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Research paper

Effect of high–hydrostatic pressure processing and sous-vide cooking on physicochemical traits of *Biceps femoris* veal patties

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ABSTRACT

The effects of non-thermal, high-hydrostatic-pressure processing (HPP) and its combination with sous vide cooking technique (HPP-SVCOOK) on physicochemical traits of veal patties elaborated with top sirloin caps (*Biceps femoris*) derived from local Pyrenean bullocks, were investigated. The patties were subjected to 13 treatment combinations of three HPP pressures (350, 475, or 600 MPa) for 5, 10, or 15 min, followed by 20 treatment combinations with subsequent SVCOOK at three cooking temperatures (55, 60 or 65 °C). Significant changes in color and texture parameters were observed in HPP and HPP-SVCOOK patties. Also, there was a significant effect of processing parameters on cooking loss. HPP-SVCOOK processing conditions dealt with several changes in texture and color of patties. For yielding the optimum processing results in terms of reduced hardness and cooking loss, veal patties should be HPP-treated at 350 MPa for 10 min., and sous-vide cooked at 55 °C.

1. Introduction

The food processing industry in the European Union is facing an increasing demand for high-quality food products made from minimally processed, local raw materials. A paradigm shift in the consumer preference towards more concern for health, awareness, and sustainability is currently recognized (Dangelico & Vocalelli, 2017; Lago et al., 2020). On the other hand, using locally available, raw materials may reduce the wastage of resources, thereby being a more sustainable and acceptable choice. Furthermore, innovative, local meat products can stimulate entrepreneurship, which brings social benefits to rural towns and, at the same time, can meet the rising consumer demands for palatable, healthy, and sustainable foods.

Non-thermal technologies are replacing the conventional processing techniques due to improved healthiness and sensory qualities of the final product (Chacha et al., 2021). High-hydrostatic-pressure processing (HPP) is a non-thermal food preservation technology where food is isostatically treated to pressure ranges from 100 to 600 MPa with adiabatic heating of 3 °C every 100 MPa (Aymerich, Picouet, & Monfort, 2008). HPP has been commercially used since the late 1980s (Duranton, Simonin, Chéret, Guillou, & de Lamballerie, 2012). HPP is effective in reducing the microbial load of food (Bajovic, Bolumar, & Heinz, 2012). The nutritional value of the meat is barely affected by HPP because it does not change the covalent bonds but only breaking the less strong ionic and hydrogen bonds leading to the disruption of the quaternary structure of proteins (Chen et al., 2018). Besides, the low-molecular weight flavor compounds and vitamins remain unaffected (Rastogi, Raghavarao, & Niranjan, 2007). HPP induces changes in meat textural properties which may facilitate development of new products and/or improve the functional properties of meat (Tewari, Jayas, & Holley, 1999). Also, HPP has improved the digestibility of meat at higher HPP ranges (Kaur et al., 2016; Xue et al., 2020). HPP favors the disruption of myofibrillar structure, a tenderizing development coming from the high hydrostatic pressure exerted on proteins (Sikes & Warner, 2016).

Sous vide cooking (SVCOOK) is well-known to produce foods with more uniform meat quality and improved organoleptic properties (Baldwin, 2012; Naqvi et al., 2021; Przybylski, Jaworska, Kajak-Siemaszko, Sałek, & Pakuła, 2021; Roldán, Antequera, Martín, Mayoral, & Ruiz, 2013). SVCOOK is a technique where the raw material is vacuum packaged and subjected to low-temperature cooking at a controlled cooking time (Gómez, Janardhanan, Ibañez, & Beriain, 2020). Lower cooking loss and lipid oxidation with simultaneous color and flavor enhancement are reported advantages of using SVCOOK (García-Segovia, Andrés-Bello, & Martínez-Monzó, 2007). Also,

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SVCOOK can improve the tenderness of inherently tough meat (Park, Lee, Oh, Kim, & Choi, 2020).

Protected Geographical Indication (PGI) labeling is a widespread source certification in the European Union that assists in adding marketing value and sustainability to autochthonous livestock and foods. This is the case of "Ternera de Navarra" (Navarra-VEAL), a meat derived from the Pyrenean breed, the genetic basis for the Navarra-VEAL PGI certification. The leanness of this unique veal is particularly appealing to health-conscious consumer groups.

Meat patties are extremely popular worldwide, and there is a vast array of hamburgers formulated and processed with different raw materials and diverse nutrient compositions. Furthermore, according to their liking for burger textural traits, diverse types of consumers have been recently identified in the USA (Ricci, 2021). Combining thermal and non-thermal technologies could be an option to overcome undesirable side effects of individual treatments (Lee, Choi, & Jun, 2016; Leistner, 2000). However, studies on the properties of veal patties subjected to a combined process of HPP and SVCOOK are lacking.

We hypothesize that the potential synergistic or additive effects of the aforementioned technologies may enhance the sensory quality of the Navarra-VEAL patties. Acting jointly, HPP and SVCOOK may become complementary and more efficient in preserving Navarra-VEAL patties by reducing their microbial load. Therefore, the aim of this study is to explore the single effect of HPP or the combined effects of HPP and SVCOOK (HPP-SVCOOK) on physicochemical traits of veal patties made with lean top sirloin caps excised from Navarra-VEAL carcasses. To achieve this goal, we used response surface methodology (RSM), which has been widely used for process optimization because it allows for finding out the best treatment condition when using a face-centered central composite design (CCD) (Montgomery, 2009).

2. Materials and methods

2.1. Samples' origin and preparation

Non-castrated male calves were reared in a semi-extensive system at the Pyrenees mountains until weaning at seven to eight months of age. After weaning, the young Pyrenean male calves (bullocks) were fed in a local feedlot on a concentrate consisting of 85% barley, 10% soybean meal, 3% vegetal fat, and 2% minerals and vitamins, and barley straw, both ad libitum. During raising and fattening at the farm, cattle management practices followed Spanish rules and regulations for animal care (Publications Office of the European Union, 2010). Bullocks (11 to 13 months of age) were slaughtered at a local abattoir (Alma Meat Co., Spain) according to Spanish rules and regulations for animal welfare (Publications Office of the European Union, 2009). Therefore, the experiment complied with the official guidelines for humane treatment, care, and handling of animals. Two top-sirloin-cap roasts (*Biceps femoris* m.) were excised from three bullock carcasses at 3 days postmortem. The external connective and fat tissues were trimmed off. The lean meat was reduced to cubes and minced at low speed for 20–30 s at 20 °C using a Urbiola-CT20 electric meat grinder (Urbiola, Spain). Minced samples (150 g) were pressed into the patties' shape between two grease-proof paper sheets using a patty press. The samples were then vacuum-packaged (98%) in pouches using a Lerica - C412 vacuum packaging machine (Lerica, Italy). The samples were then stored at 4 °C for 24 h until HPP processing. A flowchart of the experimental procedures is depicted in Fig. 1.

2.2. Experimental design

A face-centered CCD was used to determine the design area which was defined as the corner and center points of the set conditions (Montgomery, 2009). The experimental design for the single (HPP)

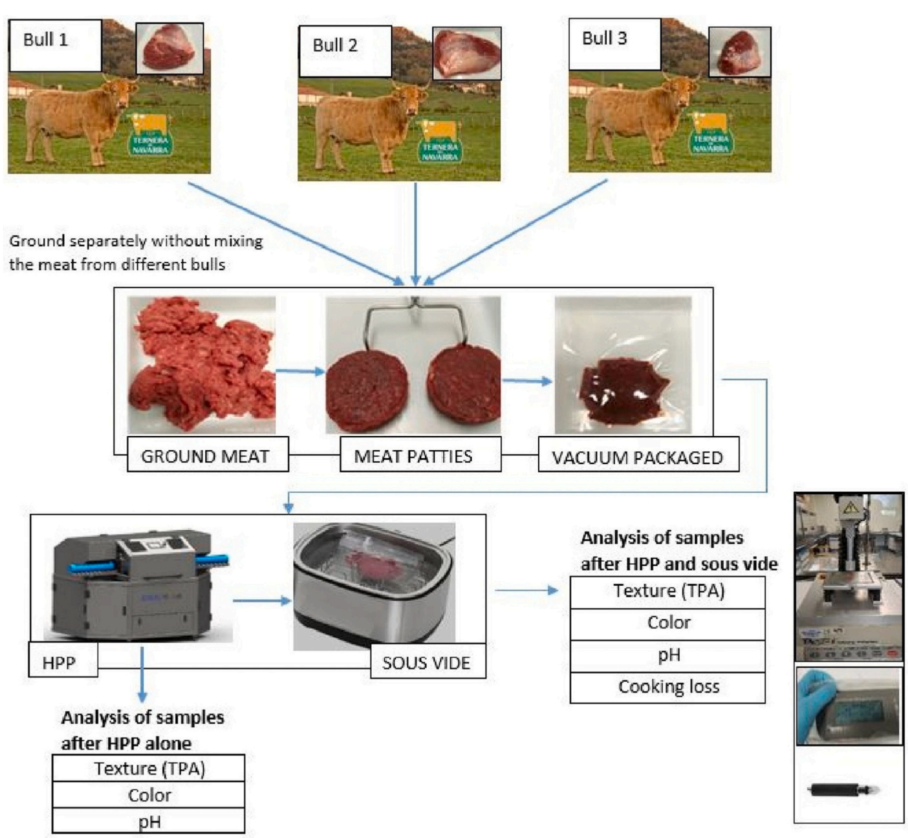

Fig. 1. Flowchart of the experiment.

experiment was an unblocked central composite full design for two continuous factors which needs13 runs. The center point was replicated five times (Table 1). The design for the combined (HPP-SVCOOK) experiment used a face-centered CCD, three blocks, for three continuous factors that required 20 runs. The meat used for the study was derived from three Navarra-VEAL bullocks which were distinctly divided into three blocks for the HPP-SVCOOK combined experiment (Table 2), whereas the veal patties to be subjected to the single HPP experiment were randomly selected (Table 1). The design depicted in Table 2 is an orthogonal design which was set up to estimate the main effects and their interactions independently of the block effects. Fifty-three veal patties were prepared. Thirteen were randomly selected and HPP treated (Table 1) while forty were divided into three blocks and subjected to HPP-SVCOOK where one sample was used for temperature monitoring during the SVCOOK treatment (Table 2).

2.3. Processing treatments

The samples were subjected to various pressure-time combinations of HPP (ranging from 350 to 600 MPa for 5 to 15 min.) according to the RSM-CCD. The interaction of different physical variables on meat properties could be successfully studied using this design. The design parameters are described in Table 1. The samples were subjected to HPP using an Idus 10-l HPP system (Metronics Technologies S.L., Navarra, Spain). It is a 600 MPa limit lab scale model, which works as a real-world industrial machine. The HPP-treated samples were stored at −18 °C until further analysis or SVCOOK.

HPP samples were cooked at a temperature range of 55–65 °C for 15 min. According to the RSM-CCD. An Orved SV thermo-top (Orved S.P.A, Venice, Italy) cooking bath was used for the low-temperature SVCOOK. Resistance temperature detector probes were used to monitor the product's core temperature. Once the core temperature reached the endpoint temperature it was maintained throughout the 15-min cooking time. The cooked samples were stored at 4 °C for 24 h until further analyses.

2.4. Proximate analysis

The proximate analysis of the raw meat samples was performed in duplicates for determining contents of moisture (International Organization for Standardization, 1997), protein (International Organization for Standardization, 1978), fat (International Organization for Standardization, 1973), and ash (International Organization for Standardization, 1998).

2.5. Instrumental texture

A Texture Profile Analysis (TPA) of the processed samples was conducted using a TA-XT2i stable microsystems texture analyzer (Stable Micro Systems Ltd., Surrey, UK). Two-cycle 50% compression with a 30 kg load cell was used for the tests. A 25 mm aluminum cylindrical probe with a pre-test, test, and post-test speed set as 2 mm/s was used. The time of compression was set to 3 s, 1.5 × 1.5 cm samples were used for the TPA analysis. Cohesiveness, springiness, hardness (N), chewiness (N), resilience, and adhesiveness (N.s) parameters were measured in six consecutive readings (Gómez, Sarriés, Ibañez, & Beriain, 2018).

Table 1
Central composite experimental design matrix for HPP treatment.

Runs	Blocks	HPP pressure (MPa)	HPP pressurization time (min.)
1	1	475	15
2	1	600	10
3	1	475	10
4	1	475	5
5	1	350	10
6	1	475	10
7	1	475	10
8	1	600	5
9	1	350	5
10	1	600	15
11	1	475	10
12	1	350	15
13	1	475	10

Table 2
Central composite experimental design matrix for HPP and SVCOOK treatment.

Runs	Blocks	HPP pressure (MPa)	HPP pressurization time (min.)	SVCOOK temperature (°C)
1	3	475	10	60
2	3	475	15	60
3	3	600	10	60
4	3	475	10	55
5	3	475	5	60
6	3	350	10	60
7	3	475	10	65
8	3	475	10	60
9	1	475	10	60
10	1	600	5	65
11	1	350	5	55
12	1	600	15	55
13	1	350	15	65
14	1	475	10	60
15	2	600	15	65
16	2	600	5	55
17	2	350	5	65
18	2	350	15	55
19	2	475	10	60
20	2	475	10	60

2.6. Instrumental color

Color parameter (L*, a*, b*) values of processed samples after the HPP and HPP-SVCOOK respective treatments were measured. The chroma, which defines color intensity ($\text{Chroma} = (a^{*2} + b^{*2})^{1/2}$) and hue ($\text{hue} = \tan^{-1}(b^*/a^*)$) were calculated. Minolta 2300-d handheld spectrophotometer was used for measuring the color parameters (Konica Minolta Business Technologies Inc., Tokyo, Japan), with D-625 illuminant with a 52 mm diameter sphere size, 8 mm /11 mm aperture size and 10° observer angle, the instrument was zero and white calibrated before use. Six consecutive readings were recorded.

2.7. pH

The pH of HPP and HPP-SVCOOK samples were measured using a pH meter (Crison Instruments S.A., Barcelona, Spain) (International Organization for Standardization, 1999). The pH meter was calibrated using pH buffer solutions of pH 4.01 and 7.00 at 25 °C. Three pH measurements per sample were taken at 25 °C and averaged to calculate the final pH value.

2.8. Cooking loss

The individual weights of the raw samples before and after SVCOOK were recorded, and the cooking loss was calculated using the formula reported by Murphy, Criner, and Gray (1975).

$$\text{Cooking loss } (\%) = \left(\frac{\text{Raw patty weight} - \text{cooked patty weight}}{\text{raw patty weight}}\right) \times 100$$

2.9. Microbial analysis

Microbial tests for the *Salmonella* species (Bird et al., 2013), *Listeria monocytogenes* (International Organization for Standardization, 2017), *Escherichia coli* B-Glucuronidase+ (International Organization for Standardization, 2001) were conducted at Eurofins Analisis Alimentario, Nordeste SL (Spain).

2.10. Data analysis and modeling

Data was analyzed by the RSM methodology using the Minitab statistical software package (Minitab® 19.2020.1 version). The effect of the independent factors: HPP pressure (350–600 MPa), time of exposure to the HPP (HPP pressurization time; 5–15 min.), SVCOOK temperature (55–65 °C) on the response variables, were studied based on the experimental designs (Tables 1, 2). A polynomial model using the Minitab software evaluated the multiple regression of the experimental data corresponding to the responses to the independent variables. The models' goodness-of-fit was evaluated by the determination coefficient (R^2), and the pure-error-lack-of-fit test. Analysis of variance (ANOVA) was conducted to test significance ($P < 0.05$) of the individual terms and the whole model. The statistically significant model with the highest R^2 was selected as the regression model of the response. The two-sided confidence level for all intervals was set at 95% for all the parameters of the models. The regression models were quadratic, two-way-interaction models and linear models. In a quadratic model, the multiplicative effect of two factors can be assessed. The optimum processing condition for the combined HPP-SVCOOK treatment according to 20 different treatment combinations was estimated (Montgomery, 2009). The response optimizer in the Minitab software was used to find the processing conditions required for the optimized product. The treatment parameter, which offered the minimum hardness and cooking loss, was selected as the optimum parameters for HPP-SVCOOK (Montgomery, 2009).

3. Results and discussions

3.1. Proximate analysis

Moisture, fat, protein, and ash percentage values for the raw meat samples are presented in Table 3. Similar values of protein content were observed by Baldwin, Korschgen, Russell, and Mabesa (1976) when analyzing the protein content of raw beef, whereas the moisture content was slightly higher compared to previous reports (Gómez et al., 2018; Gómez, Beriain, Sarriés, Insausti, & Mendizabal, 2014) due to the lower fat content of the raw Navarra-VEAL. Gómez et al. (2018) obtained similar values for fat content in the separable lean used for elaborating low-fat beef patties. The very low-fat content found in these Navarra-VEAL patties may entitle them to be described as “extra lean” according to conventional claims for nutrition labeling (U.S. Departmet of Agriculture, 2019).

3.2. Effect of HPP on textural properties, color, and pH of meat patties

3.2.1. Texture

Regression coefficients and other statistics resulting from the RSM of textural parameters are listed out in Table 4.

Hardness and chewiness values of the Navarra-VEAL patties were found to be significantly affected by HPP pressure ($P < 0.05$). HPP pressure had a linear effect on hardness and chewiness. The R^2 values of the model for hardness and chewiness were found to be 36.41 and 34.13%, respectively; therefore, the increase of HPP pressure values can be responsible for changes in these variables.

Table 3
Composition of beef samples expressed in mean and standard deviation (SD) values.

Samples	Moisture content (%) (SD)	Fat (%) (SD)	Protein (%) (SD)	Ash content (%) (SD)
Beef 1	75.7 (0.169)	1.3(0.089)	21.6(0.238)	1.2(0.014)
Beef 2	75.5 (0.027)	1.2(0.203)	23.2(0.347)	1.2(0.022)
Beef 3	74.7 (0.122)	2.0(0.157)	22.6(0.097)	1.2(0.084)

Increasing trends in hardness and adhesiveness were also observed in HPP-processed goose meat treated above 400 MPa and attributed to the unfolding of actin and sarcoplasmic proteins (Gao, Zeng, Ma, Wang, & Pan, 2015). Also, Ma and Ledward (2004) found that degree of toughness in post-rigor beef *Longissimus dorsi* augmented by increasing HPP pressure from 200 to 800 MPa.

From the estimated regression models, it was noted that the HPP pressurization time did not have a significant effect ($P > 0.05$) on the texture parameters. No significant influence of HPP pressure value or HPP pressurization time was found on cohesiveness, springiness, resilience, or adhesiveness according to the regression models ($P > 0.05$).

3.2.2. Color

L*, a* and hue values did not vary ($P > 0.05$) with HPP pressure and HPP pressurization time. However, the b* (yellow) value was significantly affected by the quadratic function of both HPP pressure and HPP pressurization time (Fig. 2, Table 4). Thus, some values of HPP pressure and time relate to a minimum b* value observed at around 475 MPa at 10 min. of pressurization. Regarding chroma, a significant effect ($P < 0.05$) of the squared term of pressurization time was noted. The chroma values followed a similar trend to that of b* values (Fig. 3).

No significant changes in color parameters were observed by Sun, Sullivan, Stratton, Bower, and Cavender (2017) in HPP-treated beef steaks under either 450 MPa or 650 MPa. An increase in yellowness (b*) like our findings were observed in beef *Longissimus dorsi* at 400 and 600 MPa of HPP, which was inferred to be due to the oxidation of ferrous myoglobin to ferric metmyoglobin leading to the brown discoloration (Marcos, Kerry, & Mullen, 2010).

3.2.3. pH

HPP pressure had a significant linear effect on the pH of meat patties ($P < 0.05$). The pH of the raw meat samples was found to be 5.47. The regression model for pH had an R^2 value of 55.65%, lower than the R^2 for the b* parameter but higher than those estimated for hardness and chewiness (Table 4). The results suggest that an increase in the HPP pressure results in a slight increase of the samples' pH. The pH values varied from 5.71 to 5.80 in the HPP samples, and maximum values were exhibited by samples treated at 600 MPa. Comparable results were observed in beef *Pectoralis profundus*, which were attributed to the decrease in available acidic groups brought about by changes in protein conformation due to protein denaturation during HPP (McArdle, Marcos, Kerry, & Mullen, 2010).

3.3. Effects of the HPP-VCOOK on textural properties, color parameters, pH, and cooking loss of meat patties

3.3.1. Texture

Results from the effect of independent variables on the response variables and regression equations are described in Table 5.

HPP pressure has a significant effect on the cohesiveness of the meat patties ($P < 0.05$). Cohesiveness exhibited a linear relationship with HPP pressure (Fig. 4). On the other hand, SVCOOK temperature, HPP pressurization time, and the interaction terms were not significant on cohesiveness. Comparable results were observed by Mor-Mur and Yuste (2003) where HPP-processed sausages (at 500 MPa, 5 or 15 min., 65 °C) were less firm and more cohesive. Botinestean, Keenan, Kerry, and Hamill (2016) also found that SVCOOK increased the cohesiveness of *Semitendinosus* steaks.

The increase in HPP pressure and SVCOOK temperature augmented springiness of the Navarra-VEAL patties (Fig. 5) whereas, the HPP pressure x SVCOOK temperature interaction suggests that at lower cooking temperature, the springiness goes up with a hike in HPP pressure, but at 65 °C a declining trend was observed with the increase in HPP pressure. It could also be observed that samples treated at the lowest HPP pressure had the highest springiness when the cooking

Table 4
Regression coefficients for response surface methodology analysis of response variables of HPP treated samples.

Parameter	Model	Constant	P	t	P^2	t^2	Pxt	R^2 (%)
Hardness (N)	Linear	2.87	0.02329*	–	–	–	–	36.41
Chewiness (N)	Linear	0.80	0.00821*	–	–	–	–	34.13
b* parameter	Quadratic	50.57	−0.0930	−1.372	0.000111*	0.0976*	−0.001420	87.89
Chroma	Quadratic	55.9	−0.1023	−1.493	0.000106	0.0723*	–	67.25
pH	Linear	5.6014	0.000297*	–	–	–	–	55.65

P – HPP pressure; t – HPP pressurization time; R^2 – determination coefficient; * significant terms in the model ($P < 0.05$).

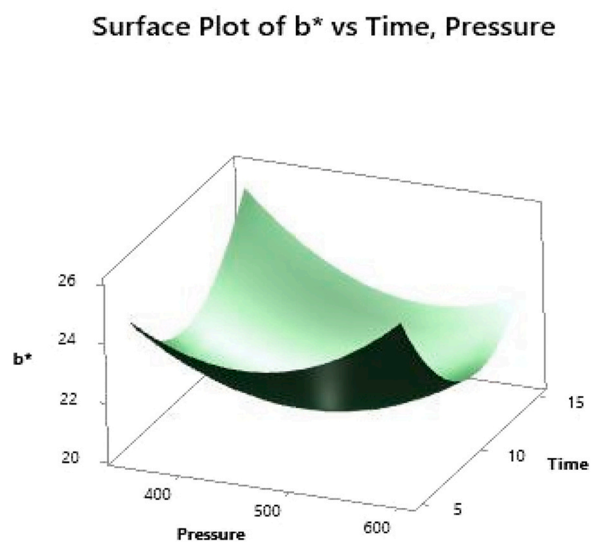

Fig. 2. Response surface plot for b* parameter.

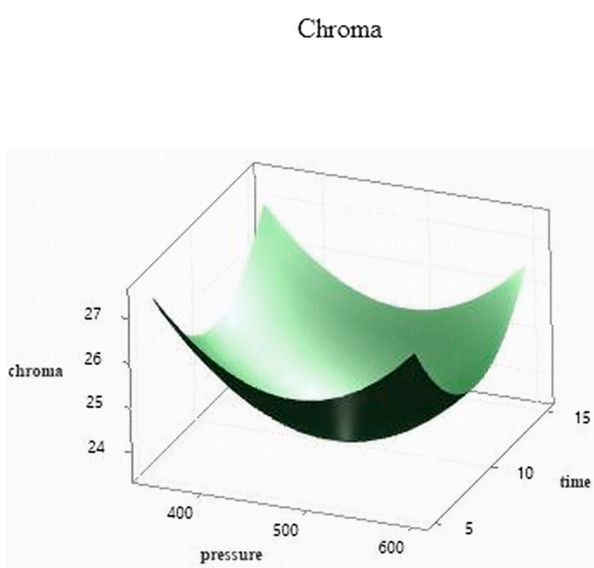

Fig. 3. Response surface plot for chroma.

temperature was the highest, but the contrary was true when the cooking temperature was the lowest. Similarly, turkey fillets HPP treated at 100–200 MPa showed a rise in springiness at the highest HPP pressure (Chan, Omana, & Betti, 2011). Roldán et al. (2013) also detected a significant effect of SVCOOK temperature on the springiness of lamb loins. However, a non-significant effect of SVCOOK was observed in springiness of *Semitendinosus* steaks (Botinestean et al., 2016). On the other hand, pressurization has increased springiness in vacuum-packaged-cooked sausages (Mor-Mur & Yuste, 2003).

A linear regression model with HPP pressure and SVCOOK temperature was significant ($P < 0.05$) for hardness. The R^2 value of the model was found to be 38.64%. HPP pressure and SVCOOK temperature were the significant terms in the model ($P < 0.05$) with no interaction between these variables. A concomitant increase in HPP pressure and SVCOOK temperature increased hardness of the Navarra-VEAL patties (Fig. 6).

Other workers (Buckow, Sikes, & Tume, 2013; Ma & Ledward, 2004) have found that toughness of beef *Longissimus dorsi* augmented with increasing pressure from 200 to 800 MP. Above 60 °C, pressure and temperature are antagonistic with respect to molecular processes (Balny & Masson, 1993) and HPP can partially offset heat denaturation (Fernández-Martín, Fernández, Carballo, & Jiménez Colmenero, 1997). Angsupanich and Ledward (1998) studied the effect of sequential HPP and heat treatments on cod texture and suggested that on HPP processing at 400 MPa, a hydrogen-bonded network is set up in fish muscle, that readily melts on subsequent treatment at 50 °C, allowing some disulfide bonds and numerous hydrophobic interactions to form a heat-set gel (Ma & Ledward, 2004).

Regarding adhesiveness, SVCOOK temperature and the HPP pressure x SVCOOK temperature interaction were the significant terms in the model ($P < 0.05$). The rise in the SVCOOK temperature increased the adhesiveness of the Navarra-VEAL patties (Fig. 7) whereas the HPP pressure x SVCOOK temperature interaction followed a similar trend to that affecting springiness. Conversely, a non-significant effect of SVCOOK temperature was observed on the adhesiveness of lamb loins (Roldán et al., 2013).

HPP pressure and SVCOOK temperature had significant but different effects on chewiness ($P < 0.05$). A rise in HPP pressure and SVCOOK temperature increased chewiness, whereas an increase in HPP pressurization time reduced the samples' chewiness (Fig. 8). A previous report also showed that an increase in SVCOOK temperature was associated with the rise in chewiness in *Semitendinosus* beef steaks (Botinestean et al., 2016). Research on HPP of sausages at mild temperatures showed that a hike in pressure reduced chewiness in contrast to temperature, which increased chewiness (500 MPa, 15 min., 65 °C) (Mor-Mur & Yuste, 2003).

A quadratic model was found to be significant for resilience with an R^2 value of 83.02% ($P < 0.05$). At higher HPP pressures and SVCOOK temperatures, meat patties displayed higher resilience values. This increasing trend in resilience could be observed in Fig. 9. Chan et al. (2011) in HPP treated turkey fillets (100–200 MPa) reported a rise in resilience at the highest applied pressure. Conversely, when beef *Semitendinosus* was cooked in a water bath at varying temperatures, no significant difference in resilience was found (Chang et al., 2011).

The changes in the texture parameters might be contributed due to the structural changes in meat protein because of the successive application of both technologies.

3.3.2. Color

The L* values of the meat patties followed a quadratic regression model (Table 5). SVCOOK temperature, HPP pressure x SVCOOK temperature, and HPP pressure x HPP pressurization time were the significant terms ($P < 0.05$) in the regression model. The curvature in the results and the quadratic effect in the model become evident from the

Table 5
Regression coefficients for response surface methodology analysis of response variables of high-hydrostatic pressured and sous vide cooked samples.

Parameter	Model	C	P	t	T	P^2	t^2	T^2	Pxt	PxT	Txt	R^2 (%)
Cohesiveness	2-way interaction	0.925	−0.001148*	0.01020	−0.00715	–	–	–	0.000014	0.000022	−0.000250	74.81
Springiness	2-way interaction	−0.898	0.002128	0.02200	0.02670*	–	–	–	0.000016	0.000036*	0.000500	74.81
Hardness (N)	Linear	−34.800	0.038800*	–	1.10100*	–	–	–	–	–	–	38.64
Adhesiveness (N.s)	2-way interaction	−3.66	0.005380	−0.0081	0.0582*	–	–	–	0.000020	−0.000088*	–	73.87
Chewiness (N)	Linear	−31.000	0.029400*	0.06100	0.63600*	–	–	–	–	–	–	52.54
Resilience	Quadratic	−0.393	−0.000530*	0.00143	0.0219*	–	0.000204	−0.000196	0.000002	0.000010	−0.000050	83.02
L* value	Quadratic	115.5	−0.0808	0.995	−1.13*	−0.000041	−0.0057	−0.0024	−0.002129*	0.002341*	0.0004	94.81
a* value	Quadratic	−6.1	−0.0228*	−0.690	0.67*	0.000035	0.02988*	−0.00266	0.001087*	−0.000468	−0.00718	96.59
b* value	Quadratic	112	0.1015*	−2.56	−3.31	−0.000012	0.0382	0.0350	0.002521*	−0.002083*	0.0085	86.63
Chroma	Quadratic	108	0.0914*	−2.63	−3.07	−0.000002	0.0446	0.0335	0.002726*	−0.002137*	0.0060	89.82
Cooking loss	Quadratic	169	0.0014*	−2.185*	−5.20*	−0.000174*	0.0050	0.0333	−0.000087	0.003035*	0.03837*	98.61

C – constant; P – HPP pressure; t – HPP pressurization time; T – SVCOOK temperature; R^2 – determination coefficient, * significant terms in the model ($P < 0.05$), all the equations are averaged over blocks.

response surface plots (Figs. 10–13) for the color parameter values (L*, a*, b*, chroma). The L* value reached its maximum value at 475 MPa. With the hike in HPP pressurization time and SVCOOK temperature, the L* value dropped. The L* value followed a rising trend with increasing HPP pressure at a shorter HPP pressurization time, whereas it showed a decreasing trend at a longer pressurization time. An apparent increase in the lightness value was observed in samples cooked at higher temperatures with increasing HPP pressure values. In contrast, samples cooked at the lowest SVCOOK temperature exhibited a reduction in lightness with the increase in the HPP pressure.

Goutefongea, Rampon, Nicolas, and Dumont (1995) suggested that color modifications and particularly lightness modifications could be a consequence of protein modifications. Cheah and Ledward (1996) noted a severe protein denaturation for HPP-treated meat with pressures above 300–400 MPa. Changes in myofibrillar and sarcoplasmic proteins due to HPP could induce meat surface changes and consequently color modifications, which could be a disadvantage for marketing pressurized (HPP) raw meat (Jung, Ghoul, & de Lamballerie-Anton, 2003). The L* value of low temperature-long time cooked *Longissimus dorsi* and *Semitendinosus* muscles from slaughter pigs and sows increased with higher cooking temperatures (Christensen, Ertbjerg, Aaslyng, & Christensen, 2011).

The a* value of Navarra-VEAL patties followed a quadratic regression model with an R^2 value of 96.59% (Table 5). The significant terms in the model were HPP pressure, SVCOOK temperature, HPP pressure x HPP pressurization time interaction, and the square of HPP pressurization time. A non-linear declining trend for a* value was observed with the increase in the HPP pressure, whereas a rising trend was noticeable with the rise in SVCOOK temperature. A minimum a* value was observed at 10 min. of HPP pressurization time, and a sudden surge occurred with both higher and lower HPP pressurization times. The interaction of HPP pressure and HPP pressurization time leads to a declining trend in redness with a hike in both HPP pressure and HPP pressurization time (Fig. 11).

HPP treatment of beef have decreased its a* value due to the oxidation of ferrous myoglobin to ferric metmyoglobin, leading to brown discoloration (Jung et al., 2003). A similar increase in redness indicated by the reduction in a* value was reported in SVCOOK of *Semimembranosus* beef muscles due to temperature induced denaturation of myoglobin (Tkacz, Modzelewska-Kapituła, Petracci, & Zduńczyk, 2021).

The b* value of the HPP-SVCOOK treated samples followed a quadratic model with an R^2 value of 86.63% (Table 5). The HPP pressure x HPP pressurization time interaction, HPP pressure, HPP pressure x SVCOOK temperature interaction were the significant terms in the model ($P < 0.05$) (Fig. 12). The b* value followed a decreasing trend with the hike in HPP pressure. The b* value exhibited a decreasing trend at higher SVCOOK temperatures, whereas at the lowest cooking temperature, it almost plateaued out with the increase in HPP pressure.

An increase in SVCOOK temperature has been associated with a higher b* value because the increased metmyoglobin content in brownish meat products (Botinestean et al., 2016; García-Segovia et al., 2007). Sun, Rasmussen, Cavender, and Sullivan (2019) observed that SVCOOK of beef steaks did not significantly ($P > 0.05$) influence the color of post-HPP beef samples except for those processed at the greatest pressure and time (600 MPa for 15 min.) where the L* and b* values were significantly different from other treatment combinations (450 MPa, 600 MPa for 2 s, or 1, 3, 6, and 10 min.).

Chroma values followed a significant quadratic model. The linear effect of HPP pressure and the interaction effect of HPP pressure x SVCOOK temperature were the significant terms in the model for chroma ($P < 0.05$). The curvature in the values (Fig. 13) could be explained by the model. Accordingly, it was observed that a rise in HPP pressure was accompanied with a decrease in the chroma value. A minimum chroma value was observed at around 10 min. of HPP pressurization time and 60 °C of SVCOOK temperature (Fig. 13). No

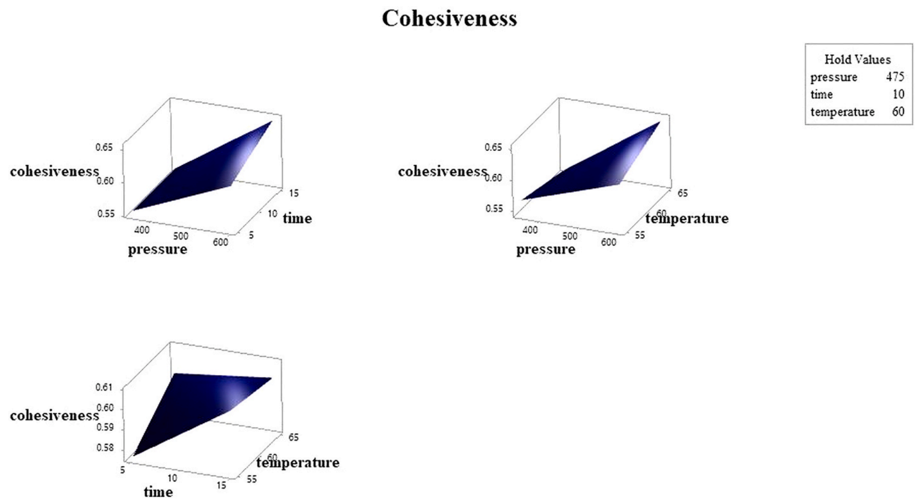

Fig. 4. Response surface plot for cohesiveness parameter.

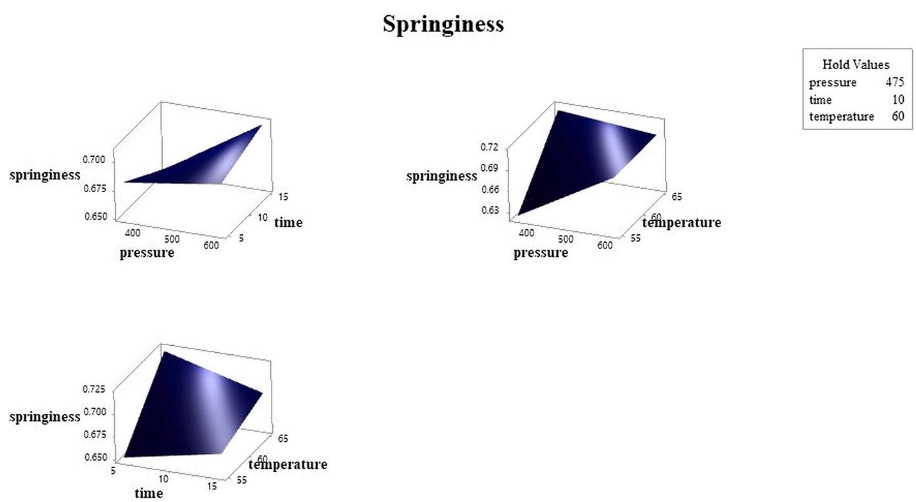

Fig. 5. Response surface plot for springiness of meat patties.

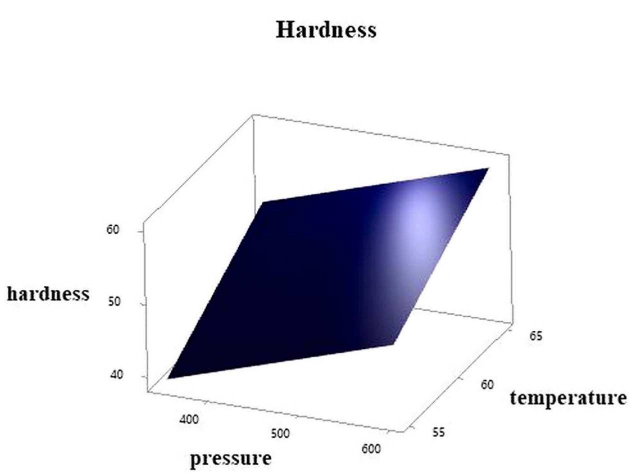

Fig. 6. Response surface plot for hardness of meat patties.

significant effect of HPP pressure, HPP pressurization time or SVCOOK temperature could be observed on the hue values of the samples.

Sun et al. (2019) reported that the internal color of beef steaks treated with HPP (450 MPa, 15 min. and 600 MPa, 10 min.) and subsequently subjected to SVCOOK (55 °C for 45 min., 120 min.) showed no significant changes in chroma or hue values.

3.3.3. pH

With the dual treatment (HPP-SVCOOK), there was no significant effect of HPP pressure, HPP pressurization time, or SVCOOK temperature on pH of the samples. Similar, non-significant pH changes in HPP-SVCOOK beef steaks were observed by Sun et al. (2017). Contrary to our findings, other researchers have found that both temperature and pressure elicit a slight, non-additive but significant increase in pH of beef, fish, and turkey due to burying of the acidic groups as proteins unfold (Angsupanich, Edde, & Ledward, 1999; Angsupanich & Ledward, 1998; Ma & Ledward, 2004).

3.3.4. Cooking loss

Cooking loss followed a quadratic regression model ($R^2 = 98.61\%$) which could explain the data curvature (Table 5). SVCOOK temperature, HPP pressure, HPP pressurization time, their interactions (HPP pressure x SVCOOK temperature and HPP pressurization time x SVCOOK temperature), and the square term of HPP pressure were the significant terms.

It was observed that with the increase in the HPP pressure, a maximum value of cooking loss was obtained at around 500 MPa followed by a slight reduction to 600 MPa, which is explained by the

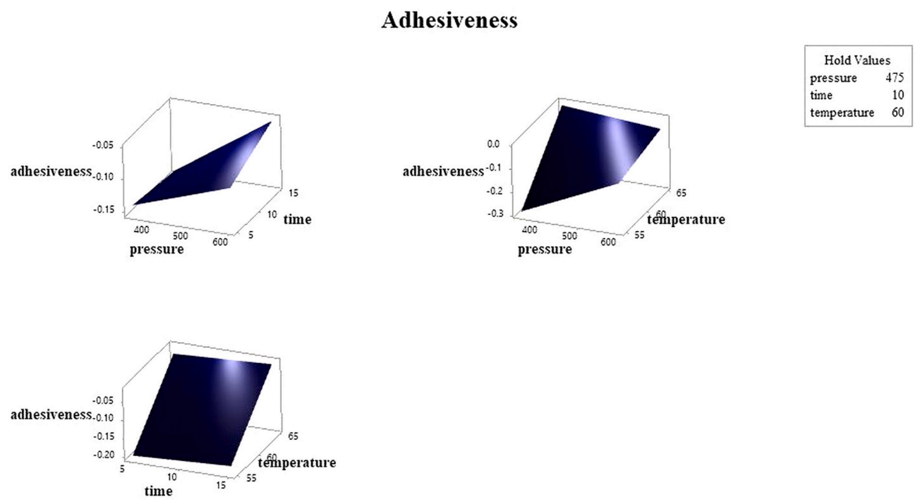

Fig. 7. Response surface plot for adhesiveness of meat patties.

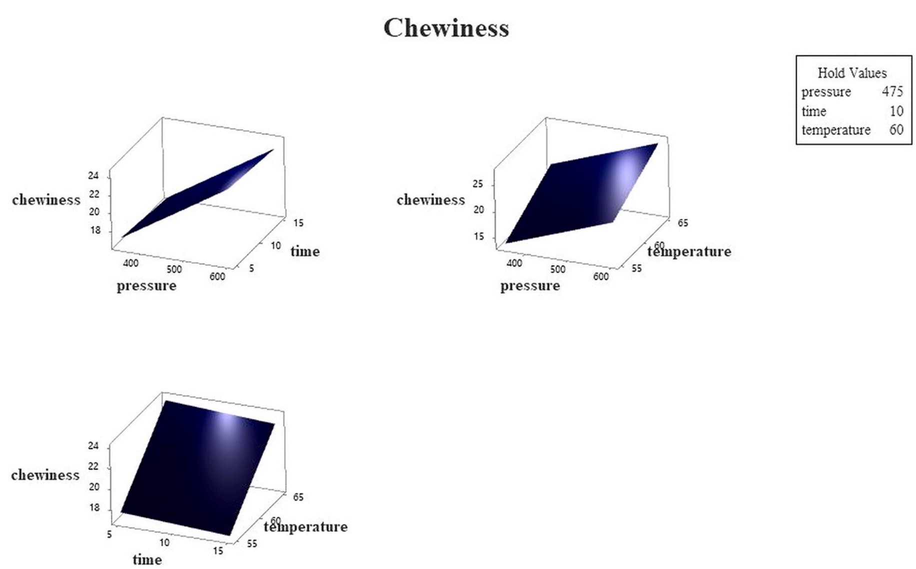

Fig. 8. Response surface plot for chewiness of meat patties.

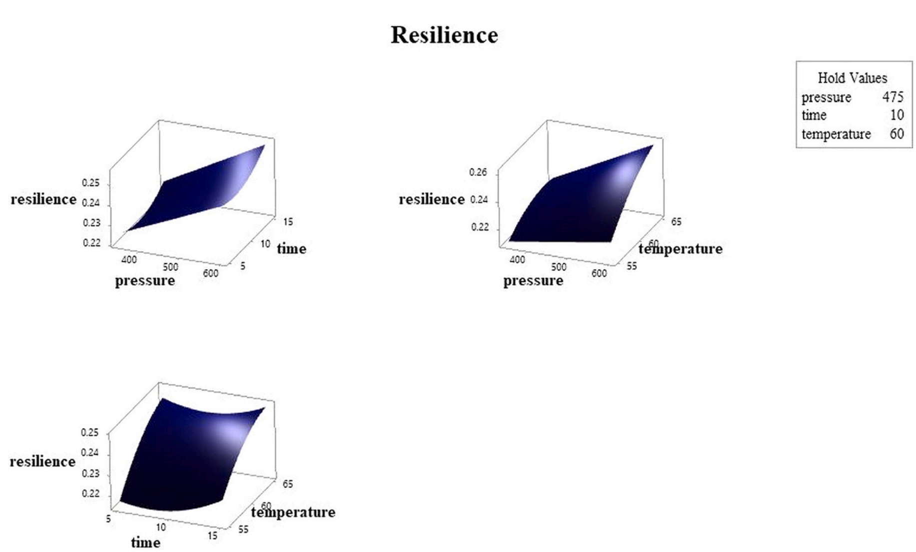

Fig. 9. Response surface plot for resilience parameter.

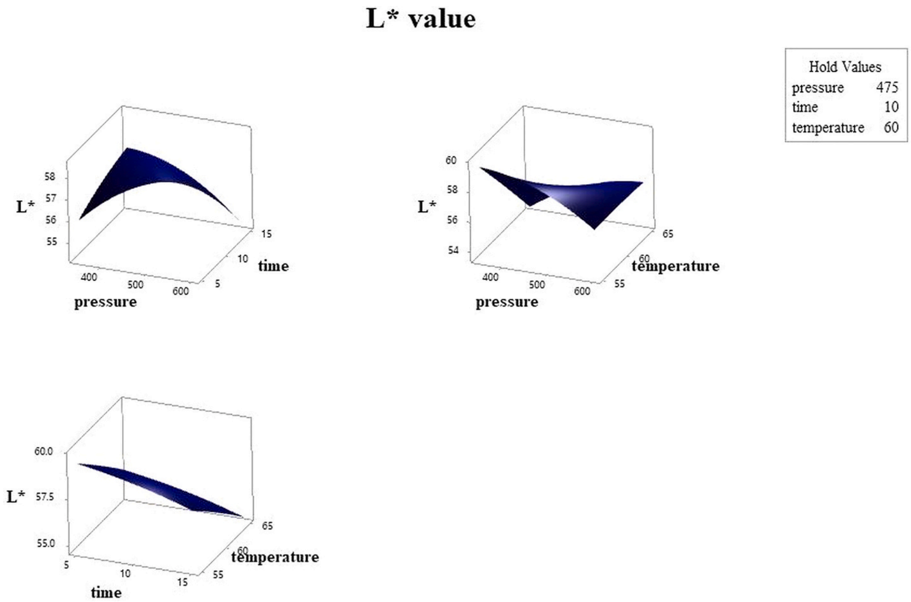

Fig. 10. Response surface plot for L* parameter.

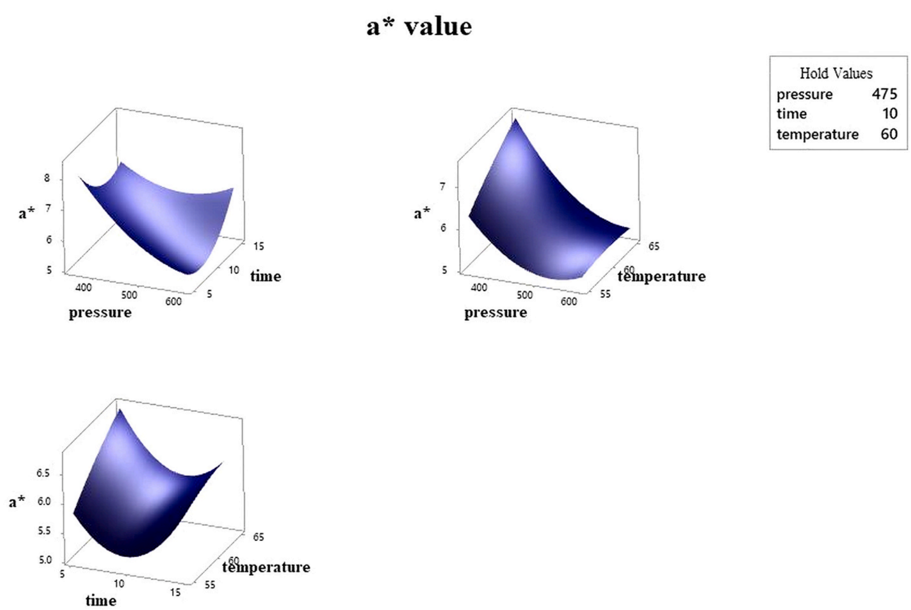

Fig. 11. Response surface plot for a* parameter.

quadratic in the regression model. When HPP pressurization time and SVCOOK temperature rose, the samples trended to increase their cooking losses (Fig. 14). The mathematical model could explain the effects of a significant interaction between HPP pressure and SVCOOK temperature.

A surge in cooking loss with the hike in SVCOOK temperature was also observed in beef *Pectoralis* steaks by García-Segovia et al. (2007) when studying the effect of different cooking methods on meat structure. Comparable results were observed in chicken breast subjected with SVCOOK at different temperature-time combinations (60 °C, 70 °C for 1 h, 2 h, 3 h) (Park et al., 2020). Several investigations have accounted for a reduced water binding capacity in meat and meat batters when processed at higher pressure ranges (Jung, Ghoul, & de Lamballerie-Anton, 2000; McArdle et al., 2010).

3.4. Optimization of the combined HPP and sous-vide cooking

The optimum parameters are shown in Table 6. The combination of 350 MPa of pressure for 10 min. SVCOOK at 55 °C offered the Navarra-VEAL patties with the least hardness and lowest cooking loss; hence, it was selected as the optimum processing protocol.

Tenderness, juiciness, flavor, and overall palatability remain the most sought-after attributes by consumers. However, recent research (Ricci, 2021) has identified four mouth-behavior types of consumers in the USA (i.e., "Chewers," "Crunchers," "Smoothers," and "Suckers") according to their textural affinities for ground beef patties of various grinds and formulations, and how these four consumer groups experience the different beef patties served at US restaurant chains. Interestingly, Miller and Vahlik as cited by Ricci (2021) studied the consumer preferences for three types of beef patties with fat levels ranging from 7 to 27%. Therefore, their findings cannot be used as a reference for veal

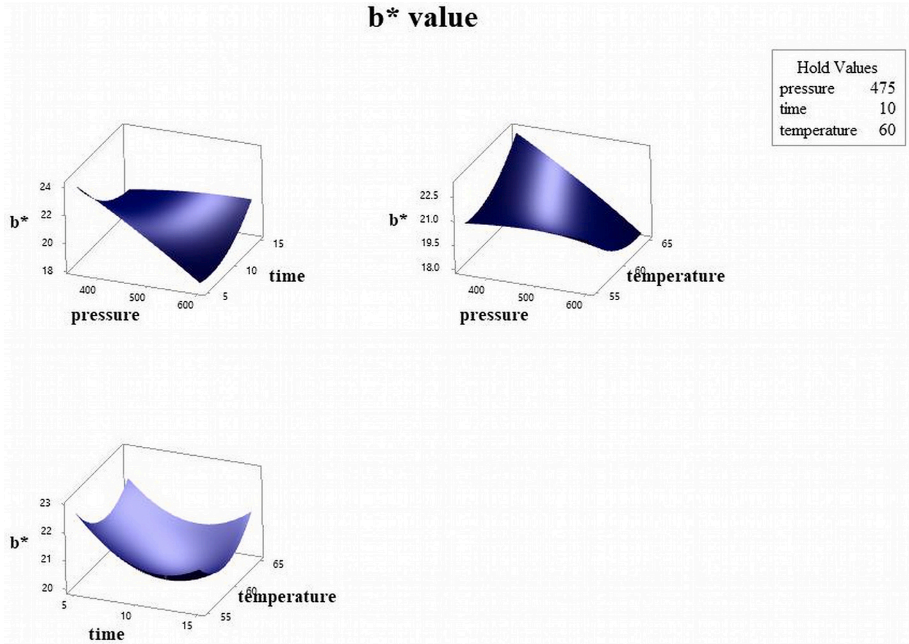

Fig. 12. Response surface plot for b* parameter.

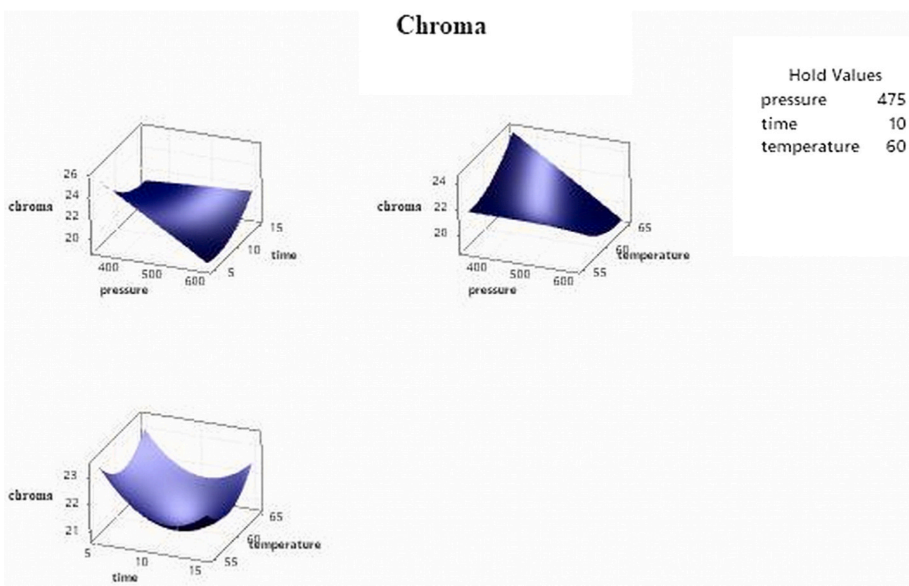

Fig. 13. Response surface plot for chroma.

patties with very low-fat content (i.e., less than 4%) as the samples used herein.

3.5. Microbial analysis

The results of microbial counts present in the optimized samples (350 MPa, 10 min., 55 °C) are shown in Table 7. All counts were found to be within the acceptable limits (Publications Office of the European Union, 2005).

The bacterial counts in HPP treated marinated beef loins were below the detection limit (600 MPa, 6 min.) as reported by Garriga, Grèbol, Aymerich, Monfort, and Hugas (2004). Sun et al. (2017) noted 4.74 and 6.23 cfu/g log reduction of *E. coli* in beef steaks HPP treated at 450 MPa for 15 min. and 550 MPa for 10 min., respectively. Prior microbial studies in beef *Longissimus dorsi* pressurized at 650 MPa and 20 °C for 10 min reported a reduction in total viable counts (TVC) and lactic acid bacteria counts (LAB), while *Enterobacteriaceae* counts remained unchanged (Fernández et al., 2007). In refrigerated beef *Pectoralis profundus samples* treated with HPP at 200, 300 and 400 MPa at 20 °C and 40 °C the *Enterobacteriacae* and LAB counts were under the detection limit (McArdle et al., 2010). Several studies have reported that HPP leads to microbial reduction with minimal effects on the sensory and nutritional profile (Campus, 2010). Similarly, SVCOOK-treated (60 °C, 270 min.) *Semitendinosus* steaks had acceptable limits for TVC, *Pseudomonas*, LAB and *Enterobacteriaceae* counts (Botinestean et al., 2016).

4. Conclusions

Beneficial effects of the combined HPP plus SVCOOK technologies on texture and color of veal patties are detected. Modification in the color

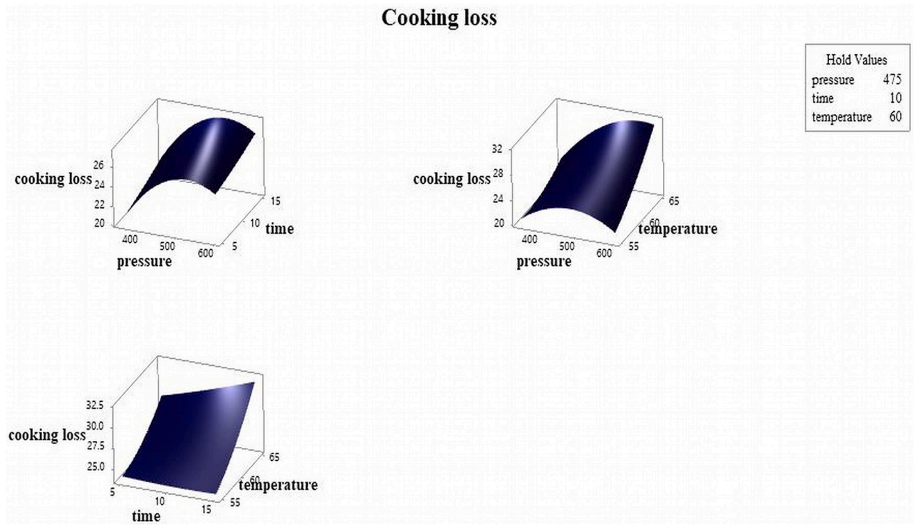

Fig. 14. Response surface plot for cooking loss parameter.

Table 6
Optimum processing conditions for simultaneous HPP and Sous-Vide cooking.

Parameter	HPP pressure (MPa)	HPP pressurization time (min.)	SVCOOK temperature (°C)
Optimum condition	350	10	55

Table 7
Microbial counts in the optimized sample.

Microorganism	Presence	Acceptable limit	Reference
Salmonella spp.	not detected/25 g	Absence in 25 g	Publications Office of the European Union (2005)
Listeria monocytogenes	not detected/25 g	Absence in 25 g	Publications Office of the European Union (2005)
Escherichia coli	< 10 cfu/g	500–5000 cfu/g	Publications Office of the European Union (2005)

values was observed in HPP-treated and post HPP-SVCOOK Navarra-VEAL patties. SVCOOK can balance out the discoloration caused by the effect of HPP. The combined treatment makes the veal patties less firm and more cohesive. For yielding the optimum processing results in terms of reduced hardness and cooking loss, meat patties should be HPP-treated at 350 MPa for 10 min., and SVCOOK at 55 °C. The processing conditions under study offered no safety risk regarding *Salmonella* and L. *monocytogenes*. The recommended HPP-SVCOOK conditions extend the possibility of using *Biceps femoris* to prepare very lean veal patties and suggest sustainable and innovative low-fat product lines for agro-food industries using PGI-Navarra Veal. However, consumer research is needed to ascertain the overall liking for these very lean veal patties. Further research is needed to discern the effect of HPP and SVCOOK on protein functionality.

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CRediT authorship contribution statement

Rasmi Janardhanan: Investigation, Data curation, Writing – original draft. **Paloma Virseda:** Writing – review & editing. **Nelson Huerta-Leidenz:** Conceptualization, Supervision, Writing – review & editing. **Maria Jose Beriain:** Conceptualization, Methodology, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare no conflict of interest.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.meatsci.2022.108772.

References

Angsupanich, K., Edde, M., & Ledward, D. A. (1999). Effects of high pressure on the myofibrillar proteins of cod and Turkey muscle. *Journal of Agricultural and Food Chemistry, 47*(1), 92–99. https://doi.org/10.1021/jf980587p

Angsupanich, K., & Ledward, D. A. (1998). High pressure treatment effects on cod (*Gadus morhua*) muscle. *Food Chemistry, 63*(1), 39–50. https://doi.org/10.1016/S0308-8146(97)00234-3

Aymerich, T., Picouet, P. A., & Monfort, J. M. (2008). Decontamination technologies for meat products. *Meat Science, 78*(1–2), 114–129. https://doi.org/10.1016/j.meatsci.2007.07.007

Bajovic, B., Bolumar, T., & Heinz, V. (2012). Quality considerations with high pressure processing of fresh and value added meat products. *Meat Science, 92*(3), 280–289. https://doi.org/10.1016/j.meatsci.2012.04.024

Baldwin, D. E. (2012). Sous vide cooking: A review. *International Journal of Gastronomy and Food Science, 1*(1), 15–30. https://doi.org/10.1016/j.ijgfs.2011.11.002

Baldwin, R. E., Korschgen, B. M., Russell, M. S., & Mabesa, L. (1976). Proximate analysis, free amino acid, vitamin and mineral content of microwave cooked meat. *Journal of Food Science, 41*(4), 762–765. https://doi.org/10.1111/j.1365-2621.1976.tb00719_41_4.x

Balny, C., & Masson, P. (1993). Effects of high pressure on proteins. *Food Reviews International, 9*(4), 611–628. https://doi.org/10.1080/87559129309540980

Bird, P., Fisher, K., Boyle, M., Huffman, T., Juenger, M., Benzinger, M. J., Jr., … Collaborators.. (2013). Evaluation of VIDAS® UP *Salmonella* (SPT) assay for the detection of *Salmonella* in a variety of foods and environmental samples: Collaborative study. *Journal of AOAC International, 96*(4), 808–821. https://doi.org/10.5740/jaoacint.CS2013_01

Botinestean, C., Keenan, D. F., Kerry, J. P., & Hamill, R. M. (2016). The effect of thermal treatments including sous-vide, blast freezing and their combinations on beef tenderness of *M. semitendinosus* steaks targeted at elderly consumers. *LWT - Food Science and Technology, 74*, 154–159. https://doi.org/10.1016/j.lwt.2016.07.026

Buckow, R., Sikes, A., & Tume, R. (2013). Effect of high pressure on physicochemical properties of meat. *Critical Reviews in Food Science and Nutrition, 53*(7), 770–786. https://doi.org/10.1080/10408398.2011.560296

Campus, M. (2010). High pressure processing of meat, meat products and seafood. *Food Engineering Reviews, 2*(4), 256–273. https://doi.org/10.1007/s12393-010-9028-y

Chacha, J. S., Zhang, L., Ofoedu, C. E., Suleiman, R. A., Dotto, J. M., Roobab, U., … Guiné, R. P. F. (2021). Revisiting non-thermal food processing and preservation methods - action mechanisms, pros and cons: A technological update (2016–2021). *Foods, 10*(6), 1430. https://doi.org/10.3390/foods10061430

Chan, J. T. Y., Omana, D. A., & Betti, M. (2011). Application of high pressure processing to improve the functional properties of pale, soft, and exudative (PSE) - like Turkey meat. *Innovative Food Science and Emerging Technologies, 12*(3), 216–225. https://doi.org/10.1016/j.ifset.2011.03.004

Chang, H., Wang, Q., Xu, X., Li, C., Huang, M., Zhou, G., & Dai, Y. (2011). Effect of heat-induced changes of connective tissue and collagen on meat texture properties of beef *semitendinosus* muscle. *International Journal of Food Properties, 14*(2), 381–396. https://doi.org/10.1080/10942910903207728

Cheah, P. B., & Ledward, D. A. (1996). High pressure effects on lipid oxidation in minced pork. *Meat Science, 43*, 123–134. https://agris.fao.org/agris-search/search.do?recordID=US201302878414.

Chen, X., Tume, R. K., Xiong, Y., Xu, X., Zhou, G., Chen, C., & Nishiumi, T. (2018). Structural modification of myofibrillar proteins by high-pressure processing for functionally improved, value-added, and healthy muscle gelled foods. *Critical Reviews in Food Science and Nutrition, 58*(17), 2981–3003. https://doi.org/10.1080/10408398.2017.1347557

Christensen, L., Ertbjerg, P., Aaslyng, M. D., & Christensen, M. (2011). Effect of prolonged heat treatment from 48 °C to 63 °C on toughness, cooking loss and color of pork. *Meat Science, 88*(2), 280–285. https://doi.org/10.1016/j.meatsci.2010.12.035

Dangelico, R. M., & Vocalelli, D. (2017). "green marketing": An analysis of definitions, strategy steps, and tools through a systematic review of the literature. *Journal of Cleaner Production, 165*, 1263–1279. https://doi.org/10.1016/j.jclepro.2017.07.184

Duranton, F., Simonin, H., Chéret, R., Guillou, S., & de Lamballerie, M. (2012). Effect of high pressure and salt on pork meat quality and microstructure. *Journal of Food Science, 77*(8), 188–194. https://doi.org/10.1111/j.1750-3841.2012.02816.x

Fernández, P. P., Sanz, P. D., Molina-García, A. D., Otero, L., Guignon, B., & Vaudagna, S. R. (2007). Conventional freezing plus high pressure–low temperature treatment: Physical properties, microbial quality and storage stability of beef meat. *Meat Science, 77*(4), 616–625. https://doi.org/10.1016/j.meatsci.2007.05.014

Fernández-Martín, F., Fernández, P., Carballo, J., & Jiménez Colmenero, F. (1997). Pressure/heat combinations on pork meat batters: Protein thermal behavior and product rheological properties. *Journal of Agricultural and Food Chemistry, 45*(11), 4440–4445. https://doi.org/10.1021/jf9702297

Gao, H., Zeng, J., Ma, H., Wang, Z., & Pan, R. (2015). Improving tenderness of goose breast by ultra-high pressure. *International Journal of Food Properties, 18*(8), 1693–1701. https://doi.org/10.1080/10942912.2014.933438

García-Segovia, P., Andrés-Bello, A., & Martínez-Monzó, J. (2007). Effect of cooking method on mechanical properties, color and structure of beef muscle (M. pectoralis). *Journal of Food Engineering, 80*(3), 813–821. https://doi.org/10.1016/j.jfoodeng.2006.07.010

Garriga, M., Grèbol, N., Aymerich, M. T., Monfort, J. M., & Hugas, M. (2004). Microbial inactivation after high-pressure processing at 600 MPa in commercial meat products over its shelf life. *Innovative Food Science and Emerging Technologies, 5*(4), 451–457. https://doi.org/10.1016/j.ifset.2004.07.001

Gómez, I., Beriain, M. J., Sarriés, M. V., Insausti, K., & Mendizabal, J. A. (2014). Low-fat beef patties with augmented omega-3 fatty acid and CLA levels and influence of grape seed extract. *Journal of Food Science, 79*(11), S2368–S2376. https://doi.org/10.1111/1750-3841.12682

Gómez, I., Janardhanan, R., Ibañez, F. C., & Beriain, M. J. (2020). The effects of processing and preservation technologies on meat quality: Sensory and nutritional aspects. *Foods, 9*(10), 1416. https://doi.org/10.3390/foods9101416

Gómez, I., Sarriés, M. V., Ibañez, F. C., & Beriain, M. J. (2018). Quality characteristics of a low-fat beef patty enriched by polyunsaturated fatty acids and vitamin D3. *Journal of Food Science, 83*(2), 454–463. https://doi.org/10.1111/1750-3841.14043

Goutefongea, R., Rampon, V., Nicolas, N., & Dumont, J. P. (1995). Meat color changes under high pressure treatment [poster presentation]. In *International Congress of Meat Science and Technology, San Antonio, United States*. August 19–26 https://hal.inrae.fr/hal-02852585.

International Organization for Standardization. (1973). Meat and meat products - determination of total fat content (ISO standard No. 1443:1973). https://www.iso.org/obp/ui/#iso:std:iso:1443:ed-1:v1:en.

International Organization for Standardization. (1978). Meat and meat products - Determination of nitrogen content (Reference method) (ISO Standard No. 937:1978). https://www.iso.org/obp/ui/#iso:std:iso:937:ed-1:v1:en.

International Organization for Standardization. (1997). Meat and meat products - Determination of moisture content (Reference method) (ISO Standard No. 1442:1997). https://www.iso.org/obp/ui/#iso:std:iso:1442:ed-2:v1:en.

International Organization for Standardization. (1998). Meat and meat products - determination of total ash (ISO standard No. 936:1998). https://www.iso.org/obp/ui/#iso:std:iso:936:ed-2:v1:en.

International Organization for Standardization. (1999). Meat and meat products - measurement of pH - reference method (ISO standard No. 2917:1999). https://www.iso.org/obp/ui/#iso:std:iso:2917:ed-2:v1:en.

International Organization for Standardization. (2001). Microbiology of food and animal feeding stuffs - horizontal method for the enumeration of beta-glucuronidase-positive *Escherichia coli* — Part 2: Colony-count technique at 44 degrees C using 5-bromo-4-chloro-3-indolyl beta-D-glucuronide (ISO standard No. 16649-2:2001). https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/02/98/29824.html.

International Organization for Standardization. (2017). Microbiology of the food chain - horizontal method for the detection and enumeration of *Listeria monocytogenes* and of Listeria spp. - part 1: Detection method (ISO standard No. 11290-1:2017). https://www.iso.org/cms/render/live/en/sites/isoorg/contents/data/standard/06/03/60313.html.

Jung, S., Ghoul, M., & de Lamballerie-Anton, M. (2000). Changes in lysosomal enzyme activities and shear values of high pressure treated meat during ageing. *Meat Science, 56*(3), 239–246. https://doi.org/10.1016/S0309-1740(00)00048-6

Jung, S., Ghoul, M., & de Lamballerie-Anton, M. (2003). Influence of high pressure on the color and microbial quality of beef meat. *LWT - Food Science and Technology, 36*(6), 625–631. https://doi.org/10.1016/S0023-6438(03)00082-3

Kaur, L., Astruc, T., Vénien, A., Loison, O., Cui, J., Irastorza, M., & Boland, M. (2016). High pressure processing of meat: Effects on ultrastructure and protein digestibility. *Food & Function, 7*(5), 2389–2397. https://doi.org/10.1039/C5FO01496D

Lago, N. C., Marcon, A., Ribeiro, J. L. D., de Medeiros, J. F., Brião, V. B., & Antoni, V. L. (2020). Determinant attributes and the compensatory judgement rules applied by young consumers to purchase environmentally sustainable food products. *Sustainable Production and Consumption, 23*, 256–273. https://doi.org/10.1016/j.spc.2020.06.003

Lee, S. H., Choi, W., & Jun, S. (2016). Conventional and emerging combination technologies for food processing. *Food Engineering Reviews, 8*(4), 414–434. https://doi.org/10.1007/s12393-016-9145-3

Leistner, L. (2000). Basic aspects of food preservation by hurdle technology. *International Journal of Food Microbiology, 55*(1), 181–186. https://doi.org/10.1016/S0168-1605(00)00161-6

Ma, H. J., & Ledward, D. A. (2004). High pressure/thermal treatment effects on the texture of beef muscle. *Meat Science, 68*(3), 347–355. https://doi.org/10.1016/j.meatsci.2004.04.001

Marcos, B., Kerry, J. P., & Mullen, A. M. (2010). High pressure induced changes on sarcoplasmic protein fraction and quality indicators. *Meat Science, 85*(1), 115–120. https://doi.org/10.1016/j.meatsci.2009.12.014

McArdle, R., Marcos, B., Kerry, J. P., & Mullen, A. (2010). Monitoring the effects of high pressure processing and temperature on selected beef quality attributes. *Meat Science, 86*(3), 629–634. https://doi.org/10.1016/j.meatsci.2010.05.001

Montgomery, D. C. (2009). *Introduction to statistical quality control* (6th ed.). John Wiley & Sons.

Mor-Mur, M., & Yuste, J. (2003). High pressure processing applied to cooked sausage manufacture: Physical properties and sensory analysis. *Meat Science, 65*(3), 1187–1191.

Murphy, E. W., Criner, P. E., & Gray, B. C. (1975). Comparisons of methods for calculating retention of nutrients in cooked foods. *Journal of Agricultural and Food Chemistry, 23*(6), 1153–1157. https://doi.org/10.1021/jf60202a021

Naqvi, Z. B., Campbell, M. A., Latif, S., Thomson, P. C., McGill, D. M., Warner, R. D., & Friend, M. A. (2021). Improving tenderness and quality of M. biceps femoris from older cows through concentrate feeding, zingibain protease and sous vide cooking. *Meat Science, 180*, Article 108563. https://doi.org/10.1016/j.meatsci.2021.108563

Park, C. H., Lee, B., Oh, E., Kim, Y. S., & Choi, Y. M. (2020). Combined effects of sous-vide cooking conditions on meat and sensory quality characteristics of chicken breast meat. *Poultry Science, 99*(6), 3286–3291. https://doi.org/10.1016/j.psj.2020.03.004

Przybylski, W., Jaworska, D., Kajak-Siemaszko, K., Sałek, P., & Pakuła, K. (2021). Effect of heat treatment by the sous-vide method on the quality of poultry meat. *Foods, 10*(7), 1610. https://doi.org/10.3390/foods10071610

Publications Office of the European Union. (2005). *Microbiological criteria for foodstuffs (council regulation (EC) 2073/2005)*. European Union, EUR-Lex. http://data.europa.eu/eli/reg/2005/2073/2020-03-08.

Publications Office of the European Union. (2009). *Protection of animals at the time of killing (council regulation (EC) no 1099/2009)*. European Union, EUR-Lex. http://data.europa.eu/eli/reg/2009/1099/oj/eng.

Publications Office of the European Union. (2010). *Protection of animals used for scientific purposes (directive 2010/63/EU)*. European Union, EUR-Lex. http://data.europa.eu/eli/dir/2010/63/oj/eng.

Rastogi, N. K., Raghavarao, K. S. M. S., & Niranjan, K. (2007). Opportunities and challenges in high pressure processing of foods. *Critical Reviews in Food Science and Nutrition, 47*, 69–112. https://doi.org/10.1080/10408390600626420

Ricci, P. T. (2021, August 12). *Mouth Behavior and Ground Beef. Meatingplace*.

Roldán, M., Antequera, T., Martín, A., Mayoral, A. I., & Ruiz, J. (2013). Effect of different temperature-time combinations on physicochemical, microbiological, textural and structural features of sous-vide cooked lamb loins. *Meat Science, 93*(3), 572–578. https://doi.org/10.1016/j.meatsci.2012.11.014

Sikes, A. L., & Warner, R. (2016). Application of high hydrostatic pressure for meat tenderization. In K. Knoerzer, P. Juliano, & G. Smithers (Eds.), *Innovative food processing technologies* (pp. 259–290). Elsevier. https://doi.org/10.1016/B978-0-08-100294-0.00010-9.

Sun, S., Rasmussen, F. D., Cavender, G. A., & Sullivan, G. A. (2019). Texture, color and sensory evaluation of sous-vide cooked beef steaks processed using high pressure processing as method of microbial control. *LWT - Food Science and Technology, 103*, 169–177. https://doi.org/10.1016/j.lwt.2018.12.072

Sun, S., Sullivan, G., Stratton, J., Bower, C., & Cavender, G. (2017). Effect of HPP treatment on the safety and quality of beef steak intended for sous vide cooking. *LWT - Food Science and Technology, 86*, 185–192. https://doi.org/10.1016/j.lwt.2017.07.037

Tewari, G., Jayas, D. S., & Holley, R. A. (1999). High pressure procteessing of foods: An overview. *Sciences des Aliments, 19*(6), 619–661.

Tkacz, K., Modzelewska-Kapituła, M., Petracci, M., & Zduńczyk, W. (2021). Improving the quality of sous-vide beef from Holstein-Friesian bulls by different marinades. *Meat Science, 182*, Article 108639. https://doi.org/10.1016/j.meatsci.2021.108639

U.S. Departmet of Agriculture. (2019, July 17). What does 'lean' and 'extra lean' beef mean on a nutrition label? AskUSDA. https://ask.usda.gov/s/article/What-does-lean-and-extra-lean-beef-mean-on-a-nutrition-label.

Xue, S., Wang, C., Kim, Y. H. B., Bian, G., Han, M., Xu, X., & Zhou, G. (2020). Application of high-pressure treatment improves the in vitro protein digestibility of gel-based meat product. *Food Chemistry, 306*, Article 125602. https://doi.org/10.1016/j.foodchem.2019.125602