Food Science of Animal Products

Research Article

Gelling characteristics of myofibrillar proteins pretreated with a low-voltage electrostatic field

Ning Ding[1,§], Peng Wang[1,§], Guangyan Zhao[2], Junyao Ma[3], Aiguo Dai[4], Yujiao Qu[5], Guohua Zhang[2] ✉, Jingxin Sun[1] ✉

[1] *Shandong Provincial Meat Product Quality Control Engineering Technology Research Center, College of Food Science & Engineering, Qingdao Agricultural University, Qingdao 266109, China*
[2] *Qingdao Xianyou Food Co., Ltd., Qingdao 266111, China*
[3] *Shiyoudaguan (Qingdao) Food R&D Co., Ltd., Qingdao 266101, China*
[4] *Qingdao Bernia Food Group Co., Ltd., Qingdao 266799, China*
[5] *Weihai Humon Mine Smelting Development Co., Ltd., Weihai 264200, China*
§ These authors contributed equally to this work.
✉Address correspondence to Guohua Zhang, 445404928@qq.com; Jingxin Sun, jxsun20000@163.com
Received: April 3, 2026; Revised: May 11, 2026; Accepted: May 20, 2026

Abstract: The effects of low-voltage electrostatic field (LVEF) treatment durations (0, 10, 20, 30, 40, 50, and 60 min) on the micro-structure and performances of myofibrillar protein (MP) gel were investigated. The results indicated that LVEF primarily altered the interactions between MPs and between MP and water by modifying the surface charge of the MP and accelerating the movement of charged particles. Compared with the 0-min group, the MP gel hardness of the 60-min group increased, while the water retention decreased. Rheological analysis showed that the thermal denaturation temperature of MP gel decreased, and the denaturation rate accelerated in the LVEF-treated group, with improvements proportional to the treatment time. Additionally, LVEF treatment resulted in finer fibers and a denser network structure in the MP gel. However, when the treatment time exceeded 40 min, the effects of LVEF were less pronounced.

Keywords: low-voltage electrostatic field; myofibrillar protein; gel properties; microstructure

Citation: N. Ding, P. Wang, G. Y. Zhao, et al., Gelling characteristics of myofibrillar proteins pretreated with a low-voltage electrostatic field, Food Sci. Anim. Prod. 4 (2026) 9240182. https://doi.org/10.26599/FSAP.2026.9240182.

1 Introduction

Applications of the electrostatic field, an important non-thermal processing technology that accelerates the movement of water molecules and induces charged molecules, have steadily increased in the food industry[1]. The electrostatic field can be divided into high-voltage (> 2 500 V) and low-voltage (< 2 500 V) electrostatic fields. However, high-voltage electrostatic fields face limitations in practical applications, such as high costs, inconvenience, and instability, making them difficult to apply in large-scale food processing in the short term. In contrast, the low-voltage electrostatic field (LVEF) offers advantages in terms of energy efficiency, safety, and practicality[2]. Currently, electrostatic fields are primarily applied in food drying[3] food preservation[4], food sterilization[5], and food thawing[6–7].

Myofibrillar protein (MP), which constitutes muscle fibers, plays a critical role in determining meat product quality. MP undergoes thermal-induced gelation in three steps: denaturation, aggregation, and crosslinking. During thermal induction, MP cross-links and polymerizes, leading to conformational changes such as the dissociation of noncovalent bonds and the exposure of reactive groups[8].

Duck meat production has increased sharply, with China, France, Vietnam, Myanmar, and Malaysia being the five largest duck meat producers globally. Prompted by customer need for the treated food, the worldwide duck meat market is anticipated to develop stably[9]. Duck meat is characterized by its dark color, strong flavor, and notably poor gelation properties attributed to its higher unsaturated fatty acid content and weaker hydrophobic interactions among MPs compared to mammalian meats[10]. Processing duck meat into minced meat can improve its acceptability; however, studies on improving duck meat gel are limited, especially research on the effects of LVEF on MP gel. Therefore, this study used LVEF as the treatment method, with duck meat as the raw material, with the aim of exploring the influences of different LVEF treatment times (10, 20, 30, 40, 50, and 60 min) on the physicochemical performances of MP gel.

2 Materials and methods

2.1 Materials

Breast meat from Cherry Valley ducks (24 h post-mortem) was purchased from Newhope Liuhe Group Co., Ltd. (Qingdao, China). Ethylenediaminetetraacetic acid and phosphate-buffered saline (PBS) were provided by Hushi Co., Ltd. (Shanghai, China). All the other reagents were used as analytical grade.

2.2 Extraction of MP

Following the approach of Wang et al.[11], MPs were extracted. Fresh duck meat was collected, delipidated, and minced. The minced meat was soaked in five times mass the extraction buffer volume (6 mmol/L Na_2HPO_4, 10 mmol/L NaCl, 2 mmol/L $MgCl_2$, 1 mmol/L ethylene glycol tetracetic acid, pH 7.0). The mix was homogenized

© Beijing Academy of Food Sciences 2026. Food Science of Animal Products published by Tsinghua University Press. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

thrice at 8 500 r/min using a homogenizer (FJ200-SH, Shanghai Huxi Industry Co., Ltd., Shanghai, China). The homogenate was centrifuged at 10 000 × *g* and 4 °C using a centrifuge for 15 min (TGL-20M, Xiangyi Centrifuge Instrument Co., Ltd., Changsha, China) to gather the precipitates. Five times the separation buffer volume (10 mmol/L NaCl, 20 mmol/L PBS, pH 6.0) was added and the mixture was centrifuged again under the same conditions after passing through a 40-mesh sieve. The precipitate thus obtained was the MP.

2.3 LVEF treatment

The MP concentration was modulated to 60 mg/mL using a 0.6 mol/L NaCl solution. MP solutions (35 mL) were divided into seven treatment groups. All samples, including the 0 min control group, were placed in the same treatment chamber and maintained under identical environmental conditions (4 °C, ambient humidity) for a total duration matching the longest treatment time (60 min). The MP samples were exposed to an LVEF generated using a 0.1 A/1 500 V field generator (AU-1.5P200, AUGU Business Corp., Japan) with parallel plate electrodes (stainless steel, 10 cm × 10 cm), an electrode spacing of 1.0 cm, and an electric field strength of 1.5 kV/cm for 0, 10, 20, 30, 40, 50, and 60 min. The MP solution was contained in cylindrical glass vials (inner diameter 3 cm, height 5 cm), ensuring the liquid height was 5 cm and the entire sample was uniformly exposed to the vertical electric field. Afterwards, the samples were preserved at 4 °C till in-depth utilization.

2.4 Determination of zeta potential of MP pre-treated with LVEF

The samples were attenuated with deionized water to a concentration of 1 mg/mL and centrifuged at 4 000 × *g* for 10 min, with the supernatant collected. Zeta potential was measured using a dynamic light scattering tool (ZEN3690, Malvern Co., Ltd., Worcester, UK) following the method described by Wang et al.[11].

2.5 Preparation of heat-induced MP gel

The MP solution (2 mL), treated with LVEF, was poured into one water bath and warmed from 25 to 85 °C at a speed of 1 °C/min. Once the temperature reached 85 °C, it was maintained for 20 min, then immediately transferred to one ice bath for 10 min. MP gels were preserved at 4 °C till in-depth utilization.

2.6 Fourier transform infrared (FTIR) spectroscopy measurement

The lyophilized MP gels were measured using a FTIR spectrometer (8400, Shimadzu Corp., Kyoto, Japan) following the approach of Wang et al.[12]. The samples were scanned at a resolution of 4 cm^{-1}, across a range of 500–4 000 cm^{-1}, with a total of 64 scans.

2.7 Raman spectroscopy measurement

Following the approach of Wang et al.[11], gel samples (2 mm × 2 mm × 1 mm) were put on glass slides and analyzed through a Raman spectrometer (INVIA REFLEX 12-80000, Renishaw, UK). The settings were listed below: power 100 mW, laser wavelength 532 nm, scanning scope 400–2 000 cm^{-1}, and resolution 4 cm^{-1}.

2.8 Water-holding capacity (WHC) measurement

The WHC of the MP gels was measured following the approach of Wang et al.[12]. Gel samples were centrifuged at 10 000 × *g* for 10 min, and the gel mass before and after centrifugation was recorded. WHC was figured out through the equation:

$$\mathrm{WHC}\,(\%) = \frac{m_1}{m_0} \times 100$$

Where m_0 and m_1 represent the weights (g) of the gel before and after centrifugation, respectively.

2.9 Textural properties measurement

A texture profiler (Texan 200, Lamy Inc., Lyon, France) was applied to measure the gel hardness. The method of Jiang et al.[5] was followed in texture profile analysis mode, with the following settings: P50 probe, 2.0 mm/s of pre-test velocity, 1.0 mm/s of test velocity, and 70% of strain.

2.10 Low field-nuclear magnetic resonance (LF-NMR) measurement

The moisture distribution in MP gels was gauged through a LF-NMR profiler (NMI20-040V-I, Suzhou Niumag Analytical Instrument Corp., Suzhou, China). Parameters were set following the method of Xie et al.[7]. The main measurement parameters were as follows: 0.6 T of magnetic field strength, 22.6 MHz of frequency, 32 °C of temperature, and 32 of scans.

2.11 Rheological behavior measurement

The rheological behavior of the MPs was investigated in frequency and temperature sweep patterns through a rheometer (MCR302, Anton Paar, Graz, Austria) following the approach of Martins et al.[13]. In short, temperature sweep conditions were set between 25 and 85 °C with a temperature change rate of 2.0 °C/min, followed by a hold at 85 °C for 5 min. Frequency sweep conditions were set from 25 °C with a strain of 2% and angular frequencies of 0–600 rad/s.

2.12 Scanning electron microscopy (SEM) observation

The gel microstructures were investigated through a scanning electron microscope (7500F, JEOL Ltd., Tokyo, Japan) following the method described by Shi et al.[10]. Briefly, the MP gel was separated into small pieces (10 mm × 10 mm × 5 mm), which were treated with 2.5% glutaraldehyde, 0.1 mol/L NaH_2PO_4 buffer, and absolute ethanol. Next, the samples were dried using liquid nitrogen before SEM observation.

2.13 Statistical analysis

SPSS V26.0 (IBM, US) was applied to analysis on variance (ANOVA), with the LSD test applied to compare means. Data was denoted as mean ± standard deviation, with triplicate determinations ($P < 0.05$).

3 Results and discussion

3.1 Zeta potential of MP pre-treated with LVEF

The changes in zeta potential of MP under LVEF treatment were measured. Generally, if the absolute value of the zeta potential becomes larger, the intermolecular repulsion will be stronger, leading to a more stable dispersion[14]. Figure 1 illustrates that the absolute value of MP zeta potential exhibits an upward trend with increasing LVEF treatment time. This suggests that LVEF enhances the electrostatic force between MP, improving their diffusion stability. The increased electrostatic repulsion between MPs inhibits their aggregation, thereby reducing the mean particle size of the

MP. In comparison to the control group (0 min), the absolute value of MP zeta potential in the 10, 20, and 30 min groups increased to 9.76, 10.97, and 15.24 mV, respectively. This increase could result from the ionized groups exposed on the surface of the MP, leading to a rise in charge[15]. With prolonged LVEF treatment, the rate of increase in the absolute value of the zeta potential slowed in 30, 40, 50, and 60 min groups, suggesting that LVEF has limitations in enhancing the charge of the MP and does not continue to improve with extended processing time.

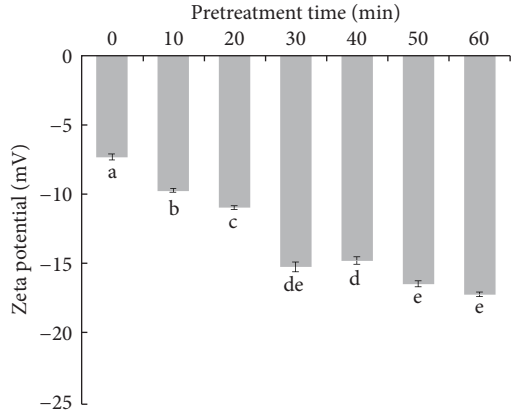


Figure 1 The effect of LVEF pretreatment time on zeta potential of MP. Different lowercase letters represent significant differences ($P < 0.05$).

3.2 FTIR spectroscopy analysis

FTIR spectroscopy was adopted to explore the intermolecular interplay within the protein matrix. As shown in Figure 2A, the MP gel spectrum exhibited characteristic bands: a water band (3 500–3 000 cm^{-1}), an amide I band (1 700–1 600 cm^{-1}), an amide II band (1 600–1 500 cm^{-1}), and an amide III band (1 330–1 200 cm^{-1}). The amide I band consisted mainly of α-helix (1 658–1 650 cm^{-1}), β-sheet (1 640–1 610 cm^{-1}), β-turn (1 670–1 660 cm^{-1}), and random coil (1 650–1 640 cm^{-1}), corresponding to prior discoveries[12].

No remarkable change was examined within overall spectral bands, indicating that no new covalent bonds were formed in the MP gel after LVEF treatment. However, with increased LVEF treatment time, the peak values of the amide I and amide II bands shifted. These changes in the amide I band suggest that LVEF treatment affected secondary structures (α-helix, β-turn, β-sheet, and random coil) of MP gels[16]. In particular, the amide II band, mainly regarding the N–H bending and C–N tensile vibrations, reflected potential modifications in the hydrogen bond network or rearrangement of side chains as electrostatic field treatment time increased. Specifically, the blue-shift of the amide I band (1 650–1 658 cm^{-1}) indicated weakened hydrogen bonding between MP molecules, while the red-shift of the amide II band (1 540–1 530 cm^{-1}) suggested the exposure of hydrophilic side chains (e.g., –OH, $–NH_2$) to the polar aqueous environment, aligning with the increased surface charge observed in zeta potential measurements. These alterations could influence protein flexibility and stability.

3.3 Raman spectra analysis

Raman spectroscopy was utilized to assess structural changes in MP gels, focusing on the amide I and amide III bands, which are indicative of secondary structures[11]. The Raman spectra (400–2 000 cm^{-1}) of MP gels subjected to varying LVEF treatment times are shown in Figure 2B, while Table 1 presents the Raman spectral fitting results. Key structural components of the MP gel included α-helix (1 654 cm^{-1}), β-sheet (1 675 cm^{-1}), β-turn (1 684 cm^{-1}), and random coil (1 664 cm^{-1}). Table 1 indicates that random coil and β-turn structures among MP gels were progressively converted to β-sheet and α-helix by varying proportions. Unlike the control group (0 min), the relative content of α-helix in MP gel appeared to increase by 52.69%, while the β-sheet relative content decreased by 29.75% in the 60 min group. This apparent increase in α-helix content does not necessarily indicate a more flexible state. Instead, it is attributed to the unfolding of globular MP structures under LVEF, which exposes internal helical domains to the solvent. These domains are reorganized into ordered α-helix stabilized by newly formed intramolecular hydrogen bonds, rather than representing a net gain of disordered structure. This conformational ordering, coupled with enhanced electrostatic repulsion and hydrophobic interactions (as evidenced by decreased $I_{760}/I_{1\ 003}$ and increased I_{850}/I_{830} ratios), promotes tighter protein packing and denser network formation, thereby explaining the increased gel hardness and reduced WHC. The increase in α-helix relative content in LVEF-treated MP gels was also linked to the rapid gel formation observed, contributing to the reduced WHC of the gels[2].

Additionally, Raman spectral bands around 760, 830, 850, and 1 453 cm^{-1} were analyzed to evaluate changes in tryptophan residues, tyrosine doublets, and aliphatic residues, respectively, reflecting hydrophobic interactions within the MP gel. As indicated in Table 1, the $I_{1\ 453}/I_{1\ 003}$ ratio did not change significantly,

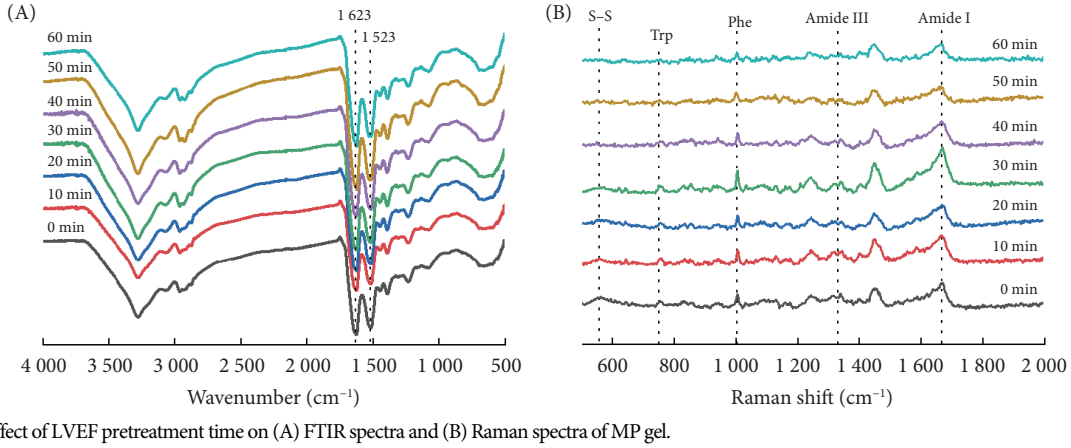


Figure 2 The effect of LVEF pretreatment time on (A) FTIR spectra and (B) Raman spectra of MP gel.

Table 1 The effect of LVEF pretreatment time on the Raman spectra of MP gel.

Pretreatment time (min)	$I_{760}/I_{1\ 003}$	I_{850}/I_{830}	$I_{1\ 453}/I_{1\ 003}$	Relative content (%)			
				α-Helix	β-Sheet	β-Turn	Random coil
0	0.55 ± 0.07^{d}	0.88 ± 0.05^{a}	1.62 ± 0.04^{a}	22.15 ± 0.40^{a}	37.41 ± 0.16^{d}	18.66 ± 0.11^{a}	21.78 ± 0.34^{c}
10	0.53 ± 0.02^{d}	0.89 ± 0.02^{a}	1.57 ± 0.07^{a}	25.46 ± 0.14^{ab}	35.28 ± 0.35^{c}	20.50 ± 0.38^{ab}	18.76 ± 0.24^{c}
20	0.46 ± 0.05^{c}	1.01 ± 0.07^{b}	1.60 ± 0.03^{a}	26.10 ± 0.34^{ab}	35.20 ± 0.18^{c}	22.76 ± 0.19^{b}	15.94 ± 0.17^{b}
30	0.50 ± 0.03^{cd}	1.03 ± 0.01^{b}	1.58 ± 0.11^{a}	31.53 ± 0.29^{c}	34.66 ± 0.15^{c}	24.63 ± 0.29^{c}	9.18 ± 0.16^{a}
40	0.47 ± 0.06^{c}	1.22 ± 0.06^{c}	1.60 ± 0.04^{a}	29.95 ± 0.14^{c}	32.06 ± 0.33^{bc}	24.10 ± 0.37^{c}	13.89 ± 0.04^{b}
50	0.38 ± 0.02^{b}	1.26 ± 0.04^{c}	1.59 ± 0.06^{a}	33.02 ± 0.15^{d}	30.17 ± 0.28^{b}	23.03 ± 0.38^{bc}	13.78 ± 0.09^{b}
60	0.31 ± 0.03^{a}	1.32 ± 0.02^{d}	1.61 ± 0.05^{a}	33.82 ± 0.33^{d}	26.28 ± 0.06^{a}	27.60 ± 0.20^{d}	12.30 ± 0.12^{ab}

Note: Different lowercase letters in the same column represent significant differences ($P < 0.05$). I_{760}, I_{830}, I_{850}, $I_{1\ 130}$, $I_{1\ 453}$ correspond to the intensities of the Raman peaks at wavenumbers of 760, 830, 850, 1 130, 1 453 cm^{-1}, respectively. $I_{760}/I_{1\ 003}$, I_{850}/I_{830}, and $I_{1\ 453}/I_{1\ 003}$ represent the normalized intensities of tryptophan, tyrosine, and aliphatic residues, respectively.

suggesting that LVEF had no effect on the exposure of aliphatic residues. However, with increasing LVEF treatment time, the $I_{760}/I_{1\ 003}$ ratio decreased markedly, with a reduction of 43.64% in the 60 min group compared to the control group (0 min). This reduction implies that LVEF exposed tryptophan residues to a polar environment, thereby enhancing their hydrophobic interactions. As reported by Wang et al.[17], similar results emerged, they observed a decline in $I_{760}/I_{1\ 003}$ strength when tryptophan residues were placed in a polar setting.

The I_{850}/I_{830} ratio was used to assess the exposure of tyrosine residues, where a ratio exceeding 1.01 suggested exposure to a polar microenvironment[7]. After 30 min of LVEF treatment, the I_{850}/I_{830} ratio of MP gel exceeded 1.01 and continued to rise as treatment time increased. This trend suggests that LVEF promoted the exposure of tyrosine residues to the polar microenvironment, accelerating MP denaturation, which aligns with the temperature scan findings.

3.4 Gel hardness and WHC

Water retention in meat products primarily affects their economic value and food quality, with higher WHC closely linked to meat quality, tenderness, and texture[10]. Figure 3A illustrates the effects of different electrostatic field treatment times on the hardness and water retention of MP gels. As LVEF treatment time increased, gel hardness gradually improved, while water retention decreased[18]. This inverse relationship arose from LVEF-induced elevation of MP surface charge, which strengthened electrostatic repulsion between MP molecules and compressed the electrical double layer surrounding protein chains. The reduced thickness of the double layer decreased the binding energy between water molecules and MP surfaces (from −12 to −8 kJ/mol, estimated via transverse relaxation time (T_2) data), leading to weaker water-protein interactions and easier water expulsion under gel compression.

Figure 3A illustrates that the WHC of the MP gel decreased from 91.32% to 86.69% after 10 min of LVEF treatment, indicating that LVEF reduces the water capture ability of MP gels[19]. As the treatment time rose to 20 min, the WHC of the gel stabilized, while the hardness of the MP gel significantly increased compared to the 0 min group. The hardness in the 20 min group significantly increased from 142.73 to 161.23 g ($P < 0.05$). This may be attributed to increased surface charge and electrostatic repulsion among MP chains. Sun et al.[20] explored factors influencing MP gel formation and suggested that the magnitude of net surface charge and electrostatic repulsion between protein chains could affect gel strength. When the LVEF treatment time increased to 30, 40, and 50 min, no remarkable variations were examined in the hardness and WHC of the MP gel, indicating that the effect of LVEF on MP was stable. However, at 60 min of treatment, the hardness of the MP gel increased while the WHC decreased. Compared with the 50 min group, hardness significantly increased from 161.97 to 174.10 g, and WHC significantly decreased from 82.47% to 76.58% ($P < 0.05$). This could be due to prolonged LVEF treatment increasing surface charge and electrostatic repulsion between MP chains. The higher net charge on the sample's surface may intensify the ozone effect, promoting the formation of disulfide bonds during MP denaturation, resulting in a tighter MP structure[6].

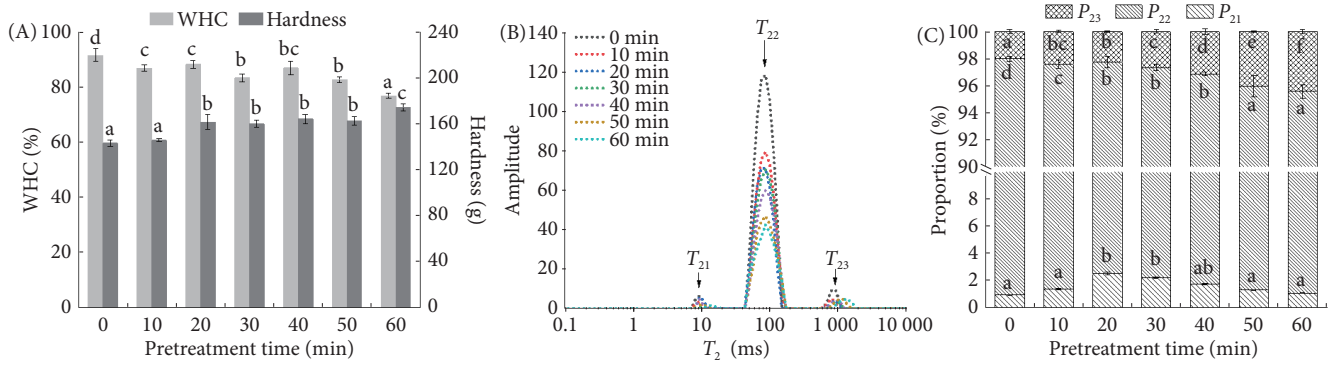


Figure 3 The effect of LVEF pretreatment time on (A) WHC and hardness, (B) water distribution, and (C) relative content of different state water. Different lowercase letters represent significant differences ($P < 0.05$).

3.5 LF-NMR analysis

The T_2 was determined using LF-NMR, with the intention of evaluating the hydration properties of MP gel[11]. Generally, shorter T_2 indicate closer binding between water and protein[21]. Figure 3B shows the water distribution curve of MP gels, which reveals three peaks corresponding to different states—bound water, immobilized water, and free water—consistent with Wang et al.[17]. In this study, T_{21}, T_{22}, and T_{23} represent the distribution of water in these different states within MP gels subjected to various LVEF treatment durations (Figure 3B), and Figure 3C shows the percentage of the peak areas for T_{21}, T_{22}, and T_{23} in the MP gel (P_{21}, P_{22}, P_{23}, respectively). Compared with the 0 min group, the relative content of P_{21} increased significantly, while P_{22} decreased significantly with prolonged LVEF treatment ($P < 0.05$). LVEF treatment may enhance electrostatic interplay between proteins, along with between water and proteins, thus trapping more molecules in the structure of the gel network[22]. Additionally, fixed water in MP gels was largely converted to free water, which may be due to the compact gel network structure and short intermolecular distances, causing immobilized water to convert to free water, thus increasing gel strength[11]. This also explains the decrease in WHC under these conditions (Figure 3A).

In contrast, the P_{21} did not change significantly, but its content increased in the 20 and 30 min groups, indicating that LVEF treatment for these durations increased the relative content of bound water in MP gels. With extended treatment, the P_{21} in the 40, 50, and 60 min groups became similar to that of the 0 min group, with changes focused primarily on the conversion from fixed water to free water[23]. Figure 3B indicates that the T_{23} in the 50 and 60 min groups significantly increased, indicating reduced water fluidity in the MP gel[12].

3.6 Rheological properties

The changes in the rheological properties of MP during the temperature sweep after LVEF treatment, as indicated in Figures 4A and B. These variations illustrate the storage modulus (G') and loss modulus (G'') of each group of MP samples at 25–80 °C, facilitating the study of the rheological properties of the gel during MP heating[13]. Generally, the initial peak of myosin thermal denaturation in MP appeared at 50–60 °C and decreased as temperature increased. These phenomena align with disulfide bond forming at the head of myosin and the enhancement of MP fluidity, accompanied by the unfolding of the myosin tail[24]. When the temperature varied between 25 and 45 °C, the G' of all sample groups remained relatively stable. G' then exhibited an upward trend, likely due to hydrogen bonds forming and myosin head aggregating[6]. At temperatures of 50–52 °C, G' in the 0 min group and 10 min group decreased, while G' in the 20, 30, 40, 50, and 60 min groups continued to rise. This may indicate that LVEF inhibits the formation of disulfide bonds in myosin, reduces the temperature required for myosin gel formation, and accelerates the development of myosin gel[10]. When the temperature increased to 60–85 °C, G' in the 0 min group continued to rise, while G' in the LVEF-treated sample groups decreased. This may be due to LVEF treatment increasing the charge and electrostatic force on the MP surface, resulting in changes in non-covalent bonds and protein networks, which concentrated the thermodynamic denaturation of proteins in the early stages of heating. The trends of G'' and G' in each group were similar. At 50 °C, LVEF treatment caused the disappearance of the first transition, and the value of G'' raised remarkably. After 70 °C, G'' in the LVEF treatment groups was lower than that in the 0 min group, indicating that LVEF treatment induced MP aggregation[25]. G' was slightly larger than G'', indicating

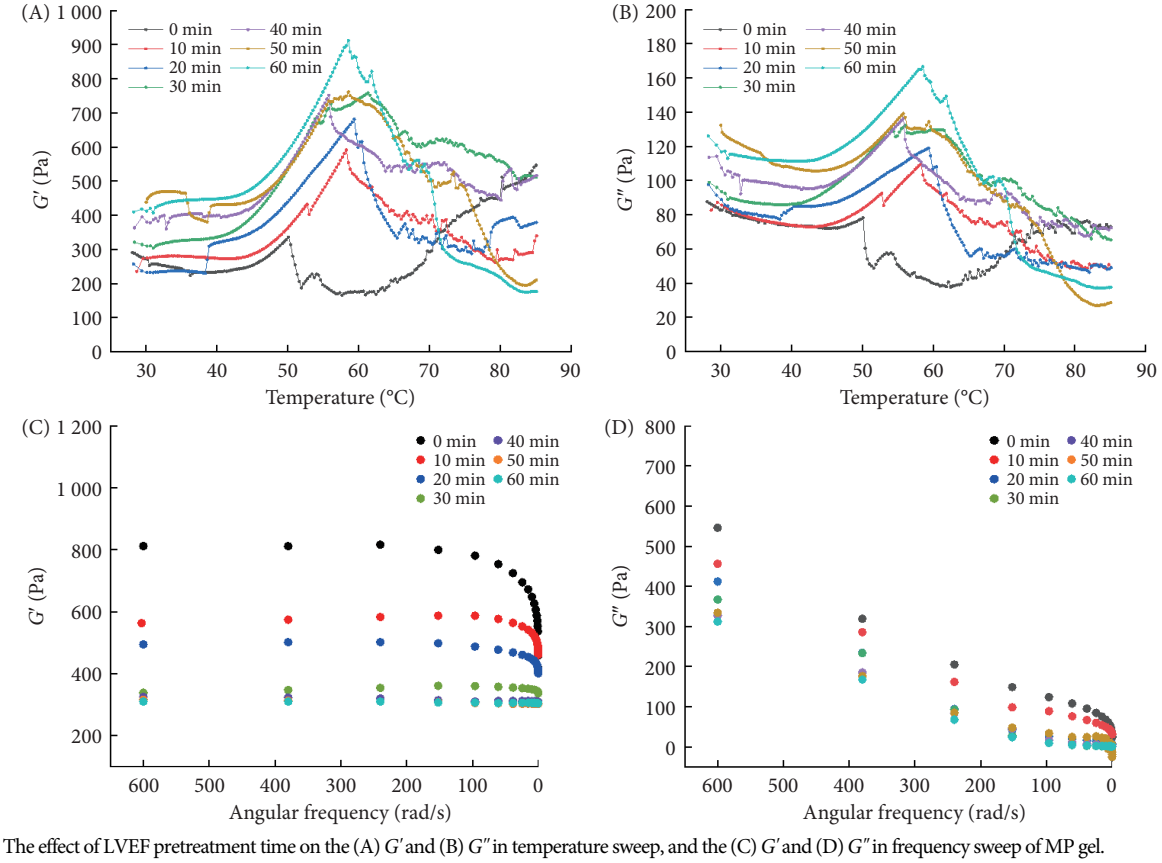


Figure 4 The effect of LVEF pretreatment time on the (A) G' and (B) G'' in temperature sweep, and the (C) G' and (D) G'' in frequency sweep of MP gel.

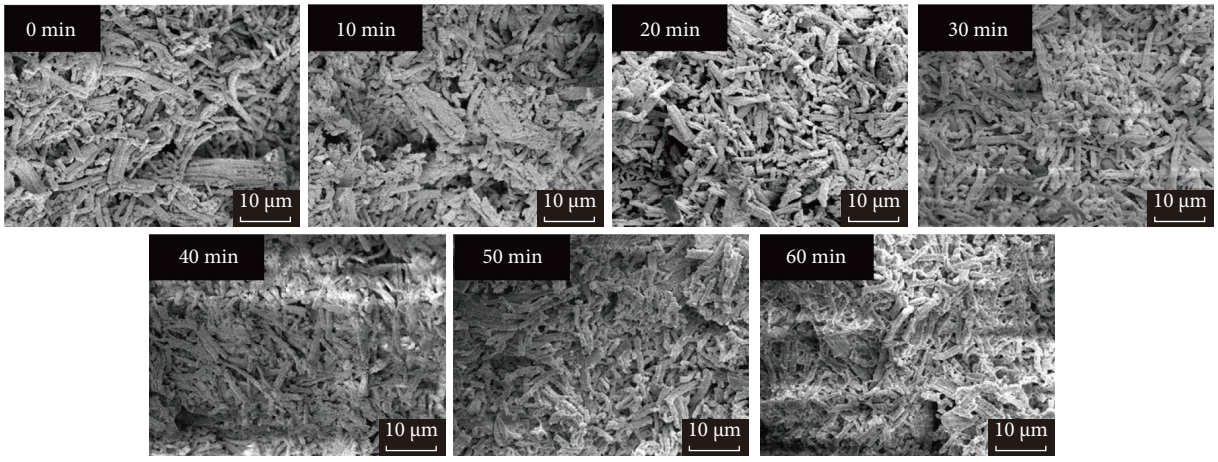


Figure 5 The effect of LVEF pretreatment time on the SEM images of MP gel (2 000×).

that the gel elasticity formed by MP was poor, with elasticity gradually increasing with increasing LVEF treatment time.

The frequency sweep reflects the relationship between the internal structure and viscoelastic behavior of MP gels, $G' > G''$ indicates that a gelatinous structure is formed and possesses good elasticity[11]. The changes in the rheological frequency sweep of MP after LVEF treatment are shown in Figures 4C and D. With the increase in angular frequency, the G' of each group initially increased (0–300 rad/s) and then tended to stabilize (300–600 rad/s). The G' of each group continued to rise, and the trend of the G'' curve was similar. With the increase in LVEF treatment time, the G' gradually decreased; however, after a treatment time exceeding 40 min, the G' of the MP gel was essentially the same across groups. This suggests that LVEF reduces the viscoelasticity of the MP gel, although the effects have limitations[21]. While LVEF treatment reduced the G' after 40 min, it enhanced the gel's solid-like behavior by narrowing the gap between G' and G''. This suggests LVEF improved the structural homogeneity of the gel network, even as overall viscoelasticity declined with prolonged treatment. With an increase in the LVEF treatment time, the gap between G' and G'' gradually decreased, indicating that the stiffness of the MP gel decreased under the influence of LVEF. This may be related to an increase in MP electrostatic interactions and the formation of a dense network structure.

3.7 Microstructure

The microstructure of the MP gel after LVEF treatment was shown in Figure 5. In the 0 min group, the fibers of the MP gel were coarse and irregular in size, exhibiting discontinuous aggregation and accumulation. After LVEF treatment, the MP gel fibers became thinner and more tightly bound. It is possible that LVEF treatment enhanced the binding between protein molecules and the orderly arrangement of the gel, which corresponded to an increase in gel hardness (Figure 3A). Simultaneously, LVEF treatment reduced the fiber diameter of the MP gels. Within a certain range, a gel with a larger pore size increases the WHC because its structure can more effectively hold water molecules[22]. Compared to the 0 min group, the 30, 40, 50, and 60 min groups exhibited smaller voids and contained fewer water molecules, which corresponded to the discoveries of WHC (Figure 3A). In comparison to the 0, 10, 20, and 30 min groups, the microstructure of the MP gel in the 40, 50, and 60 min groups was denser, and their fiber diameters were smaller. This may be attributed to long-term LVEF treatment increasing the extent of cross-linking between proteins, thereby altering the network structure of the MP gel. There were no significant differences in the MP gel network or fiber diameter among the 40, 50, and 60 min groups. Therefore, the microstructure of the MP gel indicated that LVEF treatment altered the network structure of the gel.

4 Conclusion

The effects of different LVEF treatment times on the MP gel performance were explored. Unlike the control group (0 min), the LVEF treatment prominently enhanced the structural homogeneity and hardness of MP gels, decreased the WHC of the MP gel, and was positively correlated with the electrostatic field treatment time (10–60 min). LVEF promotes the unfolding, folding, and cross-linking of MP molecules while altering the secondary construction of MP gels. Based on the reduced β-sheet relative content and altered hydrophobic microenvironment observed in Raman spectra, LVEF likely modulates the formation of disulfide bonds during thermal denaturation, thereby influencing gel network architecture. After LVEF treatment, the thermal induction process of the MP gel changed, which accelerated the denaturation rate of MP and reduced its denaturation temperature. This effect was more pronounced in the group treated for more than 20 min. Compared to the control group, the three-dimensional network construction of the processed gel with the LVEF was denser, with smaller pores and finer fibers. Hence, our research lays a groundwork for the LVEF application in the processing of thermally induced meat gel products.

Conflict of interest

The authors declare no conflict of interest.

Acknowledgments

This work was financially supported by the Shandong Modern Agricultural Industry and Technology System (SDAIT-11-11).

Author contributions

Ning Ding: Investigation, methodology, formal analysis and data curation. Peng Wang: Conceptualization, investigation, writing of the original draft. Guangyan Zhao: Formal analysis and data

curation. Junyao Ma: Verification of gel hardness effects. Aiguo Dai: Verification of gel water holding capacity effects. Yujiao Qu: Software, visualization. Guohua Zhang: Conceptualization, methodology from enterprise and practice. Jingxin Sun: Conceptualization, methodology, resources, supervision, project administration.

References

[1] J. Fei, B. Ding, S. W. Koh, Mechanistic investigation of electrostatic field-enhanced water evaporation, Adv. Sci. 8 (2021) e2100875. https://doi.org/10.1002/advs.202100875.

[2] Y. Xie, X. Yu, Z. Wang, et al., The synergistic effects of myofibrillar protein enrichment and homogenization on the quality of cod protein gel, Food Hydrocoll. 127 (2022) 107468. https://doi.org/10.1016/j.foodhyd.2021.107468.

[3] Z. Lu, Y. Zhou, B. Liu, Preparation of chitosan microcarriers by high voltage electrostatic field and freeze drying, J. Biosci. Bioeng. 128 (2019) 504–509. https://doi.org/10.1016/j.jbiosc.2019.03.020.

[4] Y. C. Huang, Y. H. Yang, K. Sridhar, et al., Synergies of modified atmosphere packaging and high-voltage electrostatic field to extend the shelf-life of fresh-cut cabbage and baby corn, LWT-Food Sci. Technol. 138 (2021) 110559. https://doi.org/10.1016/j.lwt.2020.110559.

[5] S. Jiang, Y. Ma, Y. Wang, et al., Effect of κ-carrageenan on the gelation properties of oyster protein, Food Chem. 382 (2022) 132329. https://doi.org/10.1016/j.foodchem.2022.132329.

[6] A. Amiri, A. Mousakhani-Ganjeh, S. Shafiekhani, et al., Effect of high voltage electrostatic field thawing on the functional and physicochemical properties of myofibrillar proteins, Innov. Food Sci. Emerg. Technol. 56 (2019) 102191. https://doi.org/10.1016/j.ifset.2019.102191.

[7] Y. Xie, B. Chen, J. Guo, et al., Effects of low voltage electrostatic field on the microstructural damage and protein structural changes in prepared beef steak during the freezing process, Meat Sci. 179 (2021) 108527. https://doi.org/10.1016/j.meatsci.2021.108527.

[8] T. Xia, Y. Xu, Y. Zhang, et al., Effect of oxidation on the process of thermal gelation of chicken breast myofibrillar protein, Food Chem. 384 (2022) 132368. https://doi.org/10.1016/j.foodchem.2022.132368.

[9] M. M. Makagon, A. B. Riber, Setting research driven duck-welfare standards: a systematic review of Pekin duck welfare research, Poult. Sci. 101 (2022) 101614. https://doi.org/10.1016/j.psj.2021.101614.

[10] H. Shi, T. Zhou, X. Wang, et al., Effects of the structure and gel properties of myofibrillar protein on chicken breast quality treated with ultrasound-assisted potassium alginate, Food Chem. 358 (2021) 129873. https://doi.org/10.1016/j.foodchem.2021.129873.

[11] P. Wang, Y. Li, Y. Qu, et al., Improving gelling properties of myofibrillar proteins incorporating with cellulose micro/nanofibres, Int. J. Food Sci. Technol. 57 (2022) 3428–3439. https://doi.org/10.1111/ijfs.15667.

[12] P. Wang, Y. Li, Y. Qu, et al., Effects of heat treatment on physicochemical and microstructure properties of myofibrillar proteins combined with glucose and cellulose nanofibers, Food Chem. 387 (2022) 132775. https://doi.org/10.1016/j.foodchem.2022.132775.

[13] A. J. Martins, A. Guimarães, P. Fuciños, et al., Food-grade bigels: evaluation of hydrogel: oleogel ratio and gelator concentration on their physicochemical properties, Food Hydrocoll. 143 (2023) 108893. https://doi.org/10.1016/j.foodhyd.2023.108893.

[14] X. Wang, M. Xia, Y. Zhou, et al., Gel properties of myofibrillar proteins heated at different heating rates under a low-frequency magnetic field, Food Chem. 321 (2020) 126728. https://doi.org/10.1016/j.foodchem.2020.126728.

[15] C. Yu, S. Li, S. Sun, et al., Modification of emulsifying properties of mussel myofibrillar proteins by high-intensity ultrasonication treatment and the stability of O/W emulsion, Colloids Surf. A Physicochem. Eng. Asp. 641 (2022) 128511. https://doi.org/10.1016/j.colsurfa.2022.128511.

[16] Y. Xue, J. Zhong, X. Liu, et al., Improved physicochemical properties of bigels produced with ethyl cellulose-based oleogel and moderately deacetylated konjac glucomannan hydrogel, Food Chem. 459 (2024) 140429. https://doi.org/10.1016/j.foodchem.2024.140429.

[17] X. Wang, L. Wang, K. Yang, et al., Radio frequency heating improves water retention of pork myofibrillar protein gel: an analysis from water distribution and structure, Food Chem. 350 (2021) 129265. https://doi.org/10.1016/j.foodchem.2021.129265.

[18] Y. Zhao, G. Wei, J. Li, et al., Comparative study on the effect of different salts on surimi gelation and gel properties, Food Hydrocoll. 144 (2023) 108982. https://doi.org/10.1016/j.foodhyd.2023.108982.

[19] C. Zhu, S. Wang, Y. Bai, et al., Effects of citrus fiber on the gel properties of mutton myofibrillar protein, Foods 12 (2023) 741. https://doi.org/10.3390/foods12040741.

[20] X. D. Sun, R. A. Holley, Factors influencing gel formation by myofibrillar proteins in muscle foods, Compr. Rev. Food Sci. Food Saf. 10 (2011) 33–51. https://doi.org/10.1111/j.1541-4337.2010.00137.x.

[21] J. Chen, B. Jia, S. Wang, et al., Inhibition of the interactions of myofibrillar proteins with gallic acid by β-cyclodextrin-metal-organic frameworks improves gel quality under oxidative stress, Food Hydrocoll. 154 (2024) 110065. https://doi.org/10.1016/j.foodhyd.2024.110065.

[22] K. Yang, Y. Zhou, J. Guo, et al., Low frequency magnetic field plus high pH promote the quality of pork myofibrillar protein gel: a novel study combined with low field NMR and Raman spectroscopy, Food Chem. 326 (2020) 126896. https://doi.org/10.1016/j.foodchem.2020.126896.

[23] H. Dai, X. Chen, L. Peng, et al., The mechanism of improved myosin gel properties by low dose rosmarinic acid addition during gel formation, Food Hydrocoll. 106 (2020) 105869. https://doi.org/10.1016/j.foodhyd.2020.105869.

[24] M. Wang, Y. Zhao, M. Wang, et al., Effects of Tenebrio molitor protein emulsion on the properties, and structure of myofibrillar protein gel, LWT-Food Sci. Technol. 189 (2023) 115511. https://doi.org/10.1016/j.lwt.2023.115511.

[25] Y. Cao, W. Ma, J. Huang, et al., Effects of sodium pyrophosphate coupled with catechin on the oxidative stability and gelling properties of myofibrillar protein, Food Hydrocoll. 104 (2020) 105722. https://doi.org/10.1016/j.foodhyd.2020.105722.