Effect of high-pressure pretreatments applied before freezing and frozen storage on the functional and sensory properties of Atlantic mackerel (*Scomber scombrus*)

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Keywords: *Scomber scombrus*, high pressure, high hydrostatic pressure processing, freezing, stored frozen

ABSTRACT

The frozen storage of Atlantic mackerel (*Scomber scombrus*) is limited by lipid damage causing sensory quality losses, an important drawback to its commercialisation. This work deals with changes in functional and sensory properties during freezing and frozen storage of Atlantic mackerel pre-treated by high hydrostatic pressure processing (HPP). Three levels of pressure (150, 300, and 450 MPa), holding time (0.0, 2.5, and 5.0 min) and frozen storage time (0, 1, and 3 months) were tested. Expressible water, CIE colour parameters, mechanical texture parameters and sensory parameters were evaluated. Results showed that HPP at low levels (150 MPa) yielded raw samples with expressible water lower than 40%, improving the quality of frozen muscle. During frozen storage, the flesh colour of the controls (no HPP) tended to yellowness, while low-pressure treatments (150 MPa) yielded samples with lightness similar to fresh muscle. HPP effects on the colour parameters were negligible. Hardness and chewiness values of HPP-treated samples and those for no-HPP controls were similar. Sensory analysis suggested that 150 MPa did not affect the flesh odour. Most importantly, the sensorial acceptability of HPP-treated samples was better than that of frozen fillet controls and similar to that of fresh mackerel.

1. Introduction

Atlantic mackerel (*Scomber scombrus*) is a small pelagic fish species captured in large amounts during periods of relatively low demand, and thus a large portion of the catch is underutilised and transformed in non human feed. Freezing followed by frozen storage is one of the best methods to retain the sensory and nutritional properties of fish products (Erickson, 1997). Although mackerel is recognised as a healthy food, it remains underutilised (Martelo-Vidal, Mesas, & Vazquez, 2012) because its frozen shelf life is limited by a rapid deterioration of sensory quality (Aubourg, Rodriguez, & Gallardo, 2005). The presence of highly unsaturated fatty acid and pro-oxidant molecules causes during frozen storage substantial enzymatic and non-enzymatic rancidity that strongly influences product quality (Richards & Hultin, 2002).

To extend shelf life as long as possible, high hydrostatic pressure processing (HPP) has been shown to retain sensory and nutritional properties, while inactivating microbial load, leading to shelf-life extension and safety enhancement (Alvarez-Virrueta, Garcia-Lopez, Montalvo-Gonzalez, Ramirez, Mata-Montes-de-Oca, & Tovar-Gomez, 2012; Escobedo-Avellaneda, Pateiro-Moure, Chotyakul, Torres, Welti-Chanes, & Perez-Lamela, 2011; Mujica-Paz, Valdez-Fragoso, Tonello Samson, Welti-Chanes, & Torres, 2011; Rios-Romero, Tabilo-Munizaga, Morales-Castro, Reyes, Perez-Won, & Araceli Ochoa-Martinez, 2012; Téllez-Luis, Ramírez, Pérez-Lamela, Vázquez, & Simal-Gándara, 2001). This technology has shown potential application in the seafood industry for the production of surimi and kamaboko (Uresti, Velazquez, Ramirez, Vazquez, & Torres, 2004; Uresti, Velazquez, Vazquez, Ramirez, & Torres, 2005; Uresti, Velazquez, Vazquez, Ramirez, & Torres, 2006), cold-smoked fish (Lakshmanan, Parkinson, & Piggott, 2007), thermal processing (Ramirez, Saraiva, Perez Lamela, &

Torres, 2009), and for pressure-assisted freezing (Alizadeh, Chapleau, de Lamballerie, & Le-Bail, 2007) and thawing (Rouille, Lebail, Ramaswamy, & Leclerc, 2002).

An additional positive effect of HPP treatment is that oxidative endogenous enzymes can be inactivated before further storage and processing of fish products (Murchie et al., 2005). For example, recent previous work demonstrated an inhibition of lipid hydrolysis in Atlantic mackerel (*S. scombrus*) samples subjected to an HPP pre-treatment before freezing and frozen storage (Vázquez, Torres, Gallardo, Saraiva, & Aubourg, 2012). The same effect was observed for Atlantic horse mackerel (*Trachurus trachurus*) samples (Torres, Vázquez, Saraiva, Gallardo, & Aubourg, 2012). However, this beneficial effect should be assessed also by determining the HPP effect on sensory and functional properties. Therefore, this study focuses on changes after freezing and frozen storage of the functional and sensory properties of Atlantic mackerel (*S. scombrus*) subjected to HPP pre-treatments throughout their frozen storage for up to three months.

2. Materials and methods

2.1. Raw fish, processing, storage and sampling

Atlantic mackerel (180 kg) caught close to the Bask coast was obtained at the Ondarroa harbour (Bizkaia, Northern Spain) and immediately transported to the AZTI Tecnalia (Derio, Spain) pilot plant for HPP treatment. Samples were packed in polyethylene bags (three whole mackerels per bag) and vacuum sealed at 400 mbar. The length and weight of the specimens was in the 28-33 cm and 230-280 g range.

HPP treatments were performed in a 55-L high pressure unit (WAVE 6000/55HT; NC HYPERBARIC, Burgos, Spain). The following HHP treatments were applied (pressure value and pressure holding time, respectively): T-1 (450 MPa, 0.0 min), T-2 (450 MPa, 2.5 min), T-3 (450 MPa, 5.0 min), T-4 (300 MPa, 0.0 min), T-5 (300 MPa, 2.5 min), T-6 (300 MPa, 2.5 min), T-7 (300 MPa, 2.5 min), T-8 (300 MPa, 5.0 min), T-9 (150 MPa, 0.0 min), T-10 (150 MPa, 2.5 min), T-11 (150 MPa, 2.5 min), T-12 (150 MPa, 5.0 min).

In all cases, water was employed as the pressurising medium applied at a 3 MPa/s rate. Come up times for 150, 300 and 450 MPa treatments were 50, 100 and 150 s, respectively, while decompression time was less than 3 s. Inlet water was adjusted to keep temperature conditions during HPP treatment at room temperature (20ºC). After HPP processing, mackerel individuals were kept frozen at –20ºC for 48 h before storage at –10ºC and sampling after 0, 1 and 3 months of storage. A relatively higher temperature (-10ºC) than that employed for commercial frozen purposes (-18ºC) was chosen so that lipid damage (the different damage pathways encountered) could be speeded up (accelerated storage test) and the effect of previous HPP treatment analyzed in a shorter duration study.

For analysis, fish samples were thawed at 4ºC for 24 h, eviscerated, bones removed manually and then filleted. Samples with no HPP treatment (frozen controls) were subjected to the same freezing and frozen storage conditions. Fresh fish with no HPP treatment (fresh controls) were also analysed. For each treatment, three batches or replicates (n=3) were analysed independently. The analytical procedures described below were carried out on the white muscle, raw or cooked. Cooked fish was prepared in an oven at 200 ºC for 10 min reaching at least 68ºC at the centre point.

2.2. Expressible water content

The expressible water content was determined for raw and cooked samples following the procedures described by Uresti, Lopez-Arias, Ramirez, & Vazquez (2003).

2.3. Colour

Colour was determined only for raw samples following the procedures described by Uresti, Lopez-Arias, Gonzalez-Cabriales, Ramirez, & Vazquez (2003) and using a X-Rite Spectrophotometer model 968 (X-Rite, Grand Rapids, MI, USA) calibrated against black and white tiles. Values of L, a*, and b* were calculated based on illuminant C and the 2° standard observer. Six samples were evaluated for each treatment.

2.4. Texture profile analysis (TPA)

The texture profile was determined in raw samples using a TA-XTplus texturometer (Stable Micro System, Viena Court, UK). Samples of raw beef patties were cut into small cubes (2 x 2 x 1.5 cm) and analyzed at room temperature. TPA was carried out using a 50-mm diameter cylindrical aluminium probe (P/50). Samples were compressed to 75% of the original height using a 60 mm/min compression speed to estimate hardness, adhesiveness, springiness, cohesiveness and chewiness values (Anton & Luciano, 2007; Castro-Briones, Calderon, Velazquez, Salud-Rubio, Vazquez, & Ramirez, 2009; Sun, 2009). Six samples were analyzed for each treatment.

2.5. Sensory analysis

Sensory evaluation of mackerel fillets was undertaken by 10 trained panellists (mean age 32 yrs, 21-45 yrs range) and were all volunteers from the University of Santiago de Compostela (Spain) exhibiting no known illness at the time of examination. Evaluations were performed in a sensory panel room at 21 ± 1 °C. Cooked fish samples were presented to panellists on individual plates. Four training sessions were organized to make sure that sensory descriptors were understood (ISO, 1993). Panellists were first asked to score the overall odour, taste and texture intensity using a six-point scale from 0 (fresh fish) to 6 (strong putrid fish). For the hedonic rating the panellists were asked to rate fish sample acceptability using a scale from 1 (dislike extremely) to 5 (like extremely).

2.6. Statistical analysis

The experimental design was statistically analysed using the Design Expert® 7.1.1 software (Stat-Ease, Inc., Minneapolis, MN). The set of experiments followed the Box-Behnken design (Box & Behnken, 1960), formed by combining two-level factorial designs with incomplete block designs. This procedure creates designs with desirable statistical properties but with only a fraction of the experiments required for a three-level factorial design. Error assessment was based on a replication of the central point for each storage time (0, 1, and 3 months) as suggested in the Box-Behnken design. The mathematical model used as a first approach to analyse the experimental data was a second order polynomial described as follows:

$$y_i = b0_i + b1_i x_1 + b2_i x_2 + b3_i x_3 + b4_i x_1 x_2 + b5_i x_1 x_3 + b6_i x_2 x_3 + b7_i x_1^2 + b8_i x_2^2 + b9_i x_3^2$$

In the above equation, x_1, x_2 and x_3 are the code variables for pressure level, holding pressure time and storage time, respectively; y_i (i=1–14) are the dependent variables (raw expressible water, cooked expressible water, L, a*, b*, hardness, adhesiveness, springiness, cohesiveness, chewiness, sensory odour, sensory taste, sensory texture, and sensory acceptability), and $b0_i ... b9_i$ are regression coefficients estimated from the experimental data by multiple linear regression. The results were analyzed using analysis of variance (ANOVA). Model terms were selected or rejected based on P-values at 95% confidence level. Partial models of the quadratic model were also obtained and analyzed by ANOVA.

3. Results and discussion

3.1. Expressible water

The expressible water of fresh mackerel muscle was 26.6 ± 2.4% before cooking and 34.6 ± 3.5% after cooking. This parameter is related to the fish meat water holding capacity and affects the product juiceness. Fish processing should have no more than a minimum effect on this parameter to retain an acceptable product sensory quality. After frozen storage for 3 months, expressible water for Atlantic mackerel muscle with no HPP treatment increased to 38.2% and 48.3% in raw and cooked muscle, respectively. HPP treatments yielded expressible water values higher than those for fresh mackerel muscle for any frozen time considered (Table 1). However, values for some HPP-treated samples were lower than those for frozen controls with no HPP treatment. Since the three independent variables (pressure level, holding time and frozen time) showed an effect on the expressible water of raw samples, a multifactor ANOVA was carried out to assess their relative influence. Thus, a significant ($p < 0.0001$) model was attained. The evaluation of the F-values of the three variables confirmed that expressible water was highly affected by the pressure level although an important effect of frozen storage could also be concluded. The correlation value r^2 of the model was 0.78. The prediction of the model obtained for the effect of the two variables that exerted a higher influence on expressible water (pressure level and frozen storage time) is shown in Figure 1. The employment of the HPP as a pre-treatment to freezing and frozen storage can lead to a significant expressible water increase if high levels of pressure are selected. However, HPP at low levels (150 MPa) yielded expressible water values lower than 40%, improving the quality of frozen muscle, implying a water holding capacity sufficient for a desirable juiceness. An expressible water of 38.7% was considered optimal for low-salt restructured fish products from Atlantic mackerel (Martelo-Vidal et al., 2012).

The effect of HPP pre-treatment and frozen storage on expressible water of cooked fishes was evaluated by multifactor ANOVA. Although an F-value of 6.17 implied that the model was significant, the correlation value r^2 was very low (0.37).

The results obtained indicate that the effect exerted on expressible water of cooked muscle by frozen storage (F-value = 17.52) was higher than that of the pressure level (F-value = 0.47) and pressure holding time (F-value = 0.53). All these statistical parameters confirm the effect of frozen storage time on expressible water of cooked muscle and the negligible effect of the HPP treatment on the expressible water of the cooked fish muscle. These results are in agreement with those of a study of the effects of pressure-shift freezing and pressure-assisted thawing on the quality of sea bass muscle (*Dicentrarchus labrax*) where high-pressure-treated samples showed a water holding capacity decrease but differences between high-pressure and conventional freezing methods disappeared after cooking (Tironi, Lebail, & De Ilamballerie, 2007).

3.2. Flesh colour

Frozen storage affected the muscle colour (Table 1). In the raw fresh muscle the mean colour parameters were: L, 44.8; a*, 5.66 and b*, 7.94. It was observed an increase of L parameter during frozen storage of controls, with values up to 63.3 at 3 months of frozen storage. The a* values decreased to 1.04 and the b* values considerably increase up to 15.25 after 3 months of frozen storage indicating flesh colour towards yellow. The effect of HPP pre-treatment and frozen storage on raw fish L value was evaluated by multifactor ANOVA. The F-value of 14.81 implied that the model was significant. The correlation value (r^2 = 0.81) can be considered good. The pressure effect exerted on the raw muscle L-value (F-value = 66.22) was higher than that of the frozen storage time (F-value = 22.34) and pressure holding time (F-value = 2.90). Figure 2 shows that the pressure level increases considerably the L value, reaching values close to 78. The storage time showed an important negative quadratic effect (F-value = 12.51) implying that the muscle lightness decreased with long storage time. 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 instance, using a pressure level around 150 MPa, lightness similar to that of fresh muscle can be obtained after 3 months of frozen storage.

The effect of HPP pre-treatment and frozen storage time on a* and b* parameters of raw fishes was also evaluated by multifactor ANOVA. For a* values, although the F-value (3.50) implied that the model was significant, the correlation value (r^2 = 0.56) was low. The results obtained indicate that changes in the a* values for raw muscle was due to the first (F-value = 17.01) and second order storage time terms (F-value = 12.30) while the HPP effect was negligible. The multifactor ANOVA for b* parameters showed also a low F-value (1.37), which implied that the model was not significant and an effect of HPP was not observed.

3.3. Textural profile analysis

The changes on textural parameters during frozen storage of controls compared with the values of fresh muscle were evaluated. All parameters were affected by freezing and frozen storage. Hardness of fresh mackerel muscle was 33.30 N increasing to 87.09 N after freezing and decreased slightly after 3 month of frozen storage (65.08 N). Adhesiveness of the frozen muscles (around -60 g·s) was lower than that of the fresh samples (-98.8 g·s). Springiness and cohesiveness were less affected. Both fresh and frozen muscles were in the narrow range, 0.20-0.30 for springiness and 0.17-0.22 for cohesiveness. Chewiness of fresh muscle was 1.33 N increasing to 6.12 N after freezing and frozen storage for 1 month decreasing after 3 months to only 2.84 N.

Table 2 shows the results of HPP as pre-treatment on frozen mackerel texture profile analysis of raw muscle. The effect of the HPP pre-treatment and frozen storage on the hardness of raw fish was evaluated by multifactor ANOVA. A significant ($p < 0.0001$) model was obtained. The evaluation of the F-values of the three variables confirmed that hardness was highly affected by the pressure level (F-value = 18.46), although an important effect of pressure holding time was also observed (F-value = 8.34). A significant interaction pressure level-pressure holding time was observed, according to their F-value score (21.83). This analysis implies that when a HPP pre-treatment is applied, the effect of frozen storage time on the hardness of muscle can be negligible.

The correlation value r^2 of the model was 0.67. The prediction of the model obtained for the effect of the two variables that exerted a higher influence on hardness (pressure level and pressure holding time) is shown in Figure 3. Pre-treatments at high pressure levels caused a significant increase in hardness. However, HPP at low levels (150 MPa) yielded hardness values below 78 N, maintaining hardness levels similar to frozen muscle without HPP pre-treatment but with the beneficial effect of lipid oxidation inhibition observed in other studies (Vazquez et al., 2012). The HPP influence on hardness has been observed also in other fish species like cod (*Gadus morhua*). An increase in hardness was observed due to pressure while only minor changes in hardness were observed during frozen storage (Matser, Stegeman, Kals, & Bartels, 2000).

The multifactor ANOVA of the effect of HPP pre-treatment and frozen storage on adhesiveness of raw muscle produced a significant model ($p < 0.0001$). The evaluation of the F-values for the three variables confirmed that adhesiveness was highly affected by the pressure level (F-value = 140.78), frozen storage time (F-value = 27.78) and the interaction pressure level-frozen storage time (F-value score = 22.04). This analysis implies that when a HPP pre-treatment is applied, the effect of pressure holding time on the adhesiveness of muscle is negligible. The correlation value r^2 of the model was 0.83. The prediction of the model obtained for the effect of pressure level and frozen storage on adhesiveness is shown in Figure 4. HPP pre-treatments caused a significant adhesiveness increase when high pressure levels and long storage time were selected. However, low pressure levels (150-175 MPa) yielded values close to 100 g·s, i.e., an adhesiveness similar to that of fresh muscle. This result is in accordance with the negative effect on adhesiveness found during freezing of salmon before smoking (Martinez, Salmeron, Guillen, & Casas, 2010).

Springiness values, 0.189-0.346 (Table 2), are in the range found for other fish products like restructured fish products (0.20-0.60) from gilthead sea bream (*Sparus aurata*) obtained by Andres-Bello, Garcia-Segovia, Ramirez, & Martinez-Monzo (2011). The multifactor ANOVA led to an F-value 5.66, which implied that the model was significant. The evaluation of the F-values showed that springiness was affected mainly by frozen storage (F-value = 8.44) and less by pressure level (F-value = 7.05) and pressure holding time (F-value = 1.51). The correlation value r^2 of the model was 0.34, suggesting that the model cannot be use for predictions and can only be use to identify trends.

The multifactor ANOVA confirmed that cohesiveness was highly affected by the pressure level (F-value = 49.57), pressure holding time (F-value = 25.82), frozen storage time (F-value = 21.67) and the interaction pressure level-pressure holding time (F-value score = 8.40). The correlation value r^2 of the model was 0.81. The HPP pre-treatment to freezing and frozen storage caused a significant increase on cohesiveness when high pressure and long storage time were selected. These results are in accordance to the effect on cohesiveness found for freezing of salmon before smoking (Martinez et al., 2010).

The cohesiveness obtained at high pressure level (0.34) is in the range observed for other fish products such as restructured fish products from gilthead sea bream (*Sparus aurata*) when values of 0.30-0.40 were obtained (Andres-Bello et al., 2011). Moreover, low pressure levels (150 MPa) yielded cohesiveness values close to 0.20-0.24, i.e., values similar to those of frozen muscle without pre-treatment.

Chewiness values were found in a wide range (3.72-29.87 N). The multifactor ANOVA led to an F-value 27.94. Chewiness was mainly affected by the pressure level-pressure holding time interaction (F-value = 50.23), followed by pressure level (F-value = 22.57), quadratic pressure level effect (F-value = 16.94), and pressure holding time (F-value = 8.05). The results suggest that the effect of frozen storage time is negligible when a HPP pre-treatment is used previous to freezing.

The correlation value r^2 of the model was 0.79. HPP pre-treatment led to a significant increase on chewiness when high levels of pressure and long pressure holding times were selected. However, low pressure levels (150 MPa) yielded chewiness values around 400-600 g, i.e., similar to those for frozen muscle without HPP pre-treatment. These chewiness values are in the range observed for restructured fish products from gilthead sea bream (Andres-Bello et al., 2011).

3.4. Sensory analysis

The evaluation of sensory odour, sensory taste and sensory texture using a scale from 1 to 6 corresponding to a sense from freshness to putridness, respectively, are shown in Table 3. The multifactor ANOVA of the parameter sensory odour led to a low F-value (0.90), showing that the HPP pre-treatment did not affect the odour of the flesh.

The multifactor ANOVA analysis of the parameter sensory taste led to an F-value 4.15, which implied that the model was significant. The evaluation of the F-values showed that sensory taste was mainly affected by pressure level (F-value = 12.09). However, the correlation value r^2 of the model was very low (0.28). Low pressure levels (150 MPa) yielded taste values similar to that of frozen fish (around 2). This result suggests that pressure treatments break membranes releasing compounds affecting the taste, a hypothesis to be studied in the future.

The multifactor ANOVA of the parameter sensory texture led to an F-value of 33.94 implying that the model was significant. The evaluation of the F-values for the showed that sensory texture was affected mainly by frozen storage time (F-value = 70.46), pressure level (F-value = 66.03) and the quadratic effect of frozen storage time (F-value = 18.21). The correlation value r^2 of the model was 0.86. The use of HPP at low levels (150 MPa) yielded mean texture values of 2.2 that are lower that those for frozen controls (3.1).

The scale of acceptability for consumers was from 1 to 5, being 5 the highest acceptability and 1 the worst. The multifactor ANOVA analysis led to an F-value 105.91, which implied that the model was significant (p-value probability > 0.0001). The evaluation of the F-values for the different independent variables showed that acceptability was affected mainly by pressure level (F-value = 480.87) followed by frozen storage time (F-value = 54.25) and the quadratic effect of pressure level (F-value = 42.47). These results suggest a very strong pressure level effect. The correlation value r^2 of the model was 0.97. The prediction of the model is shown in Figure 5 suggesting that pre-treatments at low pressure levels yield a high acceptability of cooked fish. HPP treatments at 150 MPa yielded acceptability values around 4.3-3.45 (decreasing with frozen storage), which were similar to those of fresh mackerel. Although acceptability decreased with frozen storage time, values remained above the intermediate value.

4. Conclusions

HPP pre-treatments applied before freezing and frozen storage improve some functional and sensory properties in Atlantic mackerel muscle indicating that they can be a useful alternative for fish processors seeking to better utilize this resource often used for low market value products such as a non human feed ingredient.

Acknowledgements

The authors thank Dr. María Lavilla from AZTI Tecnalia (Derio, Spain) for carrying out all HPP treatments. This work was supported by the Secretaría Xeral de I+D from the Xunta de Galicia (Spain) through Research Project 10TAL402001PR.

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Table 1

Effects on expressible water and colour of high hydrostatic pressure processing (HPP) as a pre-treatment for frozen Atlantic mackerel (*Scomber scombrus*). Experimental treatment codes use P, H and F for pressure, holding time, and frozen storage time, respectively.

Experiments	Expressible water % w/w Raw	Expressible water % w/w cooked	L raw	a* raw	b* raw
1 (P450H0F0)	40.37	40.97	57.47	6.77	13.72
2 (P450H2.5F0)	20.00	38.17	66.15	3.98	15.31
3 (P450H5F0)	42.35	38.92	69.21	1.84	10.72
4 (P300H0F0)	42.72	38.61	64.87	2.31	15.12
5 (P300H2.5F0)	33.86	47.60	52.30	4.79	13.06
6 (P300H2.5F0)	45.97	41.40	72.08	-0.09	13.75
7 (P300H2.5F0)	38.79	38.06	65.91	3.48	15.01
8 (P300H5F0)	42.69	42.10	59.73	6.40	15.13
9 (P150H0F0)	41.42	36.29	51.33	2.96	12.41
10 (P150H2.5F0)	32.24	35.97	50.58	4.74	13.38
11(P150H2.5F0)	26.21	39.41	45.87	5.63	11.47
12(H150H5F0)	36.75	37.08	45.99	1.63	7.91
13 (P450H0F1)	44.85	44.81	70.79	0.61	12.61
14 (P450H2.5F1)	54.39	41.86	71.63	2.86	15.14
15 (P450H5F1)	48.70	39.38	76.34	-0.41	10.06
16 (P300H0F1)	41.33	45.26	63.16	1.18	14.23
17 (P300H2.5F1)	47.02	43.61	71.67	1.76	15.96
18 (P300H2.5F1)	46.98	40.23	73.57	0.53	14.29
19 (P300H2.5F1)	45.28	46.47	73.44	-0.72	11.26
20 (P300H5F1)	48.15	42.62	65.82	2.07	15.41
21 (P150H0F1)	39.79	44.75	60.68	-0.44	13.90
22 (P150H2.5F1)	40.68	45.27	59.89	1.84	14.78
23 (P150H2.5F1)	33.05	46.77	61.77	1.83	15.16
24 (P150H5F1)	36.14	42.05	54.43	1.68	13.05
25 (H450H0F3)	48.94	44.00	73.06	1.93	15.20
26 (H450H2.5F3)	50.43	47.04	76.55	0.18	10.32
27 (H450H5F3)	46.63	46.07	74.19	0.44	11.52
28 (P300H0F3)	45.71	49.35	62.37	0.89	12.10
29 (P300H2.5F3)	47.94	45.38	72.90	1.36	14.25
30 (P300H2.5F3)	49.67	44.20	71.51	-0.59	11.42
31 (P300H2.5F3)	45.15	43.16	65.48	3.37	14.61
32 (P300H5F3)	48.38	50.08	77.89	-0.96	13.38
33 (P150H0F3)	35.82	44.99	50.25	0.60	11.77
34 (P150H2.5F3)	37.85	46.33	58.57	1.70	14.54
35 (P150H2.5F3)	40.15	39.82	62.72	2.84	15.80
36 (P150H5F3)	37.80	41.25	58.43	2.64	14.02

Table 2

Effect on the raw muscle texture profile analysis of high hydrostatic pressure processing (HPP) as a pre-treatment for frozen Atlantic mackerel (*Scomber scombrus*). Experimental treatment codes use P, H and F for pressure, holding time, and frozen storage time, respectively.

Experiments	Hardness (N)	Adhesiveness (g·s)	Springiness	Cohesiveness	Chewiness (N)
1 (P450H0F0)	98.27	-250	0.307	0.242	7.40
2 (P450H2.5F0)	118.59	-237	0.286	0.331	11.20
3 (P450H5F0)	170.53	-299	0.384	0.316	20.70
4 (P300H0F0)	101.27	-143	0.295	0.199	6.91
5 (P300H2.5F0)	61.44	-59	0.238	0.247	3.75
6 (P300H2.5F0)	142.56	-248	0.372	0.253	13.41
7 (P300H2.5F0)	90.36	-197	0.284	0.239	6.23
8 (P300H5F0)	120.53	-226	0.282	0.264	9.17
9 (P150H0F0)	75.26	-58	0.223	0.212	3.74
10 (P150H2.5F0)	90.54	-109	0.295	0.209	6.91
11(P150H2.5F0)	135.19	-69	0.346	0.242	11.99
12(H150H5F0)	92.44	-69	0.249	0.215	5.23
13 (P450H0F1)	104.01	-237	0.256	0.281	7.59
14 (P450H2.5F1)	89.37	-252	0.321	0.427	13.98
15 (P450H5F1)	201.28	-310	0.355	0.395	29.87
16 (P300H0F1)	95.54	-118	0.243	0.191	4.92
17 (P300H2.5F1)	145.06	-184	0.343	0.299	15.03
18 (P300H2.5F1)	108.74	-266	0.260	0.274	8.21
19 (P300H2.5F1)	94.37	-190	0.241	0.289	6.54
20 (P300H5F1)	135.68	-213	0.282	0.274	10.61
21 (P150H0F1)	127.50	-79	0.360	0.302	14.22
22 (P150H2.5F1)	82.62	-90	0.262	0.211	5.14
23 (P150H2.5F1)	96.31	-68	0.303	0.219	6.21
24 (P150H5F1)	72.49	-58	0.244	0.239	4.64
25 (H450H0F3)	102.36	-344	0.283	0.293	8.44
26 (H450H2.5F3)	133.21	-488	0.310	0.320	13.34
27 (H450H5F3)	199.74	-279	0.356	0.375	26.70
28 (P300H0F3)	69.89	-267	0.189	0.267	3.45
29 (P300H2.5F3)	93.50	-385	0.216	0.281	6.14
30 (P300H2.5F3)	117.41	-336	0.268	0.276	8.89
31 (P300H2.5F3)	125.83	-285	0.240	0.300	9.09
32 (P300H5F3)	103.64	-141	0.230	0.337	8.08
33 (P150H0F3)	82.91	-34	0.216	0.259	5.03
34 (P150H2.5F3)	80.27	-49	0.199	0.269	11.70
35 (P150H2.5F3)	129.15	-51	0.250	0.310	10.59
36 (P150H5F3)	72.30	-40	0.217	0.227	3.72

Table 3

Effects on the cooked muscle sensory analysis of high hydrostatic pressure processing (HPP) as a pre-treatment for frozen Atlantic mackerel (*Scomber scombrus*). Experimental treatment codes use P, H and F for pressure, holding time, and frozen storage time, respectively.

Experiments	Sensory odour	Sensory taste	Sensory texture	Sensory acceptability
1 (P450H0F0)	3	4	3	1
2 (P450H2.5F0)	1	3	3	1
3 (P450H5F0)	1	2	2	1.5
4 (P300H0F0)	1.5	1.5	1	2
5 (P300H2.5F0)	2	2	1.3	2.5
6 (P300H2.5F0)	2	2	1	2.5
7 (P300H2.5F0)	3	4	1.5	2
8 (P300H5F0)	3	4	2	2
9 (P150H0F0)	2.5	2.5	1	3
10 (P150H2.5F0)	2	1	1.2	4
11(P150H2.5F0)	3.5	3	1	4.5
12(H150H5F0)	4	3.5	1.5	4.5
13 (P450H0F1)	3	4	3	1.5
14 (P450H2.5F1)	4	4	3.5	1.5
15 (P450H5F1)	2	3	4	1
16 (P300H0F1)	4	5	2.8	2
17 (P300H2.5F1)	4	4	3.2	2
18 (P300H2.5F1)	3	5	3.5	2.3
19 (P300H2.5F1)	3	4	3	2
20 (P300H5F1)	3	4	2	2.5
21 (P150H0F1)	1	2	1.5	4
22 (P150H2.5F1)	2	2	1.5	4
23 (P150H2.5F1)	1	2	1.2	4
24 (P150H5F1)	2	2	2	4
25 (H450H0F3)	3	4	3	1
26 (H450H2.5F3)	3	4	4	1
27 (H450H5F3)	2	5	4.2	1
28 (P300H0F3)	3	4	2.8	2
29 (P300H2.5F3)	2	2	3	1.5
30 (P300H2.5F3)	3	4	3.5	1
31 (P300H2.5F3)	2	2	3	1.5
32 (P300H5F3)	3	4	3	1
33 (P150H0F3)	3	2	2	2
34 (P150H2.5F3)	3	3	2	3
35 (P150H2.5F3)	2	2	2	3
36 (P150H5F3)	2	1	1	4

FIGURE LEGENDS

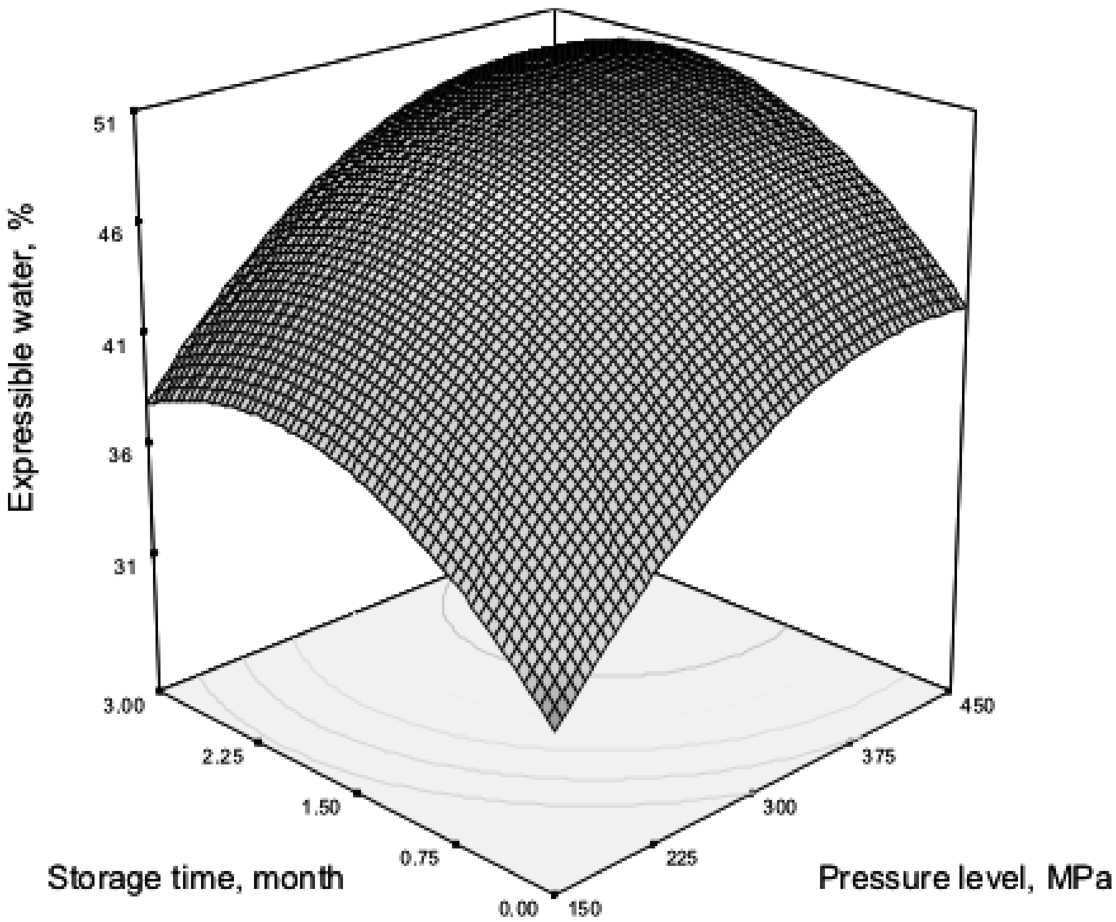
Fig 1. Model prediction for the effect of pressure level (MPa) and frozen storage time (months) on expressible water of raw muscles of Atlantic mackerel (*Scomber scombrus*). Holding time was fixed at 2.5 min.

Fig 2. Model prediction for the effect of pressure level (MPa) and frozen storage time (month) on lightness parameter (L) of raw muscle of Atlantic mackerel (*Scomber scombrus*). Holding time was fixed at 2.5 min.

Fig. 3. Model prediction for the effect of pressure level (MPa) and pressure holding time (min) on hardness of raw muscle of Atlantic mackerel (*Scomber scombrus*). Frozen storage time was fixed at 1.5 month.

Fig. 4. Model prediction for the effect of pressure level (MPa) and frozen storage time (month) on adhesiveness of raw muscle of Atlantic mackerel (*Scomber scombrus*). Holding time was fixed at 2.5 min.

Fig. 5. Model prediction for the effect of pressure level (MPa) and frozen storage time (month) on sensory acceptance of cooked fillets of Atlantic mackerel (*Scomber scombrus*). Holding time was fixed at 2.5 min.



Expressible water, %
51
46
41
36
31
3.00
2.25
1.50
0.75
0.00
Storage time, month
150
225
300
375
450
Pressure level, MPa

Figure 1

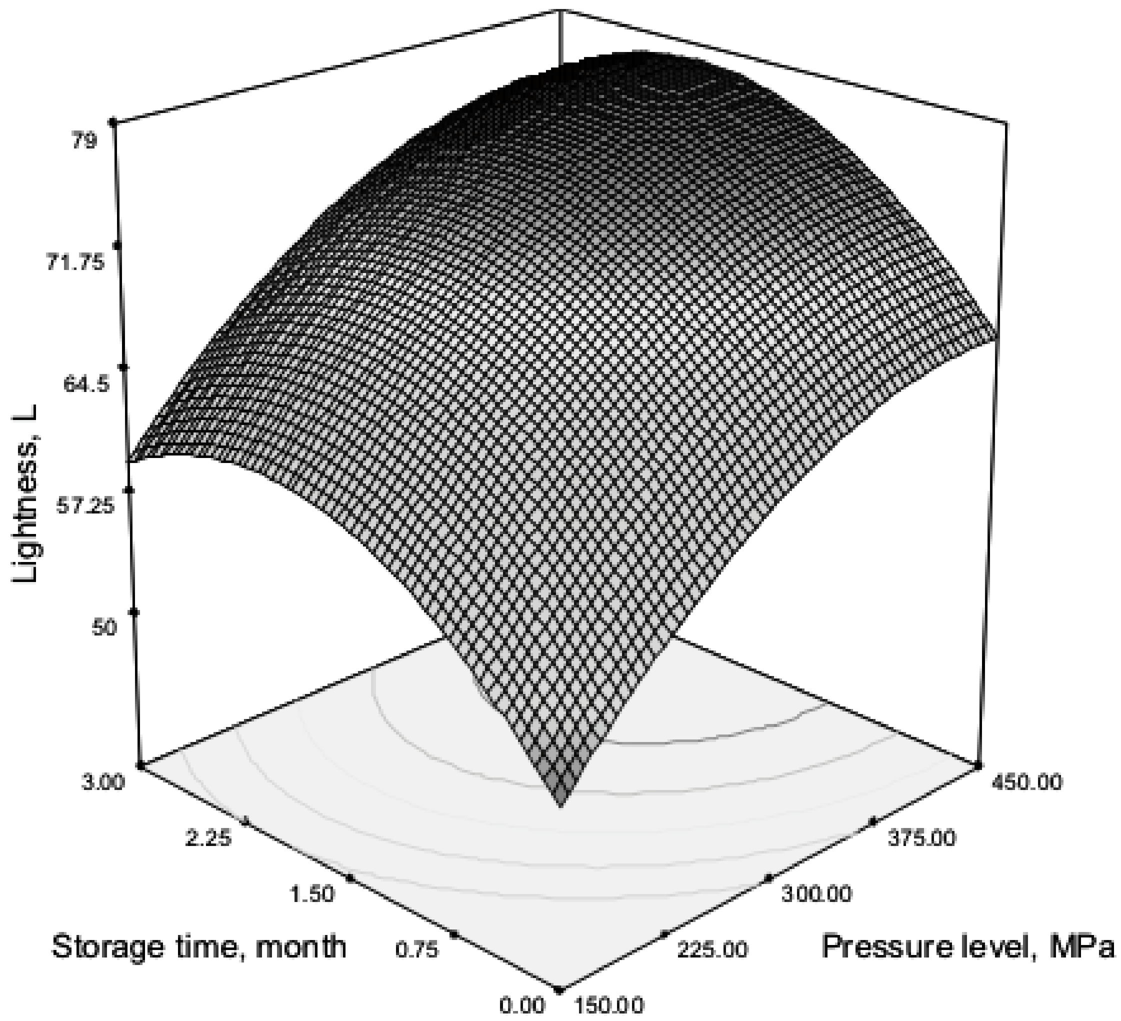

79
71.75
64.5
57.25
50
Lightness, L
3.00
2.25
1.50
0.75
0.00
Storage time, month
150.00
225.00
300.00
375.00
450.00
Pressure level, MPa

Figure 2

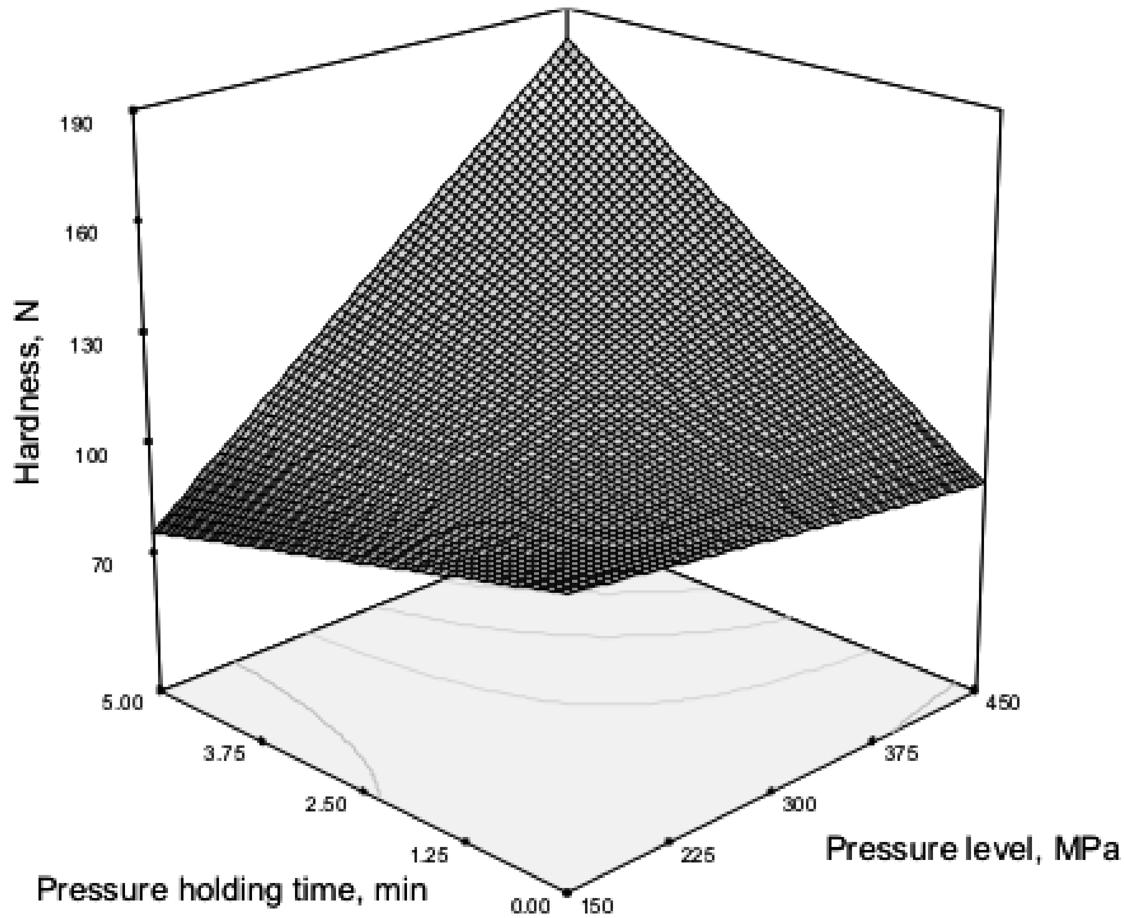

Hardness, N
190
160
130
100
70
5.00
3.75
2.50
1.25
0.00
Pressure holding time, min
150
225
300
375
450
Pressure level, MPa

Figure 3

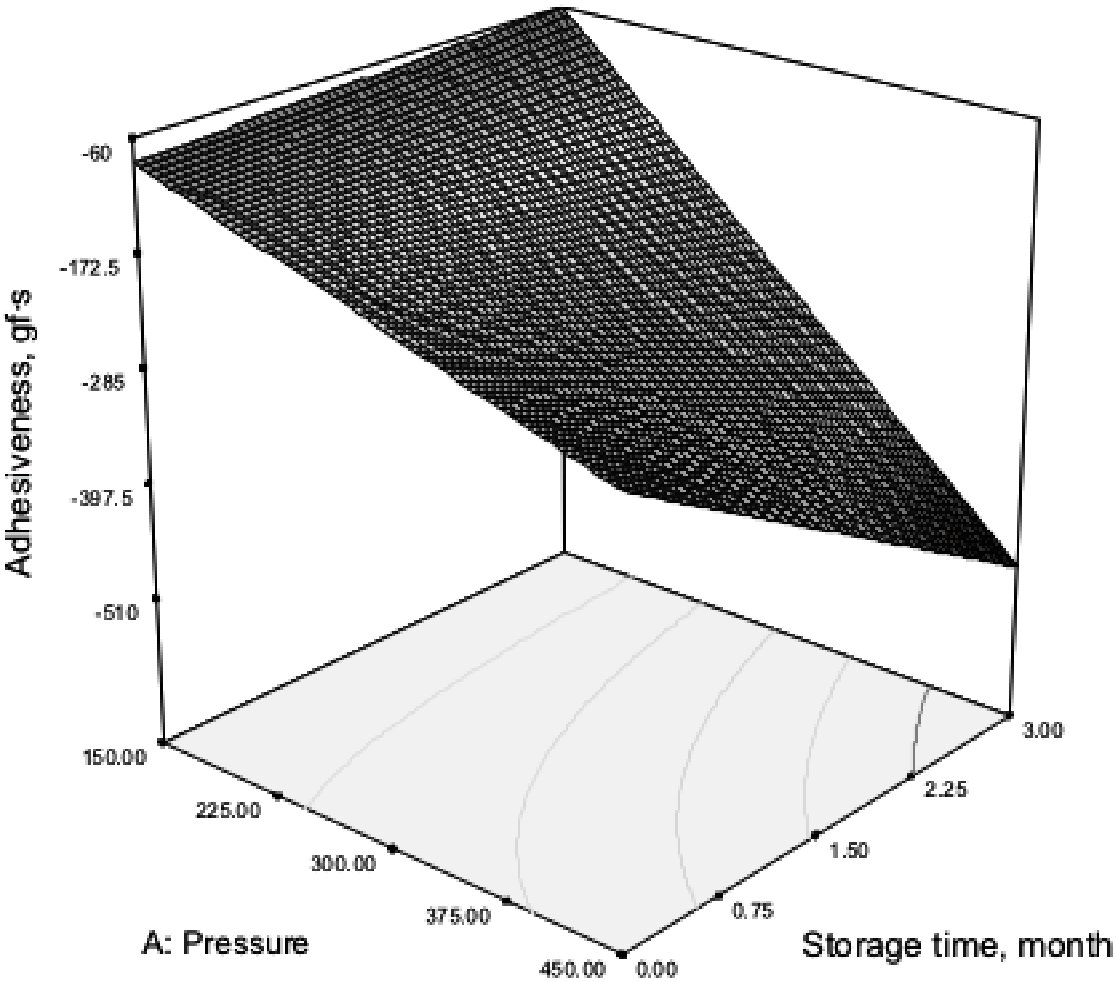

-60
-172.5
-285
-397.5
-510
Adhesiveness, gf·s
150.00
225.00
300.00
375.00
450.00
A: Pressure
0.00
0.75
1.50
2.25
3.00
Storage time, month

Figure 4

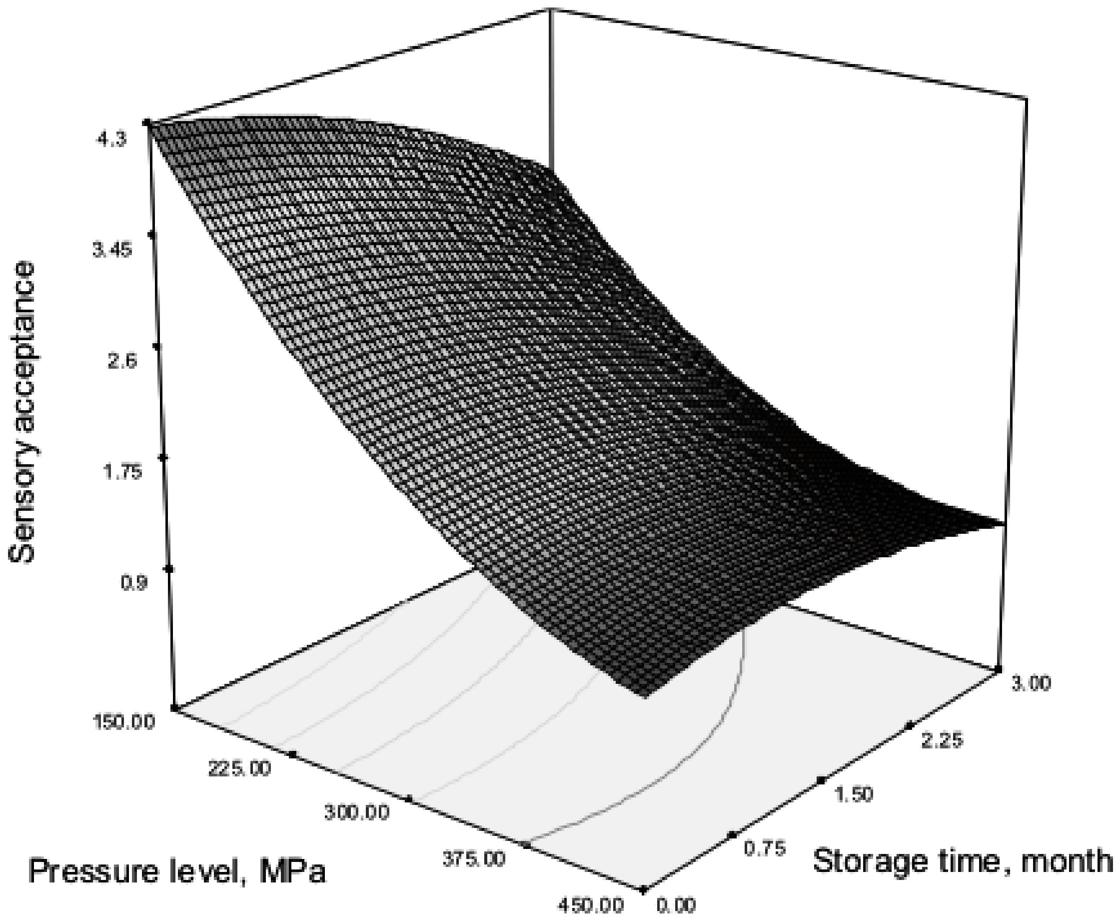

Sensory acceptance
4.3
3.45
2.6
1.75
0.9
Pressure level, MPa
150.00
225.00
300.00
375.00
450.00
Storage time, month
0.00
0.75
1.50
2.25
3.00

Figure 5