

compared to the PEF-treated samples (Figure 3A). In contrast, PEF-treated tissues achieved equilibrium more efficiently. Although PN50 exhibited the highest s_2 value under 1% brine, this may be partially attributed to the model's sensitivity to low ML_∞ ,

rather than a direct reflection of enhanced diffusion. These results reflect the static salting condition used in this study, where permeabilised membranes may facilitate rapid moisture equilibration. However, under agitated conditions, mass transfer

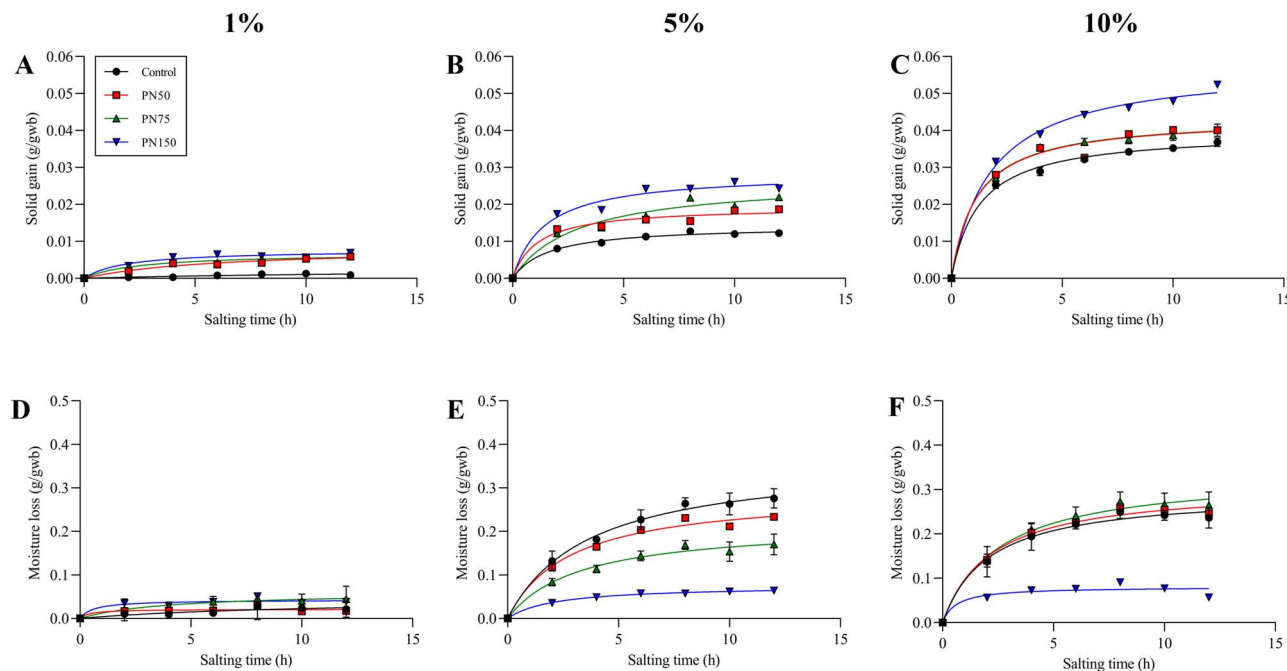


Figure 3. Solid gain and moisture loss (g/gwb) in control and PEF-treated radish at different brine concentrations over 12 hr. (A, D) 1% NaCl; (B, E) 5% NaCl; (C, F) 10% NaCl. Experimental data are shown as mean $\pm$ standard deviation ($n = 3$). Lines represent model predictions based on Azuara's model.

may be further enhanced due to reduced boundary resistance and stable osmotic gradients (Amami et al., 2005; Dermesonlouglou et al., 2018; Mari et al., 2024).

Microstructural and textural changes

Scanning electron microscopy imaging revealed that the microstructure of PN150 samples remained intact, while controls experienced substantial cell wall shrinkage under $> 5\%$ brine (Figure 4A). Pulsed electric field released turgor pressure without damaging the cell wall, in contrast to control tissues, where osmotic stress induced anisotropic shrinkage. Previous studies also confirm that PEF preserves wall structure (Kim et al., 2019; Oey et al., 2017).

Texture analysis showed that PN150 exhibited a significant reduction in cutting force (14.64 ± 2.35 N) compared to controls (41.63 ± 5.17 N). This was consistent across brine concentrations, suggesting that PEF-induced softening was primarily due to turgor loss rather than cell wall degradation. In controls, Na^+ displacement of Ca^{2+} in pectin likely increased solubility and texture deterioration (Kastner et al., 2020). Meanwhile, PN150 reached a mechanical plateau after PEF treatment, indicating stable texture postsalting. Interestingly, while PEF softened the texture, it prevented the extensive anisotropic collapse observed in controls, a phenomenon critical for maintaining product quality during mild processing. Studies in strawberry (Fauster et al., 2020) and sweet potato (Kim et al., 2023) showed that PEF forms microchannels while preserving the mechanical scaffold, thus enhancing mass transfer without compromising structure.

Fauster et al. (2020) showed that freeze-dried strawberries and bell peppers treated with PEF lost structural integrity up to 50% and firmness was reduced by 60%–70%, even at low energy inputs. These structural benefits resulted in improved homogeneity and mechanical stability, sustained during prolonged storage. Pulsed electric field-induced pore formation also assisted in moisture diffusion during freeze-drying, stabilising the internal structure, preventing collapse, and maintaining the structural properties.

A similar study by Lammerskitten et al. (2020) reported that PEF-assisted pretreatment in strawberries imparted increased tissue porosity and uniformity, directly affecting shrinkage patterns for fast drying. The study indicated that the spatially distributed microchannels facilitated balanced moisture removal, especially beneficial in the high-surface-area plant matrices. The PEF application was further demonstrated by Oey et al. (2017) in potato tissues, whereby PEF blocks the dehydration-initiated breakdown of microstructural integrity by preserving the cell wall scaffold while allowing cytoplasmic leakage. This dual effect prevented excessive collapse and irregular shrinkage, thus ensuring a more consistent product geometry, besides facilitating the maintenance of the sensory and textural traits of the product during salting and postprocessing processes like drying or storage. Collectively, these findings indicate that PEF treatment helps reduce shrinkage in radish and positively enhances the mechanical consistency of the dehydrated products.

Volume shrinkage postsalting

Visual and dimensional evidence suggested that treatment with PEF caused more cells to shrink regardless of whether they were placed under hypertonic conditions (Figure 5A). The control samples exhibited localised, directional shrinkage because of the nonuniform water loss and turgor collapse. On the contrary, the PN150 shrank uniformly. Previous work done in freeze-drying strawberries showed that PEF pretreatment formed a more uniform pore structure and lowered the amount of volume loss (Fauster et al., 2020; Lammerskitten et al., 2020).

In further research, Rahaman et al. (2019) showed that PEF pretreatment in plums not only accelerated moisture removal from drying but also produced low volumetric distortion during drying. Their findings suggested that electroporation provided microstructural stabilisation, thereby minimising tissue collapse, thereby increasing texture and rehydration properties of the product. These properties are particularly important in salt-preserved

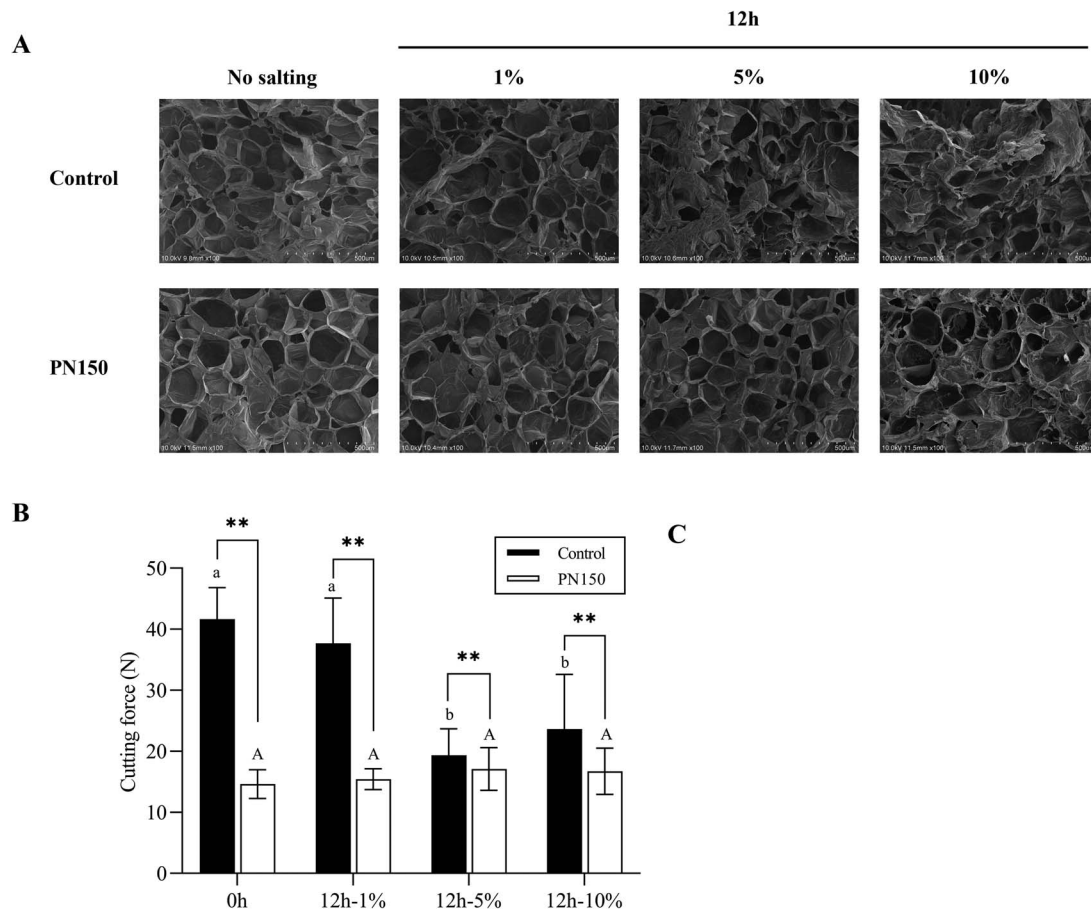


Figure 4. Microstructure (A) and cutting force (B) of radish samples (control and PN150) after 12 hr of brining at different NaCl concentrations. SEM images captured at 500 $\times$ magnification with a 500 μ m scale bar. Cutting force data are shown as mean $\pm$ standard deviation ($n=6$). Different letters indicate significant differences at $p < .05$. Asterisks (**) indicate significant differences between control and PN150 ($p < .01$) using Student's *t*-test.

products where tissue deformation may alter quality. Further evidence supporting these hypotheses was provided by Ostermeier et al. (2018), whereby application of PEF on onion was found to enhance uniform drying and minimise cracking due to moisture redistribution. This control over dehydration caused by increased membrane permeability and consequent softening of structure elevates the sensory and mechanical attributes of the vegetables.

Industrial relevance

Despite its demonstrated effectiveness at the laboratory scale, several practical considerations remain for industrial adoption of PEF technology, including equipment costs, energy consumption, and regulatory compliance. However, its successful integration into commercial potato processing lines highlights both the technical feasibility and operational benefits of PEF (Fauster et al., 2018; Hill et al., 2022). The ability of PEF to enhance membrane permeability without compromising structural integrity makes it particularly well suited for preprocessing steps such as washing and cutting. In this context, the improvements in permeability and mass transfer observed in radish tissues suggest that similar enhancements could be achieved in other vegetables subjected to brining or infusion. Provided that equivalent levels of electroporation can be maintained at scale, PEF treatment offers a promising, nonthermal strategy to improve salting efficiency and product quality across a range of plant-based food systems.

Conclusion

This study demonstrated that PEF treatment significantly enhanced the mass transfer kinetics of sodium chloride in radish tissues by increasing cell membrane permeability. The conductivity disintegration index (Z-index) correlated proportionally with pulse intensity, confirming the progressive structural disintegration that facilitated solute uptake. Kinetic modelling using Peleg, Azuara, and Crank equations revealed that Azuara's model best described the mass transfer behaviour, particularly under hypertonic conditions, with improved fits (R^2 up to 0.998, RMSE as low as 0.000). The effective diffusivity and diffusion rate constants increased with PEF intensity, confirming its role in accelerating salt penetration while controlling moisture migration.

Furthermore, PEF treatment allowed for rapid NaCl absorption under both isotonic and hypertonic conditions with minimal loss of tissue moisture. Structural assessments revealed that PEF preserved microstructural integrity and reduced volumetric shrinkage, supporting uniform dehydration and improved physical stability. Textural measurements showed that PEF-treated samples maintained mechanical integrity post-salting, indicating that softening was limited to turgor release without significant cell wall degradation.

These findings emphasise the role of PEF as a nonthermal, energy-efficient technology for enhancing salting efficiency in plant-based systems. It offers a promising approach to

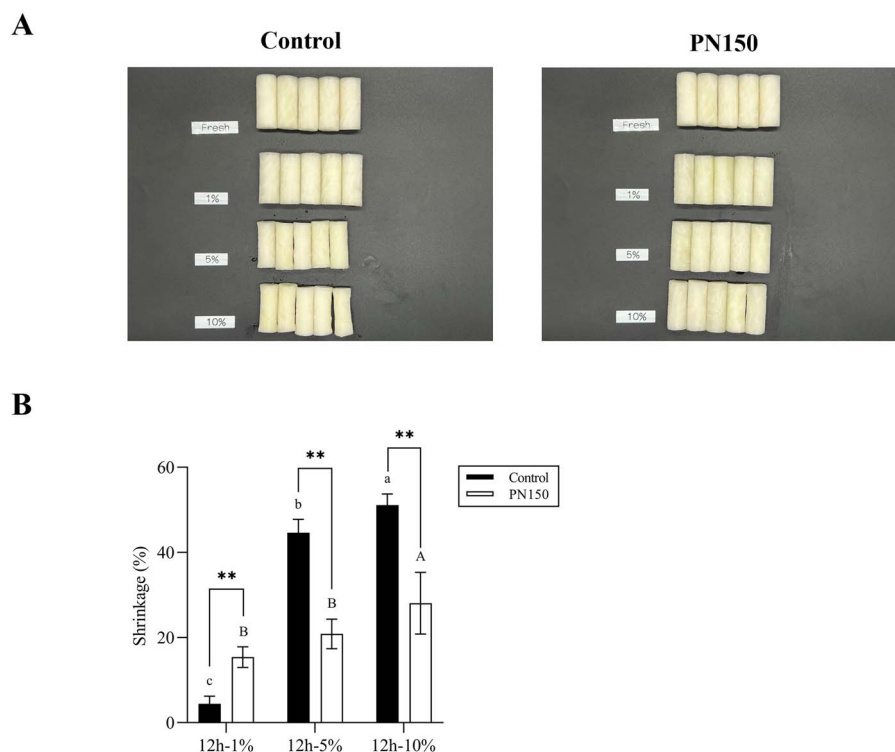


Figure 5. Visual appearance (A) and volume shrinkage (B) of radish samples (control and PN150) after 12 hr of brining across NaCl concentrations. Volume shrinkage data are expressed as mean $\pm$ standard deviation ($n = 3$). Different letters indicate significant differences at $p < .05$. Asterisks (**) denote significant differences between control and PN150 ($p < .01$) using Student's t -test.

balance rapid mass transfer with the preservation of sensory and structural quality. The present study was limited to radish tissues under fixed processing conditions, and further research is required to confirm the broader applicability of the findings to other plant matrices and industrial-scale operations. Nevertheless, the underlying principle of electroporation is inherently transferable to brining and infusion processes in a wide range of vegetables. Future investigations should focus on scale-up optimisation and explore the integration of PEF with complementary technologies such as fermentation, dehydration, and packaging, to enhance its industrial relevance and adoption.

Supplementary material

Supplementary material is available at *International Journal of Food Science and Technology* online.

Data availability

The dataset used and analysed in the current study is available from the corresponding author upon reasonable request.

Author contributions

Se-Ho Jeong (Conceptualisation, Data curation, Investigation, Writing—original draft, Writing—review & editing [lead]), Yang-An Kang (Formal analysis, Software, Validation, Visualisation [equal]), Jiyun Jung (Data curation, Writing—review & editing [equal]), Ki-Min Lee (Investigation, Visualisation [equal]), Hafiz Shahbaz (Formal analysis, Methodology, Writing—review & editing [equal]), Dong-Un Lee (Conceptualisation [lead], Funding acquisition [lead], Project administration [lead], Supervision [lead], Writing—review & editing [lead])

Funding

This work was supported by the Korea Institute of Planning and Evaluation for Technology in Food, Agriculture, Forestry (IPET) through the High Value-added Food Technology Development Program funded by the Ministry of Agriculture, Food, and Rural Affairs (MAFRA) (Grant No. 322018-04).

Conflicts of interest

None declared.

Acknowledgements

This research was supported by the Chung-Ang University Graduate Research Scholarship in 2024.

References

- Amami, E., Vorobiev, E., & Kechaou, N. (2005). Effect of pulsed electric field on the osmotic dehydration and mass transfer kinetics of apple tissue. *Drying Technology*, 23, 581–595. <https://doi.org/10.1081/DRT-200054144>
- Angersbach, A., Heinz, V., & Knorr, D. (1999). Electrophysiological model of intact and processed plant tissues: cell disintegration criteria. *Biotechnology Progress*, 15, 753–762. <https://doi.org/10.1021/bp990079f>
- Azuara, E., Cortés, R., Garcia, H. S., & Beristain, C. I. (1992). Kinetic model for osmotic dehydration and its relationship with Fick's second law. *International Journal of Food Science & Technology*, 27, 409–418. <https://doi.org/10.1111/j.1365-2621.1992.tb01206.x>
- Bhat, Z. F., Morton, J. D., Mason, S. L., & Bekhit, A. E.-D. A. (2019). Current and future prospects for the use of pulsed electric field

- in the meat industry. *Critical Reviews in Food Science and Nutrition*, 59, 1660–1674. <https://doi.org/10.1080/10408398.2018.1425825>
- Crank, J. (1979). *The mathematics of diffusion* (2nd ed.). Oxford: Clarendon Press.
- Dean, D., Ramanathan, T., Machado, D., & Sundararajan, R. (2008). Electrical impedance spectroscopy study of biological tissues. *Journal of Electrostatics*, 66, 165–177. <https://doi.org/10.1016/j.elstat.2007.11.005>
- Demir, E., Tappi, S., Dymek, K., Rocculi, P., & Galindo, F. G. (2023). Reversible electroporation caused by pulsed electric field—opportunities and challenges for the food sector. *Trends in Food Science & Technology*, 139, 104120. <https://doi.org/10.1016/j.tifs.2023.104120>
- Dermesonlouoglou, E., Chalkia, A., Dimopoulos, G., & Taoukis, P. (2018). Combined effect of pulsed electric field and osmotic dehydration pre-treatments on mass transfer and quality of air dried goji berry. *Innovative Food Science & Emerging Technologies*, 49, 106–115. <https://doi.org/10.1016/j.ifset.2018.08.003>
- Derossi, A., De Pilli, T., Severini, C., & McCarthy, M. (2008). Mass transfer during osmotic dehydration of apples. *Journal of Food Engineering*, 86, 519–528. <https://doi.org/10.1016/j.jfoodeng.2007.11.007>
- Deshmukh, S. D., Gabhane, S., & Deshmukh, D. S. (2021). Osmotic dehydration of carrot strips and modelling. *Journal of physics: Conference series* (p. 012093). IOP Publishing. <https://doi.org/10.1088/1742-6596/1913/1/012093>
- Ersus, S., & Barrett, D. M. (2010). Determination of membrane integrity in onion tissues treated by pulsed electric fields: use of microscopic images and ion leakage measurements. *Innovative Food Science & Emerging Technologies*, 11, 598–603. <https://doi.org/10.1016/j.ifset.2010.08.001>
- Faridnia, F., Burritt, D. J., Bremer, P. J., & Oey, I. (2015). Innovative approach to determine the effect of pulsed electric fields on the microstructure of whole potato tubers: Use of cell viability, microscopic images and ionic leakage measurements. *Food Research International*, 77, 556–564. <https://doi.org/10.1016/j.foodres.2015.08.028>
- Fauster, T., Giancaterino, M., Pittia, P., & Jaeger, H. (2020). Effect of pulsed electric field pretreatment on shrinkage, rehydration capacity and texture of freeze-dried plant materials. *LWT-Food Science and Technology*, 121, 108937. <https://doi.org/10.1016/j.lwt.2019.108937>
- Fauster, T., Schlossnikl, D., Rath, F., Ostermeier, R., Teufel, F., Toepfl, S., & Jaeger, H. (2018). Impact of pulsed electric field (PEF) pretreatment on process performance of industrial French fries production. *Journal of Food Engineering*, 235, 16–22. <https://doi.org/10.1016/j.jfoodeng.2018.04.023>
- Gao, X., Wang, Z., Sun, G., Zhao, Y., Tang, S., Zhu, H., & Li, Z. (2025). Pulsed electric field (PEF) technology for preserving fruits and vegetables: Applications, benefits, and comparisons. *Food Reviews International*, 1–26. <https://doi.org/10.1080/87559129.2025.2489754>
- Gavahian, M., & Farahnaky, A. (2018). Ohmic-assisted hydrodistillation technology: A review. *Trends in Food Science & Technology*, 72, 153–161. <https://doi.org/10.1016/j.tifs.2017.12.014>
- Genovese, J., Stručić, M., Serša, I., Novickij, V., Rocculi, P., Miklavčič, D., Mahnič-Kalamiza, S., & Kranjc, M. (2023). PEF treatment effect on plant tissues of heterogeneous structure no longer an enigma: MRI insights beyond the naked eye. *Food Chemistry*, 405, 134892. <https://doi.org/10.1016/j.foodchem.2022.134892>
- Hill, K., Ostermeier, R., Töpfl, S., & Heinz, V. (2022). *Pulsed electric fields in the potato industry*. Pulsed electric fields technology for the food industry: Fundamentals and applications: Springer. https://doi.org/10.1007/978-3-030-70586-2_9
- Jeong, S.-H., Jung, Y.-M., Kim, S., Kim, J.-H., Yeo, H., & Lee, D.-U. (2023). Tenderization of beef semitendinosus muscle by pulsed electric field treatment with a direct contact chamber and its impact on proteolysis and physicochemical properties. *Foods*, 12, 430. <https://doi.org/10.3390/foods12030430>
- Kastner, H., Einhorn-Stoll, U., Fatouros, A., & Drusch, S. (2020). Impact of sodium ions on material properties, gelation and storage stability of citrus pectin. *Food Hydrocolloids*, 104, 105750. <https://doi.org/10.1016/j.foodhyd.2020.105750>
- Kim, S.-Y., Gu, H. L., Ju, H., Jeon, J., Jeong, S.-H., & Lee, D.-U. (2024). Effects of pulsed electric fields on controlling fermentation rate of brined *Raphanus sativus*. *Innovative Food Science & Emerging Technologies*, 92, 103553. <https://doi.org/10.1016/j.ifset.2023.103553>
- Kim, S.-Y., Jeong, U.-C., Ju, H.-I., Jeong, S., & Lee, D.-U. (2023). Effect of pulsed electric field pretreatment on mass transfer during hot air drying: Drying and rehydration properties of sweet potato. *Innovative Food Science & Emerging Technologies*, 89, 103449. <https://doi.org/10.1016/j.ifset.2023.103449>
- Kim, Y.-N., Kwon, H.-J., & Lee, D.-U. (2019). Effects of pulsed electric field (PEF) treatment on physicochemical properties of Panax ginseng. *Innovative Food Science & Emerging Technologies*, 58, 102232. <https://doi.org/10.1016/j.ifset.2019.102232>
- Kotnik, T., Frey, W., Sack, M., Meglič, S. H., Peterka, M., & Miklavčič, D. (2015). Electroporation-based applications in biotechnology. *Trends in Biotechnology*, 33, 480–488. <https://doi.org/10.1016/j.tibtech.2015.06.002>
- Kumari, B., Tiwari, B. K., Hossain, M. B., Brunton, N. P., & Rai, D. K. (2018). Recent advances on application of ultrasound and pulsed electric field technologies in the extraction of bioactives from agro-industrial by-products. *Food and Bioprocess Technology*, 11, 223–241. <https://doi.org/10.1007/s11947-017-1961-9>
- Lammerskitten, A., Wiktor, A., Mykhailik, V., Samborska, K., Gondek, E., Witrowa-Rajchert, D., Toepfl, S., & Parniakov, O. (2020). Pulsed electric field pre-treatment improves microstructure and crunchiness of freeze-dried plant materials: Case of strawberry. *LWT-Food Science and Technology*, 134, 110266. <https://doi.org/10.1016/j.lwt.2020.110266>
- Lebovka, N., Bazhal, M., & Vorobiev, E. (2002). Estimation of characteristic damage time of food materials in pulsed-electric fields. *Journal of Food Engineering*, 54, 337–346. [https://doi.org/10.1016/S0260-8774\(01\)00220-5](https://doi.org/10.1016/S0260-8774(01)00220-5)
- Li, J., Shi, J., Wang, T., Huang, X., Zou, X., Li, Z., Zhang, D., Zhang, W., & Xu, Y. (2021). Effects of pulsed electric field pretreatment on mass transfer kinetics of pickled lotus root (*Nelumbo nucifera* Gaertn.). *LWT-Food Science and Technology*, 151, 112205. <https://doi.org/10.1016/j.lwt.2021.112205>
- López-Gámez, G., Elez-Martínez, P., Martín-Belloso, O., & Soliva-Fortuny, R. (2020). Enhancing phenolic content in carrots by pulsed electric fields during post-treatment time: Effects on cell viability and quality attributes. *Innovative Food Science & Emerging Technologies*, 59, 102252. <https://doi.org/10.1016/j.ifset.2019.102252>
- Mari, A., Parisouli, D. N., & Krokida, M. (2024). Exploring osmotic dehydration for food preservation: Methods, modelling, and modern applications. *Foods*, 13, 2783. <https://doi.org/10.3390/foods13172783>
- Mokhtar, W. M. F. W., Ghawi, S. K., & Niranjana, K. (2019). Dehydration of potato slices following brief dipping in osmotic solutions: Effect of conditions and understanding the mechanism of water loss. *Drying Technology*, 37, 885–895. <https://doi.org/10.1080/07373937.2018.1473418>
- Morales-De La Peña, M., Rábago-Panduro, L., Soliva-Fortuny, R., Martín-Belloso, O., & Welti-Chanes, J. (2021). Pulsed electric fields

- technology for healthy food products. *Food Engineering Reviews*, 13, 509–523. <https://doi.org/10.1007/s12393-020-09277-2>
- Oey, I., Faridnia, F., Leong, S. Y., Burritt, D. J., & Liu, T. (2017). *Determination of pulsed electric fields effects on the structure of potato tubers. Handbook of electroporation*. Cham: Springer.
- Ostermeier, R., Giersemehl, P., Siemer, C., Töpfl, S., & Jäger, H. (2018). Influence of pulsed electric field (PEF) pre-treatment on the convective drying kinetics of onions. *Journal of Food Engineering*, 237, 110–117. <https://doi.org/10.1016/j.jfoodeng.2018.05.010>
- Parniakov, O., Bals, O., Lebovka, N., & Vorobiev, E. (2016). Effects of pulsed electric fields assisted osmotic dehydration on freezing-thawing and texture of apple tissue. *Journal of Food Engineering*, 183, 32–38. <https://doi.org/10.1016/j.jfoodeng.2016.03.013>
- Peleg, M. (1988). An empirical model for the description of moisture sorption curves. *Journal of Food Science*, 53, 1216–1217. <https://doi.org/10.1111/j.1365-2621.1988.tb13565.x>
- Prithani, R., & Dash, K. K. (2020). Mass transfer modelling in ultrasound assisted osmotic dehydration of kiwi fruit. *Innovative Food Science & Emerging Technologies*, 64, 102407. <https://doi.org/10.1016/j.ifset.2020.102407>
- Rahaman, A., Siddeeg, A., Manzoor, M. F., Zeng, X.-A., Ali, S., Baloch, Z., Li, J., & Wen, Q.-H. (2019). Impact of pulsed electric field treatment on drying kinetics, mass transfer, colour parameters and microstructure of plum. *Journal of Food Science and Technology*, 56, 2670–2678. <https://doi.org/10.1007/s13197-019-03755-0>
- Suchanek, M., & Olejniczak, Z. (2018). Low field MRI study of the potato cell membrane electroporation by pulsed electric field. *Journal of Food Engineering*, 231, 54–60. <https://doi.org/10.1016/j.jfoodeng.2018.03.002>
- Tylewicz, U., Oliveira, G., Alminger, M., Nohynek, L., Dalla Rosa, M., & Romani, S. (2020). Antioxidant and antimicrobial properties of organic fruits subjected to PEF-assisted osmotic dehydration. *Innovative Food Science & Emerging Technologies*, 62, 102341. <https://doi.org/10.1016/j.ifset.2020.102341>
- Wiktor, A., & Witrowa-Rajchert, D. (2020). Drying kinetics and quality of carrots subjected to microwave-assisted drying preceded by combined pulsed electric field and ultrasound treatment. *Drying Technology*, 38, 176–188. <https://doi.org/10.1080/07373937.2019.1642347>
- Yu, Y., Jin, T. Z., Fan, X., & Xu, Y. (2017). Osmotic dehydration of blueberries pretreated with pulsed electric fields: Effects on dehydration kinetics, and microbiological and nutritional qualities. *Drying Technology*, 35, 1543–1551. <https://doi.org/10.1080/07373937.2016.1260583>