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Impact of high-temperature sterilization on the physicochemical and functional properties of chicken gels enriched with red algae (*Palmaria palmata*)

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Introduction: Red algae may serve as a partial and sustainable substitute in hybrid meat products. However, intensive heating applied to extend shelf life can readily induce deterioration of the gel structure, leading to reduced textural quality and moisture retention.

Methods: Chicken gels containing 0%–10.0% (w/w) Palmaria palmata (PP) were prepared, heat-induced at 80 °C for 30 min, and then subjected to high-temperature sterilization (95 °C, 30 min). The physicochemical and functional properties of the gels were then evaluated.

Results: After initial gelation, PP-containing gels exhibited higher gel strength. After high-temperature sterilization, the control group showed significant reductions in hardness (from 62.3 ± 4.3 N to 57.0 ± 1.5 N) and moisture content (from 67.22 ± 0.45% to 65.37 ± 0.77%). In contrast, gels with 2.5%–5.0% PP maintained or improved hardness, chewiness, and water-holding capacity. Low-Field Nuclear Magnetic Resonance analysis indicated that PP promoted redistribution of free water toward bound and immobilized fractions, and microstructural observations revealed a more continuous and compact network. Conversely, PP levels 7.5% led to aggregation, structural heterogeneity, and texture deterioration after reheating. PP also significantly enhanced the DPPH and ABTS radical scavenging capacities. Notably, the gel with 5.0% PP (CB-5.0) showed a marked increase in antioxidant capacity after sterilization, with DPPH values rising from 16.86 ± 0.28 to 22.48 ± 0.73 and ABTS values from 37.78 ± 0.09 to 42.63 ± 0.23.

Discussion: Moderate PP addition (2.5%–5.0%) acts as an active filler that stabilizes the chicken gel network against high-temperature sterilization, improving texture, water retention, and antioxidant activity, whereas excessive PP compromises structural uniformity.

KEYWORDS
active filler, chicken gel, *Palmaria palmata*, red algae, sterilization, thermal stability

1 Introduction

Chicken is valued for its abundant protein and relatively low fat content, making it well suited to processing by a wide range of cooking methods. As global chicken consumption continues to rise, the ways in which it is processed have become increasingly diverse. Commonly available products nowadays include meat gels, burger patties, sausages, hot dogs, and chicken nuggets (Petracci et al., 2013). Myofibrillar proteins account for more than 40% of total chicken muscle protein and consist primarily of myosin, actin, and actomyosin. They form the structural framework of heat-induced gels by promoting the assembly of an interconnected protein matrix. Insufficient protein aggregation tends to hinder the development of a firm gel matrix, whereas excessive aggregation lowers thermal stability and disrupts gel network integrity. The degree of protein aggregation is influenced by the concentration of solubilized myofibrillar proteins, the heating temperature, and the heating time. Because myofibrillar proteins are salt-soluble, a suitable ionic strength plays a crucial role in determining their solubility. Temperature is one of the key factors affecting the formation of protein gels (Sun and Holley, 2010). Myofibrillar proteins generally begin to unfold at around 65 °C, a temperature commonly regarded as their theoretical denaturation point (Sun and Holley, 2010).

For ready-to-eat foods like meatballs and sausages, thermal processing or sterilization is typically required to ensure microbial safety and shelf-life stability (Ducic et al., 2025). Although sterilization ensures microbial safety, physical and chemical changes can still impact texture and appearance. The USDA recommends that meat-based foods reach a core temperature of 73.9 °C to ensure microbiological safety (Chen et al., 2020). In practice, however, high-temperature treatments such as boiling, roasting, and frying are still commonly applied to improve the sensory quality of meat-based products. Moreover, ready-to-eat foods are often subjected to high-temperature sterilization after packaging as a means of extending shelf life. Such high-temperature processing is frequently accompanied by textural deterioration and other quality defects (Chen et al., 2021). High-intensity heating promotes protein unfolding and increases exposure of reactive sulfhydryl and hydrophobic sites. This enhances disulfide cross-links and exposure of hydrophobic groups, ultimately resulting in over-aggregation. Protein thermal stability at high temperatures can therefore be improved by inhibiting disulfide bond formation and hydrophobic interactions, thereby preserving a stable, continuous gel network. The combined HPH–H_2O_2 treatment has been shown to suppress disulfide bond formation and markedly attenuate protein aggregation driven by both covalent and non-covalent interactions during heating (Chen et al., 2019). In addition, the incorporation of hydrophobic molecules such as octenyl succinic anhydride (OSA) is reported to interact non-covalently with hydrophobic protein regions, enhancing protein thermal stability, delaying denaturation, and inhibiting excessive aggregation (Chen et al., 2021). Similarly, chitooligo saccharides (CO) weaken hydrophobic interactions among chicken myofibrillar proteins (MP) and reduce protein aggregation (Wang et al., 2024). Beyond the suppression of disulfide-mediated crosslinking and hydrophobic association, filler effects are considered to enhance the thermal stability of MP gel networks (Zhang et al., 2015). Although several approaches are currently available to attenuate hydrophobic interactions or disulfide bond formation, safety concerns limit their industrial application. There remains a strong need for green, low-cost strategies that can enhance the texture of MP gels formed at high temperatures. Seaweeds have become promising sources of natural additives due to their high renewability and rich nutritional composition. Nevertheless, not all algae are suitable for meat processing. Therefore, identifying stable algal sources that are compatible with meat products has become an important direction in meat product development.

Seaweeds are rich in proteins, polysaccharides, and other bioactive compounds, and are expected to improve the antioxidant capacity and microbial stability of meat products (Jiang et al., 2026). The red alga *Palmaria palmata* has been shown to strengthen hydrogen bonding and hydrophobic interactions in chicken gels, thereby increasing network cross-linking, improving texture, and enhancing water retention (Jiang et al., 2026). Moreover, the red coloration of *P. palmata* lends a visually compatible appearance to meat gel products, offering a potential advantage over other algal species in terms of consumer acceptance. Unlike typical red algae rich in sulfated galactans, *P. palmata* is characterized by xylan-dominated cell walls (Lahaye et al., 2003; Viana et al., 2011). In addition to xylan, the cell wall contains floridosides and glucans (Xu et al., 2024). However, the sterilization stability of red algae–chicken gels has not been clearly established. Accordingly, in the present study, heat-induced gels were subjected to high-temperature sterilization to investigate how red algae incorporation affects the thermal stability of chicken gel systems.

This study investigated the post-sterilization thermal stability of red algae–chicken gels. Alterations of texture, moisture content, color, and antioxidant capacity were examined in gels formulated with different levels of *Palmaria palmata* following sterilization. Confocal laser scanning microscopy (CLSM) and scanning electron microscopy (SEM) were employed to examine microstructural alterations and phase distributions within the gel matrix.

2 Materials and methods

2.1 Materials

Chicken breast fillets were obtained from a retail market in Guangzhou, China. These fillets consisted of individually quick-frozen white-feathered chicken breast products supplied by CP Foods and were kept at −18 °C. Corn germ oil (Q/LLH0014S) was sourced from Shandong Luhua Group Co., Ltd. *P. palmata* was collected from the coastal waters of Shantou, China and processed following the procedure reported by Jiang et al. (2026). The fresh algal samples were first rinsed thoroughly with distilled water to remove salts and surface contaminants. Then, the cleaned algae were dried, milled, and sieved to obtain 60-mesh powder.

2.2 Preparation of chicken gels and sterilization

Chicken breast gels were prepared according to our previously reported method (Jiang et al., 2026). Thawed chicken breast was cleaned, chopped, and combined with sodium chloride (1.5%, w/w), sodium tripolyphosphate (0.3%, w/w), ice water (20%, w/w), and corn oil (3%, w/w). Red algae powder was added to replace part of the chicken breast at proportions of 0%, 2.5%, 5.0%, 7.5%, and 10.0%

(w/w). The meat batters were chopped under temperature-controlled conditions until homogeneous, placed in centrifuge tubes, then centrifuged to eliminate entrapped air. Gelation was induced by heating the samples at 80 °C ± 1 °C for 30 min to a final core temperature of 72 °C ± 2 °C, and then cooled to room temperature. The obtained gels were designated as CB-0 to CB-10.0.

The gel samples were vacuum-packed in vacuum cooking bags and heated in a water bath at 95 °C for 30 min. After heating, they were cooled to room temperature by rinsing with cold water. Gels before and after the 95 °C treatment were subjected to physicochemical analysis. The heat-treated samples were designated as CBP-0 to CBP-10.0.

2.3 Microorganisms analysis

After sterilization, Total viable count (TVC) and *Escherichia coli* in CBP samples were determined using PCA and VRBA, respectively. Samples were homogenized with sterile buffered peptone water at 1:9, serially diluted, and plated at 10^{-1} and 10^{-2}. PCA plates were incubated at 30 °C ± 1 °C for 72 h, while VRBA plates were incubated at 36 °C ± 1 °C for 24 ± 2 h.

2.4 Texture profile analysis (TPA)

After cooking, TPA measurement was performed following Jiang et al. (2026), using a texture analyzer (TA.XT. plus, Stable Micro Systems, United Kingdom). The pre-test, test, and post-test speeds were set to 2.00, 1.00, and 5.00 mm/s, respectively, with a trigger force of 5 g. The compression strain was 40% of the sample height.

2.5 Moisture content

The gel samples (≈4.0 g) containing 0%–10.0% red algae powder underwent drying at 105 °C for 2–4 h after weighing. After drying, the samples were cooled before reweighing. Drying was then continued in 1 h intervals until a constant mass was reached, defined as a mass difference (≤2 mg) between two consecutive measurements. Moisture content was calculated from the mass loss after drying.

2.6 Color

The L^*, a^*, and b^* values of the samples were determined using a colorimeter (NR20XE, 3NH, China) under a D65 illuminant. Color measurements of gel samples were taken at six different positions on each sample. The mean values were calculated for subsequent analysis. Whiteness was calculated according to the following Equation 1.

$$Whiteness = 100\text{-}\sqrt{(100\text{-}L^*)^2 + a^{*2} + b^{*2}} \quad (1)$$

2.7 Antioxidant capacity

2.7.1 DPPH radical scavenging activity

Lyophilized gels (1 g) were ground, mixed with 20 mL of absolute ethanol, homogenized at 5,000 rpm, and centrifuged at 10,000 rpm for 10 min. For the DPPH assay, A_1 contained the filtrate and 0.1 mmol/L DPPH solution at a ratio of 1:5 (v/v). A_2 was prepared by replacing the filtrate with distilled water, while A_3 was prepared by replacing DPPH solution with absolute ethanol at the same ratio. The DPPH radical scavenging activity was calculated using Equation 2.

$$DPPH\ radical\ scavenging\ activity = \frac{1 - (A_1 - A_3)}{A_2} \quad (2)$$

2.7.2 ABTS radical scavenging activity

The supernatant prepared in Section 2.7.1 was used for the ABTS radical scavenging assay (Solarbio Life Sciences, China; Cat. No. BC4770, Lot No. 20200026), which was performed using a commercial kit according to the manufacturer's instructions.

2.8 Low-field nuclear magnetic resonance (LF-NMR)

LF-NMR analysis was conducted following the method of Li et al. (2025), using a Bruker MQ20 NMR analyzer (Bruker BioSpin GmbH, Germany) with the CPMG sequence. The main parameters were set as a sampling frequency of 250 kHz, resonance frequency of 23 MHz, echo time of 0.080 ms, 3500 echoes, and 8 scans.

2.9 Scanning electron microscope (SEM)

SEM specimens were prepared according to Fu et al. (2023) with minor modifications. CB and CBP gel specimens were cut into regular blocks of approximately 5 mm × 5 mm × 3 mm for subsequent analysis. The blocks were thoroughly rinsed with 0.2 mol/L PBS (pH 7.0) to remove surface impurities and residual particles. After rinsing, they were fixed in 2.5% glutaraldehyde fixative overnight at 4 °C. After fixation, the specimens were rinsed in 0.2 mol/L NaH_2PO_4 buffer for three 10 min cycles to completely eliminate residual fixative. The specimens were vacuum freeze-dried for 24 h with an FDU-1200 freeze dryer (Shanghai Ailang Instrument Co., Ltd., China). The dehydrated specimens were gold-coated in an EM ACE600 sputter coater (Leica Microsystems, Germany), and SEM images were acquired on an EVO MA 15 microscope (Carl Zeiss, Germany).

2.10 Confocal laser scanning microscopy

CLSM was performed following the method of Zhang et al. (2023), with slight modifications. Gel samples were carefully sliced into sections of about 1 mm in thickness. The sections were stained with a mixed dye solution containing 0.01% (w/v) Nile red (CAS No. 7385-67-3), Nile blue (CAS No. 3625-57-8), and Calcofluor White. After staining, the slices were gently rinsed with distilled water to remove residual dye from the surface. The prepared samples were then placed on single-well slides, covered with coverslips, and kept away from light before microscopic observation. Confocal images were obtained with a confocal laser scanning microscope (TCS SP8 STED 3X, Leica, Germany). Nile red, Nile blue, and Calcofluor White signals were collected at excitation/emission wavelengths of 488/572–598 nm, 633/650–670 nm, and 405/423–443 nm, respectively.

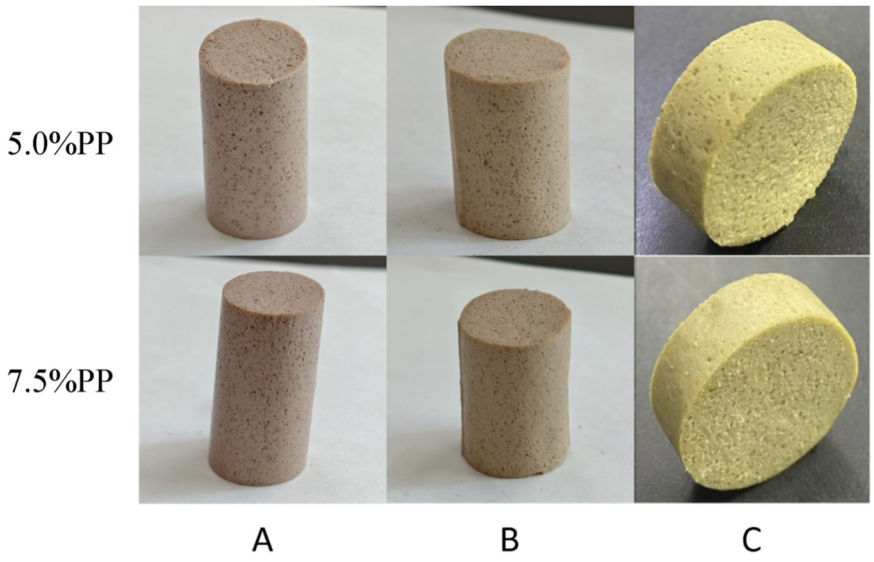


FIGURE 1
Appearance changes of red algae-chicken gel before sterilization **(A)**, after 95 °C 30 min high-temperature heating **(B)**, and after autoclaving **(C)**.

2.11 Statistical analysis

Statistical analysis was completed using IBM SPSS Statistics 25.0 (IBM Corporation, Armonk, NY, United States). Data from triplicate measurements were shown as mean ± SD. Differences between groups were tested by one-way ANOVA, and mean comparisons were made using Duncan's multiple range test at a significance level of $P < 0.05$.

3 Results and discussion

3.1 Microbial safety and thermal processing

Meat products are high in protein and moisture, creating a favorable environment for microbial growth and proliferation. Improper control may promote spoilage and microbial toxin production, including toxins produced by *Clostridium botulinum*. Consequently, gel-based products like sausages and meatballs are commonly subjected to high-temperature and high-pressure sterilization during industrial production to ensure shelf stability at ambient temperature (Ahn et al., 2024). As shown in Figure 1, the color of red algae–enhanced chicken gels shifted markedly toward green after high-temperature and high-pressure autoclaving. It is proposed that phycobiliproteins (red) were degraded while the remaining chlorophyll (green) became the dominant pigment. In contrast, the high-temperature pasteurization (95 °C for 30 min) partially preserved the original reddish hue of the samples, owing to the milder thermal intensity. Accordingly, heating at 95 °C for 30 min in a water bath was selected in the present study to improve microbial safety while preserving color quality. As shown in Table 1, no detectable total viable counts or *Escherichia coli* were observed in any of the pasteurized samples (CBP), indicating that this sterilization effectively controlled spoilage and pathogenic bacteria. Furthermore, the gels exhibited good microbial stability during 4 °C storage, suggesting extended shelf life (short term) by refrigeration.

3.2 Texture properties

Texture properties reflect changes in the gel network structure of red algae–chicken gels after secondary heating. As shown in Table 2, after initial gelation (CB), as the red algae addition increased from 0% to 10.0%, sample hardness increased from 62.3 ± 4.3 N to 91.2 ± 7.1 N, while gumminess and chewiness also increased with increasing addition levels. Red algae components were incorporated into the myofibrillar protein network, increasing the compactness of the network. After sterilization (CBP), the hardness of the control sample (CBP-0) decreased significantly to 57.0 ± 1.5 N ($P < 0.05$), and gumminess and chewiness demonstrated the same trend. This may be attributed to further MP aggregation induced by secondary high-temperature treatment, which caused deterioration of the gel network, structural loosening, and moisture loss (Chen et al., 2020). By contrast, the samples containing 2.5% and 5.0% red algae exhibited higher hardness and better chewiness after reheating. This may be attributed to the red algae, which acted as a supporting framework within the system, thereby improving the gel's resistance to reheating. After the second heat treatment, SEM observations showed that the gels containing 2.5%–5.0% red algae still maintained a continuous and dense three-dimensional network, whereas higher levels of red algae promoted the development of large protein aggregates and irregular pores, thereby reducing structural uniformity. At moderate levels, red algae acted as an active filler in network construction; non-covalent interactions between the polysaccharide framework and proteins, such as hydrogen bonding and hydrophobic interactions, together with increased effective load-bearing area provided by particulate filling, enhanced network compactness and resistance to heat-induced collapse. When the red algae addition increased to 7.5%–10.0%, hardness, gumminess, and chewiness decreased significantly after

TABLE 1 Detection of microorganisms in gel samples after high-temperature treatment, including total plate count and *E. coli* count.

Species	CBP-0	CBP-2.5	CBP-5.0	CBP-7.5	CBP-10.0
Total plate count (TPC)	ND	ND	ND	ND	ND
Escherichia coli	ND	ND	ND	ND	ND

ND indicates that no microorganisms were detected.

TABLE 2 Effects of sterilization on textural properties of chicken gels with PP.

Samples	Hardness (N)	Adhesive force (g)	Resilience	Springiness	Gumminess (N)	Chewiness (N)
CB-0	62.3 ± 4.3^{Ac}	8 ± 1.7^{Ac}	0.15 ± 0.01	4.28 ± 0.03	36.2 ± 2.5^{Ab}	1.5 ± 0.1^{Aa}
CB-2.5	67.6 ± 5.5^{Bbc}	108 ± 38^{Aa}	0.18 ± 0.02	4.11 ± 0.32	38.5 ± 2.0^{Ab}	1.6 ± 0.2^{Aa}
CB-5.0	68.1 ± 3.2^{Abc}	116.2 ± 21.2^{Aa}	0.15 ± 0.01	4.01 ± 0.12	33.6 ± 2.1^{Ab}	1.3 ± 0.1^{Ab}
CB-7.5	71.5 ± 4.3^{Ab}	38.26 ± 10.7^{Ab}	0.18 ± 0.05	4.1 ± 0.06	36.8 ± 3.9^{Ab}	1.5 ± 0.1^{Ab}
CB-10.0	91.2 ± 7.1^{Aa}	106 ± 18.0^{Aa}	0.15 ± 0.03	4.02 ± 0.12	44.1 ± 3.6^{Aa}	1.7 ± 0.2^{Aa}
CBP-0	57.0 ± 1.5^{Bd}	10.7 ± 2.5^{Ac}	0.13 ± 0.01	4.45 ± 0.08	30.6 ± 2.3^{Ab}	1.3 ± 0.1^{Ab}
CBP-2.5	75.4 ± 1.0^{Ab}	100.9 ± 37^{Aa}	0.16 ± 0.02	4.27 ± 0.08	42.1 ± 2.9^{Aa}	1.8 ± 0.1^{Aa}
CBP-5.0	69.0 ± 3.9^{Ac}	111.5 ± 44.2^{Aa}	0.14 ± 0.02	4.22 ± 0.05	32.8 ± 5.3^{Ab}	1.4 ± 0.2^{Ab}
CBP-7.5	73.1 ± 2.7^{Abc}	66.3 ± 20.6^{Ab}	0.11 ± 0.01	4.08 ± 0.13	30.7 ± 3.5^{Bb}	1.2 ± 0.1^{Bb}
CBP-10.0	80.4 ± 3.2^{Ba}	66.6 ± 17.2^{Bb}	0.1 ± 0.01	4.2 ± 0.13	32.2 ± 2.3^{Bb}	1.3 ± 0.1^{Bb}

Lowercase letters (a–d) indicate significant differences ($P < 0.05$) among gels with different PP levels. Uppercase letters (A, B) denote significant differences ($P < 0.05$) between CB and CBP treatments at the same PP level.

secondary heating ($P < 0.05$). In contrast, the strong water-binding of red algae may competitively associate with free water, forcing exposed hydrophobic groups to approach each other, thereby accelerating protein aggregation and reducing thermal stability (Jiang et al., 2026; Yuan et al., 2023). This water-binding characteristic may be attributed to the red algae polysaccharides. Excess polysaccharides may induce localized phase separation or the formation of large aggregates with myofibrillar proteins. However, under the thermal stress imposed by secondary heating, the gels suffered water migration and network contraction, which eventually resulted in a brittle structure. In these samples, resilience and springiness showed little change before and after high-temperature sterilization, indicating that high-temperature sterilization primarily affected strength-related texture parameters, while exerting limited influence on instantaneous elastic recovery. This further supports the role of red algae in modulating gel texture mainly through a filling mechanism (Zhong et al., 2025).

3.3 Color and appearance

Color parameters (L*, a*, b*, and whiteness) are critical factors influencing consumer purchase intention and serve as important indicators of pigment stability during high-temperature sterilization. As shown in Table 3, in the initially heated gels (CB group), red algae significantly altered the initial color tone of the gels. With increasing addition levels, redness (a*) increased significantly ($P < 0.05$), whereas lightness (L*) and yellowness (b*) decreased slightly and whiteness declined markedly. After high-temperature sterilization (CBP group), no significant changes were observed in L*, a*, or whiteness for the control sample (CBP-0); however, b* increased significantly to 11.07 ± 0.15 ($P < 0.05$), which further confirmed the color change observed in Figure 1. This indicated that repeated thermal treatment promoted the formation of yellow–brown products, thereby increasing yellowness. This change may be associated with the combined effects of heat-induced browning product accumulation and oxidation-related color development. In gels containing red algae, a* values generally demonstrated a slight decrease after secondary heating, whereas b* values increased, with this trend being more pronounced at higher addition levels. Specifically, b* increased to 11.21 ± 0.13 and 10.62 ± 0.15 in CBP-7.5 and CBP-10.0, respectively. These changes were closely related to the thermal stability of red algae pigments and the occurrence of Maillard reactions during secondary heating. On one hand, the phycobiliprotein pigment phycoerythrin (PE) in red algae is relatively sensitive to temperature. High-temperature sterilization may induce conformational changes or partial unfolding of the protein, altering the microenvironment surrounding the chromophore and weakening its characteristic absorption, which manifested as red color fading and a decrease in a* (Pereira et al., 2020). On the other hand, proteins/amino compounds and reducing sugars in the system are more prone to Maillard reactions at elevated temperatures, generating browning-related products, while thermal processing may also promote oxidation-associated color changes. Together, these processes led to increased b* and a slight reduction in L* (Zhu et al., 2020).

TABLE 3 Changes in color values (L, *a*, b*, and whiteness) of chicken gels with PP before (CB) and after (CBP) sterilization.

Samples	L*	a*	b*	Whiteness
CB-0	87.42 ± 2.26^{a}	2.63 ± 0.41^{Ac}	10.46 ± 0.07^{Ba}	83.37 ± 1.78^{a}
CB-2.5	71.79 ± 1.11^{b}	6.02 ± 0.12^{Ab}	9.05 ± 0.19^{Bc}	69.77 ± 1.03^{b}
CB-5.0	61.71 ± 1.07^{c}	9.08 ± 0.36^{Aa}	8.36 ± 0.26^{Bd}	59.77 ± 1.05^{c}
CB-7.5	54.66 ± 1.72^{days}	9.19 ± 0.13^{Aa}	9.38 ± 0.18^{Bb}	52.80 ± 1.61^{day}
CB-10.0	51.05 ± 1.34^{e}	9.13 ± 0.12^{Aa}	9.04 ± 0.19^{Bc}	49.38 ± 1.26^{e}
CBP-0	88.39 ± 0.75^{a}	2.68 ± 0.22^{Ac}	11.07 ± 0.15^{Aa}	83.73 ± 0.56^{a}
CBP-2.5	71.69 ± 1.24^{b}	5.58 ± 0.17^{Bb}	9.94 ± 0.53^{Ac}	69.47 ± 1.02^{b}
CBP-5.0	60.32 ± 1.02^{c}	8.67 ± 0.25^{Ba}	9.50 ± 0.12^{Ad}	58.29 ± 0.95^{c}
CBP-7.5	56.38 ± 0.96^{days}	8.61 ± 0.20^{Ba}	11.21 ± 0.13^{Aa}	54.15 ± 0.91^{day}
CBP-10.0	50.64 ± 1.13^{e}	8.39 ± 0.30^{Ba}	10.62 ± 0.15^{Ab}	48.82 ± 1.04^{e}

Lowercase letters (a–d) indicate significant differences ($P < 0.05$) among different PP levels. Uppercase letters (A, B) denote significant differences ($P < 0.05$) between CB and CBP at the same PP level.

3.4 Moisture content

Moisture content reflects the ability of red algae–chicken gels to retain water after high-temperature sterilization. As shown in Figure 2, before high-temperature sterilization, CB-2.5 showed the highest moisture content (71.08% ± 0.46%), exceeding CB-0 (67.22% ± 0.45%, $P < 0.05$). The values for CB-5.0, CB-7.5, and CB-10.0 were statistically comparable. These results indicated that red algae improved water retention in the gel matrix. After high-temperature sterilization (CBP group), moisture content demonstrated a slight overall decrease, and the control group exhibited the greatest decline, from 67.22% ± 0.45% to 65.37% ± 0.77% ($P < 0.05$). High-temperature sterilization may further promote MP aggregation, leading to a reduction in non-covalent interactions that help stabilize the gel matrix. This process promoted network contraction and pore formation, ultimately leading to partial moisture loss (Chen et al., 2020). The insufficient thermal stability of the MP gel network under repeated heating may render the structure more fragile. In contrast, the moisture content of CB-5.0 after sterilization remained statistically unchanged compared with that before sterilization ($P > 0.05$). A similar result was reported by Feng et al., 2022, who found that potato fiber helped maintain the quality of chicken patties after heating through water immobilization and filler effects. Apart from its active filler role, *Palmaria palmata* is rich in hydrophilic xylan, which can bind water through hydrogen bonding. Therefore, an appropriate level of red algae contributed to preserving gel structural integrity and water-binding capacity during reheating. After secondary heating, the moisture content of CB-10.0 decreased significantly from 70.16% ± 0.29% to 65.99% ± 0.26% ($P < 0.05$), resulting in the lowest moisture content among the CBP samples. Over-addition of red algae may have caused regional phase separation within the gel matrix, provided channels for water migration, and reduced network continuity. Overall, an appropriate level of red algae improved moisture retention in chicken gels after the second heat treatment; Notably with the 5.0% group performing most effectively.

3.5 pH value

The pH value may reflect variations in acidic groups, ionic components, and heat-induced chemical reactions in the red algae–chicken gel matrix. As shown in Figure 3, before high-temperature sterilization, the pH values of all samples fluctuated within a narrow range of approximately 6.5–6.6, indicating that red algae exerted a limited effect on the initial acid–base balance. The buffering capacity was attributed to proteins and salts released from disrupted algal cells. After secondary heating, the pH values of all samples decreased significantly ($P < 0.05$). This decrease may be attributed to moisture loss during high-temperature sterilization, which concentrates soluble components in the system and consequently decreases pH (Leygonie et al., 2012). In addition, secondary thermal treatment may induce further protein denaturation, accompanied by the release of hydrogen ions within the system (Leygonie et al., 2011). Differences in red algae addition levels also resulted in varying degrees of pH modulation after high-temperature sterilization.

3.6 Antioxidant capacity

During high-temperature sterilization, thermal processing may accelerate oxidative chain reactions of unsaturated fatty acids and promote lipid–protein co-oxidation, thereby impairing the quality stability of ready-to-eat comminuted meat gels (Wang et al., 2023). At the same time, high temperatures induce protein denaturation, exposing hydrophobic groups and reactive sites, which further accelerates lipid–protein co-oxidation (Traore et al., 2012). As shown in Figure 4, in the CB group without secondary heating, DPPH radical scavenging activity increased overall with increasing red algae addition. Compared with CB-0, the DPPH scavenging rate increased from 12.21% to 21.85% in CB-10.0 ($P < 0.05$), and the ABTS results showed a similar trend. Red algae may participate in gel formation as a structural filler, while its bioactive compounds may also provide reducing sites and hydrogen-/electron-donating capacity, thereby improving the antioxidant activity of the system. This effect may be attributed to bioactive components in red algae,

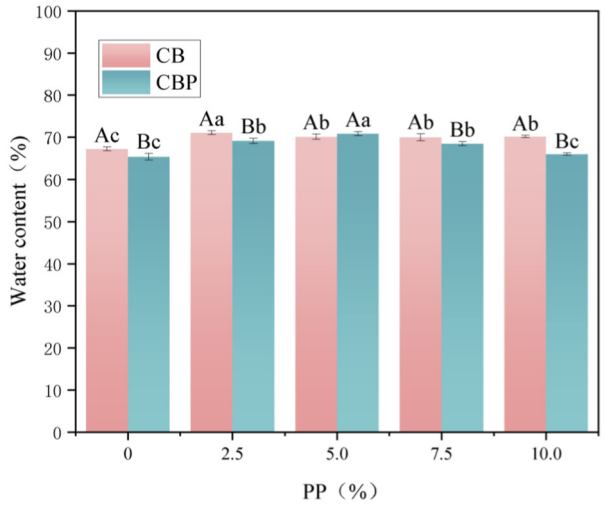


FIGURE 2
Effects of sterilization on the moisture content of chicken gels containing red algae (*Palmaria palmata*, PP). CB represents the gel samples before sterilization, and CBP represents the gels after sterilization. Lowercase letters (a–c) indicate significant differences ($P < 0.05$) among different PP levels. Uppercase letters (A, B) indicate significant differences ($P < 0.05$) between CB and CBP at the same PP level.

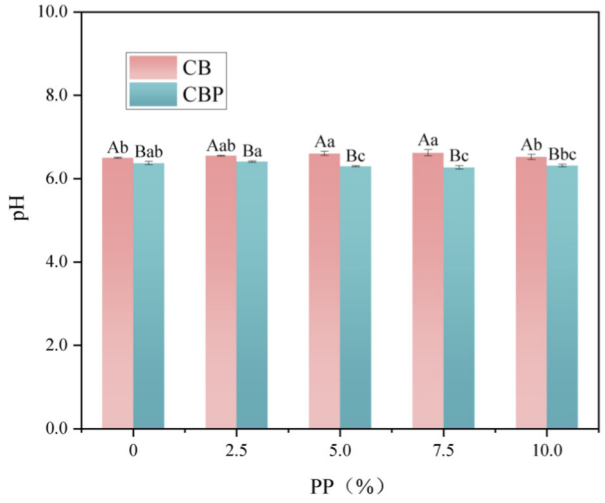


FIGURE 3
Effects of sterilization on the pH value of chicken gels. Lowercase letters (a–c) indicate significant differences ($P < 0.05$) in pH among chicken gels with different PP addition levels. Uppercase letters (A, B) indicate significant differences ($P < 0.05$) in pH influenced by sterilization at the same PP level.

such as polyphenols, carotenoids, and phycobiliproteins. Phycobiliproteins, in particular, are regarded as strong radical scavengers owing to their tetrapyrrole chromophore structure (Plaza et al., 2008). After high-temperature sterilization (CBP group), both scavenging capacities were further enhanced, and the improvement was largely found in samples containing red algae. No significant change was observed for CBP-0 compared with CB-0; however, significantly higher scavenging activities were observed in CBP samples of 2.5%–10.0% red algae than their corresponding CB counterparts. This indicated that secondary heating promoted, to some extent, the release of antioxidant compounds from *Palmaria palmata* cells. Meanwhile, thermal treatment accelerated Maillard reactions between chicken proteins and reducing sugars, resulting in more antioxidant compounds and therefore increasing the radical scavenging capacity of the system. Notably, DPPH and ABTS radical scavenging capacities peaked at approximately 5.0% red algae addition. This may be explained by the limited availability of radical reaction sites and the influence of seaweed drying conditions. Meanwhile, heat-sensitive antioxidant compounds, such as phycobiliproteins and carotenoids, may have been partially degraded at elevated temperatures. Moreover, aggregation or phase separation induced by excessive red algae may reduce the exposure of active antioxidant compounds. Based on the superior water retention and texture stability of the 5.0% red algae gels after high-temperature sterilization, therefore, an appropriate level of red algae may function as an active filler and contribute to the thermal stability of red algae–chicken gels by improving their antioxidant performance.

3.7 Microstructure

3.7.1 SEM

Scanning electron microscopy (SEM) observations demonstrated that high-temperature sterilization markedly changed the surface microstructure of red algae–chicken gels. The structural protection provided by red algae varied with the addition level. As presented in Figure 5, without red algae addition, the gel network prior to secondary heating was relatively loose, with large and unevenly distributed pores, and sheet-like or block-shaped protein aggregates appeared in some areas. After high-temperature sterilization, the pores further expanded, the pore walls became thicker, and fractures appeared. This phenomenon may result from excessive MP aggregation during reheating, leading to collapse of the gel structure, reduced water confinement in the gel network, and enhanced water migration and loss (Wang et al., 2024). Before high-temperature sterilization, gels containing 2.5%–5.0% red algae developed a dense and continuous network. Small and uniformly distributed pores were observed, and red algae particles were distributed within the spaces between protein filaments. After secondary heating, the overall structure remained intact, accompanied by mild contraction and a slight increase in pore size. This continuous and compact network with reduced fracture formation was consistent with the observed improvements in hardness and chewiness. Xylan components in red algae may interact with chicken MP during heat-induced gelation, contributing to a more stable framework while particulate filling contributed to a denser and more continuous structure. The dispersed red algae particles may have supported the gel matrix during the second heating. By reducing heat-induced damage to the protein network, they contributed to preserving the overall structural stability of the gel. However, at red algae levels of 7.5%–10.0%, large polysaccharide–protein aggregates and uneven pores became apparent. In contrast, after high-temperature sterilization, the aggregate–matrix interfaces became indistinct

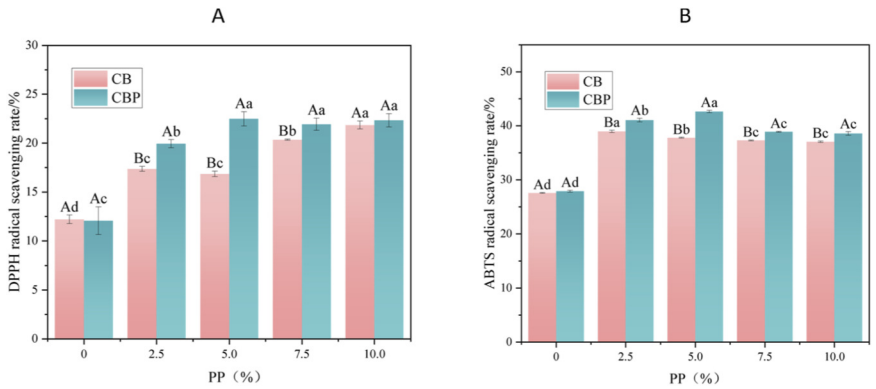


FIGURE 4
Effects of sterilization on the DPPH **(A)** and ABTS **(B)** radical scavenging rate of chicken gels. Lowercase letters (a–c) indicate significant differences ($P < 0.05$) in DPPH and ABTS radical scavenging rate among gels with different PP levels. Uppercase letters (A, B) denote significant differences ($P < 0.05$) of DPPH and ABTS of the samples after sterilization with same PP level.

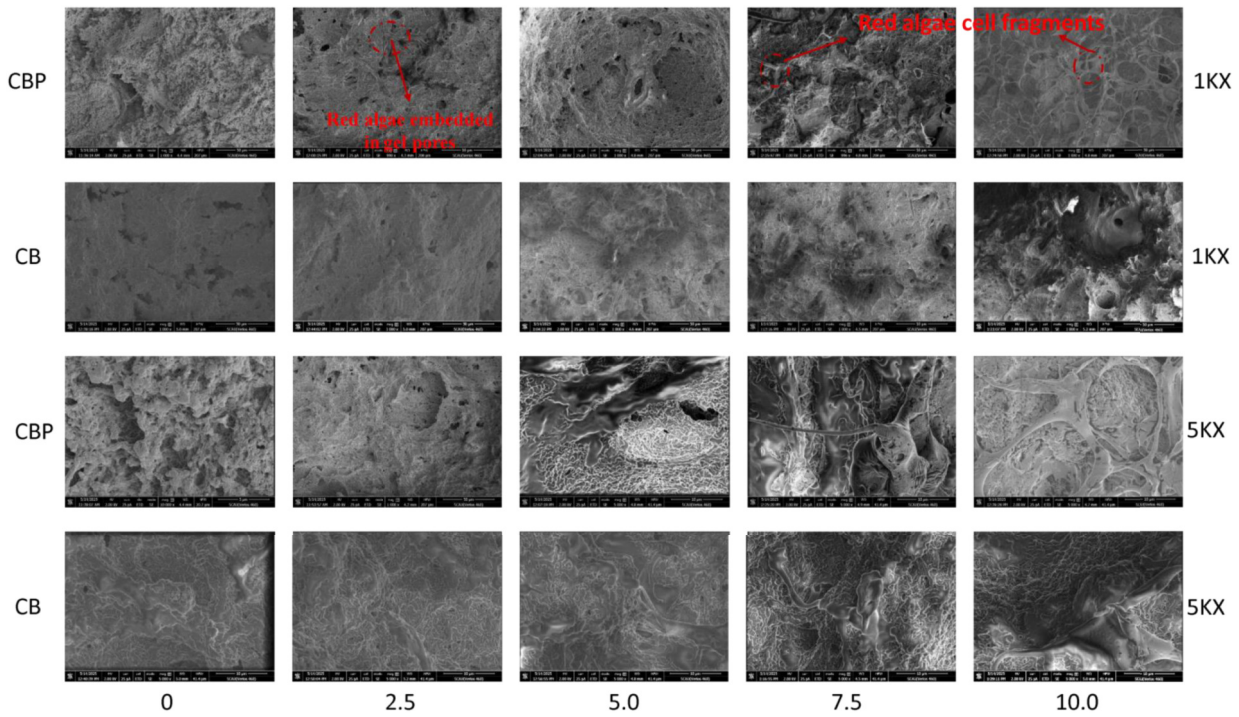


FIGURE 5
SEM images of chicken gels containing red algae (PP) (0%–10.0%) observed before (CB) sterilization and after (CBP) sterilization.

and structurally weak. This may be attributed to an excessive proportion of red algae promoting over-aggregation, which reduced network uniformity, created pathways for water migration, and ultimately weakened reheating stability.

3.7.2 CLSM

CLSM images (Figure 6) show the merged distribution of the protein fluorescence phase (blue), red algae polysaccharide fluorescence phase (green), and lipid phase (red) before and after high-temperature sterilization. The protein phase served as the main structural support matrix; the polysaccharide phase was dispersed within the gel network, and the lipid phase appeared as discrete droplets. In the CB-0 sample without red algae, the protein phase displayed relatively non-uniform fluorescence intensity, accompanied by localized block-like aggregation and thick protein signal clusters. After high-temperature sterilization (CBP-0), the protein phase aggregated into sheet-like and blocky structures, with wider interstitial spaces and reduced overall continuity and uniformity. This suggested that repeated heating

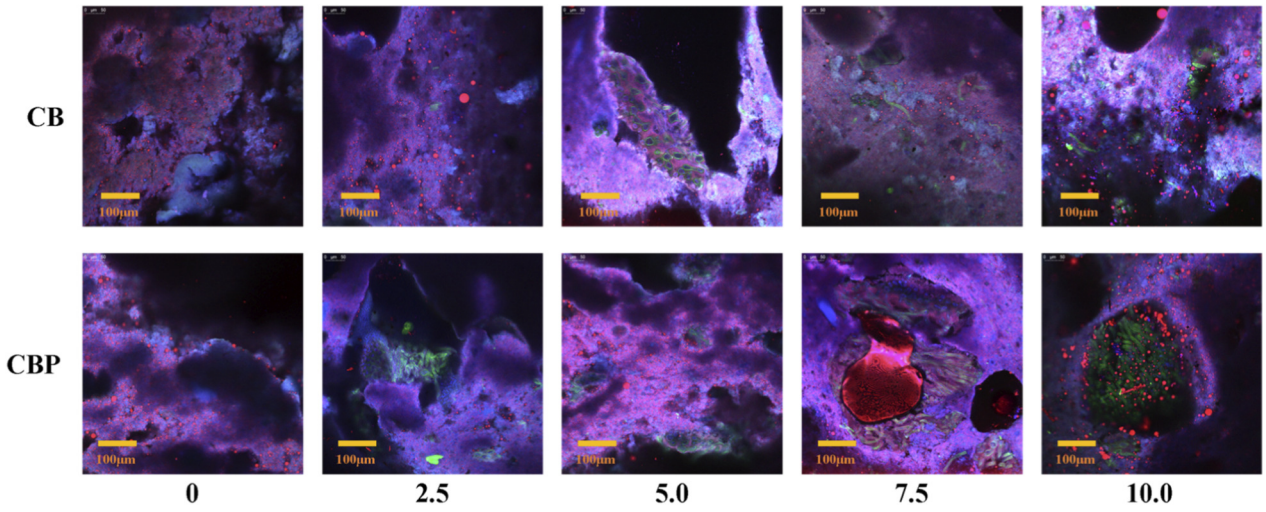


FIGURE 6
CLSM images of chicken gels containing red algae (PP) with different incorporation levels before (CB) and after (CBP) sterilization. The colors of blue, green, and red represent protein, polysaccharide, and lipid, respectively.

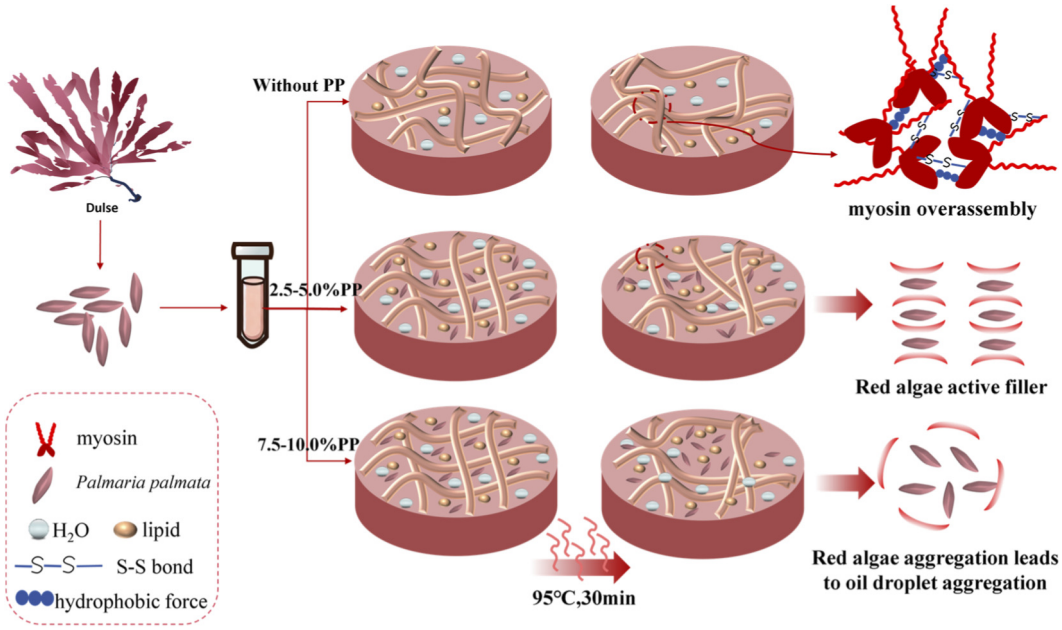


FIGURE 7
Schematic illustration of chicken-red algae gel regulated by sterilization.

may have facilitated further aggregation of myofibrillar proteins. In the CB-2.5 and CB-5.0 images, the protein matrix appeared more homogeneous, while fine polysaccharide domains were distributed within the interspaces and around the junctions of the protein network. The association between polysaccharides and proteins appeared more intimate, and the composite structure showed stronger interconnectivity. This compact matrix was mostly retained after sterilization, showing only slight contraction and no obvious large fractures or coarse aggregates, which helped limit moisture migration and loss (Zhuang et al., 2020). However, when the red algae addition increased to 7.5%–10.0%, the polysaccharide channel more frequently displayed larger continuous signal clusters. In the merged images, these polysaccharide-enriched domains showed sharper boundaries and locally block-like aggregation, indicating increased structural heterogeneity. After high-temperature sterilization (CBP-7.5 and CBP-10.0), the interfaces surrounding the aggregated domains became indistinct or discontinuous, and structural uniformity

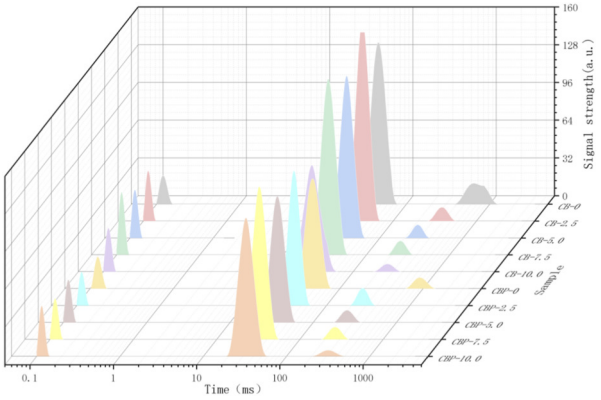


FIGURE 8
LF-NMR relaxation time (T_2) distribution of chicken gels with different PP incorporation levels before (CB) and after (CBP) sterilization.

further declined. Together with SEM observations of coarse aggregates and irregular pores after secondary heating at these addition levels, it could be inferred that excessive red algae more readily induced localized phase separation or aggregate formation in chicken gels, thereby compromising network continuity and creating pathways for water migration, ultimately reducing reheating stability. Localized phase separation may further exacerbate moisture loss by disrupting network continuity (Xu et al., 2022). The droplet size of the lipid phase and whether coalescence occurs reflected interfacial stability during secondary thermal processing (Xu et al., 2022). In the CB group, lipid droplets in all samples mainly appeared as relatively small, discrete red fluorescent droplets, and most were embedded within the protein–polysaccharide composite matrix, indicating that the system could entrap and immobilize the lipid phase after initial gelation. After high-temperature sterilization, a markedly enlarged lipid droplet was observed in CBP-7.5, suggesting that reheating induced lipid droplet coalescence; this indicated that, at this addition level, secondary thermal treatment may have weakened lipid–protein interfacial stability, allowing initially dispersed small droplets to merge during heating. Based on these observations, a schematic mechanism was proposed in Figure 7 to illustrate how red algae addition regulated protein aggregation behavior and network formation in chicken gels during high-temperature sterilization. A suitable degree of protein aggregation is important for developing desirable textural characteristics in meat gels. High-temperature sterilization often leads to textural deterioration and moisture loss in meat gels. In the absence of red algae, severe heating induces protein unfolding, exposing more sulfhydryl and hydrophobic groups and thereby promoting excessive protein aggregation through disulfide cross-linking and hydrophobic association. Red algae at 2.5%–5.0% enhanced and stabilized the gel matrix during high-temperature treatment by acting as an active filler, which reduced textural deterioration associated with network degradation and limited water and oil loss. At higher addition levels, red algae might have promoted protein aggregation and localized phase separation, reducing the thermal stability of the gel.

3.8 LF-NMR

LF-NMR was used to characterize water distribution and migration in gel samples and clarify the effect of red algae on water distribution before and after high-temperature sterilization. According to the T_2 relaxation times, the water fractions were assigned to bound water (T_2b, 0–10 ms), immobilized water ($T_2$1/$T_2$2, 10–100 ms), and free water ($T_2$3, 100–3,000 ms). Immobilized water is usually the major water fraction in meat gels. It was mainly confined within the gel network and contributed to gel juiciness (Zhang and McCarthy, 2012). As shown in Figure 8 and Table 4, in CB-0, free water represented 14.63%. With the incorporation of red algae, the proportion of free water declined markedly to below 5.37%, accompanied by increases in the proportions of bound and immobilized water. This indicated that red algae-derived hydrophilic polysaccharides, particularly xylan, enhanced water binding within the system, promoting the shift of water from free water toward less mobile fractions and

TABLE 4 Proportions (%) of water populations in chicken gels incorporated with different levels of red algae (PP) before (CB) and after (CBP) sterilization, as determined by low-field nuclear magnetic resonance (LF-NMR) relaxation time analysis.

Samples	PT2b (0–10 ms)	PT21 (10–100 ms)	PT23 (100–3,000 ms)
CB-0	7.21%	78.16%	14.63%
CB-2.5	9.68%	84.95%	5.37%
CB-5.0	11.02%	83.72%	5.26%
CB-7.5	12.06%	82.91%	5.03%
CB-10.0	11.95%	83.83%	4.22%
CBP-0	11.75%	80.86%	7.39%
CBP-2.5	9.90%	80.66%	9.44%
CBP-5.0	12.04%	81.12%	6.84%
CBP-7.5	9.78%	84.29%	5.94%
CBP-10.0	12.10%	84.44%	3.46%

improving water immobilization within the matrix. This result was consistent with the improved moisture retention and textural properties observed in the CB samples. After secondary heat treatment, free water in the control sample decreased from 14.63% to 7.39%, while bound water and immobilized water increased accordingly. However, this shift may be partly result from the partial loss of free water during secondary heating. The red algae-containing samples still maintained relatively low free water proportions after secondary sterilization. Within the 2.5%–5.0% addition range, free water was more effectively converted into immobilized and bound water, which helped maintain a continuous and compact network structure after secondary high-temperature sterilization.

4 Conclusion

Palmaria palmata (PP) is an edible red alga with high nutritional value, but its application in meat gels may be limited by structural changes during sterilization. This study examined the effect of introducing PP as an active filler on the thermal stability of chicken myofibrillar protein (MP) gels after high-temperature sterilization at 95 °C for 30 min. The optimal PP addition level is found to be 2.5%–5.0%. Within this range, the gels show better moisture retention and higher texture-related parameters, including hardness, gumminess, and chewiness, after reheating, indicating improved resistance to secondary heating. SEM images show that appropriate PP addition helps form a more continuous and compact gel network with smaller pores. LF-NMR analysis further indicates that PP promotes the shift of water from the free state toward bound and immobilized states, thereby strengthening water immobilization in the gel matrix. In addition, PP increases DPPH and ABTS radical scavenging activities, which are further enhanced after secondary heating, possibly due to the release of active compounds or the formation of antioxidant-active products during heating. In contrast, PP at levels of 7.5% and 10.0% results in reduced texture and structural homogeneity after secondary high-temperature sterilization, manifests as aggregates and irregular pores, which may be associated with localized phase separation or excessive aggregation. Overall, an appropriate level of PP (2.5%–5.0%) synergistically improves structural stability, water retention, and antioxidant functionality of chicken gels under sterilization.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

Ethics statement

The manuscript presents research on animals that do not require ethical approval for their study.

Author contributions

LJ: Formal Analysis, Investigation, Writing – review and editing, Writing – original draft. QL: Writing – review and editing, Formal Analysis. ZC: Investigation, Writing – review and editing, Formal Analysis. XJ: Investigation, Writing – review and editing. SW: Project administration, Conceptualization, Visualization, Writing – review and editing, Funding acquisition, Supervision.

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Conflict of interest

The author(s) declared that this work was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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References

Ahn, H. S., Yu, S. S., Kim, C. Y., Kim, Y. W., Yoon, Y., Lee, H., et al. (2024). Heat penetration and quality attributes of superheated steam sterilization (SHS) home meal replacement (HMR) meat products stew. *LWT*, 191, 115621. doi:10.1016/j.lwt.2023.115621

Chen, X., Xiong, Y. L., and Xu, X. (2019). High-pressure homogenization combined with sulfhydryl blockage by hydrogen peroxide enhance the thermal stability of chicken breast myofibrillar protein aqueous solution. *Food Chem.* 285, 31–38. doi:10.1016/j.foodchem.2019.01.131

Chen, B., Zhou, K., Wang, Y., Xie, Y., Wang, Z., Li, P., et al. (2020). Insight into the mechanism of textural deterioration of myofibrillar protein gels at high temperature conditions. *Food Chem.*, 330, 127186. doi:10.1016/j.foodchem.2020.127186

Chen, B., Guo, J., Xie, Y., Zhou, K., Li, P., and Xu, B. (2021). Modulating the aggregation of myofibrillar protein to alleviate the textural deterioration of protein gels at high temperature: the effect of hydrophobic interactions. *Food Chem.* 341, 128274. doi:10.1016/j.foodchem.2020.128274

Ducic, M., Petrovic, J., Vranesevic, J., Vranic, D., Baltic, M., and Torovic, L. (2025). Quality assessment of sremska, nitrite-free dry fermented sausage pasteurized with mild heat treatment. *Foods* 14, 3339. doi:10.3390/foods14193339

Feng, J., Kong, B., Sun, F., and Xia, X. (2022). Effect of potato dietary fiber on the quality, microstructure, and thermal stability of chicken patty. *Foods* 11, 3978. doi:10.3390/foods11243978

Fu, Q., Yang, J., Lv, L., Shen, T., Peng, Y., and Zhang, W. (2023). Effects of replacing chicken breast meat with Agaricus bisporus mushrooms on the qualities of emulsion-type sausages. *LWT* 184, 114983. doi:10.1016/j.lwt.2023.114983

Jiang, L., Turchiuli, C., Xu, Z., Li, J., and Wu, S. (2026). Effects of red algae on the properties of chicken gels: appearance, gelation, texture. *Innovative Food Sci. Emerg. Technol.* 107, 104325. doi:10.1016/j.ifset.2025.104325

Lahaye, M., Rondeau-Mouro, C., Deniaud, E., and Buléon, A. (2003). Solid-state 13C NMR spectroscopy studies of xylans in the cell wall of Palmaria palmata (L. Kuntze, rhodophyta). *Carbohydr. Res.* 338(15), 1559–1569. doi:10.1016/S0008-6215(03)00241-6

Leygonie, C., Britz, T. J., and Hoffman, L. C. (2011). Oxidative stability of previously frozen ostrich muscularis iliofibularis packaged under different modified atmospheric conditions. *Int. J. Food Sci. Technol.* 46 (6), 1171–1178. doi:10.1111/j.1365-2621.2011.02603.x

Leygonie, C., Britz, T. J., and Hoffman, L. C. (2012). Impact of freezing and thawing on the quality of meat: review. *Meat Sci.* 91 (2), 93–98. doi:10.1016/j.meatsci.2012.01.013

Li, M., Jiang, L., Guo, Z., Lin, J., Zheng, H., Lin, W., et al. (2025). Exploring the gelation potentials of chicken heart batter: from by-product to product. *Food Chem.*, 468, 142316. doi:10.1016/j.foodchem.2024.142316

Pereira, T., Barroso, S., Mendes, S., and Gil, M. M. (2020). Stability, kinetics, and application study of phycobiliprotein pigments extracted from red algae Gracilaria gracilis. *J. Food Sci.* 85(10), 3400–3405. doi:10.1111/1750-3841.15422

Petracci, M., Sirri, F., Mazzoni, M., and Meluzzi, A. (2013). Comparison of breast muscle traits and meat quality characteristics in 2 commercial chicken hybrids. *Poult. Sci.* 92(9), 2438–2447. doi:10.3382/ps.2013-03087

Plaza, M., Cifuentes, A., and Ibáñez, E. (2008). In the search of new functional food ingredients from algae. *Trends Food Sci. and Technol.* 19(1), 31–39. doi:10.1016/j.tifs.2007.07.012

Sun, X., and Holley, R. (2010). Factors influencing gel formation by myofibrillar proteins in muscle foods. *Compr. Rev. Food Sci. Food Saf.* 10, 33–51. doi:10.1111/j.1541-4337.2010.00137.x

Traore, S., Aubry, L., Gatellier, P., Przybylski, W., Jaworska, D., Kajak-Siemaszko, K., et al. (2012). Effect of heat treatment on protein oxidation in pig meat. *Meat Sci.* 91(1), 14–21. doi:10.1016/j.meatsci.2011.11.037

Viana, A. G., Noseda, M. D., Gonçalves, A. G., Duarte, M. E. R., Yokoya, N., Matulewicz, M. C., et al. (2011). β-d-(1→4), β-d-(1→3) 'mixed linkage' xylans from red seaweeds of the order Nemaliales and Palmariales. *Carbohydr. Res.* 346(8), 1023–1028. doi:10.1016/j.carres.2011.03.013

Wang, D., Xiao, H., Lyu, X., Chen, H., and Wei, F. (2023). Lipid oxidation in food science and nutritional health: a comprehensive review. *Oil Crop Sci.* 8(1), 35–44. doi:10.1016/j.ocsci.2023.02.002

Wang, Y., Chen, J., Li, R., Wang, S., Li, K., Wang, Y., et al. (2024). Effect of chitooligosaccharides in inhibiting textural deterioration of chicken myofibril protein gel induced by high temperature. *Food Hydrocoll.* 153, 110031. doi:10.1016/j.foodhyd.2024.110031

Xu, L., Wang, J., Lv, Y., Su, Y., Chang, C., Gu, L., et al. (2022). Influence of konjac glucomannan on the emulsion-filled/non-filled chicken gel: study on intermolecular forces, microstructure and gelling properties. *Food Hydrocoll.* 124, 107269. doi:10.1016/j.foodhyd.2021.107269

Xu, M., Zhang, Y., Wu, B., Zhang, Y., Qiao, M., Singh, G., et al. (2024). A critical review of the edible seaweed Palmaria palmata (L.) weber and mohr and its bioactive compounds in the "omics" era. *Algal Res.* 82, 103606. doi:10.1016/j.algal.2024.103606

Yuan, D., Xu, Y., Kong, B., Cao, C., Zhang, F., Xia, X., et al. (2023). Application of seaweed dietary fiber as a potential alternative to phosphates in frankfurters with healthier profiles. *Meat Sci.* 196, 109044. doi:10.1016/j.meatsci.2022.109044

Zhang, L., and McCarthy, M. J. (2012). Black heart characterization and detection in pomegranate using NMR relaxometry and MR imaging. *Postharvest Biol. Technol.* 67, 96–101. doi:10.1016/j.postharvbio.2011.12.018

Zhang, L., Zhang, F., and Wang, X. (2015). Effects of hydrolyzed wheat gluten on the properties of high-temperature (≥100 °C) treated surimi gels. *Food Hydrocoll.* 45, 196–202. doi:10.1016/j.foodhyd.2014.11.016

Zhang, T., Chen, S., Xu, X., Zhuang, X., Chen, Y., Xue, Y., et al. (2023). Effects of konjac glucomannan on physical properties and microstructure of fish myofibrillar protein gel: phase behaviours involved. *Food Hydrocoll.* 134, 108034. doi:10.1016/j.foodhyd.2022.108034

Zhong, P., Yu, Q., Guo, Z. L., Zheng, H., Lin, J., Lei, H. T., et al. (2025). Pea protein as filler particles in dual-protein hybrid emulsified gels: focus on the particle reinforcement theory. *FOOD Netherl.* 46, 100480. doi:10.1016/j.foostr.2025.100480

Zhu, Z., Fang, R., Huang, M., Wei, Y., and Zhou, G. (2020). Oxidation combined with maillard reaction induced free and protein-bound Nε-carboxymethyllysine and Nε-carboxyethyllysine formation during braised chicken processing. *Food Sci. Hum. Wellness* 9(4), 383–393. doi:10.1016/j.fshw.2020.05.013

Zhuang, X., Jiang, X., Zhou, H., Chen, Y., Zhao, Y., Yang, H., et al. (2020). Insight into the mechanism of physicochemical influence by three polysaccharides on myofibrillar protein gelation. *Carbohydr. Polym.* 229, 115449. doi:10.1016/j.carbpol.2019.115449