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ARTICLE

Effects of High-Pressure, Sous-Vide Cooking and Commercial Freezing on the Physicochemical Properties of Moisture-Enhanced Restructured Pork

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Abstract Pretreatments, including heating or freezing for the handling of restructured meat, can cause quality deterioration during cooking due to excessive drip loss. This study investigated the effects of high-pressure (HP) processing (200 MPa for 15 min), cooking methods, and freezing on the quality characteristics of moisture-enhanced restructured pork (MERP). The MERP was formulated to 84% moisture and compared with a control with 74% moisture. The MERP was applied to conventional cooking (75°C for 30 min) and sous-vide cooking (55°C for 24 h), and parts of sous-vide cooked MERP were frozen at –30°C for 24 h to assess quality deterioration. Results revealed that HP cooking effectively bound meat cubes in MERP, and further cooking enhanced the binding strength of MERP products. During cooking, sous-vide improved the moisture retention of MERP. However, freezing increased the cooking loss of MERP, particularly of frozen and reheated MERP, which exhibited the highest cooking loss among the treatments. Despite the fact that the moisture loss of freezing treatments negatively affected the tenderness of the MERP products, frozen MERP retained a tender texture compared with the unfrozen control. HP combined with sous-vide cooking rarely affected the cooked color of MERP, and the MERP products exhibited normal cooked color of meat products. Therefore, the present study indicated that HP and sous-vide cooking improved the quality characteristics of MERP, which suggested that MERP could achieve better consumer preference than typically manufactured restructured meat products.

Keywords moisture enhancement, restructured pork, high pressure, sous-vide, freezing

Introduction

Restructured meat, also referred to as reformed meat, is a type of meat product that is processed using flaked or chunked meat pieces of meat. Compared with ground and comminuted meat products, restructured products provide textural and sensory qualities similar to intact steaks and chops, thus enabling the conversion of less-preferable parts of meat, such as pork loins, to high-value products (Lonergan et al., 2019). As meat pieces do not bind to each other before cooking, restructured products are typically handled by preheating or freezing (Tangwatcharin et al., 2019). However, these handling processes generate large amounts of drip, which subsequently results in a tough texture and poor eating quality after reheating or thawing (Parvin et al., 2020). Moisture enhancement is a commonly applied meat processing technique that ensures juiciness and tenderness in the final meat products. As brine or pickle solutions are injected into the meat for moisture enhancement, this technique effectively improves the texture and flavor of the products. Although moisture enhancement can compensate for moisture loss in restructured products during handling and cooking, it interferes with the binding of meat pieces and causes significant physical damage to meat tissues when the products are frozen (Ji et al., 2019; Kim et al., 2020).

Additional techniques to minimize moisture loss in restructured products are required to improve consumer preference, and high pressure (HP) can be a viable solution for restructured meat production. Although HP has been introduced as a nonthermal pasteurization technique, effective microbial inactivation in meat requires excessive HP (>400 MPa), which leads to irreversible protein denaturation, meat discoloration, and oxidative deterioration, thereby restricting HP application in the meat industry (Bak et al., 2019; Nawawi et al., 2023; Sazonova et al., 2019). Alternately, moderate HP (100–300 MPa) is reportedly advantageous for meat quality as this technique not only improves water-holding capacity but also stabilizes meat color during preservation (Bak et al., 2019; Sazonova et al., 2019). Notably, HP has potential applications in binding meat pieces without thermal treatment. A previous study demonstrated that addition of carrageenan was necessary for effective meat binding under HP, with successful binding was obtained at 200 MPa (Hong et al., 2008). However, the effect of HP combined with binding agents on the quality of moisture-enhanced restructured pork (MERP) products has yet to be explored.

Sous-vide is another technique that can produce tender and juicy meat products. Tangwatcharin et al. (2019) used sous-vide to restructure goat steak and reported that sous-vide cooked products exhibited better qualities than those cooked via conventional heating. Sous-vide cooking reduced moisture loss and improved the tenderness of meat products owing to the low processing temperature (Latoch et al., 2023), and these advantages might be particularly effective for moisture-enhanced meat products such as MERP.

In addition to handling purposes, freezing restructured meat products is essential not only for the distribution of the products but also for preserving any unused portions after use. However, water increases the specific heat capacity of MERP products, significantly delaying the overall freezing process time. Thus, the slow freezing process can lead to severe tissue damage, potentially reducing consumer preference. The use of HP and sous-vide cooking can minimize moisture loss during reheating after freezing, thereby enhancing overall consumer preference (Ji et al., 2019; Li, 2022). Nevertheless, the physicochemical changes that occur in frozen restructured meat products have been rarely studied. Therefore, this study investigated the effects of applicable unit operations, such as HP, heating methods, and freezing, on the quality characteristics of MERP.

Materials and Methods

Materials and sample preparation

A total of six pork loins (*longissimus dorsi*) were randomly purchased at 24 h post-mortem from a local market (Seoul, Korea). The visible fat and connective tissues were removed, and the lean meat (71.5% moisture content) was cut into 1 cm cubes. All cubes from the six loins were combined to ensure uniform sample preparation. The control group was formulated by 98% (w/w) meat cubes, 1% (w/w) NaCl, and 1% (w/w) κ-carrageenan. In contrast, the MERP samples were prepared with

60% (w/w) meat cubes, 1% (w/w) NaCl, 1% (w/w) κ-carrageenan, and 38% (v/w) distilled water, providing 10% moisture enhancement. After mixing the meat cubes and additives manually for 3 min, 200 g portions of the mixture were filled into fibrous casing (45 mm in diameter) and vacuum-sealed in high-density polyethylene bags. The MERP samples were divided into five treatment groups, as shown in Table 1. HP was applied using a laboratory-assembled device (2 L working volume) as previously described (Kim et al., 2020) at the Biopolymer Research Center for Advanced Materials (Seoul, Korea). HP parameters were set to a compression speed of 25 MPa/s, a target pressure level of 200 MPa, and a holding time of 15 min at 4°C. For freezing treatments, a T-type thermocouple was inserted into the geometric center of a random sample, and samples were stored at –30°C for 24 h. Effective freezing time was estimated as the time taken for the core temperature to reach –10°C from the onset of freezing, and the freezing rate was calculated by dividing the measured freezing time by the sample radius (2.5 cm). Two thermal treatments were applied for cooking MERP samples. For conventional cooking, samples were immersed in a 75°C water bath for 30 min, while sous-vide cooking was conducted in a 55°C water bath for 24 h. For frozen treatments (ME-PFS and ME-PSFS), sous-vide cooking was directly applied without thawing process. The cooked samples were then cooled in ice water for 1 h and kept at 4°C before quality analysis. The entire sample preparation was repeated three times with another batch of pork loins for experimental replications.

Scanning electron microscopy

The microstructure of the samples was observed using a scanning electron microscope (TM4000Plus, Hitachi High-Technologies, Tokyo, Japan). Approximately 2 mm slices were obtained from the junction points between meat cubes and freeze-dried at 0.1 Torr for 24 h using a freeze dryer (GP10, Ilshin BioBase, Dongducheon, Korea). Images of the dried samples were taken at a magnification of ×500 with an acceleration voltage of 15 kV.

Water-binding properties

The weights of three samples from each treatment group were measured immediately after preparation and after cooking. Cooking loss of the samples was calculated as the percentage change in weight following cooking. The moisture content of the cooked samples was determined in triplicate based on the hot air drying method at 105°C.

Table 1. Manufacturing procedure of restructured pork and description of treatments

Treatments[1)]	Manufacturing procedure				
	Moisture enhancement	High pressure	Heating	Freezing	Post heating
Control	N/A	N/A	Conventional	N/A	N/A
ME-C	Enhanced	N/A	Conventional	N/A	N/A
ME-PC	Enhanced	Pressurized	Conventional	N/A	N/A
ME-PS	Enhanced	Pressurized	Sous-vide	N/A	N/A
ME-PFS	Enhanced	Pressurized	N/A	Frozen	Sous-vide
ME-PSFS	Enhanced	Pressurized	Sous-vide	Frozen	Sous-vide

[1)] ME, 10% moisture enhanced; C, conventional cooking at 75°C for 30 min; P, pressurization at 200 MPa for 15 min under 4°C; S, sous-vide cooking at 55°C for 24 h; F, freezing at –30°C for 24 h.
N/A, not applied.

Binding strength

The binding strength of the meat cubes was determined following the method described by Saavedra Isusi et al. (2023), with minor modifications. Each cooked sample was sliced to a 2-cm thickness, and six cylinders from each treatment were tested using a texture analyzer (CT-3, Brookfield Engineering Lab, Middleboro, MA, USA) equipped with a cylindrical standard probe (50.8 mm in diameter; TA-25/1000, Brookfield Engineering Lab). The analysis conditions were set to a trigger load of 0.05 N and a test speed of 1 mm/s. Stress and strain at failure were recorded, and Young's modulus was calculated using the ratio of stress to strain.

Texture profile analysis

To measure textural properties, each cooked sample was sliced to a 1-cm thickness, and nine cylindrical samples were obtained from each treatment. Each sample was compressed twice using a texture analyzer (CT-3, Brookfield Engineering Lab) equipped with a probe (TA-25/1000, Brookfield Engineering Lab). Primary textural properties, including hardness, cohesiveness, and springiness, were measured under the following conditions: trigger load of 0.05 N, test speed of 1 mm/s, and 70% compression of the initial height of the cylinder.

Instrumental color

From each treatment, four cylindrical slices with a thickness of 1 cm were obtained and kept at ambient temperature (~20℃) for 15 min. The color of each treatment was measured at the center of each cylinder using a color reader (CR-10, Konica Minolta Sensing, Tokyo, Japan) calibrated with a white standard board. The CIE L*, CIE a*, and CIE b* values were recorded as indicators of lightness, redness, and yellowness, respectively.

Statistical analysis

A completely randomized design was adopted to evaluate the main effect (moisture enhancement, HP, cooking method, and freezing). Data obtained from each experiment were averaged, and the mean and SD were calculated from the averages of three entirely repeated experiments (n=3). One-way analysis of variance was conducted using SPSS software (ver. 18, SPSS, Chicago, IL, USA), and Duncan's multiple range test was performed as a post-hoc procedure when the main effect was statistically significant ($p<0.05$).

Results and Discussion

Morphology and microstructure

The morphology and microstructure of the samples are shown in Fig. 1. As hypothesized, HP played a crucial role in binding the meat pieces of the MERP product. Despite the addition of κ-carrageenan, the morphology of the unpressurized treatments (control and ME-C) showed a relatively uneven structure with visible cracks caused by separation of meat cubes, and particularly ME-C showed poor network structuring. The structural inconsistency of the ME-C treatment reflected that a cohesive network structuring among meat cubes was not achieved by thermal treatment alone. The addition of a small amount of κ-carrageenan improved the gel strength of protein-based gels since it occupied void spaces in the protein gel network (Chen et al., 2024). However, due to thermodynamic incompatibility, the large amount of κ-carrageenan could interfere with

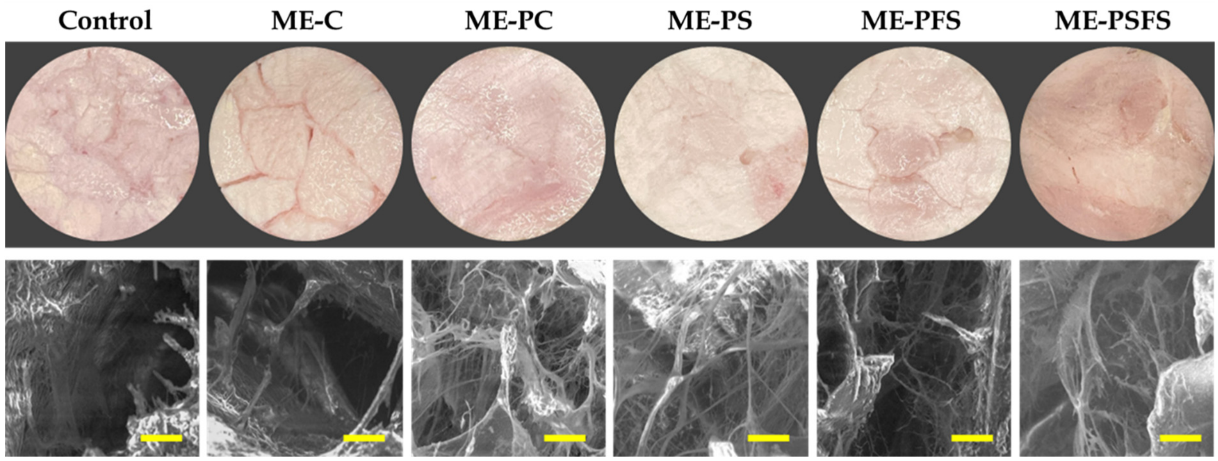

Fig. 1. Morphology and microstructure of moisture-enhanced restructured pork. ME, 10% moisture enhanced; C, conventional cooking at 75°C for 30 min; P, pressurization at 200 MPa for 15 min under 4°C; S, sous-vide cooking at 55°C for 24 h; F, freezing at –30°C for 24 h. Scale bars=50 μm.

crosslinking of proteins (Li et al., 2024), and the added κ-carrageenan in MERP products accumulated only on the surface of meat cubes, interfering protein–protein interactions at the junction of meat cubes during heating. In addition, the moisture enhancement caused a diluting effect of extracted myofibrillar proteins, and meat pieces in the ME-C treatment were easily separated by applied external force such as cutting and slicing.

HP treatments (ME-PC and ME-PS) exhibited an intact muscle-like structure due to strong network structuring at the meat cube junctions. As previously reported, the addition of κ-carrageenan in meat products supported a continuous thick fibrous network formation with meat proteins under HP (Hong et al., 2008), and the network structure was stabilized by subsequently applied thermal treatment, promoting crosslinking of meat proteins more intensely than HP. However, freezing (ME-PFS) manifested disintegration of the network structure, which was not observed when the MERP was cooked before freezing (ME-PSFS). The network retained a large amount of moisture due to the hydrophilic nature of carrageenan. Cooking caused a release of moisture from the network structure, resulting in a dense structural integrity of the network. However, freezing-mediated ice crystallization would account for the disintegration of the network structure (Wang et al., 2024), thereby showing the evidence of poor binding of meat cubes to ME-PFS treatment. Therefore, the current study demonstrated that HP played a critical role in binding meat cubes within MERP. However, freezing the HP-treated products without cooking could negatively affect the binding of meat cubes in restructured products.

Binding strength

Rheological parameters to estimate the binding strength at failure among meat cubes are given in Table 2. The stress of ME-C treatment was 1.23 kPa and significantly lower than 1.47 kPa of the control ($p<0.05$). As previously shown, κ-carrageenan alone could not act as a meat-binding agent unless HP was applied (Fig. 1), and the addition of hydrocolloids reportedly interfered with protein–protein interactions (Yang and Xiang, 2022). Although the strain of ME-C did not differ from that of the control, variation in stress of the treatment led to a significantly lower Young's modulus than the control ($p<0.05$). Since carrageenan could not contribute to the binding of meat cubes in ME-C treatment, the primary binding among meat cubes in this treatment would be achieved through crosslinking of meat proteins. However, diluting the extracted meat proteins by moisture enhancement accounted for the weak binding strength of ME-C treatment compared with the control.

Table 2. Binding strength of moisture-enhanced restructured pork

Treatments[1)]	Stress (kPa)	Strain	Young's modulus (kPa)
Control	1.47±0.08^{b}	0.74±0.05^{b}	1.99±0.21^{ab}
ME-C	1.23±0.10^{c}	0.80±0.09^{ab}	1.53±0.19^{c}
ME-PC	1.83±0.11^{a}	0.84±0.05^{a}	2.20±0.23^{a}
ME-PS	1.49±0.06^{b}	0.87±0.06^{a}	1.74±0.28^{bc}
ME-PFS	0.96±0.12^{d}	0.87±0.04^{a}	1.17±0.27^{d}
ME-PSFS	1.01±0.12^{d}	0.72±0.02^{b}	1.41±0.19^{cd}

Results are presented as mean±SD (n=3).
[1)] ME, 10% moisture enhanced; C, conventional cooking at 75°C for 30 min; P, pressurization at 200 MPa for 15 min under 4°C; S, sous-vide cooking at 55°C for 24 h; F, freezing at –30°C for 24 h.
[a–d] Different superscript letters within a column indicate a significant difference (p<0.05).

Alternately, HP was effective to bind meat cubes, and stress and strain of ME-PC were greater than those of the control without moisture enhancement (p<0.05). In particular, the ME-PC treatment showed the highest Young's modulus among all treatments (p<0.05), suggesting that HP followed by conventional cooking could bind meat particles effectively, allowing them to form a cohesive structure similar to a single muscle. As evident by the microstructure, HP promoted continuous network structure at the junction points of meat cubes, showing a higher binding strength of MERP than the control. Since cooking promoted an intermolecular hydrophobic interaction among meat proteins (Walayat et al., 2021), cooking could enhance the binding strength of meat cubes in MERP products.

However, the impact of HP was not obviously observed when the MERP was cooked via sous-vide, and ME-PS exhibited a slight increase in strain alone compared with the control (p<0.05). Moreover, the stress and Young's modulus of the ME-PS treatment were lower than those of the ME-PC treatment (p<0.05). The result could be explained by the fact that thermal unfolding and crosslinking of proteins were prerequisites for effective protein gel network formation, and low-temperature sous-vide cooking (55°C) could not promote an intensive intermolecular crosslinking of meat proteins (Latoch et al., 2023). Nevertheless, HP followed by sous-vide (ME-PS) led to better binding of meat cubes than that engendered by conventional cooking alone without HP (ME-C).

Freezing lowered the binding properties of MERP products, and the ME-PFS treatment showed 0.96 kPa of the lowest stress among all treatments (p<0.05). Additionally, the strain of this treatment was still higher than that of the control (p<0.05), resulting in the lowest Young's modulus among all the tested treatments. The thermal stability of κ-carrageenan to form a gel network could be destabilized by freezing and thawing (McKee and Alvarado, 2004). Although sous-vide cooking before freezing (ME-PSFS) tended to increase binding strength compared with the ME-PFS treatment, the binding impact among meat cubes was not yet recovered to the level observed in the unfreezing treatments. Although a fibrous network was formed at the junction points of the meat cubes, results indicated that the ice crystals formed during freezing negatively affected the network structure, lowering the binding strength of the MERP products. To prevent changes in the binding strength of frozen MERP products, further exploration and optimization of processing parameters, such as pressure levels, heat treatment conditions, and alternative binding agents, is warranted.

Water-binding properties

As shown in Fig. 2A, the cooking loss of all the treatments ranged from 20.5% to 29.9%, which was significantly higher than 11.8% of the control (p<0.05). MERP was formulated with 83% final moisture compared with 73% of the control,

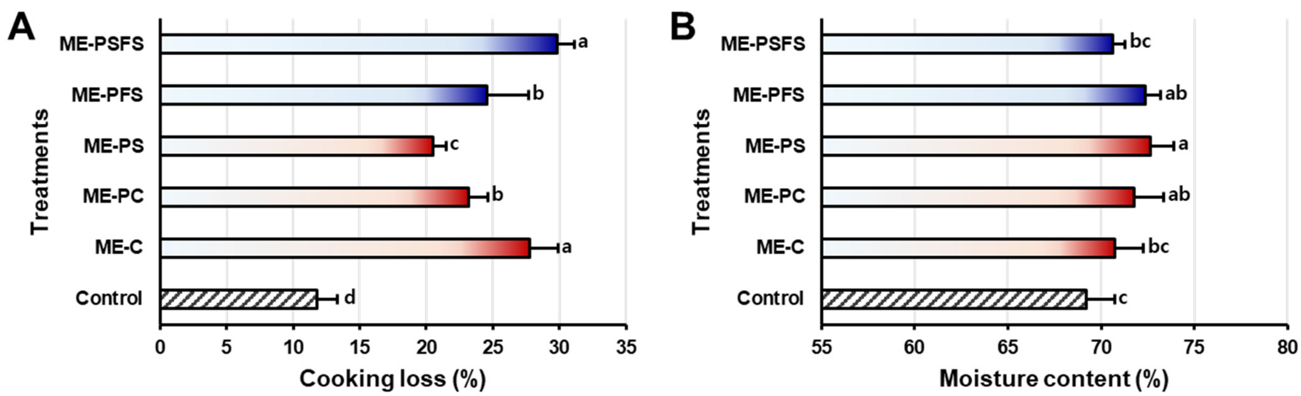

Fig. 2. Water-binding properties of moisture-enhanced restructured pork. (A) Cooking loss. (B) Moisture content. ME, 10% moisture enhanced; C, conventional cooking at 75℃ for 30 min; P, pressurization at 200 MPa for 15 min under 4℃; S, sous-vide cooking at 55℃ for 24 h; F, freezing at –30℃ for 24 h. Vertical bars indicate SDs (n=3). [a–d] Means with different letters are significantly different ($p<0.05$).

accounting for the larger cooking loss of MERP treatments. Among the treatments, HP exhibited an advantage of reducing the cooking loss of sample, and HP-treated MERP (ME-PC and ME-PS) exhibited significantly lower cooking loss than unpressurized ME-C–treated MERP ($p<0.05$). For heating method, sous-vide-treated ME-PS exhibited better stability of moisture retention during thermal processing than conventionally cooked ME-PC treatment ($p<0.05$). Moderate HP improved the water-holding capacity of meat because noncovalent interactions, destabilized by HP, were replaced by protein–water interactions (Sazonova et al., 2019; Ye et al., 2024). Additionally, a transverse contract of muscle fiber in low-temperature sous-vide expanded interfibrillar space, accommodating more moisture within the myofibrillar space (Lotoch et al., 2023). These results suggest that HP followed by sous-vide was an effective procedure for moisture retention in MERP and exhibited a similar trend in the final moisture content of the product (Fig. 2B). Moisture enhancement caused significant moisture loss compared with the control, and the moisture content of ME-C treatment did not show a significant difference from the control. However, compared with the control, HP treatments (ME-PC and ME-PS) exhibited a significantly higher moisture content ($p<0.05$). Therefore, the result reflected that moisture enhancement could improve the tenderness of the MERP products, positively contributing to consumer preference.

Moreover, freezing compensated for the impact of HP and sous-vide on the moisture retention of the MERP. The cooking loss treatment of ME-PFS was 24.5%, which was significantly greater than that of ME-PS ($p<0.05$). The result indicated that the addition of a large amount of moisture affected the freezing rate of the product, likely leading to severe tissue damage (Li, 2022). The moisture content of ME-PFS was significantly higher than that of the control ($p<0.05$), and sous-vide could be adopted for effective thawing and cooking frozen MERP products compared with conventional heating methods. Alternatively, heating and reheating via sous-vide (ME-PSFS) resulted in high cooking losses in the samples. Although sous-vide cooking could accelerate the freezing rate from 0.42 cm/h (freezing without cooking) to 0.57 cm/h (Fig. 3), it was not effective in preventing moisture loss during heating and reheating, resulting in the highest cooking loss along with the ME-C treatment among the treatments. Conversely, the moisture content of the ME-PSFS treatment did not show any significant difference from that of the control, despite freezing and two cycles of heating. This finding would suggest that sous-vide reheating could be a potential solution to overcome the drawbacks of drip loss and increased toughness typically observed in frozen meat products.

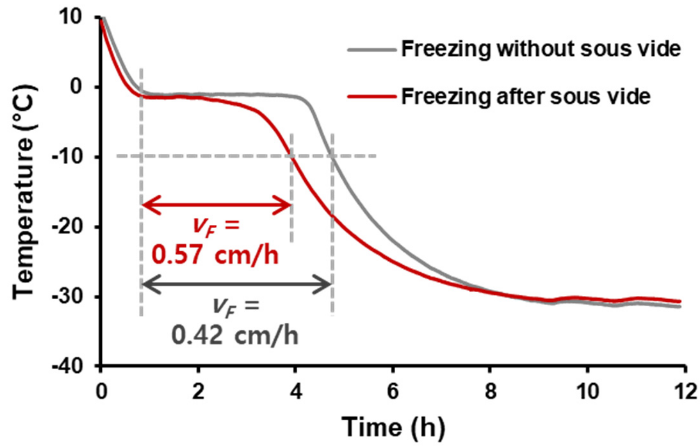

Fig. 3. Freezing profiles of moisture-enhanced restructured pork with and without sous-vide cooking. v_F indicates the freezing rate of the sample.

Texture profile analysis

Table 3 compares the primary textural properties of MERP processed by various methods with those of the control. Moisture enhancement (ME-C) decreased the hardness and cohesiveness of MERP compared with the control ($p<0.05$). The result was commonly observed in meat products formulated with a large amount of added moisture, possibly due to the partial replacement of protein–protein interactions into protein–water interactions, imparting a ductile texture to the products. Moreover, HP steeply increased the hardness and cohesiveness of MERP. Although the springiness of the ME-PC treatment was not different from that of the control, the treatment exhibited higher hardness and cohesiveness than the control ($p<0.05$), and particularly, ME-PC exhibited the highest hardness among all the treatments ($p<0.05$). This result was consistent with those of previous studies, and reportedly, HP affected not only thermal stability of connective tissue but also the volume of myofibrils (Akhtar and Abrha, 2022).

However, sous-vide manifested the tender texture of the MEPR product. Although the cohesiveness and springiness of the ME-PS treatment did not differ from those of the ME-PC, the ME-PS treatment showed the lowest hardness among all the treatments ($p<0.05$). The tenderness of meat depended on the structural changes of muscle fibers and connective tissue. In addition to the solubilization of connective tissue proteins, sous-vide reportedly contracts muscle fibers transversely compared

Table 3. Primary texture profiles of moisture-enhanced restructured pork

Treatments[1)]	Hardness (N)	Cohesiveness	Springiness (mm)
Control	463±34.3^{b}	0.45±0.02^{b}	0.66±0.02^{b}
ME-C	393±31.0^{c}	0.41±0.03^{d}	0.61±0.06^{b}
ME-PC	547±24.0^{a}	0.55±0.04^{a}	0.68±0.04^{ab}
ME-PS	224±22.3^{e}	0.53±0.02^{a}	0.75±0.07^{a}
ME-PFS	306±37.4^{d}	0.42±0.03^{bc}	0.67±0.01^{ab}
ME-PSFS	319±35.2^{d}	0.41±0.01^{d}	0.68±0.04^{ab}

Results are presented as mean±SD (n=3).
[1)] ME, 10% moisture enhanced; C, conventional cooking at 75°C for 30 min; P, pressurization at 200 MPa for 15 min under 4°C; S, sous-vide cooking at 55°C for 24 h; F, freezing at –30°C for 24 h.
$^{a–e}$ Different superscript letters within a column indicate a significant difference ($p<0.05$).

with longitudinal shrinkage during conventional cooking, resulting in better water retention and a tender texture of meat (Latoch et al., 2023). The results were consistent with those of previous reports and indicated that sous-vide was an effective cooking method for preventing toughness in restructured meat products, which are generally manufactured by combining lean meat.

Compared with ME-PS treatment, freezing did not affect the springiness of the MERP products. However, freezing treatments (ME-PSF and ME-PSFS) exhibited higher hardness and lower cohesiveness than ME-PS treatment ($p<0.05$). Drip generation would explain the tough texture of meat caused by freezing treatment, which was commonly reported in frozen meat products (Li, 2022). In addition, the added moisture remained primarily at the junctions between meat cubes in MERP rather than penetrating within the meat cubes. As mentioned in the microstructure, the added moisture could form large ice crystals, which weakened the binding strength among the meat cubes, likely leading to a decrease in the cohesiveness of meat cubes following freezing treatments. Conversely, the freezing treatments exhibited lower hardness than the control ($p<0.05$) without differences in cohesiveness and springiness. Thus, freezing treatments suggest that MERP can prevent quality deterioration better than normal restructured products, through cooking, freezing, and reheating.

Instrumental color

The eventual color characteristics of all the treatments are compared in Table 4. The color parameters of the ME-P treatment did not differ from those of the control, whereas ME-PC showed significantly lower CIE a* and CIE b* values than the control ($p<0.05$). The difference would reflect the level of processing that affected meat discoloration (Suman et al., 2016). Pressurized meat exhibited a lighter appearance, which was explained by myoglobin denaturation. Myofibrillar protein denaturation caused by HP changed the light reflectance of the meat surface, causing discoloration (Akhtar and Abrha, 2022). Even with the application of cooking at the same thermal intensity, ME-PC treatment resulted in greater myoglobin denaturation than ME-C, leading to a different color than that of the control.

Moreover, sous-vide-cooked meat exhibited a brighter and redder color than conventionally cooked meat (Latoch et al., 2023). Although a bright red color is generally preferred by consumers when purchasing meat, a pink color after cooking is considered undesirable, as it may be perceived as undercooked and unsafe (Suman et al., 2016). Herein, the CIE a* and CIE b* values of ME-PS were not different with those of ME-PC, although sous-vide cooking caused greater CIE L* among all the treatments ($p<0.05$). The former identical CIE a* and CIE b* values could be explained by the processing level as mentioned in ME-PC, whereas the latter light appearance would result from the moisture retention of sous-vide treatments.

Table 4. Instrumental color parameters of moisture-enhanced restructured pork

Treatments[1)]	CIE L*	CIE a*	CIE b*
Control	67.3 ± 2.65^{c}	6.60 ± 0.50^{a}	14.1 ± 1.56^{ab}
ME-C	69.4 ± 2.36^{bc}	6.05 ± 0.83^{a}	14.5 ± 1.01^{a}
ME-PC	69.2 ± 2.45^{bc}	4.58 ± 0.53^{b}	12.6 ± 0.74^{b}
ME-PS	72.8 ± 0.90^{a}	4.80 ± 0.16^{b}	14.1 ± 0.20^{ab}
ME-PFS	68.6 ± 0.97^{bc}	5.92 ± 0.55^{a}	13.4 ± 0.85^{ab}
ME-PSFS	71.1 ± 0.79^{ab}	4.92 ± 0.46^{b}	13.4 ± 0.17^{ab}

Results are presented as mean±SD (n=3).
[1)] ME, 10% moisture enhanced; C, conventional cooking at 75°C for 30 min; P, pressurization at 200 MPa for 15 min under 4°C; S, sous-vide cooking at 55°C for 24 h; F, freezing at –30°C for 24 h.
[a–c] Different superscript letters within a column indicate a significant difference ($p<0.05$).

For the color of freezing treatments, ME-PFS exhibited higher CIE a* values than ME-PSFS treatment. However, the color characteristics of frozen MERP showed little change even after freezing and subsequent heating. These results suggest that HP effectively controlled the persistence of redness that could potentially occur with sous-vide cooking, suggesting that it was unlikely to negatively affect consumer preference for MERP consumption.

Conclusion

Based on results, HP combined with the addition of κ-carrageenan was effective to bind meat cubes even in moisture-enhanced meat products formulating low salt content, and it was possible that freezing of MERP was not necessary for handling of the products without preheating. Cooking could enhance the binding of meat cubes in MERP, and sous-vide provided various advantages of moisture retention and tender textural properties of MERP. Freezing manifested quality deteriorations compared with the corresponding unfreezing treatment. However, the MERP formulated in this study showed the possibility of effectively controlling quality deterioration caused by freezing and reheating compared with conventional products. Although further research for improving the quality characteristics and consumer preference of MERP were warranted, this study demonstrated that the combination of unit operations including moisture enhancement, HP, and sous-vide cooking has the potential to positively impact consumer preference for restructured meat products.

Conflicts of Interest

The authors declare no potential conflicts of interest.

Acknowledgements

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Author Contributions

Conceptualization: Hong GP. Data curation: Yoon Y, Lee MY. Formal analysis: Yoon Y, Lee MY. Methodology: Lee SY, Hong GP. Software: Yoon Y, Lee MY. Validation: Yoon Y, Lee SY. Investigation: Lee MY, Hong GP. Writing - original draft: Yoon Y, Lee MY. Writing - review & editing: Yoon Y, Lee MY, Lee SY, Hong GP.

Ethics Approval

This article does not require IRB/IACUC approval because there are no human and animal participants.

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