

Accelerated Quality-Retentive Radio Frequency Drying of Squid with Pretreatment

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Research Article

Keywords: squid, drying pretreatment, osmotic dehydration, pulsed electric field

Posted Date: August 6th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10537184/v1>

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Additional Declarations: No competing interests reported.

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Abstract

Squid is a highly perishable yet economically important seafood, and drying is an effective preservation method. Although hot-air-assisted radio frequency (HA-RF) drying can improve heating uniformity and accelerate surface moisture evaporation, the dense microstructure of squid muscle restricts moisture migration and RF energy coupling, potentially limiting drying efficiency. Selecting an appropriate pretreatment is therefore critical for optimizing HA-RF drying process. This study compared the effects of brining-induced osmotic dehydration, ethanol dehydration, and pulsed electric field (PEF) pretreatment on the drying kinetics and quality of squid subjected to HA-RF drying. Mass transfer during brining-induced osmotic dehydration stabilized after 4 h, while ultrasound-assisted ethanol dehydration reached equilibrium within 30 min. PEF at 20 pulses induced uniform micropores on the squid surface without excessive structural damage. Brined samples exhibited a near-zero drying rate below 1.56 g/g moisture content, limiting further moisture removal. Ethanol reduced the drying rate (0.84 g/(g.h)) compared with the untreated control (0.98 g/(g.h)), whereas PEF increased the rate to 1.12 g/(g.h). PEF-treated samples showed the smallest color change ($\Delta E = 20.95 \pm 1.85$), the highest rehydration capacity, and the lowest lipid oxidation ($TBARS = 0.53$ mg MDA/kg) among all groups. Microstructural analysis revealed that brining formed a dense surface salt crust hindering complete drying, ethanol caused noticeable tissue shrinkage, and PEF produced a porous, uniform microstructure without surface damage. These results demonstrate that PEF (20 pulses) offers optimum overall performance for enhancing HA-RF drying efficiency and

40 preserving squid quality, making it a suitable pretreatment for squid drying applications.

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42 ***Keywords:*** squid; drying pretreatment; osmotic dehydration; pulsed electric field

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1 Introduction

Squid is an economically important marine resource with substantial global market demand. Drying is an effective preservation method that enhances the value of squid products. Dried squid is particularly popular in Asian markets, including China, Japan, and South Korea, owing to its distinctive flavor and texture. Hot air drying remains the most widely adopted conventional technology for dried squid production. Although inexpensive, this method suffers from low thermal efficiency and, because squid muscle is rich in heat-sensitive components such as proteins and free amino acids, it is susceptible to quality degradation during prolonged thermal processing (Pankyamma et al., 2019). In conventional hot air drying, the inward heat flux opposes the outward moisture migration, rendering internal moisture diffusion the rate-limiting step (Srikiatden & Roberts, 2007). Emerging technologies such as microwave, radio frequency (RF), and infrared heating enable non-contact volumetric heating (Wang et al., 2023), each with distinct mechanisms suited to different food matrices (Shahriar et al., 2022). RF drying, in particular, operates by coupling electromagnetic energy with water molecules within the material, generating internal heat that drives moisture evaporation. Because RF energy penetrates deeply, it produces volumetric heating throughout the material (Skara et al., 2023), aligning heat and mass transfer in the same direction. This significantly reduces internal mass-transfer resistance and energy consumption compared with conventional heating (Mao & Wang, 2023), offering improved heating uniformity, higher drying efficiency, and better preservation of nutritional and sensory quality.

Despite the rapid volumetric heating effect of RF, auxiliary measures are needed to establish concentration gradients that accelerate moisture migration. To overcome the inherent limitations of RF drying while leveraging its advantages, RF is frequently combined with hot air (HA) assist to enhance moisture diffusion. Özbek (2021) reported that HA-RF drying (10 kW, 27.12 MHz) reduced carrot drying time by 45% compared with hot air alone (50 °C, 1.5 m/s), while the retention of beta-carotene, ascorbic acid, total phenolics, and antioxidant activity (80.26%, 45.33%, 72.42%, and 67.49%, respectively) approached those of freeze-dried samples (89.36%, 47.02%, 79.98%, 70.61%). Mahmood et al. (2022) found that the volumetric heating of HA-RF accelerated paddy drying; under optimal conditions, RF increased the drying rate by 62.5% relative to hot air alone, with only a marginal increase in the heating uniformity index (0.02) and a 13% reduction in the cracking rate. Research on RF drying of aquatic products remains limited. Cao et al. (2021) compared hot air and HA-RF drying of tilapia fillets and observed that the HA-RF drying rate was 1.1-1.4 times that of hot air alone, while the rehydration ratio increased by 0.3-3.1% and volume shrinkage decreased by 5.0-9.2%. A two-stage combined drying approach (HA-RF followed by cold-air RF) proposed by Zhang et al. (2025) achieved a drying rate of 0.77 g/(g·h) with a specific energy demand of 39.92 ± 2.67 kWh/kg, while color quality was retained as indicated by a browning index of 35.13.

To improve the color, sensory properties, and nutritional quality of dried products, various pretreatment strategies have been investigated prior to drying aquatic products, including osmotic dehydration, ultrasound, and pulsed electric field (PEF). Osmotic

dehydration is driven by the osmotic pressure differential between a hypertonic solution and the food tissue, effecting water removal coupled with controlled solute impregnation. This method is energy-efficient and capable of removing a fraction of the free moisture prior to the main drying stage, thereby reducing the subsequent drying load and duration while improving product structural integrity and rehydration capacity (Bekele & Ramaswamy, 2010). Ultrasound pretreatment generates strong shear forces and micro-jets through mechanical and cavitation effects, disrupting surface and internal tissue to form microscopic channels that reduce mass-transfer resistance and enhance moisture migration (Ruan et al., 2024). PEF pretreatment creates reversible or irreversible micropores in cell membranes via electroporation, substantially increasing membrane permeability (Lu et al., 2023) and accelerating moisture diffusion during subsequent drying (Punthi et al., 2022). Basak et al. (2023) reported that brine soaking (10-30%, w/v) combined with heating (60-90 °C) of sun-dried tilapia reduced final moisture content by 6.76% compared with the control, while preserving higher protein, total essential amino acid, and omega-3 polyunsaturated fatty acid levels; the 10% salt plus 75 °C treatment yielded the highest rehydration ratio (66.63%). Li et al. (2017) found that ultrasound-assisted osmotic dehydration of heat-pump-dried tilapia fillets under optimized conditions (400 W, 75 min) increased whiteness by 9.74%, Ca^{2+} -ATPase activity by 45.6%, and rehydration ratio by 109.3%, better preserved myosin integrity, and produced a softer, more palatable texture. Pérez-Won et al. (2023) showed that PEF combined with vacuum-microwave drying reduced Chilean abalone drying time by 67% relative to freeze-drying with PEF and by 83% relative to freeze-drying

alone, while also reducing hardness. Beno et al. (2023) demonstrated that PEF-induced electroporation formed micropores, increased membrane permeability, disrupted muscle fibers and connective tissue, and accelerated beef drying while improving tenderness (optimal: 0.75 kV/cm, 100 pulses). However, systematic investigations into the efficacy of these pretreatments for RF drying of squid are currently lacking.

Given the high moisture content and compact surface morphology of squid mantle, which restrict moisture migration and RF energy coupling, the present study evaluated three pretreatment strategies: osmotic dehydration (including brine immersion and ethanol dehydration) and PEF. Brining-induced osmotic dehydration exploits the osmotic pressure gradient between a hypertonic solution and the intracellular water pool to effect partial moisture removal while concurrently inducing structural modification. Ethanol dehydration, assisted by ultrasound, accelerates dewatering via cavitation-enhanced mass transfer permeability. PEF induces electroporation of cell membranes, creating micropores that increase tissue permeability and facilitate water diffusion. The objective of this study was to systematically compare the effects of these pretreatments on the drying kinetics and quality attributes of squid during subsequent HA-RF drying, thereby providing a theoretical basis and technical guidance for optimizing efficient, high-quality squid drying processes.

2 Materials and methods

2.1 Materials

Frozen equatorial squid (*Equatorial Loligo*) were purchased online from a seafood supplier in Lianyungang, Jiangsu Province, and transported to the laboratory

by courier. Upon arrival, samples were stored at -20 °C. Prior to each experiment, squid were thawed at 4 °C, decapitated, de-skinned, and cut along the midline of the mantle cavity to the tail tip to obtain symmetric fillets. After removing bones and viscera, the fillets were rinsed to eliminate dirt and mucus, and surface moisture was blotted with filter paper. The mantle was cut into pieces measuring $8.0 \times 8.0 \times 0.8$ cm (weight: 43.05 ± 4.37 g) for subsequent experiments.

2.2 Pretreatment experiments

2.2.1 Brining-induced osmotic treatment

Squid samples were immersed in a 200 g/L NaCl solution at a solid-to-liquid ratio of 1:10 (w/v) at 25 °C. Samples were withdrawn every hour from 0 to 6 h (six groups total). After weighing, the samples were oven-dried to constant weight to determine moisture content, water loss, and solid gain during brining-induced osmotic dehydration.

2.2.2 Ultrasound-assisted ethanol treatment

Squid samples were immersed in 250 mL of absolute ethanol in a beaker. To assist ethanol dehydration, the beaker was placed in an ultrasonic water bath operating at 40 kHz and 150 W (KQ3200E, Kunshan Ultrasonic Instruments Co., Ltd., China), with the bath temperature maintained at 25 °C by circulating water. Samples were withdrawn every 10 min, weighed, and oven-dried to constant weight to determine the moisture content, water loss, and solid loss.

2.2.3 Pulsed electric field (PEF) treatment

A custom-built PEF device (Yang et al., 2024) at Shanghai Ocean University was

used for pretreatment (Fig. 1). The upper and lower electrodes consisted of copper plates equipped with 20×20 tungsten needles for discharge, and the maximum output voltage was 18 kV. Squid samples were placed in a glass Petri dish (diameter 100 mm) inside the treatment chamber and exposed to PEF in air. The electrode gap was set to 1 cm and the voltage to 15 kV, yielding an electric field strength of 15 kV/cm. Samples were treated with 10, 20, 30, 40, or 50 pulses. Treated samples were subsequently used for drying experiments.

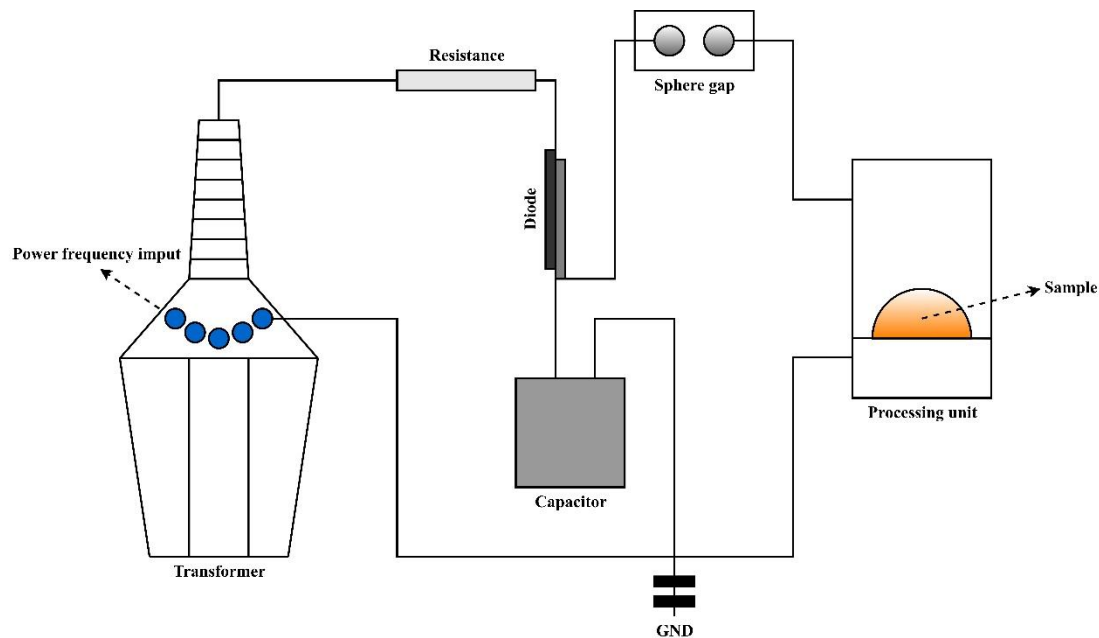


Fig. 1. Schematic diagram of the pulsed electric field (PEF) pretreatment device

(adapted from Yang et al., 2024)

2.3 Dielectric loss tangent measurement

The dielectric loss tangent $\tan \delta$ is a key parameter reflecting the ability of a material to absorb electromagnetic energy: a higher $\tan \delta$ indicates greater energy absorption and, consequently, more pronounced dielectric heating. Dielectric properties of squid samples before and after brining-induced osmotic dehydration at different

moisture contents and temperatures were measured using a vector network analyzer (N1500A E5071C, Agilent Technologies, Santa Clara, CA, USA) equipped with a high-temperature dielectric probe. Samples with varying moisture contents were ground into a paste or powder, loaded into sample holders, and compacted to eliminate air gaps and ensure intimate probe contact. Calibration was performed against air, a short circuit, and deionized water at 25 °C. Temperature was controlled with a water bath, and the dielectric properties of samples were captured immediately once the center temperature reached the target value. The dielectric loss tangent ($\tan \delta$) was calculated from the measured relative dielectric constant (ϵ') and dielectric loss (ϵ'') as follows:

$$\tan \delta = \frac{\epsilon''}{\epsilon'} \quad (1)$$

where $\tan \delta$ is the dielectric loss tangent (-), and ϵ' and ϵ'' are the relative dielectric constant and dielectric loss, respectively (-).

2.4 Drying experiments

Prior to HA-RF drying, the combined RF drying system (GZX-9076MBE, Shanghai Boxun Industrial Co., Ltd. Medical Equipment Factory, Shanghai, China) and hot-air convection system (GJD-12A-27-JY, Hebei Huashi Jiyuan High-Frequency Equipment Co., Ltd., Shijiazhuang, China) were preheated. The electrode gap was adjusted to 120 mm, and hot air preheated to 60 °C at 1 m/s was supplied. Once steady-state conditions were established, nine pretreated squid pieces were placed on a polypropylene mesh tray positioned in the center of the RF cavity. Three fiber-optic temperature probes were inserted into the geometric centers of representative samples to record real-time temperature profiles. Samples were weighed at hourly intervals

within 1 min of removal from the chamber and immediately returned; this cycle was repeated until the moisture content attained 0.25 ± 0.05 g/g (dry basis, d.b.).

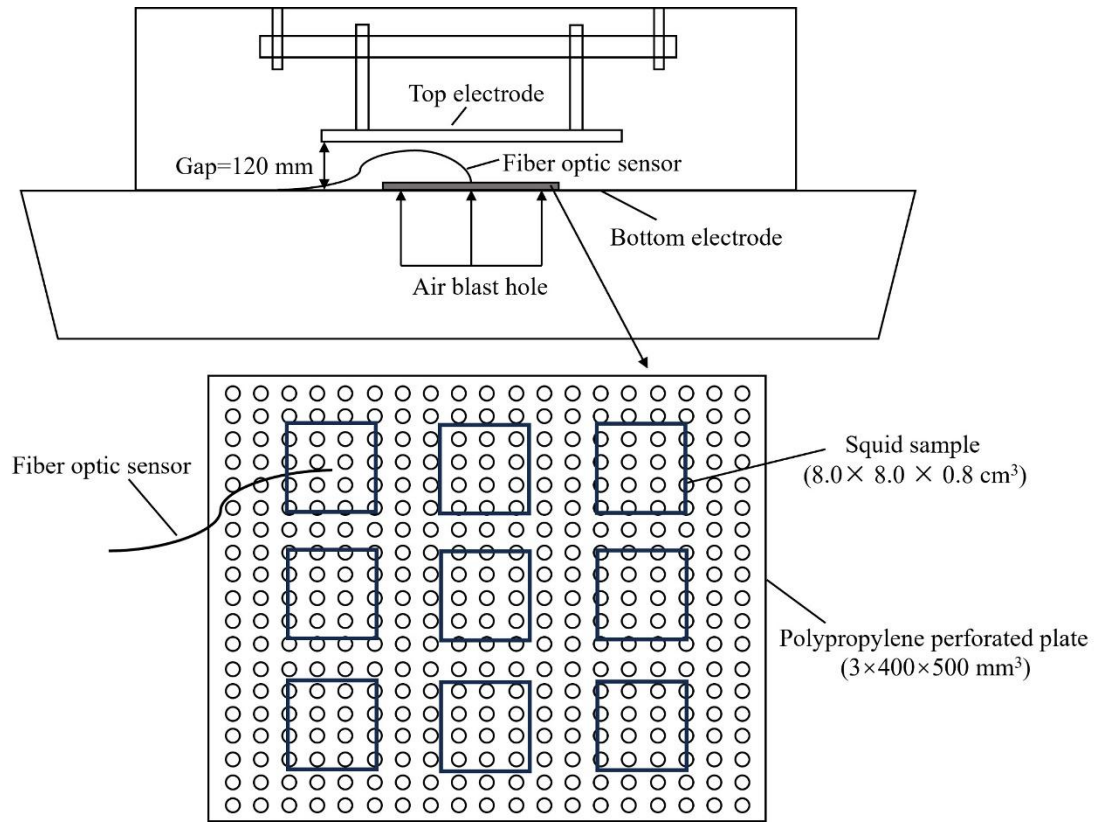


Fig. 2. Schematic diagram of radio frequency combined air drying equipment and the squid sample layout

2.5 Quality evaluation

2.5.1 Moisture content, water loss, solid gain/loss

The initial moisture content of squid samples was determined by the oven-drying method. The measured initial wet-basis moisture content was 77.7%, corresponding to a dry-basis moisture content of 3.48 ± 0.02 g water/g dry solid. The dry-basis moisture content at a given time during drying was calculated as:

$$M_t = \frac{W_t - W_{ds}}{W_{ds}} \quad (2)$$

where M_t is the moisture content at time t (d.b., g water/g dry solid), W_t is the weight of

the sample at time t (g), and W_{ds} is the dry solid content of the sample (g).

During brining-induced osmotic dehydration and ethanol immersion, the moisture content, water loss, and solid gain/loss of squid samples were measured over time to characterize the mass-transfer properties of the osmotic dehydration process and to determine the effective dehydration time. For brining-induced osmotic dehydration, samples were taken every 1 h; for ethanol immersion, samples were taken every 10 min for weight measurement. Water loss (WL), dry matter gain (DMG), and dry matter loss (DML) were calculated according to Zhou et al. (2021).

$$WL = \frac{(M_o - m_o) - (M_t - m_t)}{M_o - m_o} \quad (3)$$

$$DMG = \frac{m_t - m_o}{m_o} \quad (4)$$

$$DML = \frac{m_o - m_t}{m_o} \quad (5)$$

where WL , DMG , and DML are water loss, solid gain, and solid loss (%), respectively; M_o and M_t are the sample weights before and at time t (g); m_o and m_t are the dry matter weights before and at time t (g).

2.5.2 Microstructure

The surface microstructure of squid samples after PEF treatment at varying pulse numbers was examined using a scanning electron microscope (SU5000, Hitachi High-Technologies Corporation, Tokyo, Japan). Squid samples ($5 \times 5 \times 1$ mm) were excised from the same squid mantle region, fixed in 2.5% glutaraldehyde at 4 °C for 24 h, rinsed with 0.2 mol/L phosphate buffer (pH 7.5) and distilled water, dehydrated through a graded ethanol series, and freeze-dried (SCIENTZ-10N, Ningbo Xinzhi Biotechnology Co., Ltd., Ningbo, China). Dried squid samples were mounted on

aluminum stubs with double-sided conductive tape, sputter-coated with gold, and observed at an accelerating voltage of 10 kV at 1000× magnification.

The surface microstructure of dried squid after different PEF treatments and pretreatment combinations was also examined with the same equipment and procedure for comparison.

2.5.3 Color

Surface color characteristics of squid samples were measured using a colorimeter (CR-400, Konica Minolta, Osaka, Japan) before drying and after each pretreatment. The instrument was calibrated against a standard white plate prior to measurement. During each measurement, the sample surface was placed in firm contact with the colorimeter probe. Three replicate readings were recorded per sample, and the CIE L^* , a^* , and b^* values were obtained, where L^* denotes lightness (+white/−black), a^* denotes redness (+red/−green), and b^* denotes yellowness (+yellow/−blue). The total color difference (ΔE) was calculated using the following equation:

$$\Delta E = \sqrt{(L^* - L_0^*)^2 + (a^* - a_0^*)^2 + (b^* - b_0^*)^2} \quad (6)$$

where L_0^* , a_0^* , b_0^* and L^* , a^* , b^* are the color parameters of the samples before and after drying, respectively.

2.5.4 Rehydration ratio

Rehydration ratio (RR) was determined according to the method of Lewicki (1998). Dried squid samples from each pretreatment group were cut into $50 \times 50 \times 2 \text{ mm}^3$ pieces from the mantle portion and immersed in a water bath at $40 \pm 1 \text{ }^\circ\text{C}$ for 1 h. Samples were removed at 5, 10, 15, 20, 25, 30, 40, 50, and 60 min, briefly blotted to remove

surface water, and accurately weighed. *RR* was calculated using the following equation:

$$RR = \frac{M_f}{M_0} \quad (7)$$

where *RR* is the rehydration ratio (g/g), *M_f* is the mass of the rehydrated sample (g), and *M₀* is the mass of the dried sample prior to rehydration (g). A higher *RR* value indicates better product quality and greater similarity of the rehydrated product to the fresh sample.

2.5.5 Lipid oxidation

The thiobarbituric acid reactive substances (*TBARS*) value (expressed as mg MDA/kg) was used as an indicator of lipid oxidation during drying, storage, and processing. *TBARS* values of dried squid from each pretreatment group were measured using the thiobarbituric acid (TBA) method. A 2 g sample was homogenized with 10 mL of 7.5% (w/v) trichloroacetic acid (TCA) solution, incubated at 30 °C for 30 min, and then filtered. An aliquot of 2 mL of the filtrate was mixed with 2 mL of 0.02 mol/L TBA solution, heated at 90 °C for 40 min, and cooled to room temperature. The absorbance of the resulting solution was measured at 532 nm and 600 nm using a UV–Vis spectrophotometer (UV-1800, Shimadzu, Kyoto, Japan). The *TBARS* value was calculated using the following equation:

$$TBARS(mg\ MDA/kg) = \frac{(A_{532} - A_{600})}{155} \times \frac{1}{10} \times 72.6 \times 100 \quad (8)$$

where *A₅₃₂* and *A₆₀₀* are the absorbances at 532 nm and 600 nm, respectively; 155 is the molar extinction coefficient of the TBA-MDA complex; and 72.6 is a conversion factor.

2.6 Statistical analysis

All experiments were performed in triplicate. Data were processed and analyzed

using Excel and Origin 2023. One-way analysis of variance (ANOVA) followed by Duncan multiple-range test (SPSS 27, IBM) was used to evaluate significant differences in color and *TBARS* data ($p < 0.05$). Drying curves were fitted to mathematical models using MATLAB 2023, and goodness of fit was evaluated by the coefficient of determination (R^2), root mean square error (*RMSE*), and sum of squared errors (*SSE*).

3 Results and discussion

3.1 Effect of pretreatments on drying kinetics

3.1.1 Mass transfer during brining-induced osmotic dehydration

Fig. 3 presents the changes in moisture content, water loss, and solid gain of squid during brining-induced osmotic dehydration. Moisture content decreased progressively with brining-induced osmotic dehydration time, declining rapidly within the first 4 h and stabilizing at approximately 3.16 g/g thereafter. This initial steep reduction is attributable to the osmotic gradient driving water from the tissue interior toward the brine, with the system approaching osmotic equilibrium over time (Kroehnke et al., 2021). Water loss followed a similar trend, increasing sharply during the first 4 h before plateauing, consistent with the characteristic kinetics of osmotic dehydration: a large initial moisture gradient promotes rapid water migration, while the semipermeable nature of the cell membrane and the eventual equilibration of solute concentrations limit further dehydration. Solid gain increased with brining-induced osmotic dehydration time and also stabilized after 4 h, indicating that salt and other solutes had substantially completed their diffusion into the squid tissue by this point. Accordingly, 4 h was

identified as the optimal brining-induced osmotic dehydration time, providing adequate moisture removal to establish favorable pretreatment conditions for subsequent hot air-assisted radio frequency drying.

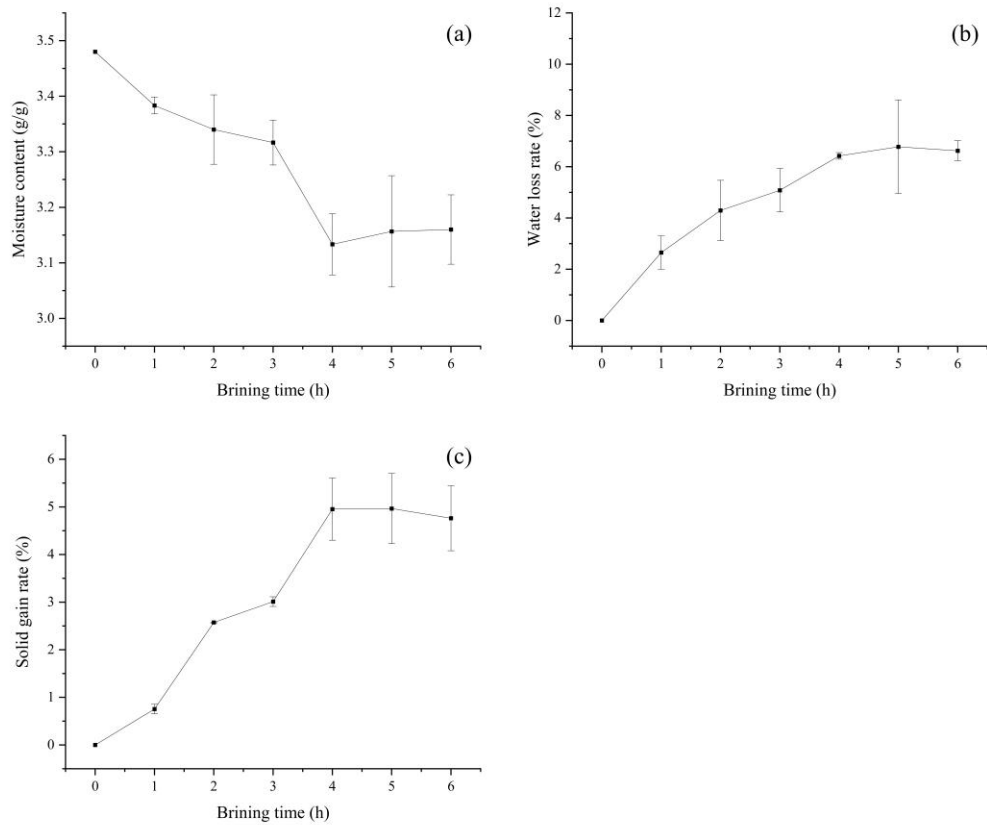


Fig. 3. Mass transfer characteristics of squid during brining: (a) Variation of water content. (b) Changes in water loss rate. (c) Changes in the rate of dry matter gain.

3.1.2 Mass transfer during ethanol treatment

Fig. 4 presents the changes in moisture content, water loss, and solid loss during ethanol treatment. Both ethanol alone and ultrasound-assisted ethanol treatments reduced moisture content more rapidly than brining-induced osmotic dehydration, with ultrasound assistance producing a faster initial decrease — likely attributable to cavitation-induced enhancement of cell wall permeability and accelerated dehydration.

Water loss increased sharply within the first 30 min before plateauing, indicating that the dehydration rate was highest during this initial window as the system approached osmotic balance. Ultrasound-assisted ethanol treatment yielded slightly higher water loss than ethanol alone, consistent with previous findings that ultrasound enhances ethanol-driven dehydration (Zhou et al., 2021). Solid loss increased within the first 10 min and stabilized after 30 min; notably, ultrasound-assisted treatment resulted in lower solid loss than ethanol alone, suggesting that ultrasound promoted water migration while reducing excessive dry matter loss, thereby helping to preserve product quality. Based on these results, 30 min of ultrasound-assisted ethanol treatment was selected as the optimal condition, reducing moisture content to 2.78 g/g within a relatively short time.

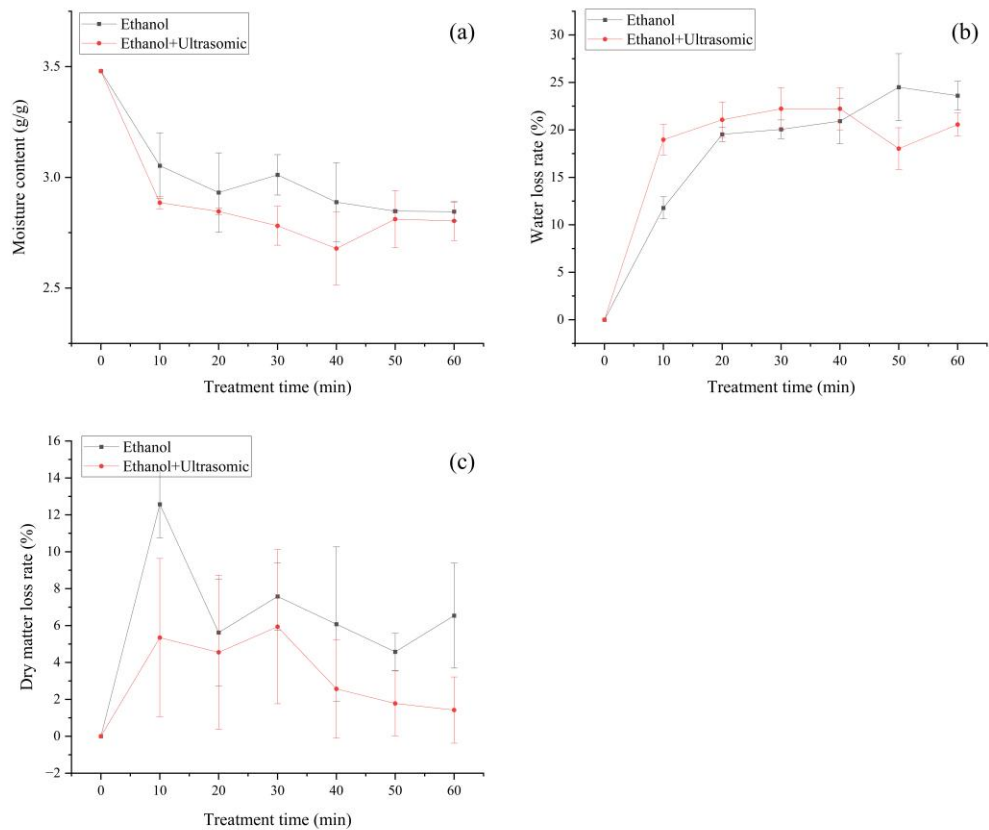


Fig. 4. Mass transfer characteristics of squid during ethanol treatment: (a) water content; (b) water loss rate; (c) dry matter loss rate.

3.1.3 Effect of PEF on surface structure

Fig. 5 presents the surface microstructure of squid after PEF treatment with varying pulse numbers. The untreated squid exhibited a dense surface with tightly packed muscle fibers and virtually no visible pores. As the pulse number increased, small pores gradually emerged and the tissue structure became looser. After 20 pulses, numerous uniformly distributed pore channels were formed, indicating that PEF induced electroporation of cell membranes, which facilitated water diffusion capacity in the tissue. Llavata et al. (2025) similarly observed electroporation and extensive pore formation on pumpkin cell membranes at appropriate PEF treatment levels. However, at 30, 40, and 50 pulses, the surface structure was severely damaged — large pores, tissue collapse, and extensive fractures were evident — suggesting that excessive PEF intensity may cause irreversible cell membrane damage and disruption of myofibrillar structure, potentially compromising the quality of the dried product. Trusinska et al. (2023) also reported greater tissue damage in apple samples treated with higher electric field intensities. Balancing the promotion of moisture migration against structural integrity, 20 pulses was selected as the optimal PEF pretreatment condition, as it effectively increased cell membrane permeability and facilitated moisture diffusion without inducing excessive structural damage.

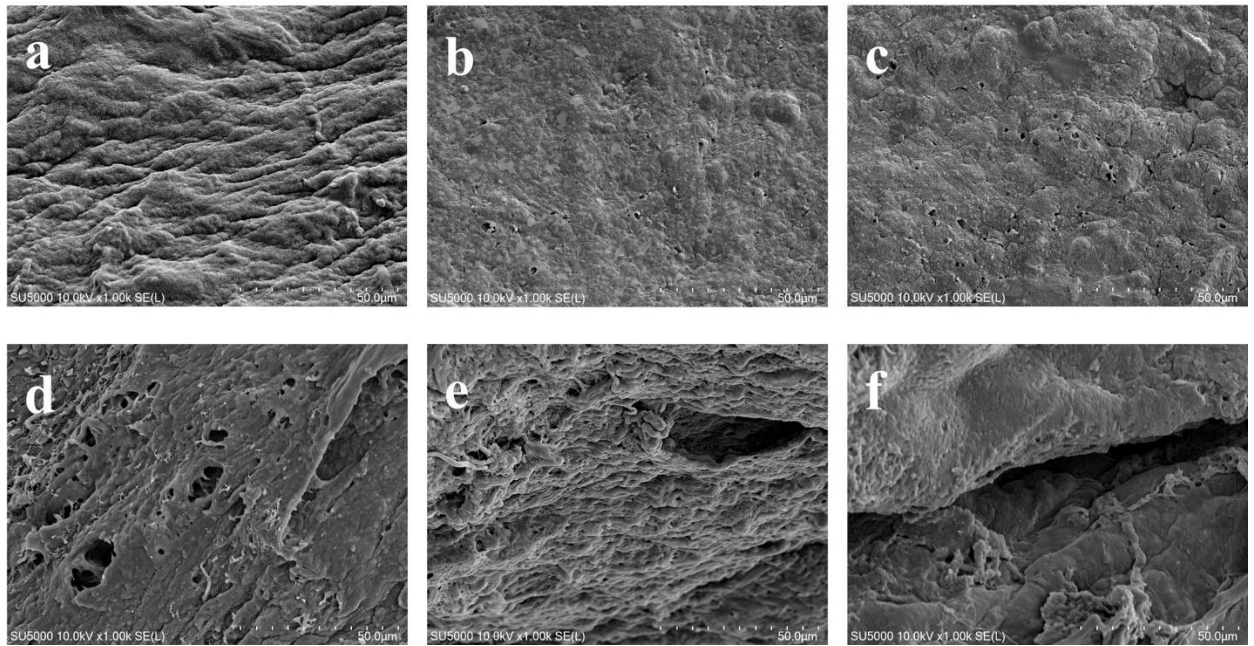
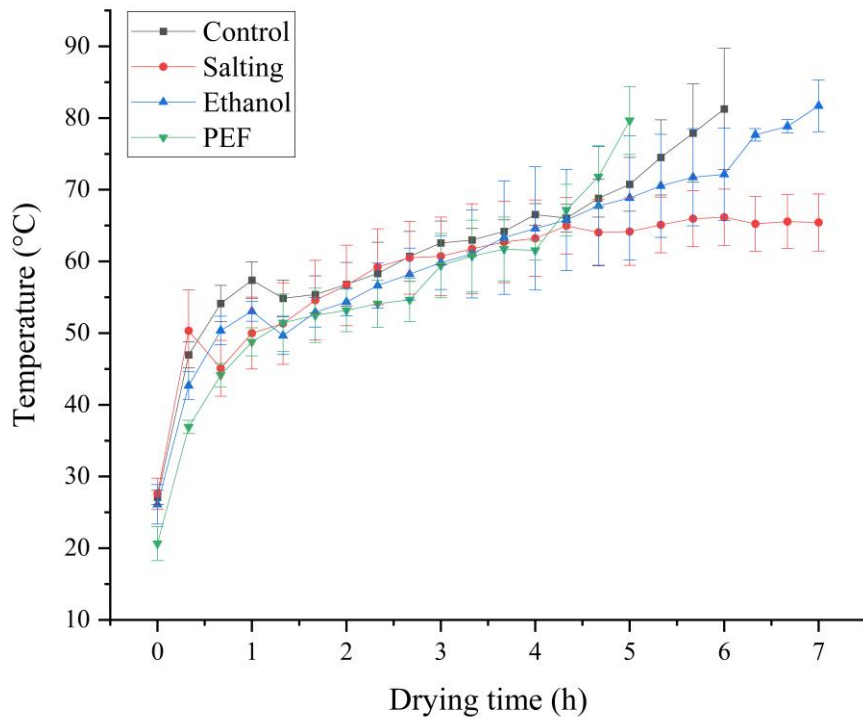


Fig. 5. Microstructures of the surface of squid before and after pulsed electric field treatment. a. Raw squid. b-f: Squid after 10, 20, 30, 40, and 50 pulses PEF treatment, respectively.

3.1.4 Temperature-time curve during drying

Fig. 6 presents the time–temperature profiles of squid during hot air-assisted radio frequency drying after different pretreatments. The heating rate varied markedly with pretreatment type. During the initial stage, the control and ethanol-treated groups exhibited relatively rapid temperature increases, likely because ethanol treatment did not substantially alter the thermal conduction properties of the tissue, allowing the radio frequency field to continue heating the sample interior efficiently. The brined group, by contrast, showed a slower heating rate, which may be attributable to the formation of a surface salt crust that hindered moisture evaporation and thus suppressed temperature rise. As drying progressed, the temperature curves of all groups gradually plateaued, indicating that the rates of surface evaporation and internal moisture diffusion had

352 reached a dynamic equilibrium, maintaining a relatively stable temperature without
 353 further increase. During the later stage, the brined group remained at approximately
 354 60 °C, whereas the temperature of the other groups rose again. This divergence can be
 355 attributed to two factors: the altered dielectric properties of the brined tissue and the
 356 barrier effect of the surface salt layer, which together limited further moisture
 357 evaporation and heat accumulation. In contrast, the control, ethanol-treated, and PEF-
 358 treated groups retained stronger moisture migration capacity, enabling continued
 359 evaporation and progressive heat accumulation from the radio frequency field, thereby
 360 driving the sample temperature higher.



361
 362 **Fig. 6.** Time-temperature curves for the process of drying squid after different
 363 pretreatments

364 3.1.5 Drying kinetics after pretreatments

Fig. 7 presents the drying curves of squid during hot air-assisted radio frequency drying after different pretreatments (brining, ethanol, and PEF). The initial moisture content of the PEF-treated and control samples was comparable, whereas the brined and ethanol-treated groups started from a lower initial moisture content as a result of osmotic dehydration during each respective pretreatment.

The drying behavior differed markedly across groups. The brined samples dried to 1.56 g/g after 3 h, after which the curve plateaued — the sample temperature stabilized at approximately 60 °C (Fig. 6) and further moisture removal was severely impeded. To elucidate this phenomenon, the dielectric loss tangent ($\tan \delta$) of brined and untreated squid was measured (Fig. 8). The $\tan \delta$ of the brined group was approximately two-fold lower than that of the untreated group. $\tan \delta$ reflects the ability of a material to absorb radio frequency energy: higher values indicate stronger coupling with the RF field and more efficient conversion of RF energy into heat, thereby accelerating moisture evaporation (Lei et al., 2024). At 60 °C, the $\tan \delta$ of the brined group decreased markedly once the moisture content fell below 1.5 g/g, indicating that the RF energy coupling capacity was substantially diminished, further limiting moisture migration. Consequently, beyond 1.5 g/g moisture content, the absorbed RF energy was insufficient to raise the sample temperature above 60 °C and could not provide the thermal driving force needed to evaporate the remaining water, effectively arresting further drying. Concurrently, as drying progressed, surface moisture evaporation intensified, leading to salt accumulation on the surface and the formation of a dense “salt crust” (Fig. 10). This crust not only reduced the number of surface moisture

diffusion pathways but also altered the moisture gradient between the surface and interior, hindering further water migration from the inner tissue. In combination, the reduction in RF energy coupling caused by the decreased $\tan \delta$ and the barrier effect of the salt crust prevented the brined samples from reaching the target moisture content after the 1.5 g/g threshold.

For the ethanol-treated group, the total drying time was 1 h longer than that of the untreated control. This may be attributable to ethanol-induced contraction of the protein structure, which reduced the moisture diffusion pathways within the tissue and consequently lowered the drying rate.

The PEF-treated group required the shortest drying time (5 h), likely because electroporation enhanced cell membrane permeability, facilitating moisture diffusion and enabling more efficient water removal under RF heating. Kim et al. (2023) reported that PEF pretreatment reduced hot-air drying time by 16% in sweet potatoes, with higher PEF intensity associated with faster water removal from intercellular spaces and shorter processing times. Beno et al. (2023) similarly found that PEF pretreatment positively influenced the drying rate of beef mince: after 2 h of drying, samples treated with 100 pulses showed an 18% increase in water evaporation.

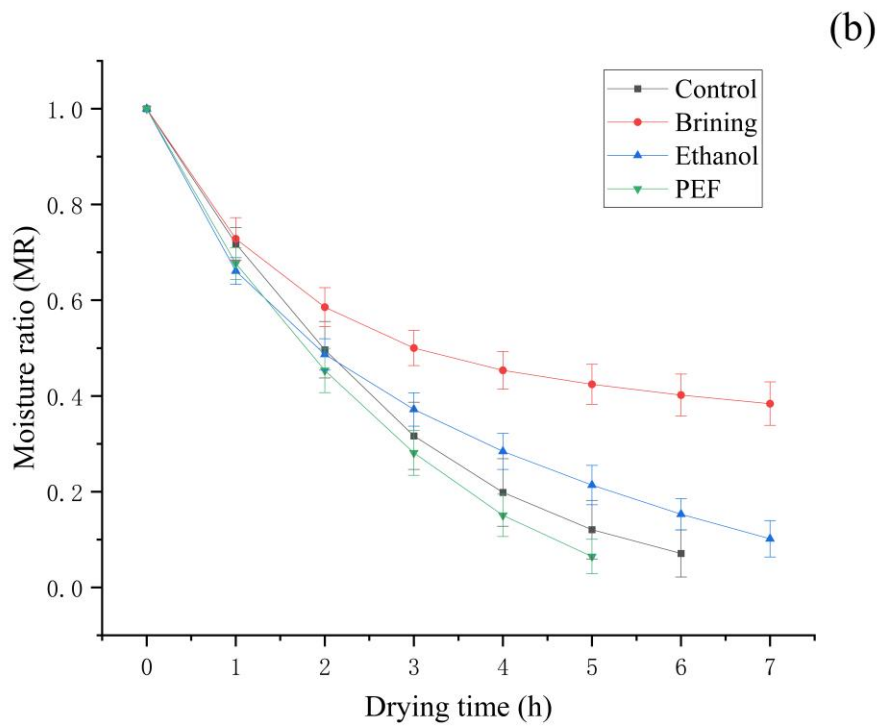
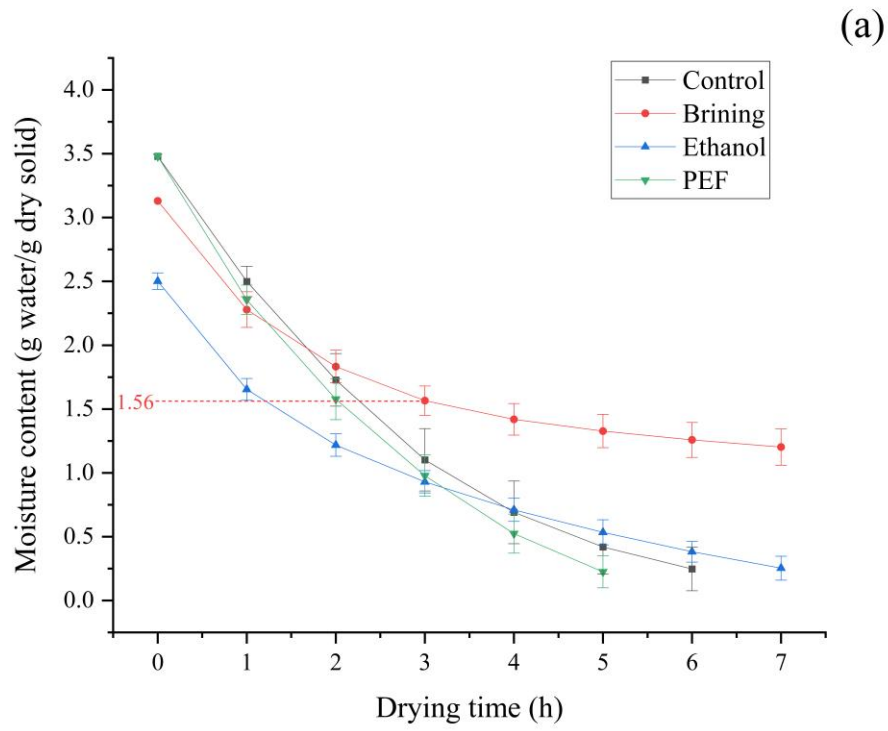


Fig. 7. Drying curves of squid in hot air assisted RF drying after different pretreatments: (a) Drying curve, (b) Moisture ratio.

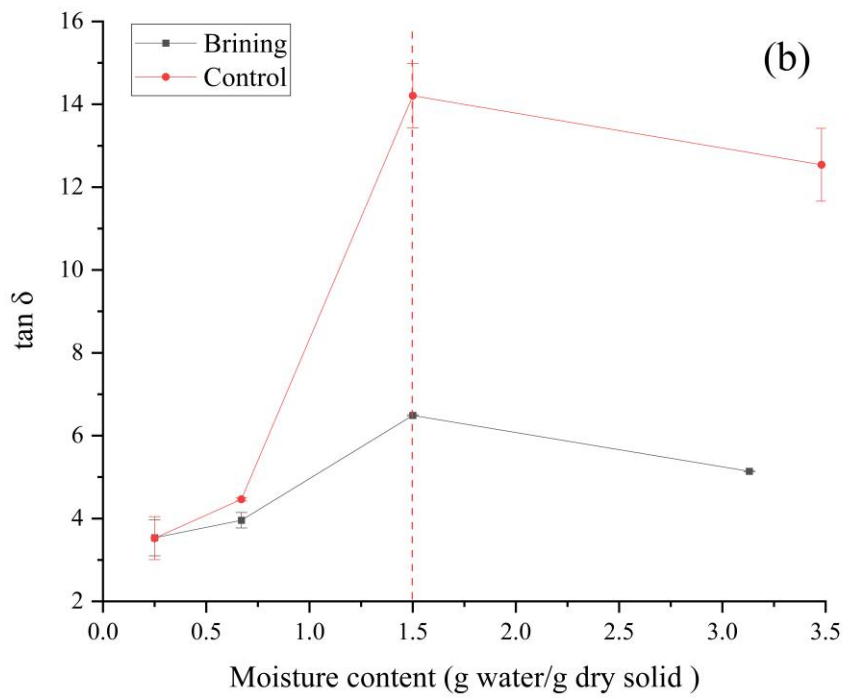
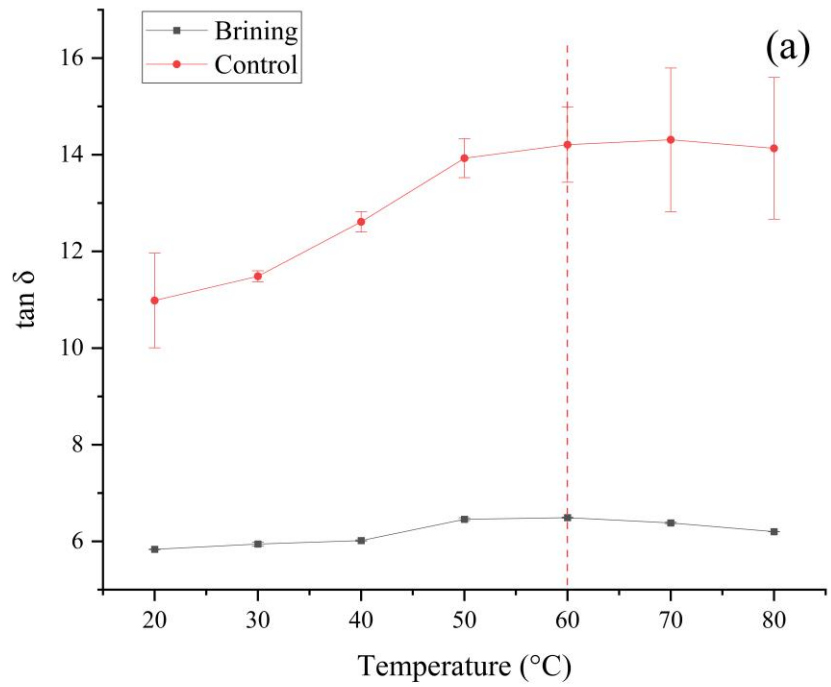
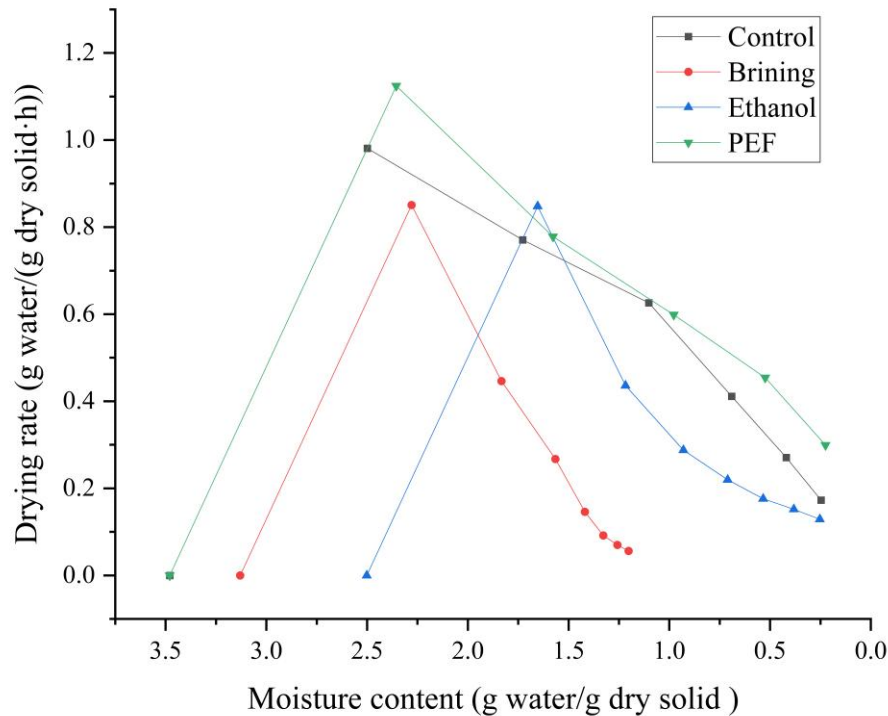


Fig. 8. Effect of osmotic dehydration using brine on the tangent of the dielectric loss angle of squid: (a) Variation of $\tan \delta$ with temperature for squid at 1.5 g/g moisture content, (b) Variation of $\tan \delta$ of squid with moisture content at 60 °C.

Fig. 9 presents the drying rate as a function of moisture content for squid subjected to different pretreatments. In the control group, after reaching a peak, the drying rate declined through two distinct stages: a gradual initial decrease followed by a rapid drop. All three pretreatments altered this pattern, reducing the drying process to a single falling-rate period after the peak, suggesting that each pretreatment modified the moisture diffusion kinetics of the tissue and thereby eliminated the rate transition. The PEF-treated group exhibited the highest peak drying rate ($1.124 \text{ g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$) and maintained a consistently faster drying rate throughout the process, likely attributable to enhanced cell membrane permeability and reduced internal resistance to moisture diffusion. The drying rate of the PEF-treated samples decreased smoothly without a segmented pattern, indicating that PEF may have improved drying uniformity and sustained continuous moisture migration. The ethanol-treated group and the brined group showed similar peak drying rates of $0.848 \text{ g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$ and $0.850 \text{ g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$, respectively — both lower than that of the control group ($0.980 \text{ g}\cdot\text{g}^{-1}\cdot\text{h}^{-1}$) — and their rates declined more rapidly. For the ethanol group, this may reflect ethanol-induced protein denaturation that, while enhancing initial surface evaporation, ultimately compromised internal tissue integrity and reduced moisture transport capacity in the later stages. For the brined group, the drying rate approached zero once the moisture content fell below 1.5 g/g , further supporting the role of the salt crust barrier in impeding moisture diffusion and forcing an early transition to a low-rate phase. Collectively, these results indicate that pretreatment type not only governs initial drying efficiency but also shapes the entire drying kinetics profile by modifying tissue

433 structure and moisture diffusion characteristics.



434
435 **Fig. 9.** Drying rate of squid after different pretreatments

436 Five mathematical models — Lewis, Henderson and Pabis, Logarithmic, Page,
437 and Jena — were fitted to the moisture ratio curves of squid dried after different
438 pretreatments (Fig. 7b). The Lewis model is a simple exponential decay function that
439 assumes a constant drying rate. The Henderson and Pabis model introduce a correction
440 coefficient a to improve fitting accuracy. The Logarithmic model adds an offset
441 parameter b to accommodate more diverse drying curve shapes. The Page model
442 incorporates an exponent n to better describe moisture diffusion behavior during the
443 falling-rate period. The Jena model further extends Page by adding a square-root term
444 and an offset, making it more suitable for complex, multi-stage drying processes.

445 Table 1 summarizes the fitted parameters and goodness-of-fit statistics for all

models. The rate parameter k was influenced not only by model structure but also by the experimental conditions. For the Lewis and Henderson and Pabis models, k primarily reflects the overall exponential decay rate with minimal correction parameters, and therefore aligns more closely with the experimentally observed drying rate: the PEF-treated group showed the highest k values (0.4311 and 0.4388), the brined group the lowest (0.1847 and 0.1564), consistent with their respective drying curves. For the Logarithmic model, k may be over- or underestimated, complicating direct interpretation. In the Page model, k was confounded by the exponent n and thus cannot be used alone as a rate indicator. Similarly, the k of the Jena model, affected by the square-root term, is not directly comparable across groups. Additionally, the initial moisture contents of the brined and ethanol-treated groups differed from those of the control and PEF-treated groups owing to osmotic dehydration during pretreatment. Although the ethanol-treated group reached the target final moisture content, its terminal moisture ratio was relatively high, which may have affected the k fitting. For the brined group, drying effectively ceased at 1.2 g/g moisture content because of the reduced $\tan \delta$ and the salt crust barrier, resulting in an incomplete drying curve that may have narrowed the fitting range and led to overestimation of k .

To identify the optimal model, the coefficient of determination (R^2), root mean square error ($RMSE$), and sum of squared errors (SSE) were compared. The Lewis and Henderson and Pabis models yielded relatively low R^2 values (0.8531–0.9949), indicating limited fitting quality. In contrast, the Logarithmic, Page, and Jena models all achieved $R^2 > 0.99$. The Jena model exhibited the highest fitting accuracy but

introduced more parameters, increasing computational complexity and limiting practical applicability. Balancing fitting accuracy, parameter stability, and computational simplicity, the Page model was selected as the most suitable for describing the drying kinetics of squid, offering high precision while remaining straightforward to apply for predicting drying curves after pretreatment. Kim et al. (2023) also successfully used the Page model to describe the drying behavior of PEF-pretreated sweet potatoes. Substituting the fitted k and n values into the Page model yielded the following equations for each treatment group:

$$MR = \exp(-0.3194t^{1.1687}) \quad (9)$$

$$MR = \exp(-0.3579t^{0.5363}) \quad (10)$$

$$MR = \exp(-0.3973t^{0.8558}) \quad (11)$$

$$MR = \exp(-0.3636t^{1.1794}) \quad (12)$$

In the Page model, k and n jointly characterize the drying behavior: k reflects the overall drying rate, while n governs the shape of the drying curve. The PEF-treated group showed the highest n value (1.1794), indicating sustained moisture diffusion during the later stages and a pronounced downward curve. The ethanol-treated group exhibited a relatively high k (0.3973) but a low n (0.8558), suggesting rapid initial drying followed by limited moisture diffusion and a flattening curve. The brined group had the lowest k (0.3579) and the smallest n (0.5363), indicating rapid early moisture loss but a sharp decline in drying rate thereafter, with the curve nearly plateauing after 3 h. These parameter trends are consistent with the observed drying curve characteristics across all groups.

Table 1 Estimated coefficients and statistics from different drying models

Model	Parameter	Pretreatment method			
		Control	Brining	Ethanol	PEF
Henderson and Pabis	a	1.0224	0.9029	0.9699	1.0180
	k	0.3912	0.1564	0.3223	0.4388
	R^2	0.9949	0.8999	0.9937	0.9923
	$RMSE$	0.0268	0.0721	0.0259	0.0344
	SSE	0.0036	0.0312	0.0040	0.0047
Jena	a	1.0520	0.6327	1.1211	-0.0867
	b	0.0961	-0.1235	-0.2200	1.9226
	c	-0.0524	0.3674	-0.1207	1.0868
	k	0.4019	0.4419	0.1459	0.3663
	R^2	0.9998	0.9998	0.9999	1.0000
	$RMSE$	0.0073	0.0036	0.0047	0.0017
	SSE	0.0002	0.0001	0.0001	0
Logarithmic	a	1.1190	0.6175	0.9257	1.1852
	b	-0.1122	0.3795	0.0575	-0.1866
	k	0.3117	0.5500	0.3751	0.3113
	R^2	0.9992	0.9993	0.9956	0.9999
	$RMSE$	0.0122	0.0064	0.0235	0.0045
	SSE	0.0006	0.0002	0.0028	0.0001
Page	k	0.3194	0.3579	0.3973	0.3636

	n	1.1687	0.5363	0.8558	1.1794
	R^2	0.9998	0.9922	0.9986	0.9978
	$RMSE$	0.0059	0.0201	0.0122	0.0186
	SSE	0.0002	0.0024	0.0009	0.0014
Lewis	k	0.3827	0.1847	0.3333	0.4311
	R^2	0.9940	0.8531	0.9918	0.9917
	$RMSE$	0.0265	0.0809	0.0272	0.0321
	SSE	0.0042	0.0458	0.0052	0.0051

3.2 Effect of pretreatments on color

Table 2 presents the color parameters of raw and dried squid subjected to different pretreatments, and Fig. 10 shows photographs of the corresponding samples. The control, ethanol-treated, and PEF-treated groups were all dried to 0.25 g/g; the brined group reached only 1.20 g/g and is therefore shown at that moisture content. Fresh squid exhibited the highest lightness (L^*), which decreased substantially after drying in all groups. The control and ethanol-treated groups showed the lowest L^* values (30.93 ± 2.84 and 29.90 ± 3.63 , respectively), indicating pronounced browning during processing. The PEF-treated group, by contrast, retained significantly higher L^* values (36.81 ± 3.67), suggesting that PEF-enhanced moisture diffusion improved drying uniformity and reduced surface browning. Fresh squid had the lowest b^* value, which increased after drying in all groups. The PEF-treated group exhibited the highest b^* (13.26 ± 2.84), followed by the control (9.27 ± 2.21) and ethanol-treated (8.22 ± 3.00) groups, suggesting that PEF may promote retention of certain pigments. The total color

difference (ΔE) was highest in the control group (33.37 ± 6.75) and lowest in the PEF-treated group (20.95 ± 1.85), further confirming that PEF pretreatment was most conducive to preserving the color attributes of the dried product. Yamakage et al. (2021) similarly reported that PEF pretreatment was superior to blanching for preserving the color of dried spinach, producing a product with color close to that of fresh spinach. Liu et al. (2024) found that low-intensity direct-current electric field treatment of apple juice increased L^* values, inactivating 89.24% of polyphenol oxidase at 5 V/cm after 90 min and completely inactivating peroxidase within 70 min, indicating suppression of enzymatic browning. By analogy, high-intensity PEF may exert a similar enzyme-inactivating effect on squid, thereby reducing browning during the drying process.

Table 2 Color difference values of raw and dried squid after different pretreatments

	L^*	a^*	b^*	ΔE
Fresh squid	52.95 ± 0.24^a	7.08 ± 0.56^c	5.30 ± 0.36^c	/
No pretreatment	30.93 ± 2.84^c	16.13 ± 1.90^a	9.27 ± 2.21^b	33.37 ± 6.75^a
Ethanol Pretreatment	29.90 ± 3.63^c	11.95 ± 2.36^b	8.22 ± 3.00^b	29.78 ± 6.01^a
PEF Pretreatment	36.81 ± 3.67^b	16.88 ± 1.71^a	13.26 ± 2.84^a	20.95 ± 1.85^b

*Values are presented as average $\pm$ standard deviation. Different superscript letters in same column denote significant differences ($p < 0.05$) (ANOVA).

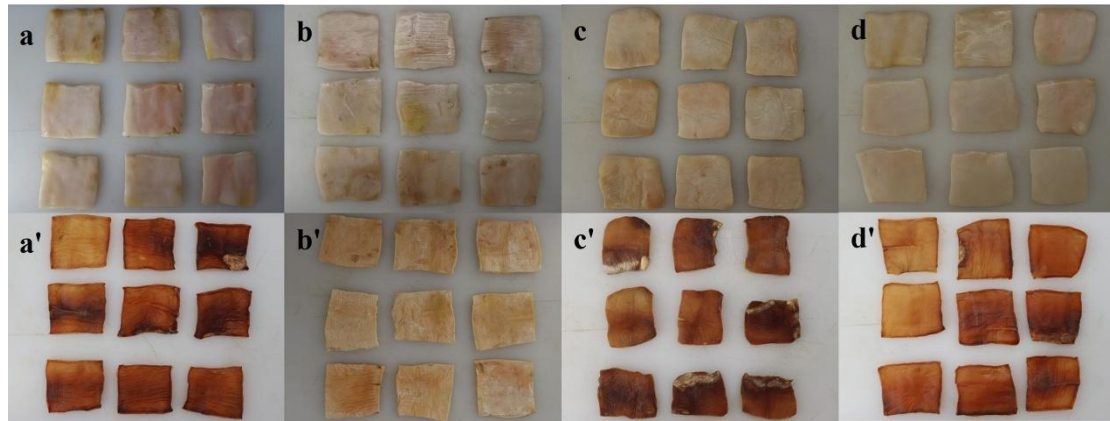


Fig. 10. Photographs of squid samples with different pretreatments. (a–d) without pretreatment, with brining, ethanol, and pulsed electric field (PEF) pretreatment groups prior to drying; (a'–d') the corresponding samples after drying.

3.3 Effect of pretreatments on rehydration ratio

Fig. 11 presents the rehydration ratio curves of dried squid after different pretreatments. The control and PEF-treated groups exhibited strong rehydration capacity throughout the 60 min period, maintaining higher rehydration ratios than the ethanol-treated group and converging to nearly the same value at the final time point. PEF has also been reported to improve the rehydration properties of dried foods such as sweet potatoes by enhancing cell membrane permeability and reducing tissue shrinkage (Fauster et al., 2020; Kim et al., 2023). However, PEF improved drying kinetics of squid without concomitant enhancement of rehydration ratio in this study. This asymmetry arises because membrane electroporation facilitates outward moisture diffusion during drying, but the ensuing rapid surface dehydration promotes protein denaturation and myofibrillar compaction—irreversible changes that impede inward water imbibition during rehydration. In contrast, the ethanol-treated group showed notably lower rehydration ratios throughout rehydration. This is likely attributable to

ethanol-induced protein denaturation and contraction of the myofibrillar structure,
 which hindered water uptake during rehydration (da Silva et al., 2025).

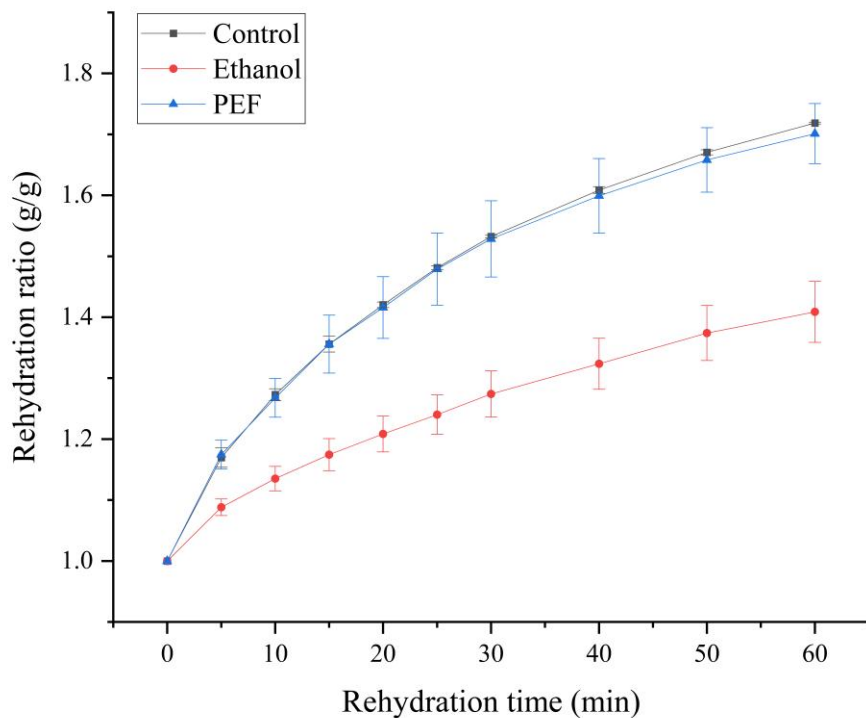


Fig. 11. Rehydration ratio curves of dried squid obtained by drying after different pretreatments

3.4 Effect of pretreatments on lipid oxidation

The TBARS values reflected the extent of lipid oxidation in dried squid after different pretreatments (Fig. 12). The control group exhibited the highest *TBARS* value (0.88 mg MDA/kg), significantly higher than those of the ethanol-treated and PEF-treated groups ($p < 0.05$). This indicates that untreated samples underwent substantial lipid oxidation during drying, likely attributable to the elevated temperatures of hot air-assisted radio frequency drying accelerating lipid degradation and the generation of malondialdehyde (MDA) and other oxidation products. Both ethanol and PEF

pretreatments significantly reduced *TBARS* values, demonstrating their inhibitory effect on lipid oxidation. The ethanol-treated group showed a *TBARS* value of approximately 0.61 mg MDA/kg, which may be associated with the antioxidant properties of ethanol and its effects on protein structure. The PEF-treated group displayed the lowest *TBARS* value (0.53 mg MDA/kg), possibly because pulsed electric field treatment promoted the inactivation of endogenous oxidative enzymes, thereby mitigating lipid oxidation.

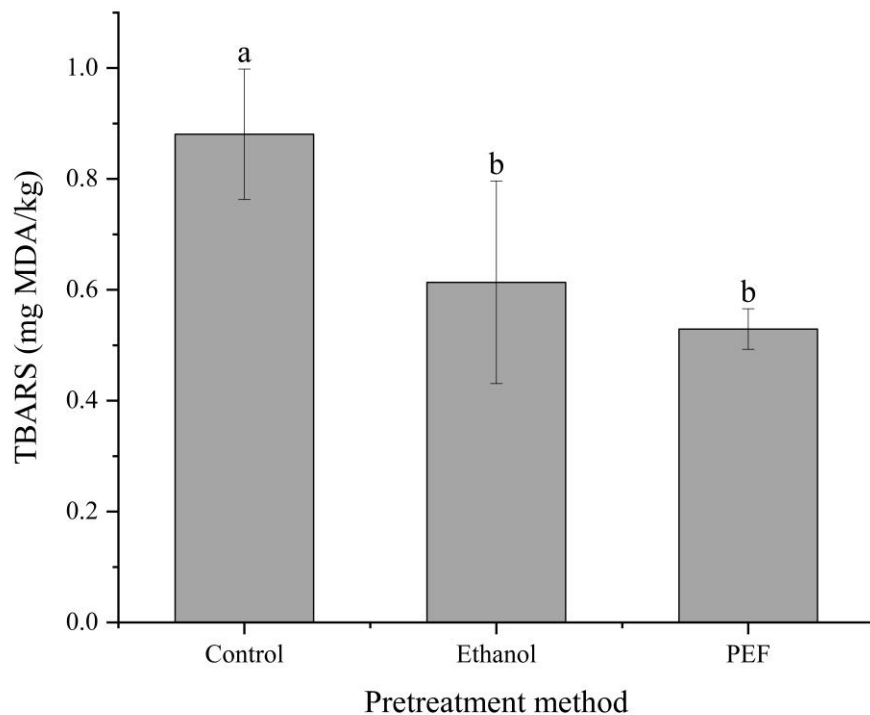


Fig. 12. TBARS values of dried squid obtained by drying after different pretreatments.

* Different letters denote significant differences ($p < 0.05$) (ANOVA)

3.5 Effect of pretreatments on microstructure

Fig. 13 presents the surface microstructures of dried squid after hot air-assisted radio frequency drying with different pretreatments. In the untreated group, the

penetrating heating effect of RF energy caused rapid internal moisture vaporization and migration to the surface, leading to tissue shrinkage and the formation of uneven pore structures. The brined group (dried to 1.20 g/g) exhibited a denser surface with fewer pores, likely because progressive salt crystallization on the squid surface formed a hard crust that limited moisture diffusion and produced a compact surface layer — consistent with the brined product photographs in Fig. 10. The ethanol-treated group showed pronounced surface shrinkage after drying, attributable to ethanol-induced dehydration accelerating protein denaturation and contraction, causing premature surface moisture loss and tissue collapse, which likely contributed to the reduced rehydration capacity observed in this group. Liang et al. (2024) similarly reported that ethanol-pretreated vacuum freeze-dried *Phyllanthus emblica* exhibited the smallest pores and the highest hardness compared with microwave and hot air pre-dehydration. The PEF-treated group formed abundant pore structures on the surface with more uniform morphology than the control group, and the dried product surface appeared relatively intact (Fig. 10). This may reflect PEF-enhanced cell membrane permeability, which facilitated moisture migration and diffusion during drying, thereby reducing localized moisture accumulation and overheating.

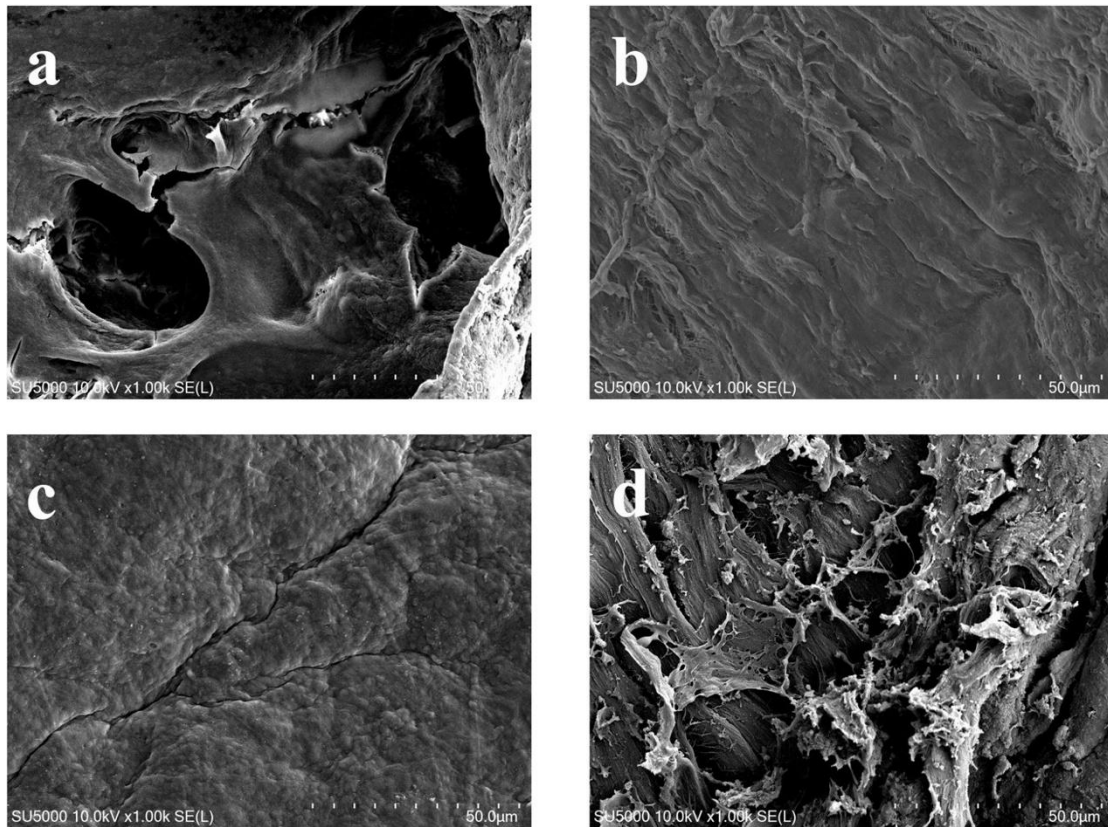


Fig. 13. Microstructures of dried squid surfaces dried after different pretreatments. a. Control group b. Brining treatment group c. Ethanol treatment group d. Pulsed electric field treatment group

4 Conclusions

This study compared the effects of three pretreatments — brining-induced osmotic dehydration, ethanol soaking, and pulsed electric field (PEF) — on the drying kinetics and product quality of squid during hot air-assisted radio frequency drying. PEF pretreatment (20 pulses) achieved the highest drying rate ($1.12 \text{ g} \cdot \text{g}^{-1} \cdot \text{h}^{-1}$), the smallest total color difference ($\Delta E = 20.95 \pm 1.85$), and superior rehydration capacity compared with both the ethanol-treated group ($RR = 1.41 \text{ g/g}$) and the control. PEF pretreatment also suppressed lipid oxidation in the dried product ($TBARS = 0.53 \text{ mg MDA/kg}$) and produced a porous surface microstructure. Overall, PEF pretreatment offered the

optimum combination of drying efficiency and product quality among the three pretreatment methods evaluated. The Page model provided a high goodness-of-fit for describing the drying kinetics across all pretreatment groups.

Beyond the drying kinetics and rehydration performance examined herein, the impacts of these pretreatments on flavor compounds, protein denaturation, and nutrient retention warrant further investigation in the future. Likewise, quantitative modeling of cell-level structural changes and their coupling to mass transfer kinetics remains to be addressed. The synergistic effects of other emerging physical field pretreatments combined with PEF also warrant investigation to further improve drying efficiency and product quality.

CRedit authorship contribution statement

Zitian Xia: Methodology, Investigation, Formal analysis, Visualization, Writing - original draft. **Feilong Zhang:** Writing - review and editing. **Xuqi Ge:** Writing - review and editing. **Yongyang Xu:** Validation, Writing - review and editing. **Yinzhe Jin:** Writing - review and editing. **Wenzheng Shi:** Writing - review and editing. **Juming Tang:** Writing - review and editing. **Fanbin Kong:** Writing - review and editing. **José V. García-Pérez:** Writing - review and editing. **Yang Jiao:** Conceptualization, Supervision, Writing - review and editing.

Declaration of competing interest

The authors declare no conflict of interest.

Acknowledgments

N/A.

Funding Declaration

No funding was received for conducting this study.

Data availability statements

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request.

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