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Preserving colour and texture in canned Atlantic chub mackerel: Influence of high-pressure processing and frozen storage

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ABSTRACT

Atlantic chub mackerel (*Scomber colias*), a nutritionally valuable yet highly perishable species, is prone to quality degradation during frozen storage and canning. This study evaluated the effects of high-pressure processing (HPP; 200–600 MPa) applied prior to freezing (−30 °C, 48 h), followed by frozen storage (−18 °C for 0, 3, 6, 10, or 15 months), canning, and post-canning storage (3 months at 20 °C), on the mechanical properties and colour of mackerel muscle. The aim of the study was to assess whether HPP can mitigate quality losses typically associated with long-term frozen storage and thermal processing. HPP initially reduced hardness and chewiness due to partial protein denaturation, but after storage and canning, samples treated at 200 and 600 MPa exhibited enhanced hardness, chewiness, and cohesiveness compared to untreated controls, suggesting structural reorganization over time. Adhesiveness decreased with pressure and storage, indicating greater compactness, while chewiness was best preserved at 600 MPa. CIELAB colour analysis revealed that HPP influenced visual appearance during storage. Lightness (L*) was best preserved at 200 MPa, while 600 MPa samples became darker, possibly due to pigment concentration or tissue compaction. Redness (a*) and yellowness (b*) also varied with pressure and storage duration, though less markedly. Overall, applying HPP prior to freezing enhanced the long-term quality of canned mackerel, supporting its potential as a pre-treatment strategy to preserve texture and appearance. These findings promote a better utilization of pelagic species and improved consumer appeal in the canned seafood industry.

1. Introduction

Mackerel (*Scomber* spp.), a widely consumed pelagic fish, is highly valued for its rich nutritional composition, particularly long-chain omega-3 fatty acids, high-quality proteins, and essential minerals. However, as a fatty fish, mackerel is highly susceptible to spoilage due to lipid oxidation and protein degradation during storage and processing. Traditional preservation methods such as frozen storage and canning effectively extend shelf life but are frequently associated with undesirable quality losses, particularly in texture and colour, which significantly impact consumer acceptance and market value.

In recent years, high-pressure processing (HPP) has gained prominence as a promising non-thermal technology in the seafood industry. HPP involves subjecting food to pressures between 100 and 600 MPa, which inactivates spoilage microorganisms and enzymes while minimizing thermal degradation. HPP has been shown to enhance the safety, sensory quality, and shelf life of various fish species, including mackerel, making it a viable pre-treatment option prior to storage and canning.

One of the key challenges in preserving mackerel muscle quality during frozen storage and canning lies in maintaining desirable textural properties. Textural degradation often results from protein denaturation, muscle fiber disintegration, and water loss during freezing and thermal sterilization. However, prior HPP treatment has been reported to improve texture stability by reducing expressible water and strengthening the muscle structure. For instance, Atlantic mackerel subjected to 150 MPa showed improved water retention and a texture profile more comparable to fresh fish after frozen storage (Aubourg et al., 2013). Likewise, similar benefits were observed in horse mackerel, where moderate HPP levels preserved mechanical texture parameters

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and resulted in higher sensory acceptability scores (Torres et al., 2014).

Another critical quality attribute in processed fish is colour, which often undergoes noticeable deterioration due to oxidation of muscle pigments and structural changes. HPP can either preserve or alter colour, depending on the intensity of applied pressure. Treatments above 200 MPa may lead to a cooked appearance, while moderate pressures around 150 MPa are generally effective in retaining the lightness and redness of fish muscle during storage (Matser et al., 2000). In mackerel, it was reported that HPP treatments at 200–500 MPa significantly increased muscle hardness and lightness, indicating structural protein changes with minimal species-specific variability (Christensen et al., 2017).

Besides sensory properties, HPP has also been shown to affect biochemical processes in fish muscle. HPP effectively inhibited free fatty acid formation and volatile amines in canned mackerel, particularly after extended frozen storage, suggesting protection against lipid hydrolysis and microbial spoilage (Prego, Fidalgo, et al., 2021). Similarly, HPP at 175–200 MPa inhibited tertiary lipid oxidation and partially preserved protein integrity during 9-month frozen storage in Atlantic mackerel (Pazos et al., 2015).

The effectiveness of HPP in preserving mackerel quality has also been explored in terms of mineral retention and chemical composition post-canning. Prior HPP, combined with frozen storage and canning, was associated with significant modifications in essential and toxic element concentrations, reflecting the complex interactions between pressure-induced denaturation, water loss, and packaging medium exchange (Prego, Martínez, et al., 2021).

Furthermore, the synergistic effects of HPP with other preservation methods, such as brine salting, have shown improved microbial inactivation and moderated colour and texture changes. For instance, mackerel fillets treated with both brining and HPP at 400 MPa retained better colour values (lower ΔE values) and showed acceptable texture and microbial counts compared to HPP or brining alone (Huang et al., 2022). In addition, it was reported that HPP at ≥300 MPa significantly reduced histamine formation and improved texture in spotted mackerel during refrigerated storage, suggesting a protective effect against spoilage and scombrotoxin development (Lin et al., 2021).

While the aforementioned studies underscore the potential of HPP to enhance fish quality during processing and storage, research specifically focused on the cumulative impact of HPP on mackerel muscle through the entire frozen storage and canning sequence remains limited. Most investigations isolate individual processing stages or evaluate only short-term effects. This fragmented understanding limits the development of optimized processing protocols that could extend the shelf life and preserve the quality of canned mackerel more effectively.

In previous research, the use of HPP as a pre-treatment prior to frozen storage and canning was evaluated for the first time in relation to lipid damage (hydrolysis and oxidation) and volatile amine formation in canned Atlantic chub mackerel (*Scomber colias*) (Prego, Fidalgo, et al., 2021). While these biochemical markers provided valuable insights into oxidative stability and spoilage potential, they do not directly reflect the attributes most relevant to consumer perception.

Therefore, the present study represents the next step in a sequential research strategy, focusing on instrumental evaluation of texture and colour. These properties are critical determinants of consumer acceptance and marketability of canned fish, yet remain underexplored in the context of cumulative processing chains combining HPP, long-term frozen storage, and canning. By maintaining a consistent methodological design with earlier work, this study provides complementary and comparable data that extend the understanding of how HPP influences fish quality throughout industrially relevant processing. The most previous studies have isolated individual processing stages or focused only on short-term effects. The present study fills this gap by providing a complementary instrumental assessment of consumer-relevant properties (texture and colour) over industrially relevant timelines, thereby enabling a comprehensive understanding of how HPP can be integrated with long-term frozen storage to optimize canned mackerel quality.

Ultimately, this approach allows us to build a comprehensive framework, starting from biochemical stability, advancing to instrumental texture and colour, and paving the way for future sensory studies with consumers. In this way, the present work contributes novel and essential evidence on the potential of HPP to preserve consumer-oriented quality traits of canned Atlantic chub mackerel.

Therefore, this research analyzes the effect of different pressure levels (0.1-control, 200, 400, and 600 MPa) and frozen storage durations (0–15 months) to inform evidence-based processing strategies that improve product quality, safety, and consumer satisfaction.

2. Materials and methods

Fig. 1 presents the flow diagram of the process developed in this study, outlining the main steps and operations involved. Each stage of

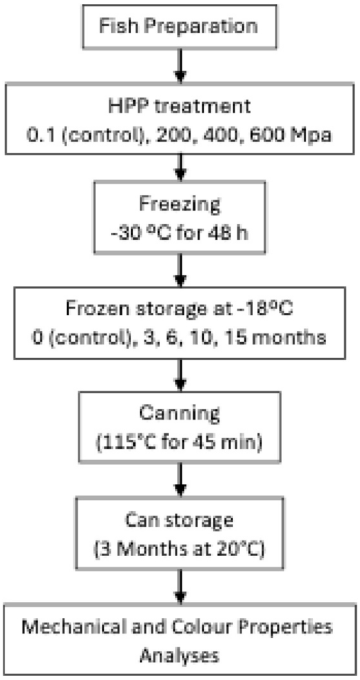

Fig. 1. Flow diagram of the experimental workflow for Atlantic chub mackerel (*Scomber colias*).

the process is described in detail in the following sections to provide a comprehensive understanding of the methodology and rationale behind the chosen approach. It is important to note that the processing sequence evaluated here (HPP, followed by freezing, prolonged frozen storage, thawing, and canning) was specifically designed to simulate a realistic industrial scenario rather than an idealized laboratory approach. In many seafood canneries, reliance on frozen raw material is routine due to seasonal catch variations, requiring long-term storage prior to canning. By incorporating HPP as a pre-freezing step, our study explores its potential to improve raw material quality not only during immediate post-processing, but throughout the entire storage and canning chain. Testing HPP in this multi-step sequence thus responds to common industry challenges, allowing for evidence-based recommendations even under intensive processing conditions. All treatments shared identical frozen storage, thawing, and canning parameters, with HPP as the only variable, ensuring reliable attribution of any quality improvements to the pressure intervention. These findings can inform processors about the cumulative benefits of HPP for preserving critical quality attributes over extended storage and complex workflow scenarios.

2.1. Sample collection and preparation

A total of 126 Atlantic Chub mackerel (*Scomber colias*) specimens, ranging in length from 24.5 to 28.0 cm and weighing between 157 and 175 g, were sourced from the fish auction at Vigo Port (NW Spain). The fish were transported to the laboratory under iced conditions immediately after landing. Upon arrival, six individuals were randomly selected for baseline analysis. These specimens were manually processed (beheaded, eviscerated, and filleted) and the resulting white muscle tissue was divided into three analytical groups ($n = 3$, two fish per group), serving as the initial reference.

The remaining 120 fish were allocated into 20 vacuum-sealable polyethylene bags, with each bag containing six whole fish. These bags were vacuum-packed at 150 mbar using a commercial vacuum sealing unit (Culinary model, Albipack Packaging Systems, Agueda, Portugal), then sorted into four distinct experimental groups (five bags per group) for subsequent treatment.

One group, which served as the non-HPP control (0.1 MPa), was immediately frozen at −30 °C for 48 h in a static freezer. The remaining three groups were subjected to HPP at 200, 400, or 600 MPa for 2 min using a 55-L HPP unit (WAVE 6000/55 HT, NC Hiperbaric, Burgos, Spain). Pressurization was performed with water as the transmission medium at a rate of 3 MPa/s, achieving respective come-up times of approximately 67, 133, and 200 s. Decompression was completed in less than 3 s. Following HPP treatment, all samples were frozen identically to the control group at −30 °C for 48 h.

2.2. Frozen storage and canning procedure

Post-freezing, one bag from each treatment group (control and three HPP levels) was thawed at 4 °C overnight and subsequently subjected to the canning process (month 0; initial canning condition. The remaining bags were transferred to a long-term storage freezer at −18 °C and retrieved at intervals of 3, 6, 10 and 15 months. At each time point, one bag from each group was thawed under the same refrigerated conditions for further canning.

In order to carry out the canning process, each 45-g portion of fillet (representing one fish) was placed into a rectangular can (105 × 60 × 25 mm, 150 mL capacity) and filled with a 2 % (*w/v*) sodium chloride brine solution. Cans were vacuum-sealed and thermally sterilized in a steam retort system (CIFP Coroso, Ribeira, A Coruña, Spain) at 115 °C for 45 min, achieving a lethality value (F_0) of 7 min. This value ensures sufficient thermal lethality to inactivate *Clostridium botulinum* spores and other spoilage microorganisms while balancing sensory quality retention. According to FAO guidelines for fish canning thermal processing, typical F_0 values range between 6 and 8 min for safe and effective sterilization, depending on container size, product composition, and process parameters (https://www.fao.org/4/r6918e/r6918e02.htm). After sterilization, steam was replaced with compressed air and the cans were water-cooled under vacuum to halt cooking.

2.3. Post-canning analysis

The cans were opened after 3 months of storage in an incubator chamber maintained at 20 °C. The liquid content was drained, weighed, and filtered through standard filter paper. The white muscle tissue was collected, wrapped in fresh filter paper to remove residual moisture, and subjected to analytical evaluation. For each sampling point, muscle from two cans was pooled to ensure consistency, and all analyses were conducted in triplicate ($n = 3$ per group).

2.4. Mechanical and colour properties

Samples were equilibrated at room temperature for 30 min in plastic bags to avoid dehydration. Then restructured products were cut into cube of 2 × 2 × 2 cm. Mechanical properties were determined using a TA-XTplus (StableMicro System, Viena Court, UK). Texture Profile Analysis (TPA) was carried on using cylindrical aluminium probe (P/50) of 50 mm of diameter. Samples were compressed to 75 % of their original height using a compression speed of 60 mm/min (Andrés-Bello et al., 2011). Hardness, adhesiveness, springiness, cohesiveness and chewiness were determined for each treatment and ten samples were analysed for each treatment (Aubourg et al., 2013).

Colour was assessed following the method described previously (Uresti et al., 2003). A colorimeter ColorStriker (Mathai, Hannover, Germany) was used. The L*, a*, and b* parameters were measured, with ten samples analysed per treatment. The total colour difference (ΔE_{00}) was evaluated using the CIEDE2000 method (Sharma et al., 2005).

2.5. Statistical analysis

Data obtained from texture and colour parameters were subjected to the analysis of variance (ANOVA) method to explore differences resulting from the effect of the previous HPP, temperature and storage time. Both texture and colour parameters were statistically analysed by the Design Expert® 7.1.1 software (Stat-Ease, Inc., MN, USA) for obtaining mathematical models for predictive purposes. Principal Component Analysis (PCA) was performed by Unscrambler software (version X 10.2; CAMO ASA, Oslo, Norway).

3. Results and discussion

It is important to note that the processing sequence evaluated (HPP followed by freezing, frozen storage, thawing, and canning) does not

Table 1
Effect of High-Pressure Processing and Frozen Storage as Pre-Treatments on Texture Profile Analysis of Canned Chub Atlantic Mackerel (*Scomber colias*) after 3-month storage. Experimental treatment codes use P and T for pressure (MPa) and frozen storage time (month), respectively. The control without HPP pre-treatment is labelled as P0.1.

Experiments	Hardness (g)	Adhesiveness (g·s)	Springiness	Cohesiveness	Chewiness
P0.1T0	14,339	−68	0.540	0.481	4035
P200T0	9958	−70	0.554	0.468	2581
P400T0	8500	−156	0.505	0.456	2065
P600T0	11,987	−52	0.516	0.469	2954
P0.1T3	13,224	−32	0.597	0.512	4095
P200T3	14,096	−186	0.694	0.578	5742
P400T3	15,533	−291	0.608	0.564	5805
P600T3	16,373	−161	0.638	0.557	5973
P0.1T6	13,924	−28	0.655	0.535	5029
P200T6	10,330	−196	0.555	0.486	2972
P400T6	11,059	−265	0.543	0.511	3148
P600T6	11,534	−122	0.533	0.501	3118
P0.1T10	12,328	−30	0.655	0.523	4274
P200T10	9632	−95	0.71	0.521	3602
P400T10	9355	−182	0.559	0.485	2753
P600T10	13,781	−134	0.606	0.558	4749
P0.1T15	21,104	−16	0.672	0.521	7593
P200T15	19,013	−253	0.688	0.581	7734
P400T15	15,500	−216	0.567	0.488	4589
P600T15	19,807	−149	0.581	0.516	6216

reflect the most conventional approach for this species. Rather, it was designed to simulate a realistic industrial scenario. In practice, canneries often depend on frozen raw material to ensure year-round production, since fresh catches are highly seasonal and cannot guarantee continuous supply. Freezing and long-term frozen storage prior to canning are therefore frequent strategies at industrial scale. Incorporating HPP prior to freezing was tested as an innovative approach to improve the raw material quality during subsequent storage and processing, thus extending the potential applications of HPP beyond its traditional role as a single preservation step.

Freezing and thawing themselves strongly affect fish texture due to ice crystal formation. Precisely for this reason, it is relevant to assess whether HPP applied prior to freezing may mitigate or exacerbate such effects, particularly in a multi-step sequence culminating in canning. Our aim was not to isolate HPP under idealized conditions, but rather to evaluate its cumulative contribution within a realistic processing chain. To achieve this, all treatments were subjected to the same freezing, storage, thawing, and canning steps, with HPP as the only variable factor, thus allowing the identification of its discrete influence despite the intensity of subsequent processing.

While HPP offers clear benefits in preserving textural and colour quality in canned mackerel, it is important to balance these advantages against practical considerations of cost, time, and energy consumption. HPP equipment represents a significant capital investment, and the pressure-holding phases add to overall processing time compared to conventional freezing and canning alone. Additionally, energy demands for operating high-pressure units can be substantial, especially when applied to large volumes of raw material prior to freezing. These factors may limit adoption in smaller or cost-sensitive operations. However, in canneries handling high volumes with seasonal raw material variability, the potential for improved product quality, extended shelf life, and reduced waste may justify the additional processing costs and complexity. A techno-economic analysis tailored to specific industrial contexts is presented in the section below to optimize HPP parameters and assess overall process sustainability. The trade-offs discussed therein are critical in strategizing commercial scale-up and realizing the full quality preservation potential demonstrated in this study.

3.1. Texture profile analysis (TPA) of canned Atlantic mackerel

The effect of high-pressure processing (HPP) applied prior to frozen storage on the texture of canned *Scomber colias* was evaluated through hardness, adhesiveness, springiness, cohesiveness, and chewiness (Table 1).

Hardness varied notably with both pressure intensity and frozen storage time. Immediately after processing (T0), the control (P0.1T0) exhibited the highest hardness (14,339 g), while HPP-treated samples, particularly at 400 MPa, showed significantly lower values (8500 g). After 3 months (T3), hardness increased in all HPP samples, peaking at 600 MPa (16,373 g), suggesting structural reorganization during frozen storage. After 15 months, high values persisted in P200T15 and P600T15 (19,013 and 19,807 g, respectively), while P400T15 showed less recovery (15,500 g), indicating a potential threshold for reversible denaturation.

Multifactor ANOVA confirmed significant effects of pressure and storage ($p < 0.003$, $R^2 = 0.86$). Hardness was mainly influenced by the linear and cubic terms of storage time ($F = 8.90$ and 17.90) and the quadratic term of pressure ($F = 9.02$). The regression model was:

$$\begin{aligned}\text{Hardness} = {} & 13,135 – 11.98^{*}\ \text{HPP Pressure} \\ & + 1218.7^{*}\ \text{Frozen Storage Time} \\ & + 0.50^{*}\ \text{HPP Pressure}^{*}\ \text{Frozen Storage Time} \\ & - 0.003^{*}\ \text{HPP Pressure}^{2} – 234.19^{*}\ \text{Frozen Storage Time}^{2} \\ & + 0.071417^{*}\ \text{HPP Pressure}^{2*}\ \text{Frozen Storage Time} \\ & - 0.051^{*}\ \text{HPP Pressure}^{*}\ \text{Frozen Storage Time}^{2} \\ & + 10.294^{*}\ \text{Frozen Storage Time}^{3}\end{aligned} \tag{1}$$

Fig. 2 shows the combined effect of HPP pressure and frozen storage

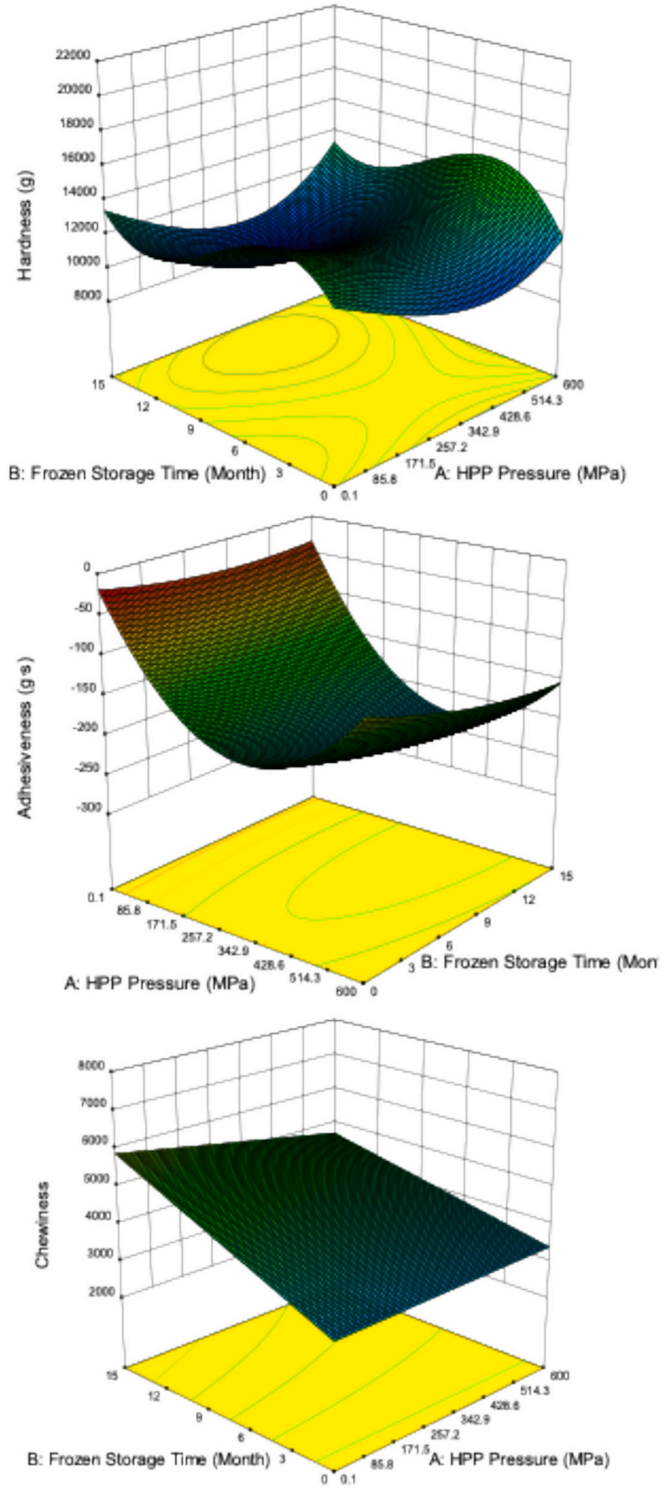

Fig. 2. Predicted effects of HPP pretreatment and frozen storage duration on the texture parameters of Atlantic Chub mackerel (*Scomber colias*) muscle after canning and subsequent 3-month storage.

time, with a sigmoidal trend and maximum hardness at 3 months. The initial softening at higher pressures aligns with reported protein denaturation and fiber disruption (Arnaud et al., 2018; Fidalgo et al., 2014), whereas the subsequent hardening during storage, especially at 200–600 MPa, may result from protein reorganization and network stabilization (Matser et al., 2000).

Adhesiveness became more negative in HPP-treated and long-stored samples (e.g., P400T3 = −291 g·s; P200T15 = −253 g·s) compared with controls (P0.1T0 = −68 g·s), indicating greater structural compactness. ANOVA yielded a significant model ($p < 0.002$, $R^2 = 0.70$), with strong influence from the linear and quadratic terms of pressure (F = 8.32 and 21.20). The regression model was:

$$\begin{aligned}\text{Adhesiveness} = & -18.966 - 0.959^{*}\ \text{HPP Pressure} \\ & - 4.144^{*}\ \text{Frozen Storage Time} \\ & - 0,0052^{*}\ \text{HPP Pressure}^{*}\ \text{Frozen Storage Time} \\ & + 0.0014^{*}\ \text{HPP Pressure}^{2} \\ & + 0.2103^{*}\ \text{Frozen Storage Time}^{2}\end{aligned} \quad (2)$$

PCA confirmed adhesiveness as one of the most negative loadings on PC2, separating samples treated at ≥400 MPa (Fig. 3). These results suggest that pressure intensification alters surface and internal cohesion through protein compaction and water redistribution, consistent with previous findings in frozen-stored salmon (Martinez et al., 2010).

Springiness ranged from 0.20 to 0.60, similar to restructured fish products (Andrés-Bello et al., 2011). Moderate pressures and extended storage tended to enhance elasticity, though effects were variable. ANOVA was significant ($p < 0.021$, $R^2 = 0.36$), indicating trends rather than predictive power. PCA showed springiness with strong positive loading on PC1, separating treatments by textural integrity. HPP initially reduced springiness (e.g., P400T0 = 0.505) due to compression, while frozen storage promoted partial recovery, likely linked to protein reorganization. Overall, springiness decreased with pressure and increased with storage time, reflecting the balance between compression and structural recovery.

Cohesiveness ranged from 0.456 (P400T0) to 0.581 (P200T15) and slightly increased during storage, particularly under moderate pressures. Although the ANOVA model was not significant, PCA identified cohesiveness as a major contributor to PC1, grouping treatments with higher cohesiveness exposed to mid-to-high pressure and long storage. These results suggest that HPP, combined with frozen storage, may enhance bonding strength within the muscle, likely through pressure-induced protein interactions that resist breakdown during canning.

Chewiness, derived from hardness, cohesiveness, and springiness, varied widely (2065–7734), consistent with differences among treatments and within the range of restructured fish products (Andrés-Bello et al., 2011). HPP initially reduced chewiness (e.g., P200T0, P400T0) due to softening, but long-term frozen storage (e.g., P0.1T15 and P200T15) enhanced it, suggesting reorganization of the muscle structure and water redistribution. The ANOVA was significant (F = 2.61; $R^2 = 0.33$), with frozen storage time as the main factor (F = 6.94). PCA grouped high-chewiness treatments along PC1, corresponding to samples combining moderate-to-high pressure and prolonged storage. These findings indicate synergistic effects between HPP and frozen storage in reinforcing muscle integrity.

Overall, chewiness emerges as a sensitive indicator of textural quality in canned mackerel. The combination of HPP and frozen storage stabilizes muscle texture while offering additional benefits such as improved lipid oxidation resistance and microbial stability (Martelo-Vidal et al., 2012; Prego, Fidalgo, et al., 2021; Prego, Martínez, et al., 2021). These results support that moderate HPP levels (200 MPa) applied before freezing enables reversible structural changes and optimal texture restoration during extended frozen storage, whereas high pressures can promote more pronounced network reformation due to greater denaturation.

Texture recovery during frozen storage, especially in springiness and chewiness, is consistent with findings that frozen holding can allow partial structural reorganization in muscle tissues post-HPP. The increase in cohesiveness and chewiness in later months, particularly under moderate HPP, is in agreement with reports that long-term frozen storage can enhance gel-like structures in fish muscle proteins when combined with HPP (Campus, 2010).

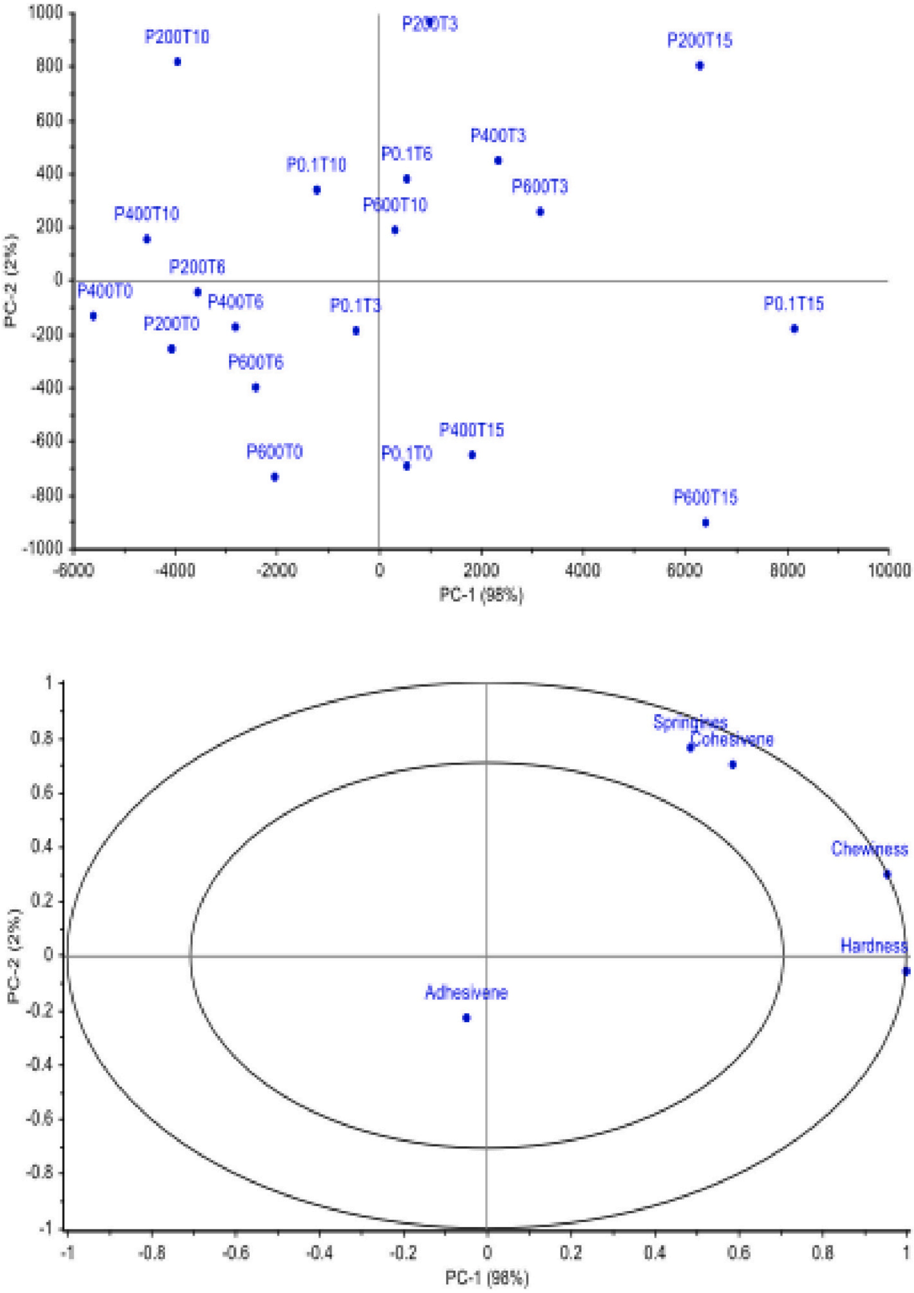

Fig. 3. Scores and loadings from principal component analysis of atlantic chub (*Scomber colias*) mackerel textural properties after canning and subsequent 3-month storage.

PCA was carried out to visualize the clustering of samples based on instrumental texture attributes and facilitate interpretation of multivariate differences between treatments. PC1 accounted for the largest variance in the dataset and was primarily associated with textural integrity, as indicated by high positive loadings for hardness, chewiness, and cohesiveness. Treatments with higher PC1 scores exhibited improved firmness and resilience, corresponding to samples subjected to moderate HPP and longer frozen storage. In contrast, PC2 separated groups based on adhesiveness, reflecting changes in muscle compactness and visual appearance linked to higher pressure levels or extended processing.

The clustering seen in the PCA score plot (Fig. 3) highlights that moderate HPP treatments (notably 200 MPa) result in a unique balance of mechanical strength and colour stability, which distinguishes these samples from both controls and high-pressure groups. Inclusion of variable loadings in the manuscript allows readers to understand which properties drive grouping patterns, making the results more accessible for readers less familiar with multivariate statistical techniques. Overall, PCA confirms that pressures of 200–400 MPa, combined with adequate frozen storage, achieve optimal preservation of key quality traits in canned mackerel muscle.

The observed recovery and enhancement of hardness and chewiness in samples treated with moderate HPP pressure levels (200 MPa) during prolonged frozen storage may be attributed to protein structural reorganization over time. This hypothesis aligns with previous findings indicating that HPP induces partial protein denaturation and unfolding, which subsequently facilitates protein network stabilization or reaggregation during frozen storage, thus reinforcing textural integrity (Fidalgo et al., 2014; Matser et al., 2000). However, this mechanistic interpretation remains tentative, as the present study did not include

Table 2
Effect of high hydrostatic pressure (HPP) processing and frozen storage as pre-treatments prior to canning on the colour analysis of canned Atlantic Chub mackerel (*Scomber colias*) after 3-month storage. Experimental treatment codes use P and T for pressure (MPa), and frozen storage time (month), respectively. The control without HPP pre-treatment is labelled as P0.1.

Experiments	L*	a*	b*	ΔE₀₀ vs P0.1T0
P0.1T0	66.23	5.75	18.65	0.00
P200T0	66.51	4.99	19.25	0.99
P400T0	64.14	5.79	18.54	1.72
P600T0	58.93	7.55	18.35	6.50
P0.1T3	62.81	5.08	15.50	3.36
P200T3	64.70	4.72	16.32	2.82
P400T3	67.15	3.65	16.21	2.79
P600T3	57.23	7.16	18.08	7.93
P0.1T6	68.13	3.21	16.57	2.93
P200T6	63.89	5.78	18.60	2.37
P400T6	60.67	5.33	18.59	5.26
P600T6	60.18	6.01	19.49	5.99
P0.1T10	66.20	3.70	19.10	2.19
P200T10	67.33	4.40	19.51	1.95
P400T10	63.04	4.64	17.07	3.49
P600T10	58.94	6.84	17.88	6.28
P0.1T15	67.34	5.34	15.84	2.99
P200T15	68.98	4.80	16.50	3.36
P400T15	64.52	5.44	16.81	2.47
P600T15	57.50	6.28	18.05	7.08

direct molecular or ultrastructural analyses such as SDS-PAGE, differential scanning calorimetry, or electron microscopy. Future research incorporating these techniques is warranted to substantiate and elucidate the molecular basis of the textural modifications observed, thereby strengthening the link between HPP-induced protein changes and functional muscle properties in canned fish.

3.2. Colour analysis

Colour is a critical sensory attribute in fish quality evaluation, particularly for canned products, where visual appearance influences consumer perception and market acceptance. In this study, the effect of HPP applied prior to frozen storage was assessed on the CIELAB colour coordinates (lightness (L*), redness (a*), and yellowness (b*)) of canned mackerel muscle. Results after 3, 6, 10, and 15 months of frozen storage are summarized in Table 2.

The L* values (indicating muscle lightness) ranged from 57.23 to 68.98 across treatments. The control samples without HPP (P0.1) showed moderate fluctuations over storage time, with L* values decreasing at 3 months (62.81) and peaking at 6 and 15 months (68.13 and 67.34, respectively), possibly due to partial water loss and tissue densification during storage.

Pressure-treated samples exhibited a clear pressure-dependent trend. Moderate pressures (200–400 MPa) tended to preserve or enhance lightness, particularly at longer storage durations (e.g., P200T15 = 68.98, the highest L* in the dataset). This fact suggests a potential stabilizing effect of moderate HPP on muscle structure, which may help retain moisture and limit darkening from oxidation.

In contrast, samples treated at 600 MPa consistently displayed lower L* values across all storage durations (e.g., P600T0 = 58.93; P600T3 = 57.23; P600T15 = 57.50). These results are in line with previous observations that high pressures induce protein denaturation and pigment concentration or redistribution, leading to a darker appearance typically associated with a cooked-like visual quality.

The effect of HPP pre-treatment and frozen storage duration on the L* value (lightness) of canned fish was analysed using multifactor ANOVA. The model was significant (F = 11.44) and showed a good fit, with a correlation coefficient of $R^2 = 0.80$. Pressure level had a markedly greater influence on the L value (F = 40.48) compared to frozen storage time (F = 0.02). The predicted response was described by the following regression equation:

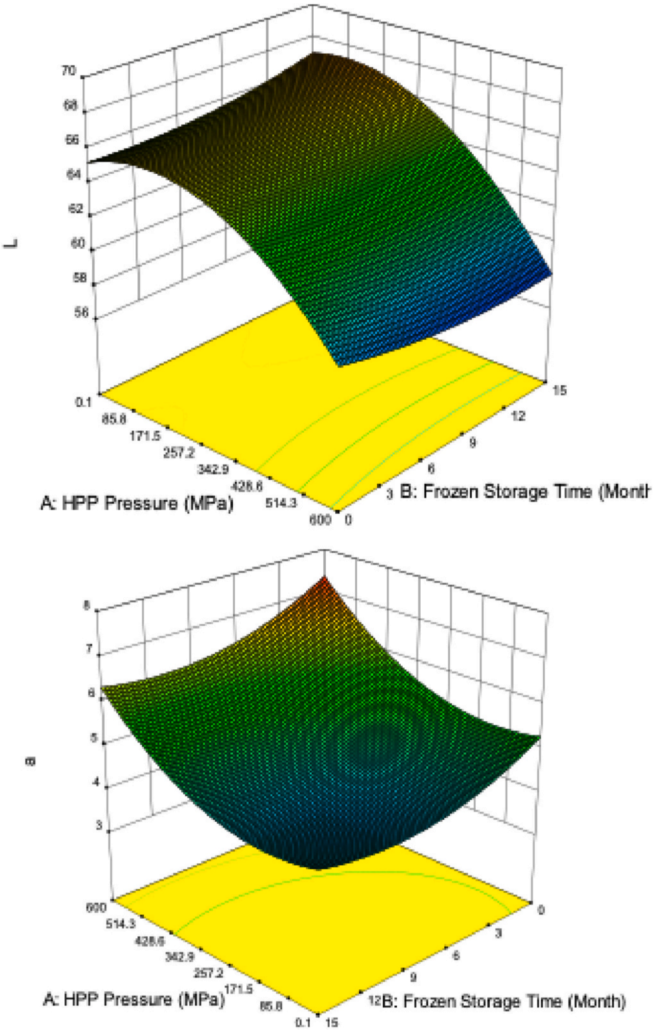

Fig. 4. Predicted effects of HPP pretreatment and frozen storage duration on the colour parameters of Atlantic Chub mackerel (*Scomber colias*) muscle after canning and subsequent 3-month storage.

$$L = 65.24 + 0.01^{*}\ \text{HPP Pressure} - 0.04^{*}\ \text{Frozen Storage Time} + 0,01^{*}\ \text{Frozen Storage Time}^{2} \quad (3)$$

Fig. 4 shows that pressure level at 200 MPa increases the L* value considerably, reaching values close to 68. However, higher HPP showed a negative effect implying that the muscle lightness decreased. Similar effects of high-pressure treatments on colour were observed in the muscle of sea bass (*Dicentrarchus labrax*) where an increase on the value of L* was observed with the pressure (Tironi et al., 2007). The model obtained for L* can be used to select a desirable lightness. For example, applying a pressure level of approximately 200 MPa resulted in lightness values comparable to those of fresh muscle after 15 months of frozen storage.

The a* values (indicating redness) ranged from 3.21 to 7.55. The control samples (P0.1) generally exhibited moderate redness, with the lowest value observed at 6 months (3.21), indicating pigment loss or transformation over time.

HPP significantly influenced the a* parameter, with higher pressures (especially 600 MPa) resulting in consistently elevated redness values across all storage durations. For example, P600T0, P600T3, and P600T15 recorded a* values of 7.55, 7.16, and 6.28, respectively. This increase in redness is typically attributed to the denaturation of myoglobin and hemoproteins under high pressure, which imparts a reddish-cooked appearance to raw muscle.

On the other hand, moderate pressures (200 and 400 MPa) generally maintained or slightly reduced redness compared to the control, particularly at early storage times (e.g., P400T3 = 3.65). This is consistent with previous findings suggesting that HPP below 400 MPa can inhibit enzymatic and microbial activity without significantly altering colour-forming proteins.

The effect of HPP pre-treatment and frozen storage time on the a value (redness) of canned fish was also evaluated using multifactor ANOVA. Although the model was statistically significant (F = 5.32), the correlation coefficient (R^2 = 0.65) indicated moderate explanatory power. Variation in a* values was mainly influenced by the linear (F = 17.18) and quadratic (F = 4.46) terms of pressure level, while the effect of frozen storage time was negligible. The predicted response surface is shown in Fig. 3 and described by the following regression equation:

$$a^{*} = 5.28 - 0.0021^{*}\ \text{HPP Pressure} - 0.1947^{*}\ \text{Frozen Storage Time} - 0{,}0094^{*}\ \text{Frozen Storage Time}^{2} \tag{4}$$

Yellowness (b*) showed more subtle variation, ranging from 15.50 to 19.51 across treatments. The control at 3 months (P0.1T3 = 15.50) showed the lowest b* value, suggesting early pigment degradation or reduced chromaticity. This trend was counteracted in HPP-treated samples, where moderate-to-high pressures appeared to mitigate yellow colour loss. Notably, P200T10 and P600T6 reached b* values of 19.51 and 19.49, respectively (the highest values recorded) indicating that HPP may help retain the yellow pigmentation, potentially by reducing lipid oxidation and preserving carotenoid-like compounds.

The effect of HPP pre-treatment and frozen storage duration on the b* values (yellowness) of canned fish was evaluated using multifactor ANOVA. The analysis yielded a low F-value (1.29), indicating that the model was not statistically significant and that no clear effect of pressure or storage time on b* can be established.

Overall, b* values did not exhibit a consistent linear trend in response to increasing pressure or storage duration. However, a slight stabilizing effect of HPP was observed, particularly after prolonged frozen storage, suggesting a potential protective role of moderate pressure treatments in preserving the yellowness of mackerel muscle.

Table 2 also presents the total colour difference (ΔE_{00}) between treated samples and the control (P0.1T0), calculated using the CIEDE2000 formula. This approach provides the most accurate assessment of perceptible colour differences in CIELAB coordinates. (Table 2). A ΔE_{00} value below 1 is generally considered imperceptible; values between 1 and 2 are barely perceptible; those between 2 and 3.5 can be perceived by a trained eye; values from 3.5 to 5 indicate a clear difference; and values above 5 represent a very evident colour difference.

After 15 months of frozen storage, treatments at 600 MPa induced the largest ΔE_{00} values, reflecting substantial modifications in L and a, which are likely perceptible to the average observer. In contrast, moderate pressures such as P200T15 (ΔE_{00} = 3.36) produced colour changes detectable only by a trained eye, indicating that these conditions effectively preserve the visual appearance of the samples. This suggests that while high-pressure treatments can significantly alter colour over long-term storage, moderate HPP treatments achieve a balance between processing effects and maintaining an acceptable appearance.

The colour analysis demonstrates that high-pressure processing has a pronounced impact on the visual appearance of mackerel muscle prior to canning. Moderate pressures (200–400 MPa) appear optimal for maintaining lightness and limiting undesirable increases in redness, while also providing some protection against yellow pigment loss over frozen storage. Conversely, high pressures (600 MPa) consistently induce a darker, redder appearance that may resemble cooked muscle and alter consumer perception of the canned product. These findings support the selection of moderate HPP levels as a viable pre-treatment strategy for improving the visual quality of canned mackerel.

Overall, these findings have clear implications for the seafood industry and commercial canning operations. By demonstrating that moderate HPP pre-treatment (particularly at 200 MPa) effectively maintains textural integrity and visual quality of mackerel following extended frozen storage and canning, our work provides evidence-based recommendations for optimizing processing protocols. This approach could help processors to extend product shelf life, minimize quality losses associated with long storage chains, and enhance consumer appeal, key competitive advantages in markets reliant on seasonal catches and frozen raw material. Adoption of HPP as a pre-freezing step may therefore support higher-quality canned products, offering improved structural stability and appearance that align with consumer preferences and commercial requirements.

While this study provides comprehensive instrumental evaluation of texture and colour properties in canned Atlantic chub mackerel, it is important to acknowledge the limitations inherent in relying solely on these analytical methods. Instrumental texture profile analysis and colourimetry offer objective, reproducible metrics; however, they do not fully capture the complexity of consumer sensory perception, including aroma, flavor, and mouthfeel nuances. Consumer acceptance depends on a holistic sensory experience that integrates multiple attributes, which can only be assessed convincingly through sensory panels or consumer testing.

Therefore, it is recognized that the interpretation of improved textural and colour parameters as indicators of enhanced consumer appeal remains speculative at this stage. Future research should prioritize systematic sensory evaluation to validate these instrumental findings and establish direct correlations between pressure treatments, storage conditions, and consumer preferences. Such studies will be essential to confirm the market relevance of HPP pre-treatment strategies and optimize processing parameters towards products that meet both safety standards and sensory acceptance criteria.

3.3. *Cost and energy analysis*

A quantitative analysis was conducted to determine the key cost and energy parameters in industrial-scale high-pressure processing (200–600 MPa). The analysis was based on process and cost data supplied by Hiperbaric (Burgos, Spain), the leading global manufacturer of HPP equipment for the food industry.

Each cycle in a 55 L vessel comprises a machine time of 1.08 min, pressure build-up of 1.52 min, and a holding time of 2 min, resulting in a total cycle duration of approximately 4.6 min. Machine time includes loading and unloading products, plugs opening and closure, low pressure filling of vessel and depressurization.

With a vessel filling ratio of 50 %, the unit operates with one intensifier (45 kW), delivering hourly production rates of 358 kg, corresponding to daily and annual outputs of 5.7 tons and 1720 tons, respectively.

The treatment cost per kg includes depreciation (€0.063), wear parts (€0.036), and energy (€0.003), totaling €0.102 per kg processed. Energy consumption for 200–600 MPa operation is approximately 26 kWh per hour. On a per-cycle basis, costs comprise depreciation (€1.73), wear parts (€1.00), and energy (€0.08), for a total of €2.81 per cycle. The system is typically operated for 16 h daily, 300 days annually. The investment cost, including equipment, basket handling systems, installation, and start-up is around €540,000 with a depreciation period of 5 years.

Scaling up to a 420 L vessel capacity leads to significant changes in process efficiency, output, and unit costs compared to the smaller 55 L system. The larger system utilizes 8 intensifiers, operates with a vessel filling ratio of 60 %. This results in an hourly production of 2921 kg, with daily and yearly outputs rising to 46.7 tons and 14,020 tons, substantially higher than the smaller scale.

Despite the greater investment cost (€1,950,000 vs €540,000), the treatment cost per kg is markedly reduced at €0.046 for the 420 L equipment, compared to €0.102/kg for the 55 L unit. These scale-up effects demonstrate that larger vessels not only improve production rates and lower unit processing costs, but also intensify energy demand and capital investment. The ratio of output to energy and cost per kg becomes more favorable at a larger scale, underscoring the economic and operational advantages of industrial-scale processing for HPP in food applications.

4. Conclusions

This study demonstrates that HPP applied prior to frozen storage can significantly influence the texture and colour attributes of canned Atlantic chub mackerel (*Scomber colias*), with effects varying according to pressure intensity and storage duration.

Regarding textural properties, initial HPP treatment led to a reduction in hardness and chewiness, likely due to muscle fiber disruption and protein denaturation. However, prolonged frozen storage up to 15 months promoted a remarkable recovery or even enhancement of these parameters, especially at 200 and 600 MPa, indicating the formation of more stable and structured protein matrices over time. Chewiness and hardness, in particular, were significantly restored, with values surpassing those of non-HPP controls in several cases. Springiness and cohesiveness also benefited from combined HPP and frozen storage, although the effects were less pronounced and more variable. Adhesiveness showed a general decrease (more negative values) in pressurized samples, potentially reflecting structural compaction and altered water dynamics.

Multifactor ANOVA and PCA analyses confirmed that both HPP and storage duration interact synergistically to define the final texture profile of canned mackerel, with frozen storage playing a dominant role in the restoration of firmness and chewiness. Notably, the most consistent improvements were observed at moderate pressure levels (200 MPa), which enhanced structural attributes without causing excessive softening.

In terms of colour, moderate HPP (especially at 200 MPa) preserved or improved lightness (L*) during extended frozen storage, offering a brighter and more appealing visual appearance. Conversely, higher pressure treatments (600 MPa) consistently led to darker muscle tones, potentially due to pigment concentration and intensified protein denaturation. Redness (a*) and yellowness (b*) also showed distinct responses to HPP and time, indicating that both colour stability and textural integrity must be considered when optimizing processing conditions.

the application of HPP prior to frozen storage and canning emerges as a promising strategy to enhance and preserve the quality of canned mackerel. Specifically, treatments at 200 MPa and 600 MPa, when combined with adequate frozen storage, can mitigate the detrimental effects of conventional processing by improving firmness, chewiness, and lightness, while also maintaining structural cohesiveness and acceptable springiness. These findings provide valuable insights for the seafood industry in developing high-quality canned fish products with extended shelf-life and improved consumer appeal.

This study presents a comprehensive evaluation of the combined effects of high-pressure processing, frozen storage, and thermal canning on the quality attributes of Atlantic chub mackerel, contributing novel insights relevant to the seafood industry. The key strength of the work lies in its realistic simulation of industrial processing sequences, providing valuable data on the preservation of texture and colour under conditions that closely mimic commercial scenarios. The multi-variate analytical approach further enhances the understanding of how different pressures and storage times interact to influence product quality.

Nevertheless, certain limitations should be acknowledged. The reliance on instrumental measurements without accompanying sensory evaluation constrains the direct applicability of findings to consumer preferences, an aspect that warrants further investigation. Mechanistic interpretations regarding protein structure changes remain hypothetical without molecular-level analyses such as proteomics or microscopy.

Overall, these findings establish a solid foundation for future research aimed at optimizing processing parameters and validating consumer acceptance, thereby bridging the gap between technological innovation and market implementation.

While this work demonstrates the effectiveness of moderate HPP treatment in preserving instrumental texture and colour during industrially relevant frozen storage and canning, direct validation of these findings via comprehensive sensory evaluation will be essential. Such studies will determine the true market viability and consumer acceptance of HPP-assisted canned mackerel products.

CRediT authorship contribution statement

Esther Guerra-Rodríguez: Writing – original draft, Investigation. **Patricia Cazón:** Writing – review & editing, Formal analysis. **Santiago P. Aubourg:** Writing – review & editing, Supervision. **Manuel Vázquez:** Writing – review & editing, Project administration, Methodology, Conceptualization.

Declaration of generative AI and AI-assisted technologies in the writing process

During the preparation of this work, the authors used Chatgpt to correct spelling and grammatical errors. After using this tool/service, they reviewed and edited the content as needed and assume full responsibility for the content of the publication.

Declaration of competing interest

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

Data availability

Data will be made available on request.

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