

Effect of pulsed electric field on the quality of PSE-like chicken breast meat: Insights into water distribution and structural rearrangement

Tian Chen

Nanjing Agricultural University

Shuangshuang Jin

Yunfu Branch Center of Lingnan Modern Agricultural Science and Technology Guangdong Provincial Laboratory

Yun Bai

Nanjing Agricultural University

Chencheng Zhang

Nanjing Agricultural University

Xinglian Xu

Nanjing Agricultural University

Xinqing Lu

Dalian Dingtong Technology Development Co., Ltd

Minyi Han

myhan@njau.edu.cn

Nanjing Agricultural University

Research Article

Keywords: Pulsed electric field, PSE-like chicken, Water-holding capacity, T2 relaxation properties, Microstructure, Texture properties

Posted Date: September 14th, 2026

DOI: <https://doi.org/10.21203/rs.3.rs-10866955/v1>

License:   This work is licensed under a Creative Commons Attribution 4.0 International License.

[Read Full License](#)

Additional Declarations: No competing interests reported.

Abstract

PSE (pale, soft and exudative)-like meat is a common poultry quality defect characterized by pale color, soft texture, and poor water-holding capacity (WHC). This study explored the effects of different electric field strengths (0–4 kV/cm) on PSE-like chicken breast quality, focusing on water distribution and structural changes. The results indicated that pulsed electric field (PEF) treatment with high field strength partially improved the pale appearance of PSE-like meat. Notably, moderate treatment at 2 kV/cm yielded significant improvements, driving cooking loss down from 20.24% to 16.45% and reducing centrifugal loss from 21.16% to 14.14% ($p < 0.05$). These improvements diminished as the electric field strength increased to 4 kV/cm. Texture profile analysis (TPA) showed that PEF treatment decreased hardness and shear force, suggesting that improved WHC was accompanied by enhanced tenderness. Low-field nuclear magnetic resonance (LF-NMR) analysis showed that P_{21} increased from 93.78% to 95.33% at 2 kV/cm, In contrast, high-intensity treatment (4 kV/cm) increased P_{22} from 1.74% to 3.06%. Scanning electron microscope (SEM) images further showed that moderate PEF treatment resulted in a more uniform and porous microstructure, which contributed to enhanced water retention, whereas excessive treatment caused structural damage. Notably, PEF treatment improved quality attributes without markedly affecting the physicochemical stability of the meat. Principal component analysis (PCA) revealed significant correlations between PEF intensity and quality-related parameters. Overall, PEF treatment modulated PSE-like chicken breast quality in a field strength-dependent manner, with 2 kV/cm showing the best effects.

1. Introduction

With the continuous increase in the demand for meat and meat products, chicken serves as an important protein source. It is favored for its nutrition, affordability, and wide applicability. (B. Li et al., 2026). However, the rapid growth of the bird, along with challenges associated with transportation and pre-slaughter handling, has led to a decline in chicken meat quality in some cases. Among these quality defects, pale, soft and exudative-like (PSE-like) meat is one of the most prevalent and economically significant issues in the poultry industry. It is mainly identified by a pale appearance, low water retention, and soft texture (Dong et al., 2020). PSE-like meat reduces the sensory quality of fresh meat and negatively affects the yield and textural uniformity of further processed products. Conventional approaches to improving PSE-like meat have mainly focused on optimizing texture or addressing individual functional defects (Y. Jiang et al., 2025; L. Wang et al., 2025), which remain insufficient for achieving a systematic improvement in overall quality. Therefore, the development and application of emerging technologies to effectively enhance the quality of PSE-like meat has become a key research focus in the field of meat science.

Pulsed electric field (PEF), as an emerging non-thermal processing technology, has attracted considerable attention in the field of food processing in recent years (L. Chen et al., 2026). PEF applies brief high-voltage pulses to generate a strong electric field. This field induces electroporation in cell membranes with minimal thermal impact. This process disrupts the structural integrity of muscle cells

and modifies myofibrillar architecture, thereby influencing the migration and redistribution of water among different binding states (Arroyo, Eslami, et al., 2015a; Sitzmann et al., 2016). Meanwhile, this membrane permeabilization process enhances postmortem tenderization in a controlled manner by promoting calcium ion release and activating endogenous proteases (C. Chen et al., 2026). Previous studies have also demonstrated that PEF altered the conformation of myofibrillar proteins and modulated their interactions with water molecules, thereby further improving functional properties such as water-holding capacity (WHC) (Roobab, Chen, Madni, Tong, et al., 2024b). And PEF treatment has been shown to effectively enhance the tenderness and water retention of goose meat during cold storage (C. Chen et al., 2026).

However, current investigations on PEF treatment have predominantly focused on normal pork and beef (X. Li et al., 2025; Vojtisek et al., 2025), and research on its potential to improve the quality of PSE-like meat remains limited. Given the distinct characteristics of PSE-like meat, its response to PEF may differ from that of normal muscle systems. In particular, the relatively loose protein structure in PSE-like meat may facilitate electric field induced structural rearrangement or ion migration.

The effects of PEF treatment at different electric field strengths on the quality characteristics of PSE-like chicken breast were investigated in this study. Changes in water distribution, physicochemical properties, and muscle microstructure were analyzed using low-field nuclear magnetic resonance (LF-NMR), scanning electron microscopy (SEM), and principal component analysis (PCA). Particular attention was given to the relationship between structural modification and water migration in PSE-like muscle tissue after PEF treatment, with the aim of improving the utilization of low-quality meat raw materials.

2. Materials and Methods

2.1 Meat sample preparation

PSE-like chicken breast muscle (boneless and skinless *pectoralis major*) were obtained from Guannan Wens Foodstuff Co., Ltd. (Lianyungang, Jiangsu province, China). The broilers were 45 days of age with an average live weight of 2.3 kg. Preliminary screening of PSE-like meat was conducted based on $L^* > 53$ measured at 1 h postmortem (K. Li et al., 2014). The samples were transported to the laboratory within 3 h post-slaughter under a 4°C cold chain. At 24 h postmortem, L^* and pH were measured again. PSE-like samples were identified based on the criteria described by Li et al. (2014) ($L^* > 53$, pH < 5.7). Only samples with comparable L^* values and pH were selected for further experiments. Subsequently, all visible fascia and adipose tissue were carefully trimmed from the samples prior to further analysis. The samples were then cut into blocks with an average weight of approximately 155 g and dimensions of 10 cm × 5 cm × 3 cm (length × width × height) for further analysis.

2.2 PEF processing

PEF treatments were performed using a DMC-200 high-voltage pulse generator (Dalian Dingtong Technology Development Co., Ltd., Dalian, Liaoning Province, China) equipped with a cylindrical treatment chamber (20 cm in inner diameter) and a maximum adjustable electrode gap of 13 cm. The system operated in a monopolar square-wave mode with a maximum output voltage of 70 kV.

Treatment conditions were selected based on preliminary experiments and previous work by Guo et al. (2025). PSE-like chicken breast samples were placed at the center of the chamber. The muscle fiber direction was set perpendicular to the electric field direction. The electrode gap was fixed at 3 cm. Each sample was placed in full contact with the electrode plates, and no immersion medium was used during treatment. The electric field strength was adjusted by changing the output voltage (0, 3, 6, 9, and 12 kV), corresponding to field strengths of 0, 1, 2, 3, and 4 kV/cm, respectively. Treatments were applied at 250 Hz for 30 s, resulting in a total of 7500 pulses with a pulse width of 800 μ s. Each treatment condition was performed in triplicate using independent biological samples obtained from different carcasses.

During processing, the surface temperature of the samples was continuously monitored using a calibrated thermocouple thermometer (ZG-8051, Guangzhou Zhigao Refrigeration Equipment Co., Ltd., Guangzhou, Guangdong Province, China). The temperature increase remained below 3°C in all treatments. This slight temperature rise suggests that the observed changes were mainly associated with the electric field effect, although the contribution of localized heating cannot be fully excluded.

2.3 pH

Treated samples were measured for pH using a Testo portable meter (Testo 205, Detu Instruments International Trade Co., Ltd., Shanghai, China). Each group measures at least three times at different positions of each sample, takes the average.

2.4 Color

A portable colorimeter (CR-400, Konica Minolta, Tokyo, Japan) was used to measure the lightness (L^*), green-red coordinate (a^*), and blue-yellow coordinate (b^*) of the samples. The instrument was calibrated with a standard white plate ($L^* = 97.50$, $a^* = 0.60$, $b^* = 2.30$) under a D65 illuminant prior to measurement.

2.5 Shear force

Shear force was determined following the procedure described by Çimen et al. (2024), with minor adjustments. Prior to analysis, samples from each treatment group were carefully trimmed to obtain uniform dimensions, ensuring consistency in both geometry and fiber orientation across replicates.

Measurements were performed using a C-LM3B shear force analyzer (College of Engineering, Northeast Agricultural University, Harbin, Heilongjiang Province, China). During testing, samples were sheared at a constant crosshead speed of 5 mm/s. The peak force required to completely cut through each specimen was recorded as the shear force value, and results were expressed in Newtons (N).

2.6 Texture profile analysis (TPA)

TPA was carried out using a TA-XT Plus texture analyzer (Stable Micro Systems, London, UK) equipped with a cylindrical P50 probe operating in compression mode. For each treatment group, samples were cut into uniform cubes to minimize variability prior to measurement. Compression was set to 30% of the original sample height. The testing sequence consisted of pre-test, compression, and post-test movements, with corresponding speeds of 5, 1, and 5 mm·s⁻¹ respectively.

2.7 Stress-strain

Stress-strain behavior was evaluated using the same texture analyzer fitted with a P50 probe. The experimental setup was adapted from U-chupaj et al. (2017) with modifications tailored to the present study.

Measurements were performed in “Return to Start” mode. Samples were compressed at 3.0 mm/s to a strain of 40%, with a 1 s holding period at maximum deformation. A trigger force of 5 g was applied to standardize the initial contact point. The resulting force-deformation data were used to generate stress-strain curves for subsequent analysis.

2.8 Centrifugal loss

The centrifugal loss was assessed using a slightly modified version of the method described by Wu et al. (2021). Samples from each treatment group were cut into portions of 20 g. Each portion was wrapped with double-layer qualitative filter paper and placed in a centrifuge. Centrifugation was performed at 4°C and 4000 ×g for 15 min. The sample mass before and after centrifugation were recorded, and the centrifugal loss of the sample was expressed as a percentage of the weight change.

$$\text{Centrifugal loss (\%)} = \frac{Q_1 - Q_2}{Q_1} \times 100$$

The sample mass before centrifugation is denoted as Q_1 (g), and the mass after centrifugation as Q_2 (g).

2.9 Cooking loss

Cooking loss was determined as described by Li et al. (2024) with slight modification. The cooking loss rate was calculated as the percentage of the mass difference before and after cooking relative to the mass before cooking.

$$\text{Cooking loss (\%)} = \frac{M_1 - M_2}{M_1} \times 100$$

The sample mass before cooking is denoted as M_1 (g), and the mass after cooking as M_2 (g).

2.10 Thiobarbituric acid reactive substances (TBARS)

Lipid oxidation was evaluated by measuring TBARS following the method of Nam et al. (2003), with minor modifications. Briefly, minced samples were homogenized in a solution containing trichloroacetic acid (TCA) and EDTA-2Na using a high-speed homogenizer at 10,000 rpm under 4°C for three 20 s

intervals. After homogenization, the mixture was centrifuged for 5 min (10000rpm, 4°C), and the resulting supernatant was collected for analysis. An aliquot of the extract was reacted with an equal volume of 0.02 mol/L thiobarbituric acid (TBA) solution and incubated in boiling water to develop color. Following cooling, absorbance was recorded at 531 nm using a SpectraMax M2e microplate reader (Molecular Devices, Sunnyvale, California, USA). TBARS values were calculated based on a malondialdehyde (MDA) standard calibration curve.

2.10 Total volatile basic nitrogen (TVB-N)

TVB-N content was measured according to the method described by Gharibzahedi et al. (2017) using an automatic Kjeldahl analyzer (Kjeltec 8400, FOSS, Hillerød, Denmark). Minced samples were mixed with magnesium oxide prior to steam distillation. The released volatile basic nitrogen compounds were collected in 2% boric acid solution containing a bromocresol green–methyl red mixed indicator. The distillate was then titrated with 0.1001 mol/L HCl until the endpoint was reached, and the TVB-N content was calculated and expressed as mg/kg meat.

2.11 LF-NMR

The distribution of transverse relaxation time (T_2) was determined using an LF-NMR analyzer (NMI20-040H-I, Niumag Corporation, Suzhou, Jiangsu Province, China), with slight modifications to the protocol reported by Gao et al. (2024). All samples were wrapped tightly with plastic film to reduce moisture loss during testing. The CPMG pulse sequence was adopted to acquire relaxation signals under the following instrumental parameters: SF = 40 MHz, SW = 200 kHz, P_1 = 8.00 μ s, P_2 = 15.52 μ s, TW = 4000 ms, TE = 0.300 ms, NS = 4, and NECH = 3200.

2.12 Microstructure

The procedure of Gao et al. (2024) was adapted with minor adjustments. Samples were cut into small pieces and fixed in 2.5% glutaraldehyde at 4°C. After fixation, the specimens were rinsed with 0.1 mol·L⁻¹ phosphate buffer (pH 7.0) to remove residual fixative, followed by dehydration through a graded ethanol series. The dehydrated samples were freeze-dried under low-temperature conditions and then sputter-coated with a thin layer of gold. Morphological observations were performed using a scanning electron microscope (MIRA4, TESCAN, Brno, Czech Republic) at 8000× magnification.

2.13 Statistical analysis

All experiments were carried out in triplicate, and the data were analyzed using SPSS 27.0 (IBM Corp., Armonk, NY, USA). Differences among groups were evaluated by one-way analysis of variance (ANOVA), followed by Duncan's multiple range test at $p < 0.05$. Values are presented as mean $\pm$ standard deviation. PCA was performed to summarize the overall trends in the dataset. Figures were prepared with Origin 2026 (OriginLab Corporation, Northampton, MA, USA).

3. Results and Discussion

3.1 Color and pH

Meat color is a critical indicator of meat quality for customer’s purchase decisions regarding meat products (L. Jiang et al., 2026; Y. Wu et al., 2024). However, in PSE-like meat, postmortem low pH induces protein denaturation, leading to myofibrillar shrinkage and altered light-scattering properties, which results in excessively high L^* values and an undesirably pale appearance (Dong et al., 2021; Z. Wang et al., 2022). After PEF treatment, the L^* value decreased from 60.86 ± 0.81 to 59.44 ± 1.00 at an electric field strength of 4 kV/cm ($p < 0.05$), indicating reduced lightness and a partial alleviation of the pale appearance (Table 1). Meanwhile, when the field strength exceeded 2 kV/cm, the a^* value significantly increased from 0.88 ± 0.08 in the control group to 1.24 ± 0.19 ($p < 0.05$), suggesting that PEF treatment enhanced redness to some extent and thereby improved overall color attributes (Kim et al., 2010; Y. Wu et al., 2024). In comparison, the results of the b^* values between groups indicate that PEF has a limited effect on yellowing, which is consistent with previous reports (Karki, Oey, Bremer, & Silcock, 2023b; Roobab et al., 2023). Notably, no significant differences ($p > 0.05$) were found in pH values between treated and control groups, indicating that PEF did not change the acid–base status of the muscle. Therefore, the observed decrease in L^* was unlikely to be primarily driven by pH variation, which is in agreement with earlier studies (Faridnia et al., 2014; McDonnell et al., 2014; Suwandy et al., 2015). Previous studies have suggested that PEF can induce electroporation, thereby modifying cell membrane permeability and subsequently affecting myofibrillar structure and intracellular water distribution. These changes may alter the light scattering and reflection properties of muscle (Baldi et al., 2021; Chang et al., 2023; Jeong et al., 2023; J. Wang, Li, et al., 2022). These factors may partially explain the color changes observed in the present study.

Table 1
PEF at different electric field strengths on color parameters and pH values.

Electric field strengths	L^*	a^*	b^*	pH
Control	60.86 ± 0.81^a	0.88 ± 0.08^c	7.21 ± 0.75^a	5.68 ± 0.45^a
1 kV/cm	60.95 ± 0.81^a	0.56 ± 0.15^d	5.20 ± 0.54^b	5.64 ± 0.52^a
2 kV/cm	60.29 ± 0.68^{ab}	1.64 ± 0.11^a	7.10 ± 0.37^a	5.64 ± 0.38^a
3 kV/cm	60.43 ± 1.16^{ab}	1.22 ± 0.10^b	5.62 ± 0.30^b	5.67 ± 0.66^a
4 kV/cm	59.44 ± 1.00^b	1.24 ± 0.19^b	6.66 ± 0.23^a	5.66 ± 0.45^a
Note: Different lowercase letters (a-c) within the same column indicated significant differences among groups ($p < 0.05$).				

Table 2
Effect of PEF at different electric field strengths on texture properties and shear force.

Electric field strengths	Hardness (g)	Springiness	Cohesiveness	Chewiness	Shear force (N)
Control	1883.7 ± 139.9 ^a	0.73 ± 0.09 ^a	0.41 ± 0.03 ^{ab}	569.4 ± 95.2 ^a	13.18 ± 0.73 ^a
1 kV/cm	1233.5 ± 159.2 ^{bc}	0.68 ± 0.03 ^a	0.39 ± 0.02 ^b	326.4 ± 30.6 ^{cd}	12.32 ± 0.91 ^a
2 kV/cm	1174.8 ± 73.2 ^c	0.63 ± 0.05 ^a	0.38 ± 0.02 ^b	286.7 ± 29.6 ^d	9.16 ± 0.87 ^b
3 kV/cm	1300.6 ± 125.9 ^{bc}	0.69 ± 0.02 ^a	0.42 ± 0.02 ^{ab}	381.9 ± 52.8 ^{bc}	9.74 ± 1.95 ^b
4 kV/cm	1411.2 ± 140.4 ^b	0.67 ± 0.08 ^a	0.44 ± 0.02 ^a	411.7 ± 53.4 ^b	7.29 ± 0.99 ^c
Note: Different lowercase letters (a-c) within the same column indicated significant differences among groups ($p < 0.05$).					

3.2 TPA and Shear force

PEF treatment significantly reduced the hardness of PSE-like chicken breast compared with the control group ($p < 0.05$), with the lowest value observed at 2 kV/cm. Although hardness slightly increased at 3 and 4 kV/cm, it remained lower than that of the untreated samples. Chewiness showed a trend similar to hardness, suggesting that both parameters responded similarly to PEF treatment. In contrast, cohesiveness decreased under relatively low electric field strengths, while springiness was not significantly affected ($p > 0.05$). Shear force also declined progressively with increasing field strength, decreasing from 13.18 ± 0.73 N in the control group to 7.29 ± 0.99 N after treatment at 4 kV/cm ($p < 0.05$). These results suggest that moderate PEF treatment can effectively alter the texture properties of PSE-like chicken breast, which is consistent with previous studies (Benoit et al., 2023; Chian et al., 2019; Karki et al., 2023a; Mungure et al., 2023). The reductions in hardness and chewiness at lower field strengths may be associated with PEF-induced structural disruption, which could contribute to the weakening of muscle structure and subsequent tenderization (Jeong et al., 2024; Karki, Oey, Bremer, Leong, et al., 2023a). At higher electric field strengths, the slight recovery in hardness may indicate additional structural changes within the muscle tissue. Moreover, the absence of significant changes in springiness suggests that the overall structural continuity of the muscle was not markedly affected, despite the occurrence of localized structural alterations (Toepfl et al., 2006; Tornberg, 2005).

The PEF-induced reduction in hardness observed in this study is likely associated with structural modifications and changes in water distribution.

3.3 Stress–strain behavior

Figure 1A shows that the stress values of PEF-treated samples were generally lower than those of the control group at the same strain level, indicating reduced resistance to deformation after PEF treatment. This difference became more pronounced at 3 kV/cm, where the lowest stress values were observed across the compression range. This result suggests that moderate PEF treatment promoted structural loosening of the muscle matrix, making the tissue more susceptible to compression. Similar trends have been reported in previous studies, where PEF treatment altered muscle structure and weakened its mechanical resistance (C. Chen et al., 2026; Suchanek & Olejniczak, 2018). When the electric field strength increased to 4 kV/cm, the stress–strain curve showed a slight upward shift compared with the 3 kV/cm group, indicating a partial recovery of mechanical resistance. This trend was consistent with the changes observed in hardness and chewiness. The result suggests that excessive electric field intensity may weaken the tenderizing effect of PEF. This may be associated with additional structural changes in muscle tissue under stronger electrical stimulation (Farahmand et al., 2026).

As shown in Fig. 1B, at the same force level, PEF-treated samples generally exhibited higher strain values than the control group. This indicates an improved deformation capacity and lower resistance to external force. Among all treatment groups, the 3 kV/cm treatment showed the highest strain values, further confirming its strongest softening effect. However, a slight reduction in strain was observed at 4 kV/cm, suggesting that the positive effect of PEF on meat deformability gradually diminished at higher field strengths, although the underlying mechanism remains to be further elucidated.

Overall, the stress–strain results indicate that moderate PEF treatment improved the deformability of PSE-like chicken breast and reduced its mechanical resistance. These changes were in agreement with the texture profile results and may be related to structural modifications and water redistribution within the muscle matrix.

3.4 Microstructure

The changes in color parameters may be related to variations in light scattering properties, which are governed by the microstructure of muscle tissue. To better understand these changes, microstructural observations were performed. Muscle fiber diameter, density, and structural compactness are key determinants of meat quality attributes (Cheng et al., 2025; Mehmood & Zhang, 2020).

As shown in Fig. 2, PEF treatment induced obvious microstructural alterations in PSE-like chicken breast compared with the control group. The control samples exhibited irregular muscle fiber arrangement with small inter-myofibrillar gaps, which is likely due to rapid postmortem pH decline and associated protein denaturation (Suliga et al., 2024; N. Yang et al., 2022).

With increasing electric field strength, structural loosening became more apparent. At low treatment intensity (1 kV/cm), only slight separation between fibers was observed. When the field strength reached 2 kV/cm, fiber spacing increased and pores were more uniformly distributed, while the overall structure remained relatively stable. This stage may contribute to improved structural openness in PSE-like meat (Nowacka et al., 2024; Rondineli & Silva, 2024).

At higher field strength (3 kV/cm), pronounced structural disruption was observed, including enlarged inter-fiber gaps and partial fiber breakage. These changes suggest a stronger impact of PEF on the muscle structure under moderate electric field strength. Similar phenomena have been reported in previous studies and are generally associated with electric field-induced structural modifications in muscle systems (J. Li et al., 2026; Xiao et al., 2026). This indicates that PEF treatment may effectively weaken the structural integrity of the muscle tissue under appropriate processing conditions (Jurak et al., 2026; Koohmaraie, 1996; Novickij et al., 2019). These changes are likely responsible for the observed reduction in shear force and improvement in tenderness.

A different structural tendency was observed at 4 kV/cm. In this case, obvious longitudinal expansion of inter-fiber spaces and formation of larger pores were detected. Unlike the gradual loosening observed at moderate intensities, this suggests that excessive electric field strength may lead to over-disruption of the muscle matrix, which could negatively affect structural integrity and water retention capacity (Arroyo, Lascorz, et al., 2015b).

Overall, the microstructural evolution exhibited a transition from slight loosening under low electric field strength, to increased pore formation at moderate levels, and finally to pronounced structural disruption at the highest intensity, demonstrating a clear field-strength-dependent response of PSE-like muscle to PEF treatment.

3.5 WHC

WHC reflects the ability of muscle tissue to retain water during processing and storage and is therefore an important indicator of meat quality (Leng et al., 2025; Pearce et al., 2011; Szmańko et al., 2021). As shown in Fig. 3, the untreated PSE-like samples exhibited relatively high cooking loss and centrifugal loss. This may be related to protein denaturation and disruption of muscle fiber structure, which reduce the water-binding ability of muscle proteins (T. Yang et al., 2023).

PEF treatment significantly affected both cooking loss and centrifugal loss ($p < 0.05$). As the electric field strength increased, both parameters first decreased and then increased, with the lowest values observed at 2 kV/cm. Under this condition, cooking loss decreased from 20.24 ± 0.57 to 16.45 ± 0.72 , while centrifugal loss declined from 21.16 ± 1.70 to 14.14 ± 1.09 ($p < 0.05$). These results indicate that moderate PEF treatment improved the WHC of PSE-like chicken breast.

This improvement may be associated with changes in muscle microstructure induced by PEF. At 2 kV/cm, the muscle structure appeared more uniform, with moderate pore formation, while the overall fiber network was still largely maintained. Such structural features are considered more favorable for water retention within the muscle system (Xu et al., 2025).

With further increases in field strength, WHC declined compared with the 2 kV/cm treatment, as evidenced by increased cooking and centrifugal losses. At higher field strengths, WHC improvement was less pronounced, suggesting that excessive electric field strength may not further enhance water retention in PSE-like meat. At 4 kV/cm, cooking loss and centrifugal loss rose to 17.65 ± 0.33 and 18.57

± 0.85 , respectively, although they remained lower than those of the control group. Based on SEM observations, this trend may be attributed to partial structural disruption and reduced integrity of muscle fibers, which could impair the formation of a stable water-retaining network (Roobab, Chen, Madni, Guo, et al., 2024a). In addition, excessive PEF treatment may induce further protein denaturation and enhanced hydrophobic interactions, thereby weakening the ability of the protein matrix to retain water (Farahmand et al., 2026). Nevertheless, even at high field strength, PEF treatment appears to partially improve the structural state of muscle tissue, which may explain why the WHC remains slightly higher than that of the untreated control.

The results of microstructure and WHC indicate that the reductions in hardness and shear force are associated with moderate structural relaxation and increased WHC within the muscle matrix, rather than with a deterioration of structural integrity.

3.6 LF-NMR

To further elucidate the changes in water distribution and water mobility within the samples, LF-NMR analysis was performed to provide additional information on the migration and redistribution behavior of water after different treatments. The T_2 relaxation time distribution reflects the dynamic properties of water under different binding states and can provide insight into water mobility within the muscle system. As shown in Fig. 4, all samples exhibited a typical three-peak pattern, indicating the presence of different water populations in the muscle tissue.

As illustrated in Fig. 4A, the control group showed a relatively pronounced peak in the T_{22} region, suggesting the presence of a certain proportion of highly mobile water in PSE-like meat. Following PEF treatment, both the peak intensity and the distribution of water populations changed to varying degrees under different electric field strengths. Whereas the percentage content of bound water remained relatively stable. At electric field strengths of 1–3 kV/cm, the T_{22} peak decreased markedly. Meanwhile, P_{22} decreased and P_{21} increased, indicating a redistribution of water toward more restricted states and a reduction in overall water mobility within the muscle tissue. Notably, the 2 kV/cm group exhibited a significantly enhanced and more concentrated T_{21} peak, with P_{21} increasing from $93.78 \pm 0.63\%$ to $95.33 \pm 0.56\%$, suggesting an increased proportion of immobilized water in the samples. The improved water-holding capacity may be associated with PEF-induced alterations in muscle microstructure and myofibrillar organization, which could regulate water distribution and retention. Previous studies have suggested that moderate PEF treatment may induce conformational adjustments of muscle proteins, which could enhance the interactions between water molecules and myofibrillar structures. (Queiroz et al., 2025).

As the electric field strength further increased to 3 kV/cm, the intensity of the T_{21} peak decreased compared with that observed at 2 kV/cm, and the peak position slightly shifted toward longer relaxation times, indicating a gradual enhancement in water mobility within the muscle system. This phenomenon may be associated with further loosening of the muscle structure. However, the water population still

mainly remained in the immobilized water region (T_{21}) and had not yet been extensively transformed into free water (T_{22}).

At 4 kV/cm, the intensity of the T_{21} peak remained lower than that observed in the 2 kV/cm group. In contrast, the T_{22} peak and its corresponding proportion increased markedly, with P_{22} increasing from 1.74 ± 0.30 to 3.06 ± 0.63 , indicating an increased proportion of highly mobile water. This alteration may be associated with excessive PEF-induced changes in muscle microstructural integrity, which reduced the capacity of the muscle matrix to immobilize water and promoted water mobility. Similar phenomena have been reported under excessive PEF conditions, where structural deterioration may compromise water retention properties (Ahmed et al., 2025).

Overall, PEF processing had a pronounced influence on the water distribution profiles of PSE-like meat samples. Across all tested conditions, the 2 kV/cm treatment was most effective in increasing the fraction of immobilized water and decreasing water mobility within the muscle microstructure. In contrast, excessively high electric field intensities tended to diminish the water-holding potential of the muscle matrix to some degree. These observations were congruent with the trends in WHC detailed in Section 3.5.

3.7 Oxidative stability and freshness-related indicators

TBARS are widely used as an indicator for evaluating the extent of lipid oxidation in meat products. It has been reported that when TBARS values exceed 6.94 nmol MDA/g, off-flavors caused by lipid oxidation can be readily detected in meat samples (Shen et al., 2025). TVB-N is an important indicator of protein degradation (Manhani et al., 2018). As shown in Fig. 5, PEF treatment significantly affected both TBARS and TVB-N values in PSE-like chicken breast under different electric field strength conditions ($p < 0.05$).

Under low and moderate electric field strengths, no significant difference in TBARS values was observed compared with the control group ($p > 0.05$). When the electric field strength reached 3 kV/cm, TBARS values increased significantly from 0.71 ± 0.02 to 0.95 ± 0.04 ($p < 0.05$), and the highest value was observed at 4 kV/cm (1.20 ± 0.02). All measured TBARS values remained well below the threshold associated with perceptible off-flavors caused by lipid oxidation. A field strength-dependent pattern was evident during PEF treatment. At low to moderate intensities, TBARS showed little variation compared with the control, whereas higher electric field strengths led to a noticeable increase. Similar observations have been reported previously (Faridnia et al., 2015). On the other hand, some studies reported no significant change in TBARS after PEF processing (Luo et al., 2019; Ma et al., 2016), which suggests that lipid oxidation is likely influenced by processing conditions as well as raw material properties rather than a single factor.

For TVB-N, a slight reduction occurred under low-intensity PEF treatment. The lowest value was obtained at 3 kV/cm, decreasing from 9.90 ± 0.54 in the control group to 7.69 ± 0.30 ($p < 0.05$). This reduction suggests that moderate electric field treatment may suppress the formation of volatile nitrogenous compounds. Changes in microbial activity and endogenous enzyme behavior under PEF conditions could

partly explain this observation (J. Wang, Wang, et al., 2022). When the field strength increased to 4 kV/cm, TVB-N rose again to 9.47 ± 0.29 . A possible explanation is that stronger PEF treatment may induce more pronounced protein structural damage, which in turn accelerates protein degradation in muscle tissue. The exact mechanism behind this trend, however, remains unclear and needs further investigation.

Overall, moderate PEF treatment appeared to help maintain lower levels of lipid oxidation and protein degradation, while higher electric field strengths tended to compromise product stability in PSE-like meat.

3.8 PCA

To better characterize the overall quality changes induced by PEF treatment, PCA was applied to the measured physicochemical parameters of PSE-like chicken breast. As shown in Fig. 6, PC1 and PC2 together accounted for 82.0% of the overall variability among samples, suggesting that these two components adequately represented the major quality differences associated with different treatments. Along the PC1 axis, a clear spatial separation among samples was observed. The control group clustered distinctly on the positive side of PC1 and showed strong positive correlations with centrifugation loss, cooking loss, hardness, shear force, and TVB-N. These correlations reflect severe water loss and overall quality deterioration in PSE-like meat.

It is worth noting that PEF treatment markedly altered this spatial distribution. The 2 kV/cm group exhibited the most pronounced shift toward the negative side of PC1 and were strongly positively correlated with T_{21} . This range of electric field strengths most effectively promoted a shift of water from free to immobilized states, thereby improving WHC and tenderness. T_{21} emerged as an important variable associated with the overall quality variation. Its strong negative correlations with cooking loss, centrifugal loss, and texture parameters suggest that the conversion of free water into immobilized water plays a central role in enhancing WHC and tenderness. Water redistribution, rather than merely total water content, thus appears to be the dominant factor governing quality improvement in PSE-like meat. Interestingly, the 4 kV/cm group showed a tendency to shift back toward the origin along PC1 and displayed a clear deviation toward the TBARS vector along PC2. A possible trade-off emerges: high-intensity PEF may facilitate water retention to some extent, but it also promotes lipid oxidation and reduces product stability. The exact reason for this shift is not further explored here.

In summary, the PCA results provide clear evidence that PEF treatment significantly improved the overall quality characteristics of PSE-like meat, with 2 kV/cm representing the most favorable electric field strength for overall quality improvement under the conditions tested.

4. Conclusions

In conclusion, the quality changes of PSE-like chicken breast after PEF treatment were strongly dependent on the applied electric field strength. Treatments at 2 kV/cm produced the most favorable

effects, significantly improving WHC and textural properties. These improvements were associated with moderate modulation of muscle microstructure and water distribution, without markedly enhancing lipid oxidation or protein degradation. In contrast, high-intensity PEF treatment induced excessive structural disruption of muscle tissue, resulting in reduced water retention capacity. This was accompanied by increased lipid oxidation and protein degradation, indicating that structural integrity and oxidative stability were compromised under stronger electric field conditions.

Generally speaking, the findings suggest that appropriately controlled PEF treatment can effectively regulate water redistribution and induce microstructural remodeling in PSE-like muscle, thereby enabling targeted quality improvement. This approach improves meat quality while maintaining product stability, providing useful insights for the valorization of PSE-like meat.

Declarations

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Author Contribution

Tian Chen: Writing – review & editing, Writing – original draft, Validation, Visualization, Methodology, Formal analysis, Data curation, Conceptualization, Investigation, Software. Shuangshuang Jin: Methodology. Yun Bai: Methodology. Chencheng Zhang: Data curation, Xinglian Xu: Resources. Xinqing Lu: Methodology, Resources. Minyi Han: Methodology, Resources, Supervision, Writing – review & editing, Project administration, Funding acquisition, Software.

Acknowledgements

This research was supported by the National Natural Science Foundation of China (No. 32472259), Yunfu City 2024 Modern Agriculture Industry Cluster Innovation and Entrepreneurship Talent Project (YF2024NYRC01) and the China Agriculture Research System (CARS-41).

Data Availability

The data related to the findings of this study can be availed from the corresponding author upon request.

References

1. Ahmed, M., Ranjan, H., & Roy, S. (2025). Pulsed electric fields for sustainable meat, poultry, and fish processing: Recent advances, prospects, and industry challenges. *Innovative Food Science & Emerging Technologies*, 102. <https://doi.org/10.1016/j.ifset.2025.104008>
2. Alahakoon, A. U., Oey, I., Bremer, P., & Silcock, P. (2018). Optimisation of sous vide processing parameters for pulsed electric fields treated beef briskets. *Food and Bioprocess Technology*, 11(11), 2055–2066. <https://doi.org/10.1007/s11947-018-2155-9>
3. Arroyo, C., Eslami, S., Brunton, N. P., Arimi, J. M., Noci, F., & Lyng, J. G. (2015a). An assessment of the impact of pulsed electric fields processing factors on oxidation, color, texture, and sensory attributes of turkey breast meat. *Poultry Science*, 94(5), 1088–1095. <https://doi.org/10.3382/ps/pev097>
4. Arroyo, C., Lascorz, D., O'Dowd, L., Noci, F., Arimi, J., & Lyng, J. G. (2015b). Effect of pulsed electric field treatments at various stages during conditioning on quality attributes of beef *longissimus thoracis et lumborum* muscle. *Meat Science*, 99, 52–59. <https://doi.org/10.1016/j.meatsci.2014.08.004>
5. Baldi, G., D'Elia, F., Soglia, F., Tappi, S., Petracci, M., & Rocculi, P. (2021). Exploring the effect of pulsed electric fields on the technological properties of chicken meat. *Foods*, 10(2). Article 2. <https://doi.org/10.3390/foods10020241>
6. Beno, F., Skorpilova, T., Pohunek, V., Podskalska, T., Mrlik, M., Tobolkova, A., & Sevcik, R. (2023). Effect of pulsed electric field treatment on beef cuts properties: Tenderness, colour, drip loss, pH, electrical conductivity, water activity, cooking losses, drying. *Innovative Food Science & Emerging Technologies*, 89, 103482. <https://doi.org/10.1016/j.ifset.2023.103482>
7. Chang, C., Lung, C., Gavahian, M., Yudhistira, B., Chen, M., Santoso, S. P., & Hsieh, C. (2023). Effect of pulsed electric field-assisted thawing on the gelling properties of pekin duck meat myofibrillar protein. *Journal of Food Engineering*, 350. <https://doi.org/10.1016/j.jfoodeng.2023.111482>
8. Chen, C., Hu, Y., Sun, Y., Xia, Q., Zhou, C., & Pan, D. (2026). Pulsed electric field treatment promotes goose meat tenderness by inducing structural disruption of myofibrillar proteins during aging. *Food Chemistry*, 512, 148908. <https://doi.org/10.1016/j.foodchem.2026.148908>
9. Chen, L., Liu, J., Zhou, F., Zhang, Y., Zhao, T., Jiao, W., Liu, W., Chen, Z., Zhou, W., Huang, L., Lan, K., Zhang, Y., & Nan, H. (2026). The effect of high voltage electrostatic field-assisted thawing on the quality of ctenopharyngodon idella and myofibrillar proteins. *Food Chemistry*, 508, 148289. <https://doi.org/10.1016/j.foodchem.2026.148289>
10. Cheng, Y., Zheng, Y., Zhou, C., Huang, S., Sun, Y., Yan, H., Cao, J., Pan, D., & Xia, Q. (2025). Mechanistic insights into the modulation of myofibrillar protein microstructure and physicochemical properties in conditioned goose using pulsed electric field treatment. *International Journal of Biological Macromolecules*, 310, 143540. <https://doi.org/10.1016/j.ijbiomac.2025.143540>
11. Chian, F. M., Kaur, L., Oey, I., Astruc, T., Hodgkinson, S., & Boland, M. (2019). Effect of pulsed electric fields (PEF) on the ultrastructure and in vitro protein digestibility of bovine longissimus thoracis. *LWT-Food Science and Technology*, 103, 253–259. <https://doi.org/10.1016/j.lwt.2019.01.005>

12. Çimen, N., Unal, K., & Alp, H. (2024). Effects of ultrasound-assisted marination on spent hen meats: Microstructure, textural and technological properties. *Food Bioscience*, 61, 104563. <https://doi.org/10.1016/j.fbio.2024.104563>
13. Dong, M., Tian, H., Xu, Y., Han, M., & Xu, X. (2021). Effects of pulsed electric fields on the conformation and gelation properties of myofibrillar proteins isolated from pale, soft, exudative (PSE)-like chicken breast meat: A molecular dynamics study. *Food Chemistry*, 342, 128306. <https://doi.org/10.1016/j.foodchem.2020.128306>
14. Dong, M., Xu, Y., Zhang, Y., Han, M., Wang, P., Xu, X., & Zhou, G. (2020). Physicochemical and structural properties of myofibrillar proteins isolated from pale, soft, exudative (PSE)-like chicken breast meat: Effects of pulsed electric field (PEF). *Innovative Food Science & Emerging Technologies*, 59, 102277. <https://doi.org/10.1016/j.ifset.2019.102277>
15. Farahmand, A., Naji Tabasi, S., Ghorani, B., Emadzadeh, B., Dovom, M., A., & Toker, O. S. (2026). Enhancing quinoa protein properties: Pulsed electric fields as a sustainable green innovation for structural and functional excellence. *Innovative Food Science & Emerging Technologies*, 109. <https://doi.org/10.1016/j.ifset.2026.104433>
16. Faridnia, F., Bekhit, A. E. D. A., Niven, B., & Oey, I. (2014). Impact of pulsed electric fields and post-mortem vacuum ageing on beef longissimus thoracis muscles. *International Journal of Food Science and Technology*, 49(11), 2339–2347. <https://doi.org/10.1111/ijfs.12532>
17. Faridnia, F., Ma, Q. L., Bremer, P. J., Burritt, D. J., Hamid, N., & Oey, I. (2015). Effect of freezing as pre-treatment prior to pulsed electric field processing on quality traits of beef muscles. *Innovative Food Science & Emerging Technologies*, 29, 31–40. <https://doi.org/10.1016/j.ifset.2014.09.007>
18. Gao, J., Cheng, S., Zeng, X., Sun, X., Bai, Y., Hu, S., Yue, J., Yu, X., Zhang, M., Xu, X., & Han, M. (2024). Effects of contact ultrasound coupled with infrared radiation on drying kinetics, water migration and physical properties of beef during hot air drying. *Ultrasonics Sonochemistry*, 108. <https://doi.org/10.1016/j.ultsonch.2024.106978>
19. Gharibzahedi, S. M. T., & Mohammadnabi, S. (2017). Effect of novel bioactive edible coatings based on jujube gum and nettle oil-loaded nanoemulsions on the shelf-life of beluga sturgeon fillets. *International Journal of Biological Macromolecules*, 95, 769–777. <https://doi.org/10.1016/j.ijbiomac.2016.11.119>
20. Guo, Y., Chen, T., Hu, S., Yue, J., Yu, X., Xu, X., & Han, M. (2025). Impact of pulsed electric field pretreatment on protein and its binding with sodium ions in brined beef. *Innovative Food Science & Emerging Technologies*, 102, 104020. <https://doi.org/10.1016/j.ifset.2025.104020>
21. Jeong, S., Jung, Y., Kim, S., Kim, J., Yeo, H., & Lee, D. (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(3). <https://doi.org/10.3390/foods12030430>
22. Jeong, S., Lee, H., & Lee, D. (2024). Effects of pulsed electric field on meat tenderization and microbial decontamination: A review. *Food Science of Animal Resources*, 44(2), 239–254. <https://doi.org/10.5851/kosfa.2023.e82>

23. Jiang, L., Turchiuli, C., Xu, Z., Li, J., & Wu, S. (2026). Effects of red algae on the properties of chicken gels: Appearance, gelation, texture. *Innovative Food Science & Emerging Technologies*, 107, 104325. <https://doi.org/10.1016/j.ifset.2025.104325>
24. Jiang, Y., Gao, X., Zhang, W., Liang, H., Li, A., & Zhou, C. (2025). Gelatin and L-arginine or L-lysine interact to decrease cooking loss and increase texture of pale, soft and exudative (PSE)-like chicken sausages. *British Poultry Science*, 66(5), 625–632. <https://doi.org/10.1080/00071668.2025.2485246>
25. Jurak, M., Sujka, M., Wiacek, A. E., & Pankiewicz, U. (2026). Permeability of phospholipid membranes to divalent cations: The effect of pulsed electric field. *Molecules*, 31(1). <https://doi.org/10.3390/molecules31010151>
26. Karki, R., Oey, I., Bremer, P., Leong, S. Y., & Silcock, P. (2023a). Effect of chilled storage on the quality, in-vitro protein digestibility, and microbial growth of sous vide processed beef short ribs pre-treated with pulsed electric field (PEF). *Innovative Food Science & Emerging Technologies*, 89. <https://doi.org/10.1016/j.ifset.2023.103485>
27. Karki, R., Oey, I., Bremer, P., & Silcock, P. (2023b). Understanding the effect of meat electrical conductivity on pulsed electric field (PEF) process parameters and the ability of PEF to enhance the quality and shorten sous vide processing for beef short ribs. *Food Research International*, 163, 112251. <https://doi.org/10.1016/j.foodres.2022.112251>
28. Kim, G., Jeong, J., Hur, S., Yang, H., Jeon, J., & Joo, S. (2010). The relationship between meat color (CIE L^* and a^*), myoglobin content, and their influence on muscle fiber characteristics and pork quality. *Korean Journal for Food Science of Animal Resources*, 30(4), 626–633. <https://doi.org/10.5851/kosfa.2010.30.4.626>
29. Koohmaraie, M. (1996). Biochemical factors regulating the toughening and tenderization processes of meat. *Meat Science*, 43, S193–S201. [https://doi.org/10.1016/0309-1740\(96\)00065-4](https://doi.org/10.1016/0309-1740(96)00065-4)
30. Leng, D., Xu, Y., Wang, S., Wang, D., Wang, X., Hou, C., Li, X., & Zhang, D. (2025). Effects of static magnetic field exposure timing and duration at postmortem on water-holding capacity of fresh pork. *Innovative Food Science & Emerging Technologies*, 106. <https://doi.org/10.1016/j.ifset.2025.104287>
31. Li, B., Tang, T., Jiang, M., Chen, H., & Bai, Y. (2026). Sustained-release electrospun films incorporated with oregano essential oil: Characterization, release kinetics and active packaging application for chicken breast. *Journal of Food Engineering*, 404, 112760. <https://doi.org/10.1016/j.jfoodeng.2025.112760>
32. Li, D., Zhao, H., Muhammad, A. I., Song, L., Guo, M., & Liu, D. (2020). The comparison of ultrasound-assisted thawing, air thawing and water immersion thawing on the quality of slow/fast freezing bighead carp (*aristichthys nobilis*) fillets. *Food Chemistry*, 320, 126614. <https://doi.org/10.1016/j.foodchem.2020.126614>
33. Li, J., Huang, Y., Li, Y., Luo, S., Xiong, W., Wang, J., Cheng, J., He, T., & Zeng, X. (2026). Inhibitory effect of pulsed electric field pretreatment on acrylamide formation in air-fried french fries and its mechanism. *Food Research International*, 231. <https://doi.org/10.1016/j.foodres.2026.118783>

34. Li, J., Wang, Q., Liang, R., Mao, Y., Hopkins, D. L., Li, K., Yang, X., Luo, X., Zhu, L., & Zhang, Y. (2024). Effects and mechanism of sub-freezing storage on water holding capacity and tenderness of beef. *Meat Science*, 215, 109540. <https://doi.org/10.1016/j.meatsci.2024.109540>
35. Li, K., Kang, Z., Zhao, Y., & Xu, X. (2014). Use of high-intensity ultrasound to improve functional properties of batter suspensions prepared from PSE-like chicken breast meat. *Food and Bioprocess Technology*, 7(12), 3466–3477. <https://doi.org/10.1007/s11947-014-1358-y>
36. Li, X., Hou, F., Wang, Y., & Xiong, Q. (2025). Mechanism of needle electrode-derived pulsed electric fields on the structural and physicochemical properties of pork salting. *Food Research International*, 218. <https://doi.org/10.1016/j.foodres.2025.116766>
37. Luo, Q., Hamid, N., Oey, I., Leong, S. Y., Kantono, K., Alfaro, A., & Lu, J. (2019). Physicochemical changes in new zealand abalone (*haliotis iris*) with pulsed electric field (PEF) processing and heat treatments. *LWT - Food Science and Technology*, 115, 108438. <https://doi.org/10.1016/j.lwt.2019.108438>
38. Ma, Q., Hamid, N., Oey, I., Kantono, K., Faridnia, F., Yoo, M., & Farouk, M. (2016). Effect of chilled and freezing pre-treatments prior to pulsed electric field processing on volatile profile and sensory attributes of cooked lamb meats. *Innovative Food Science & Emerging Technologies*, 37, 359–374. <https://doi.org/10.1016/j.ifset.2016.04.009>
39. Manhani, M. R., Nicoletti, M. A., Barretto, A. C. D. S., Jesus, G. R. D., Munhoz, C. C., Abreu, G. R. D., Zaccarelli-Magalhães, J., & Fukushima, A. R. (2018). Antioxidant action of rosemary and oregano extract in pre-cooked meat hamburger. *Food and Nutrition Sciences*, 9(7), 806–817. <https://doi.org/10.4236/fns.2018.97060>
40. McDonnell, C. K., Allen, P., Chardonnerau, F. S., Arimi, J. M., & Lyng, J. G. (2014). The use of pulsed electric fields for accelerating the salting of pork. *LWT - Food Science and Technology*, 59(2), 1054–1060. <https://doi.org/10.1016/j.lwt.2014.05.053>
41. Mehmood, W., & Zhang, C. (2020). Correlations between muscle fibers characteristics and meat quality attributes of biceps femoris muscle: A comparative study of 2 distinctive broiler breeds. *Brazilian Journal of Poultry Science*, 22(4). <https://doi.org/10.1590/1806-9061-2019-1171>
42. Mungure, T. E., Farouk, M. M., Carne, A., Staincliffe, M., Stewart, I., Jowett, T., Bhat, Z. F., & Bekhit, A. E. D. A. (2023). Understanding the influence of PEF treatment on minerals and lipid oxidation of wet- and dry-aged venison *M. longissimus dorsi* muscle. *Innovative Food Science & Emerging Technologies*, 83, 103238. <https://doi.org/10.1016/j.ifset.2022.103238>
43. Nam, K. C., & Ahn, D. U. (2003). Combination of aerobic and vacuum packaging to control lipid oxidation and off-odor volatiles of irradiated raw turkey breast. *Meat Science*, 63(3), 389–395. [https://doi.org/10.1016/S0309-1740\(02\)00098-0](https://doi.org/10.1016/S0309-1740(02)00098-0)
44. Novickij, V., Cesna, R., Perminaitė, E., Zinkeviciene, A., Characiejus, D., Novickij, J., Satkauskas, S., Ruzgys, P., & Girkontaite, I. (2019). Antitumor response and immunomodulatory effects of sub-microsecond irreversible electroporation and its combination with calcium electroporation. *Cancers*, 11(11). <https://doi.org/10.3390/cancers11111763>

45. Nowacka, M., Szymanska, I., Rybak, K., Karwacka, M., Matys, A., Wiktor, A., Slowinski, M., & Rajchert, W., D (2024). Effect of PEF treatment on chosen properties of raw and hot air- and freeze-dried poultry meat. *Applied Sciences-Basel*, 14(5). <https://doi.org/10.3390/app14051808>
46. Pearce, K. L., Rosenvold, K., Andersen, H. J., & Hopkins, D. L. (2011). Water distribution and mobility in meat during the conversion of muscle to meat and ageing and the impacts on fresh meat quality attributes—A review. *Meat Science*, 89(2), 111–124. <https://doi.org/10.1016/j.meatsci.2011.04.007>
47. Queiroz, L. S., Subtil, C., Lardoux, P., Casanova, F., Jacobsen, C., & Gringer, N. (2025). Effect of emerging technologies on the physicochemical and colloidal properties of protein hydrolysate from *pandalus borealis* side-streams. *LWT-Food Science and Technology*, 233. <https://doi.org/10.1016/j.lwt.2025.118533>
48. Rondineli, A., & Silva, E. K. (2024). Pulsed electric field as a pre-treatment in food freezing processes: Fundamentals, mechanisms, applications and impacts on frozen food quality. *Food Bioscience*, 60. <https://doi.org/10.1016/j.fbio.2024.104275>
49. Roobab, U., Chen, B., Madni, G. M., Guo, S., Zeng, X., Abdi, G., & Aadil, R. M. (2024a). Enhancing chicken breast meat quality through ultrasonication: Physicochemical, palatability, and amino acid profiles. *Ultrasonics Sonochemistry*, 104, 106824. <https://doi.org/10.1016/j.ultsonch.2024.106824>
50. Roobab, U., Chen, B., Madni, G. M., Tong, Z. G., Zeng, X. A., Abdi, G., Hussain, S., & Aadil, R. M. (2024b). Evaluation of ultrasound and pulsed electric field combinations on the cooking losses, texture profile, and taste-related amino acids of chicken breast meat. *Ultrasonics Sonochemistry*, 107, 106919. <https://doi.org/10.1016/j.ultsonch.2024.106919>
51. Roobab, U., Zeng, X., Ahmed, W., Madni, G. M., Manzoor, M. F., & Aadil, R. M. (2023). Effect of pulsed electric field on the chicken meat quality and taste-related amino acid stability: Flavor simulation. *Foods*, 12(4). <https://doi.org/10.3390/foods12040710>
52. Shen, X., Xing, L., Pan, L., Miao, Y., & Zhang, W. (2025). Prediction of chicken breast meat freshness based on hyperspectral imaging technique and high-throughput sequencing. *Poultry Science*, 104(4), 104999. <https://doi.org/10.1016/j.psj.2025.104999>
53. Sitzmann, W., Vorobiev, E., & Lebovka, N. (2016). Applications of electricity and specifically pulsed electric fields in food processing: Historical backgrounds. *Innovative Food Science & Emerging Technologies, Electroporation and Pulsed Electric Fields in Bio- and Food Technologies*, 37, 302–311. <https://doi.org/10.1016/j.ifset.2016.09.021>
54. 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>
55. Suliga, P., Schneider, S., Gonzalez, J., Egelanddal, B., Alvseike, O., Abie, S. M., & Muench, D. (2024). A new histopathology scoring protocol reveals myopathy features in PSE-like pork. *Meat Science*, 216. <https://doi.org/10.1016/j.meatsci.2024.109558>
56. Suwandy, V., Carne, A., van de Ven, R., Bekhit, A. E. D. A., & Hopkins, D. L. (2015). Effect of pulsed electric field treatment on hot-boned muscles of different potential tenderness. *Meat Science*, 105,

- 25–31. <https://doi.org/10.1016/j.meatsci.2015.02.009>
57. Szymańko, T., Lesiów, T., & Górecka, J. (2021). The water-holding capacity of meat: A reference analytical method. *Food Chemistry*, 357, 129727. <https://doi.org/10.1016/j.foodchem.2021.129727>
58. Toepfl, S., Heinz, V., & Knorr, D. (2006). Applications of pulsed electric fields technology for the food industry. *Pulsed Electric Fields Technology for the Food Industry*, 197–221.
59. Tornberg, E. (2005). Effects of heat on meat proteins—Implications on structure and quality of meat products. *Meat Science*, 70(3), 493–508. <https://doi.org/10.1016/j.meatsci.2004.11.021>
60. U chupaj, J., Malila, Y., Gamonpilas, C., Kijroongrojana, K., Petracci, M., Benjakul, S., & Visessanguan, W. (2017). Differences in textural properties of cooked caponized and broiler chicken breast meat. *Poultry Science*, 96(7), 2491–2500. <https://doi.org/10.3382/ps/pex006>
61. Vojtisek, S., Beno, F., Hruska, F., Taborovec, S., Pohunek, V., & Sevcik, R. (2025). Effects of pulsed electric field and ultrasound treatment on the drying kinetics and quality of beef jerky. *Innovative Food Science & Emerging Technologies*, 106. <https://doi.org/10.1016/j.ifset.2025.104259>
62. Wang, J., Li, J., Wang, R., Xu, F., & Zeng, X. (2022). Improving water retention of chicken breast meats by CaCl₂ combined with pulsed electric fields. *International Journal of Food Science and Technology*, 57(2), 791–800. <https://doi.org/10.1111/ijfs.15397>
63. Wang, J., Wang, Q., Xu, L., & Sun, D. (2022). Effects of extremely low frequency pulsed electric field (ELF-PEF) on the quality and microstructure of tilapia during cold storage. *LWT - Food Science and Technology*, 169, 113937. <https://doi.org/10.1016/j.lwt.2022.113937>
64. Wang, L., Zhang, Y., Yang, Q., Li, K., Ma, W., & Bai, Y. (2025). A comparative study on the PSE-like chicken breast meat protein isolate-sunflower oil emulsion stability, rheological properties and gel properties by different additions of L-lysine. *Food Chemistry: X*, 29. <https://doi.org/10.1016/j.fochx.2025.102684>
65. Wang, Z., Zhou, H., Zhou, K., Tu, J., & Xu, B. (2022). An underlying softening mechanism in pale, soft and exudative – like rabbit meat: The role of reactive oxygen species – generating systems. *Food Research International*, 151, 110853. <https://doi.org/10.1016/j.foodres.2021.110853>
66. Wu, Y., Xu, Y., Shen, Q., Xu, T., Dong, Z., & Lou, A. (2024). Optimization of pulsed electric fields-assisted thawing process conditions and its effect on the quality of zhijiang duck meat. *Food Chemistry: X*, 24, 101812. <https://doi.org/10.1016/j.fochx.2024.101812>
67. Wu, Z., Ma, W., Xian, Z., Liu, Q., Hui, A., & Zhang, W. (2021). The impact of quick-freezing methods on the quality, moisture distribution and microstructure of prepared ground pork during storage duration. *Ultrasonics Sonochemistry*, 78, 105707. <https://doi.org/10.1016/j.ultsonch.2021.105707>
68. Xiao, W., Geng, Y., Gao, W., Zeng, X., Woo, M., Ma, J., & Han, Z. (2026). A comprehensive review of the applications of pulsed electric field: Primary emphasis on extraction, modification, and inactivation. *Innovative Food Science & Emerging Technologies*, 109. <https://doi.org/10.1016/j.ifset.2025.104420>
69. Xu, J., Sun, Q., Hashim, S. B. H., Ren, J., Shi, J., & Zou, X. (2025). Meat preservation innovation: Ultrasonic pretreatment-driven quality improvement in vacuum-cooled chicken breast. *Food Chemistry*, 493, 145554. <https://doi.org/10.1016/j.foodchem.2025.145554>

70. Yang, N., Liang, X., Cao, J., Zhang, Q., Tan, Y., Xu, B., Yang, Y., Wang, Y., Yang, Q., Liu, H., & Liu, J. (2022). Denaturation manner of sarcoplasmic proteins in pale, soft and exudative meat determines their positive impacts on myofibrillar water-holding capacity. *Meat Science*, 185. <https://doi.org/10.1016/j.meatsci.2021.108723>
71. Yang, T., Yang, Y., Zhang, P., Li, W., Ge, Q., Yu, H., Wu, M., Xing, L., Qian, Z., Gao, F., & Liu, R. (2023). Quantitative proteomics analysis on the meat quality of processed pale, soft, and exudative (PSE)-like broiler pectoralis major by different heating methods. *Food Chemistry*, 426, 136602. <https://doi.org/10.1016/j.foodchem.2023.136602>

Figures

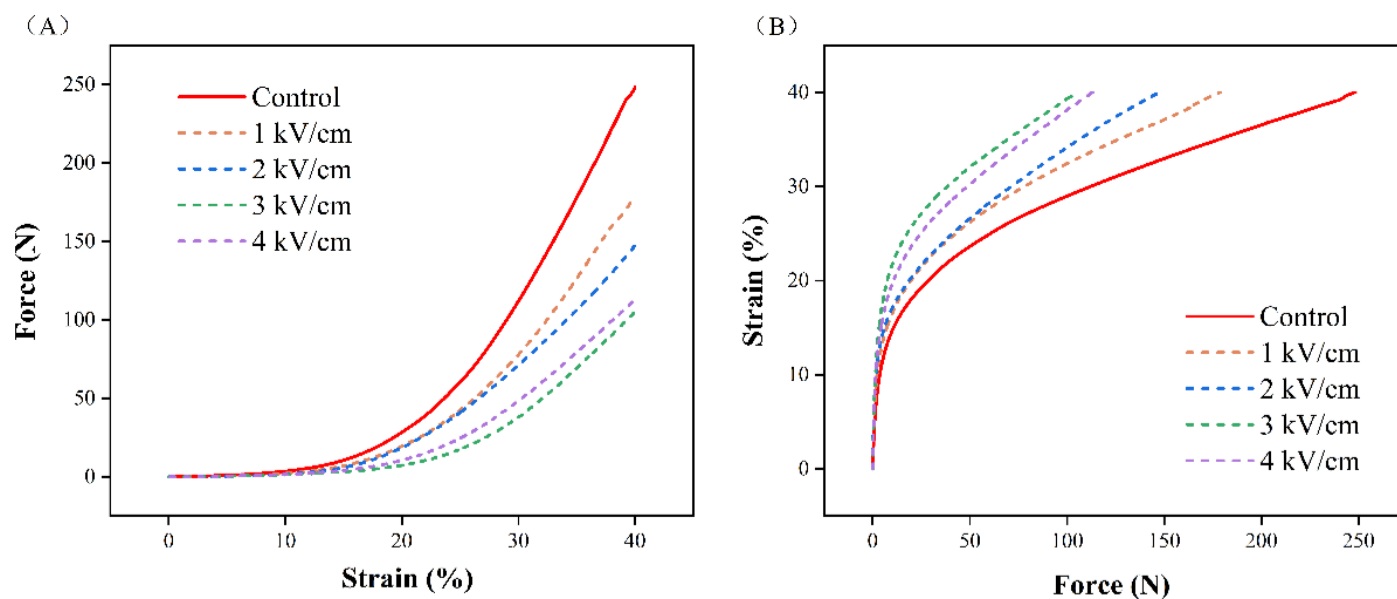


Figure 1

Effect of PEF treatment at different electric field strengths on the stress-strain curves of PSE-like meat: (A) Force-strain curve; (B) Strain-force curve.

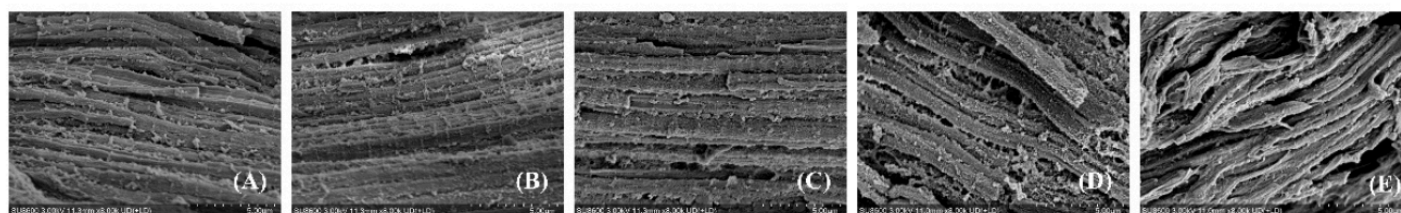


Figure 2

Effects of different electric field strengths on the microstructure of PSE-like meat.

Note: A-E correspond to the control, 1 kV/cm, 2 kV/cm, 3 kV/cm, and 4 kV/cm groups, respectively.

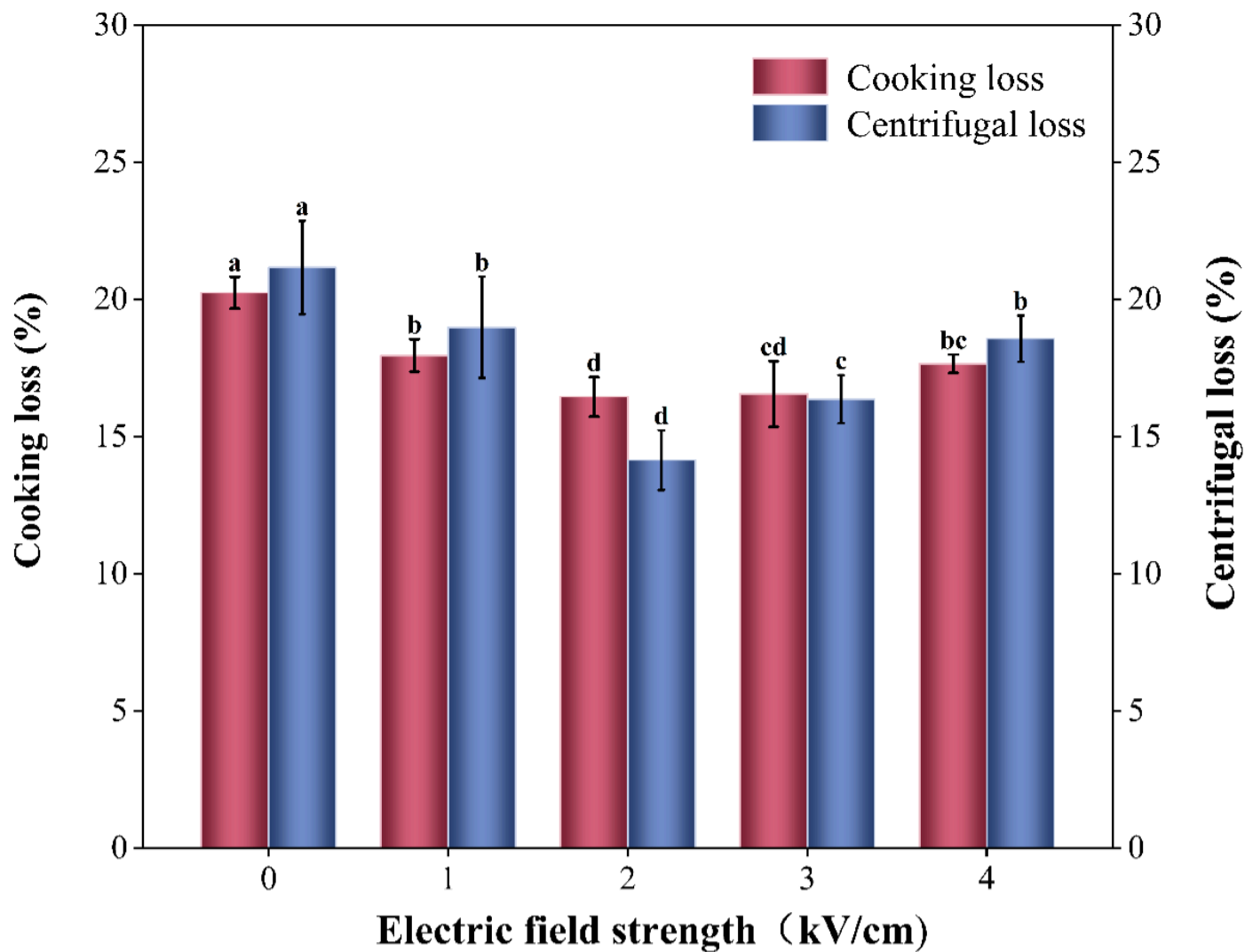


Figure 3

Effects of different electric field strengths on the water-holding capacity of PSE-like meat.

Note: Different lowercase letters (a-d) within the same indicator indicated significant differences among groups ($p < 0.05$).

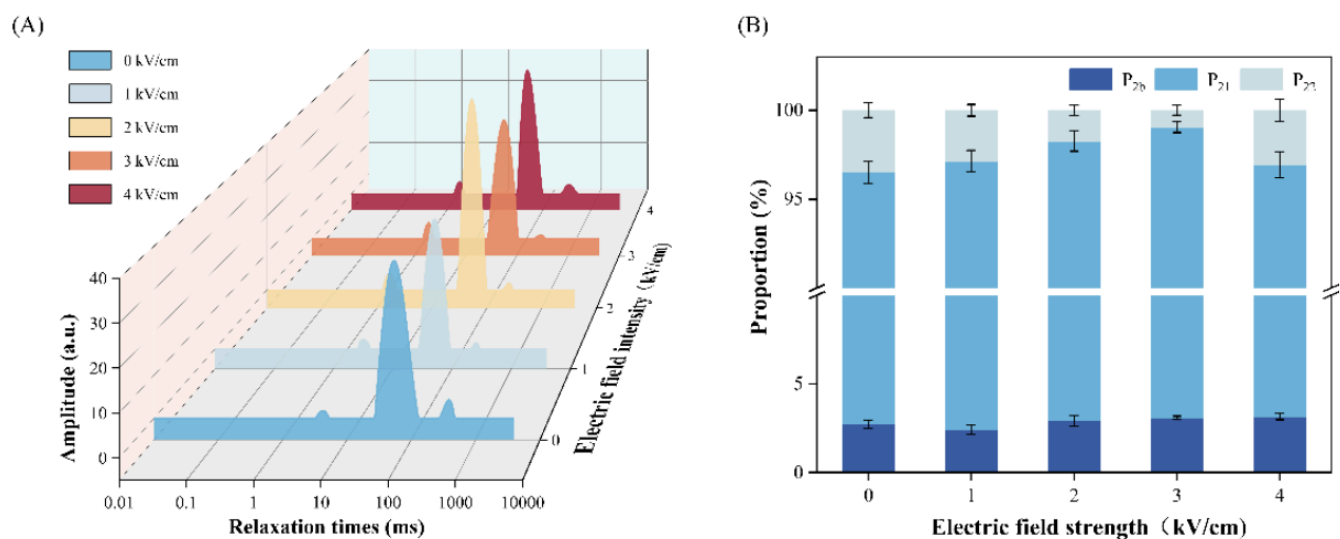


Figure 4

PEF treatment at different electric field strengths on T_2 relaxation time distribution of PSE-like chicken breast: (A) T_2 relaxation time distribution curves; (B) relative proportions of T_2 components (T_{2b} , T_{21} , and T_{22}).

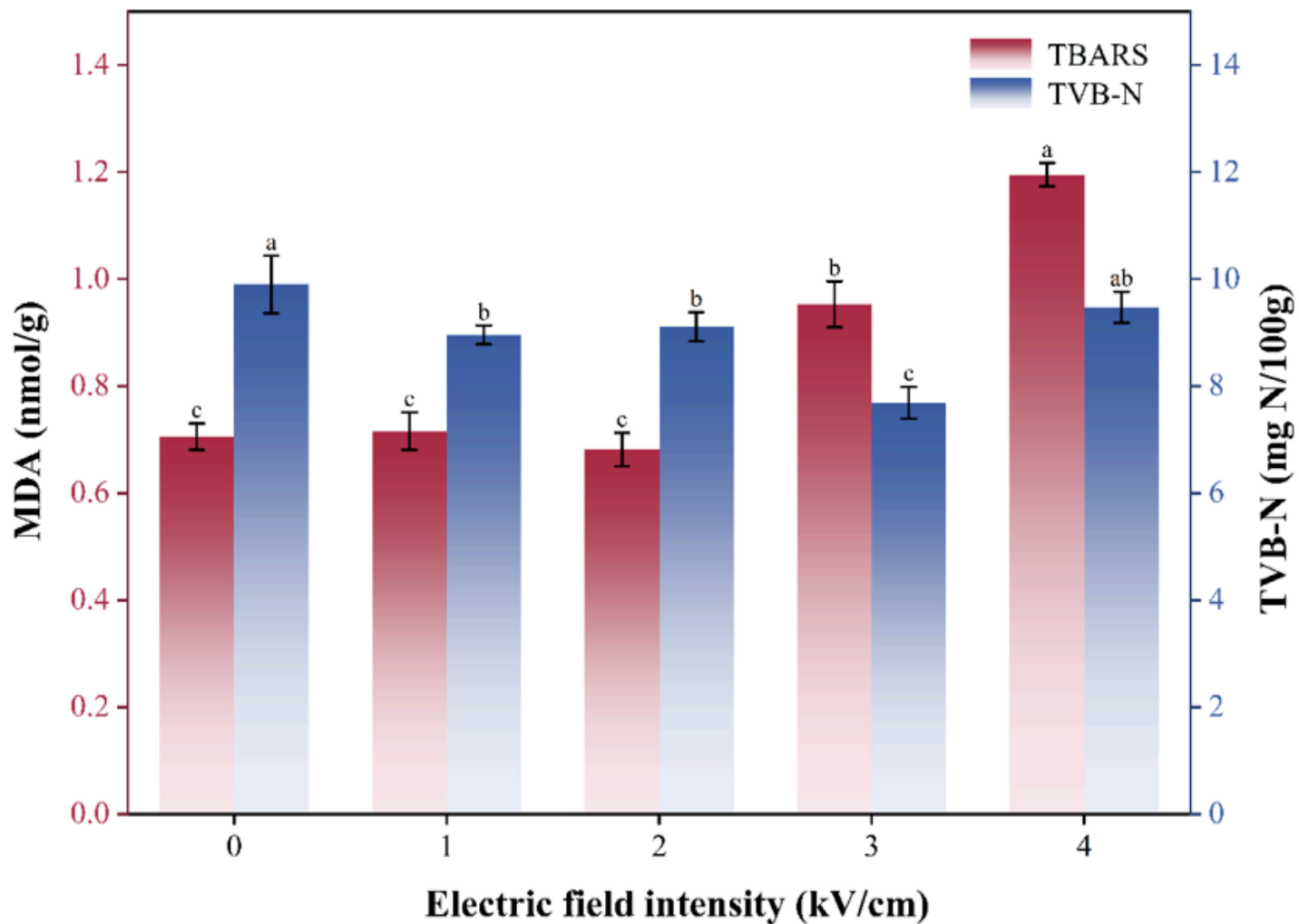


Figure 5

Effects of different electric field strengths on TBARS and TVB-N values of PSE-like meat.

Note: Different lowercase letters (a-d) within the same indicator indicated significant differences among groups ($p < 0.05$).

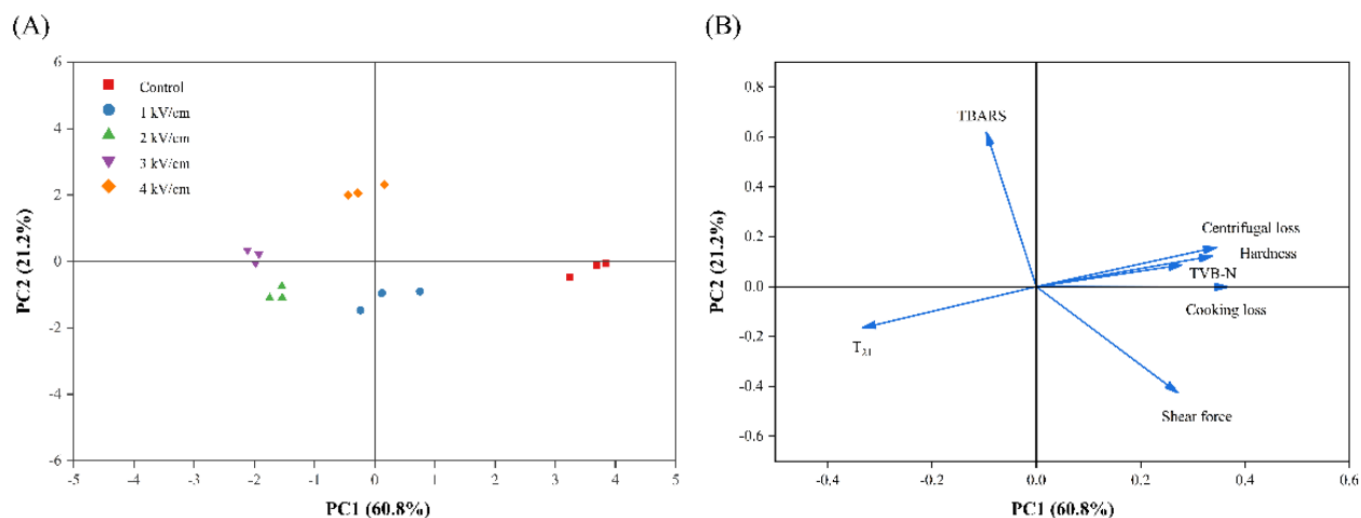


Figure 6

Principal component analysis of seven quality parameters in PSE-like chicken breast: (A) score plot; (B) loading plot. The first two principal components, PC1 and PC2, accounted for 60.8% and 21.2% of the total variance, respectively, explaining 82.0% of the cumulative variance.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- [Graphicalabstract.docx](#)
- [Hightlights.docx](#)