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Research article

Process optimization and evaluation of the effects of different time-temperature sous vide cooking on physicochemical, textural, and sensory characteristics of whiteleg shrimp (*Litopenaeus vannamei*)

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ABSTRACT

The objective of the current study was to optimize the cook-chill conditions of high-value whiteleg shrimp (*Litopenaeus vannamei*) processed using the sous vide (SV) technique and to assess the effects of various time-temperature combinations on the physicochemical, textural, and sensory qualities. For optimization, a Response Surface Methodology (RSM) approach utilizing a Central Composite Design (CCD) was adopted. Optimum SV cooking conditions to acquire minimum texture (hardness) of 7235 g was 13.48 min and 81.87 °C, expressible moisture of 18.48% was 14.5 min and 84.5 °C, and cook loss of 5.58% was 5 min and 75 °C. Texture (hardness) and expressible moisture decreased while cooking loss increased with increasing time-temperature treatment. Redness and yellowness values increased ($p < 0.05$) with increasing SV cooking time-temperature, but lightness values were nearly consistent in all treatments. With increasing time and temperature, TBARs and total carotenoid content increased ($p < 0.05$). However, the TBARs values were within accepted limits and ranged from 0.05 to 0.08 mg malonaldehyde/kg. Sensory evaluation indicated that all SV cooked samples were well accepted, with overall scores ≥7. These results suggest that the SV cooking temperature and time had a substantial impact on the textural, physicochemical, and sensory characteristics of shrimp. In addition, increasing time-temperature increased cooking and moisture loss, but decreased hardness and higher sensory scores made the product more acceptable to consumers.

1. Introduction

Shrimps are valuable seafood that is consumed globally and are valued for their distinctive texture and flavour, as well as their high nutritious content. In India, shrimps are one of the major exported fishery products, accounting for 31% and 64.1% in terms of quantity and value [1]. Whiteleg shrimp (*Litopenaeus vannamei*) has received a lot of attention recently in the American and European markets owing to its flavour and quality. Simultaneously, it gained popularity among Indian shrimp farmers due to its rapid growth and strong

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Table 1
Levels of independent variables for experimental design.

Symbol	Independent variables	Levels				
		-α (Lowest)	−1 (Low)	0 (Mid)	+1 (High)	+α (Highest)
A	Time (min)	2.93	5	10	15	17.07
B	Temperature (°C)	72.93	75	80	85	87.07

disease resistance [2]. This led to an expansion of the culture areas and exceptionally high levels of production in recent years. However, it is crucial to emphasize that India's consumption of whiteleg shrimp is either extremely low or non-existent, and the majority of the shrimp produced is exported. Since the shrimp is shipped in large quantities, maintaining its quality has become a priority. Moreover, compared to finned fish, shrimp has a much shorter shelf life and is more susceptible to post-harvest quality loss owing to their smaller size, chemical composition, and high content of non-protein nitrogenous compounds [3,4]. Therefore, it is crucial that the shrimp processing industry establish a storage method to maintain the freshness and high quality of shrimp. Although there are numerous preservation options available, freezing and cooking are the most commonly employed techniques to preserve shrimp to maintain quality and safety issues. Although freezing efficiently maintains shrimp quality, the texture of shrimp may be affected due to damage to muscle tissue during the freeze-thaw cycle [5]. Similarly, cooking can negatively affect the organoleptic characteristics of shrimp, including texture, mouthfeel, flavour, and appearance [6]. Therefore, there is still a continuous search for an alternative method that provides fresh seafood that is convenient, safe, and requires minimal processing.

A surge in ready-to-eat and convenience foods, which comprise both simplicity of preparation and product shelf life, is the result of new technologies that reflect shifting consumer behaviours [7]. Modern food technology research aims to enhance conventional techniques and develop industry-adapted food processing methods like sous vide (SV) cooking [8]. SV processing involves placing raw or partially cooked foods in a vacuum-sealed bag, followed by pasteurization, immediate cooling, and maintaining refrigeration at 3 °C until serving [9,10]. Contrary to conventional food processing, SV cooking has numerous advantages, such as a hermetic seal that prevents contamination and moisture loss during and after treatments. Additionally, the original flavour, texture, and nutritional value are maintained by the mild cooking temperature. Moreover, vacuum packaging extends the shelf life of products by inhibiting oxidation and aerobic spoilage microorganisms [11,12]. SV cooked fishery products, particularly shrimps, have received very little attention compared to other meat products. For seafood products, SV cooking is often performed between 50 and 75 °C for a few minutes to hours to stop or inhibit the growth of pathogens [13]. For instance, lobster which was SV cooked at 50 °C for 12 min, had improved taste and texture compared to normal overcooked lobster [14]. In another study, salmon slices were SV cooked at 90 °C for 15 min, which significantly increased the shelf life of fish kept at 2 °C (>45 days) and effectively inhibited the growth of aerobic and anaerobic spore-forming bacteria [15]. Singh et al. [16] optimized SV cooking conditions of seerfish steaks by using RSM with time (5–15 min), temperature (70–80 °C), and salt concentration (3–10%) as independent variables and Thiobarbituric acid reactive substances (TBARS) value as response variable; results showed that throughout the 65 days of refrigerated storage, all quality parameters were found to be within the accepted level.

The RSM approach is an experimental design strategy that makes it easier to design, develop, and optimize technologies when one or more responses may be influenced by a number of different factors [17]. The aim of the response surface approach is to make statistical predictions by using a set of mathematical and statistical techniques based on the fit of a polynomial equation to experimental data [18]. The choice of independent variables that would have a significant impact on the response of the system studied and the selection of experimental design are crucial to the effectiveness of RSM optimization [18]. In this study, RSM was used to optimize the effects of two independent variables viz SV cooking time and temperature on the texture, expressible moisture, and cook loss of SV shrimp product. The temperature and cooking time used during SV cooking have a significant impact on the quality of the final product [13]. So, the two independent variables chosen were time (5–15 min) and temperature (75–85 °C) (Table 1). For cook-chill products, the UK's Advisory Committee on the Microbiological Safety of Food recommends a heat treatment of 90 °C for 10 min or similar lethality and stringent chill conditions to reduce the risk of *Clostridium botulinum* [15]. Also, *Listeria monocytogenes* and other non-spore-forming pathogens must be destroyed with a heat treatment of 70 °C for 2 min or a comparable heating procedure [19]. Therefore, the levels of time and temperature were selected in the range of 5–15 min and 75–85 °C for process optimization, as illustrated in Table 1.

Among the numerous experimental designs in RSM, the Central Composite Design (CCD) is the most widely utilized response surface designed experiment [20]. In CCD, a group of axial points, also known as star points, are added to a factorial or fractional factorial design with center points to allow for curvature estimation [20]. This design allows for the rapid estimation of first- and second-order terms. Hence, in this study, The CCD was utilized to conduct the experiments.

The purpose of this research was to develop SV-processed shrimp product, optimize their production processes, and assess how different time-temperature combinations affected the physicochemical, textural, and sensory qualities.

2. Materials and methods

2.1. Raw materials

Freshly harvested whiteleg shrimp (*Litopenaeus vannamei*) with a size range of 15–18 cm length and an average weight range of

Table 2
Central composite design (uncoded) for texture, expressible moisture, and cook loss.

Experimental Runs	Type	Independent variables		Dependent variables		
		Time (min)	Temperature (°C)	Texture (hardness, g)	Expressible moisture (w/w %)	Cook loss (w/w%)
T1	Factorial	5	75	9200.28	30.18	5.13
T2	Factorial	15	75	9046.64	31	5.49
T3	Factorial	5	85	8677.4	31.54	7.67
T4	Factorial	15	85	8007.9	19.76	9.25
T5	Axial	2.93	80	10074.2	29.56	7.44
T6	Axial	17.07	80	7654.74	20.88	8.18
T7	Axial	10	72.93	9988.35	27.09	5.58
T8	Axial	10	87.07	8309.82	20.48	10.36
T9	Center	10	80	7778	21.42	8.61
T10	Center	10	80	7719	22.55	9.17
T11	Center	10	80	8092	24.2	9.22

35–45 g (25–30 count/kg) were obtained from shrimp farms in Vijayawada, Andhra Pradesh, India, and transported to the laboratory under iced conditions by keeping them in insulated boxes filled with crushed ice in a 1:1 ratio for further analysis.

2.2. Experimental design for optimization of SV cooking conditions

A series of experiments were designed using the Central Composite Design (CCD) of RSM to investigate the effect of SV cooking time (A) and temperature (B) on the texture (Y_1), expressible moisture (Y_2), and cook loss (Y_3) of whiteleg shrimp. Based on the preliminary experiments, the factors and their levels were chosen. Table 1 depicts the factor levels along with their coded values. The complete design was executed randomly and comprised 11 combinations with three replicates at a central point (Table 2). To analyze experimental data and fit a second-order polynomial model, multiple regression equations were used. Software (Design Expert version 8, StatEase) was used to create the model and conduct the statistical analysis. The model's validity was determined by assessing the coefficient of determination (R^2), significance of the regression coefficients, *p*-value, lack of fit, and the F-test result obtained from the analysis of variance (ANOVA).

2.3. Preparation of sous vide shrimp product

Shrimps were washed before being beheaded, peeled, deveined, and washed again in chilled potable water (1–2 °C). The shrimps were then vacuum packed in a sterile food-grade plastic (low-density polypropylene) pouch (dimension: 25 × 20 cm) using a vacuum packaging machine (Spinco, Jumbo Plus, Mylapore, Chennai, India). The pouch's seal area was wiped with tissue paper to avoid contamination. According to the experimental design, the bagged shrimps were cooked in a water bath (Racy Biotech, Delhi, India) under various time-temperature conditions. After cooking, the samples were quickly cooled in cold water and kept at a refrigerated temperature (3–4 °C) for subsequent analysis.

2.4. Proximate composition

The SV cooked shrimp samples' proximate composition was determined in accordance with AOAC [21]. The moisture content of fish muscle was measured using a moisture analyzer (Sartorius, Germany). The ash content was determined using a muffle furnace (EXPO HI-TECH, i-therm AL-7941) set to 550 °C for approximately 6–7 h. The Micro-Kjeldahl instrument was used to determine the crude protein content. Fat was extracted using a soxhlet apparatus, and petroleum ether was used as a solvent.

2.5. Analysis of quality indices

2.5.1. Texture profile analysis (TPA)

The textural characteristics of SV cooked shrimps were evaluated using a texture analyzer (TA-XT PLUS Stable Micro Systems, Surrey, England, UK). A compression plate with a 75 mm diameter and a 50 kg sensor was employed as the load cell. Each treatment had three SV cooked shrimp that were evaluated. The distance was 8 mm/s, the trigger force was 5 g, the pre-test and test speeds were 1 mm/s, while the post-test speed was 5 mm/s. The TPA parameters were calculated using the force by time data from each test. The final value of each parameter was calculated as the average of the three close values.

2.5.2. Cooking loss

The cooking loss was calculated according to the method of Chaurasiya et al. [22] with minor modifications. Briefly, shrimps were placed in a low-density polypropylene bag and cooked for the specified time and temperature combination, then cooled in iced water for 1 min before draining at 4 °C for 5 min. Weighing the shrimp before and after pre-cooking was used to determine cooking loss. Weighing the pre-cooked shrimp. The following equation (equation (1)) was used to compute the cooking loss.

$$\text{Cooking loss } (\%) = \frac{(A - B)}{A} \times 100 \tag{1}$$

Where A represents the weight before cooking and B represents the weight after cooking.

2.5.3. Expressible moisture (EM)

The methodology of Remya et al. [23] with minor modifications was used to calculate the EM content. The center of an SV cooked sample was cut into a 10 mm test piece, which was carefully weighed (W_1). The test piece was placed between two Whatman filter papers with two boards at the bottom and top of the filter paper. For 2 min, a 1 kg standard weight was placed on the board. After pressing, the test piece was precisely weighed (W_2). The following equation (equation (2)) was used to compute expressible moisture.

$$\text{Expressible moisture } (\%) = \frac{(W_1 - W_2)}{W_1} \times 100 \tag{2}$$

2.5.4. Instrumental color analysis

L^* (lightness), a^* (redness/greenness), and b^* (yellowness/blueness) were used to determine the color of SV cooked shrimps. A spectrocolorimeter (Colourflex EZ, Hunter Associates Laboratory, Inc., Reston, VA, USA) with a D 65/10° illuminant was used to measure a piece of cooked shrimp meat. The study used the CIELAB color scale and color analysis was done according to the method of Young and Whittle [24]. The ventral body (second segment) of shrimp muscle was used for color measurements.

2.5.5. Total carotenoid content (TCC)

TCC was determined according to the method of Dayakar et al. [25]. The following equation (equation (3)) was used to estimate the carotenoid content (C) of the samples:

$$C\ (\mu g / g) = \frac{(A468 \times \textit{volume of extract} \times \textit{Dilution factor})}{(0.2 \times \textit{Weight of sample used in gram})} \tag{3}$$

Where A468 is the absorbance at 468 nm; 0.2 is the absorbance value of the 1 μg/ml astaxanthin standard.

2.5.6. Thiobarbituric acid reactive substances (TBARs)

The TBARs assay was performed as described by Buege and Aust [26] and the values were expressed as mg malonaldehyde/kg of shrimp.

2.5.7. Sensory evaluation

Sensory evaluation of SV cooked shrimp samples were carried out by following the method of Meilgaard et al. [27]. In brief, a panel of 10 trained panelists were presented with SV cooked shrimp samples. Using a 9-point hedonic scale, the panelists were asked to evaluate samples as acceptable or unacceptable based on appearance, texture, juiciness, taste, flavour, aroma, colour, and overall impression. Scores of 6 and higher were regarded as acceptable and vice versa (Table S1).

2.6. Statistical analysis

All the data were analyzed using the SPSS version 22.0 for Windows (SPSS, Chicago, IL). The significance of the main effects was determined using one-way ANOVA. Duncan's Multiple Range Test was used to determine significant differences ($p < 0.05$) between the means (Post hoc analysis). Data from three independent replications ($n = 3$) are presented as mean ± standard deviation. Means in the same column with different superscripts in the lowercase letter on tables are statistically significantly different ($p < 0.05$).

2.7. Ethical statement

The experiments were conducted according to the established ethical guidelines, and informed consent was obtained from the sensory analysis participants.

3. Results and discussion

3.1. Optimization of process conditions and validation of the model

The processing conditions were optimized using a combination of RSM and CCD, accounting for the most important process factors, namely time (A, min) and temperature (B, °C), in order to achieve the minimum texture (Y_1), expressible moisture (Y_2), and cook loss (Y_3). Table 2 shows the responses of Y_1, Y_2, and Y_3. Table 3 summarizes the ANOVA for the response surface quadratic model for texture, expressible moisture, and cook loss. Fig. 1 illustrates the contour plots and 3D response surface plots of the time and temperature combination effect on the texture, expressible moisture, and cook loss. Fig. 1(A and D) shows that as time and temperature increases, texture (hardness) decreases and the minimal optimum hardness is near the high level (+1) of the experimental design. Similarly, Fig. 1(B and E) indicates that expressible moisture decreases as time and temperature increases, and that the minimal

Table 3
ANOVA for response surface quadratic models.

Source	Texture		Expressible moisture		Cook loss	
	F value	*p*-value	F value	*p*-value	F value	*p*-value
Model	5.90	*0.0368*	6.37	*0.0316*	12.14	*0.0080*
A	10.15	*0.0244*	11.83	*0.0185*	2.27	0.1925
B	8.55	*0.0329*	8.42	*0.0337*	45.50	*0.0011*
AB	0.32	0.5943	6.79	*0.0479*	0.59	0.4762
A^2	4.72	0.0820	4.18	0.0963	7.90	*0.0375*
B^2	8.62	*0.0324*	1.84	0.2325	8.10	*0.0360*
Lack of Fit	7.65	0.1178	3.78	0.2165	7.58	0.1188
	$R^2 = 0.8551$		$R^2 = 0.8643$		$R^2 = 0.9239$	
	Adj $R^2 = 0.7103$		Adj $R^2 = 0.7286$		Adj $R^2 = 0.8478$	

Italic values indicate significance of p value ($p < 0.05$).

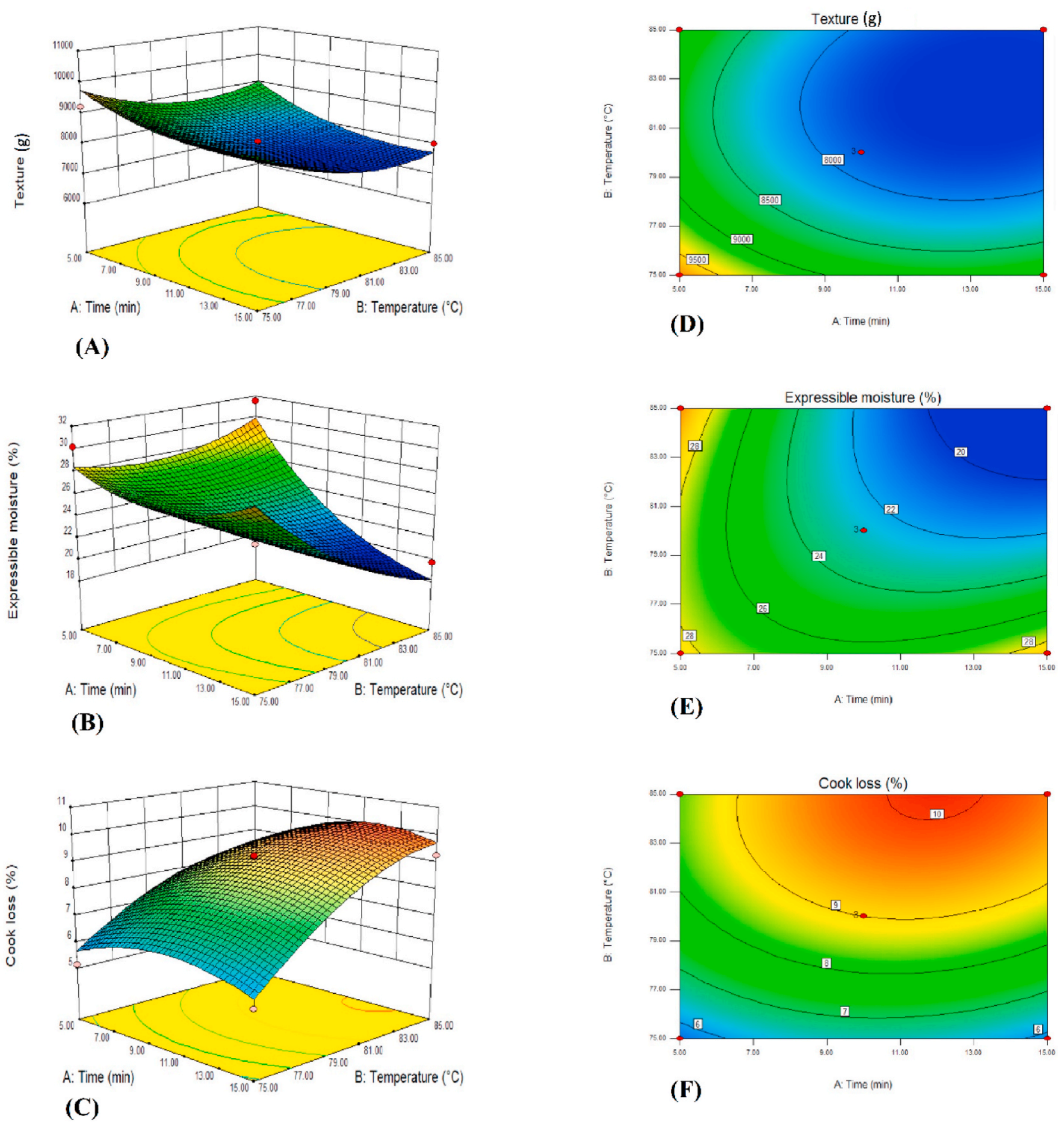

Fig. 1. Response surface plots (A, B, C) and contour plots (D, E, F) for the effect of SV cooking time and temperature on texture (hardness) (A, D), expressible moisture (B, E), and cook loss (C, F).

Table 4
Predicted and experimental values of texture (hardness), expressible moisture, and cook loss under the optimum extraction conditions.

Response variables	Optimum extraction conditions		Minimum values	
	Time (min)	Temp (°C)	Predicted	Experimental[a]
Texture (hardness, g)	13.48	81.87	7590	7235 ± 0.20
Expressible moisture (w/w %)	14.5	84.5	18.39	18.48 ± 0.16
Cook loss (w/w %)	5	75	5.67	5.58 ± 0.12

[a] Means ± standard deviation (n = 3).

Table 5
Proximate composition of sous-vide cooked shrimp product at different time-temperature treatments on a wet weight basis.

Treatments	Moisture (g/100 g)	Crude protein (g/100 g)	Fat (g/100 g)	Ash (g/100 g)
T1	72.77 ± 0.11[a]	25.37 ± 0.24[e]	0.59 ± 0.30[f]	1.46 ± 0.03[g]
T2	70.86 ± 0.22[b]	26.77 ± 0.13[d]	0.82 ± 0.41[d,e]	1.64 ± 0.04[e]
T3	69.70 ± 0.22[c,d]	27.66 ± 0.33[c]	0.88 ± 0.44[a,b,c]	1.79 ± 0.02[c,d]
T4	68.51 ± 0.12[f]	28.79 ± 0.14[a]	0.94 ± 0.47[a]	1.87 ± 0.02[a]
T5	69.90 ± 0.26[c]	27.71 ± 0.46[c]	0.85 ± 0.43[c,d,e]	1.76 ± 0.01[d]
T6	68.78 ± 0.14[e,f]	28.55 ± 0.36[a]	0.92 ± 0.05[a,b]	1.86 ± 0.03[a,b]
T7	70.97 ± 0.27[b]	26.71 ± 0.26[d]	0.80 ± 0.03[e]	1.58 ± 0.05[f]
T8	68.97 ± 0.16[e]	28.36 ± 0.28[a,b]	0.87 ± 0.43[b,c,d]	1.84 ± 0.05[a,b,c]
T9	69.65 ± 0.22[c,d]	27.71 ± 0.33[c]	0.88 ± 0.44[b,c]	1.80 ± 0.01[b,c,d]
T10	69.46 ± 0.14[d]	27.84 ± 0.43[b,c]	0.90 ± 0.04[a,b,c]	1.85 ± 0.03[a,b,c]
T11	69.58 ± 0.29[c,d]	27.77 ± 0.47[c]	0.89 ± 0.02[a,b,c]	1.83 ± 0.04[a,b,c]

Data are expressed as the mean ± SD of three independent replications (n = 3), Mean values with different letters in the same column are significantly different (p < 0.05).

optimum expressible moisture is close to the high level (+1) of the experimental design. In contrast, Fig. 1(C and F) demonstrates that cook loss increases with time and temperature, and the minimal optimum cook loss is near to the low level (−1) of the experimental design.

For determining the minimal texture (equation (4)), expressible moisture (equation (5)), and cook loss (equation (6)), the experimental data were fitted into a quadratic polynomial equation as follows:

$$\text{Texture } (Y_1) = +88.67 - 2.84A - 2.6\,B - 0.72\,AB + 2.3\,A^2 + 3.11\,B^2 \quad (4)$$

$$\text{Expressible moisture } (Y_2) = +4.77 - 0.29\,A - 0.25\,B - 0.31\,AB + 0.21\,A^2 + 0.14\,B^2 \quad (5)$$

$$\text{Cook loss } (Y_3) = +3.00 + 0.0674\,A + 0.3B + 0.049\,AB - 0.15\,A^2 - 0.15\,B^2 \quad (6)$$

The determination coefficient R^2, which explains the total variations of a model, indicates that the design is valid [28]. Table 3 shows that the R^2 values for texture, expressible moisture, and cook loss were 0.8551, 0.8643, and 0.9239, respectively, indicating that the model can account for 85.51%, 86.43% and 92.39% of the variation in the data. These values indicate that the selected model is suitable for illustrating the relationships between the chosen variables. The model's significance was demonstrated by the low p-values ($p < 0.05$) and high F values of 5.90, 6.37, and 12.14 in the ANOVA for texture, expressible moisture, and cook loss models. Additionally, the models' lack of fit for texture, expressible moisture, and cook loss were non-significant ($p > 0.05$), showing a good fit of the models [29].

Table 4 shows the predicted and experimental values of texture (hardness), expressible moisture, and cook loss under the optimum extraction conditions. The optimum SV cooking conditions were 13.48 min at 81.87 °C, 14.5 min at 84.5 °C, and 5 min at 75 °C, respectively, for minimum texture (hardness) of 7590 g, expressible moisture of 18.39%, and cook loss of 5.67%. To validate the predicted outcomes, the experiment was repeated using the optimal extraction conditions for each dependent variables. From real experiments, mean values of 7235 g texture (hardness), 18.48% expressible moisture, and 5.58% cook loss were achieved, which validated the RSM models. The results of texture, expressible moisture, and cook loss show that there was no significant difference ($p >$ 0.05) between experimental and predicted values. Therefore, the models can be employed to optimize the process conditions for the development of ready-to-eat shrimp products cooked by the SV method.

3.2. *Proximate composition*

Table 5 shows the proximate composition changes of ready-to-eat SV cooked shrimp with different temperature and time treatments. The protein, moisture, fat, and ash content differed significantly ($p < 0.05$) among treatments. With increasing time and temperature, the moisture content of SV cooked shrimp meat decreased. High temperatures and time may have a negative impact on the moisture content by denaturing muscle proteins, which reduces their ability to retain water [1,30]. Conversely, treatments that involved longer cooking times and higher temperatures had higher levels of protein, fat, and ash content. The decrease in moisture

Table 6
Carotenoid content, TBARS, and instrumental colour analysis of sous vide cooked shrimp product at different time-temperature treatments.

Treatments	Carotenoid content (μg/g)	TBARS (mg MDA/kg)	Instrumental color analysis		
			Lightness (L^*)	Redness (a^*)	Yellowness (b^*)
T1	12.65 ± 0.18^{f}	0.05 ± 0.01^{d}	70.69 ± 0.18^{b}	12.55 ± 0.08^{d}	16.73 ± 0.16^{d}
T2	16.77 ± 0.12^{e}	$0.05 \pm 0.01^{c,d}$	$70.47 \pm 0.12^{c,d}$	14.69 ± 0.17^{c}	18.55 ± 0.21^{c}
T3	20.73 ± 0.23^{d}	$0.06 \pm 0.01^{c,d}$	$70.25 \pm 0.09^{d,e}$	16.49 ± 0.18^{b}	20.43 ± 0.05^{b}
T4	25.60 ± 0.18^{a}	0.08 ± 0.01^{a}	69.70 ± 0.15^{f}	18.28 ± 0.06^{a}	22.20 ± 0.04^{a}
T5	20.76 ± 0.17^{d}	$0.06 \pm 0.01^{c,d}$	71.18 ± 0.18^{a}	14.74 ± 0.15^{c}	18.72 ± 0.17^{c}
T6	25.37 ± 0.18^{a}	$0.08 \pm 0.01^{a,b}$	$70.26 \pm 0.09^{d,e}$	18.12 ± 0.21^{a}	20.36 ± 0.09^{b}
T7	16.82 ± 0.09^{e}	$0.05 \pm 0.01^{c,d}$	$70.56 \pm 0.11^{b,c}$	14.75 ± 0.11^{c}	18.63 ± 0.05^{c}
T8	25.51 ± 0.17^{a}	$0.08 \pm 0.01^{a,b,c}$	70.34 ± 0.08^{d}	18.18 ± 0.21^{a}	20.45 ± 0.08^{b}
T9	21.75 ± 0.20^{c}	$0.06 \pm 0.01^{b,c,d}$	70.10 ± 0.12^{e}	18.04 ± 0.07^{a}	22.14 ± 0.04^{a}
T10	22.76 ± 0.16^{b}	$0.06 \pm 0.01^{c,d}$	70.33 ± 0.10^{d}	18.10 ± 0.12^{a}	20.34 ± 0.13^{b}
T11	22.94 ± 0.04^{b}	$0.07 \pm 0.01^{a,b,c,d}$	$70.26 \pm 0.07^{d,e}$	18.17 ± 0.16^{a}	20.27 ± 0.08^{b}

Data are expressed as the mean ± SD of three independent replications (n = 3), Mean values with different letters in the same column are significantly different ($p < 0.05$).

content of the samples may be responsible for the increase in protein content. Similar to our result, fat and ash content were reported to be increased in SV cooked shrimp than in raw shrimp [1].

3.3. *Physicochemical properties*

3.3.1. *Expressible moisture and cooking loss*

The expressible moisture and cook loss values of SV cooked shrimp at different time-temperature treatments are given in Table 2. Among the treatment groups, samples cooked at higher temperatures for longer time (T4, T6, T8, T9, T10, and T11) showed considerably lower expressible moisture and higher cook loss than samples cooked at lower temperatures for shorter time (T1, T2, T3, T5, and T7). The lowest expressible moisture of 19.76% was shown by treatment T4 (time: 15 min and temperature: 85 °C), while the highest expressible moisture of 31.54% was shown by treatment T3 (time: 5 min and temperature: 85 °C) followed by T1 (30.18%; time: 5 min and temperature: 75 °C), indicating that time and time-temperature combinations significantly influenced the moisture content of SV cooked shrimp. The decrease in moisture content in higher time-temperature cooked SV shrimp can be attributed to thermal denaturation and shrinkage of muscle proteins, leading to a reduction in water holding capacity [31]. Our findings are consistent with those found in other studies [32–35]. Similarly, the highest cooking loss was shown by treatment T8 (10.36%; time: 10 min and temperature: 87.07 °C), followed by T4 (9.25%; time: 15 min and temperature: 85 °C), while the lowest was shown by T1 (time: 5 min and temperature: 75 °C) which had a cooking loss of 5.13%. The increased cooking loss in SV method with increasing time and temperature is in parallel with other researchers' findings [31,36,37]. Increased time and temperature during SV cooking cause a decrease in sarcoplasmic and myofibrillar protein, which increases cooking loss [31].

3.3.2. *Color*

Color is one of the most blatant and significant sensory indicators of food quality. Due to heme and carotenoid oxidation during heat treatment, seafood products are susceptible to discolouration. Additionally, the meat will develop undesirable colours when seafood products are cooked at high temperatures for an extended period of time [38]. In contrast, seafood prepared by SV cooking maintains its consistency and appeal. The instrumental color values of SV cooked shrimp under the different time-temperature conditions are presented in Table 6. The lightness values of SV cooked shrimp were high, which ranged from 69.70 ± 0.15 to 71.18 ± 0.18 and were significantly different ($p < 0.05$) among treatments. Similarly, the redness (a^*) and yellowness (b^*) values also differed significantly ($p < 0.05$) among treatments. The yellowness values were higher than the redness values among various time-temperature treatments. The highest yellowness value was observed in T4, which was cooked at 85 °C for 15 min and the lowest was observed in T1 cooked at 75 °C for 5 min. Meat cooked for extended heating durations has higher yellowness values [39]. In addition, more cooked meat has a slight dryness and a greyish-brown colour [30]. Additionally, meat cooked with the SV technique has higher b^* values, that may be attributed to an increase in metmyoglobin, which results in brownish products [40]. The increase in redness value with increasing time-temperature treatment can be attributed to liberation of red astaxanthin during SV cooking [25]. Astaxanthin, a red carotenoid, is present in the carapace of shrimp bound to proteins as carotenoprotein complex called ovoverdin [41]. This can also be correlated to the increasing carotenoid content with increasing time and temperature in our SV cooked samples (Table 6). Another factor contributing to the increase in redness value could be the leaching of myoglobin from the shrimp muscles during SV cooking [13].

3.3.3. *TBARS*

TBARs value indicates the formation of secondary lipid oxidation products, which is particularly associated with the unpleasant flavour and odour of fisheries products. A TBARs value of less than 2 is acceptable for seafood products [42]. The TBARs value of SV cooked shrimps at different time-temperature are shown in Table 6. The TBARs value differed significantly among treatments ($p < 0.05$) with higher values of 0.08 mg MDA/kg in treatments (T4, T6, and T8) which were cooked at higher time-temperature as

Table 7
Instrumental texture parameters of raw and sous vide cooked shrimp product at different time-temperature treatments.

Treatments	Hardness (g)	Springiness (mm)	Cohesiveness	Gumminess (g)	Chewiness (g)
Raw shrimp	11755.67 ± 905.05[a]	0.55 ± 0.09[g]	0.42 ± 0.10[d]	4974.63 ± 1432.37[a,b,c]	3446.96 ± 209.00[b,c]
T1	9200.28 ± 659.81[b,c]	0.67 ± 0.04[e,f]	0.54 ± 0.04[c]	5407.04 ± 966.93[a,b,c]	3564.12 ± 333.88[b,c]
T2	9046.64 ± 673.41[b,c,d]	0.76 ± 0.03[c,d]	0.56 ± 0.04[c]	5860.77 ± 376.20[a]	4070.13 ± 117.93[b,c]
T3	8677.40 ± 880.54[c,d,e]	0.76 ± 0.06[c,d]	0.67 ± 0.09[b]	5943.25 ± 52.71[a]	5369.76 ± 1250.04[a]
T4	8007.90 ± 646.78[d,e]	0.86 ± 0.03[a]	0.78 ± 0.01[a]	4103.33 ± 188.66[b,c,d]	3391.95 ± 123.95[b,c]
T5	10074.20 ± 139.22[b]	0.70 ± 0.03[d,e]	0.55 ± 0.01[c]	5881.12 ± 248.16[a]	4226.95 ± 706.55[a,b]
T6	7654.74 ± 208.76[e]	0.79 ± 0.03[b,c]	0.75 ± 0.02[a]	3267.22 ± 511.45[d]	2648.77 ± 394.66[c]
T7	9988.35 ± 11.54[b]	0.63 ± 0.05[f]	0.55 ± 0.02[c]	5746.14 ± 455.27[a]	3306.85 ± 1010.31[b,c]
T8	8309.82 ± 338.37[c,d,e]	0.84 ± 0.03[a,b]	0.77 ± 0.02[a]	3834.62 ± 1678.50[c,d]	3192.91 ± 1289.96[b,c]
T9	7778.00 ± 446.73[e]	0.75 ± 0.02[c,d]	0.67 ± 0.03[b]	5067.72 ± 249.02[a,b,c]	3927.86 ± 285.40[b,c]
T10	7719.00 ± 701.77[e]	0.74 ± 0.005[c,d,e]	0.64 ± 0.01[b]	5420.33 ± 760.71[a,b,c]	3742.88 ± 796.52[b,c]
T11	8092.00 ± 799.57[d,e]	0.68 ± 0.01[e,f]	0.54 ± 0.02[c]	5515.28 ± 1155.48[a,b]	3750.56 ± 807.58[b,c]

Data are expressed as the mean ± SD of three independent replications (n = 3), Mean values with different letters in the same column are significantly different ($p < 0.05$).

compared to treatments (T1, T2, and T7) which were cooked at lower time-temperature with TBARs value of 0.05 mg MDA/kg. Several authors have reported that time and temperature of cooking have a significant effect on lipid oxidation in seafood products [31,43]. Moreover, higher cooking temperatures and times lead to more lipid oxidation [44]. Similar to our result, TBA value of shrimp (*Fenneropenaeus indicus*) increased slightly after SV cooking [1]. TBARs value of all the samples in this study were less than 1.0 mg malonaldehyde/kg and thus were within acceptable limits.

3.3.4. Total carotenoid content

Astaxanthin ($C_{40}H_{52}O_4$), an orange pigment and exceptionally potent antioxidant, is present in the tissues of marine animals, including shrimp [25,45,46]. The total carotenoid content of SV cooked shrimp at different time-temperature are shown in Table 6. The results indicate that with increasing time-temperature treatment, total carotenoid content increased. The highest carotenoid content of 25.60 μg/g was found in treatment T4 (time: 15 min and temperature: 85 °C), while the lowest carotenoid content of 12.65 μg/g was found in treatment T1 (time: 5 min and temperature: 75 °C). As of now, there are no reports available on the impact of SV cooking on carotenoid content of shrimps. However, there are reports suggesting that carotenoid content increases in vegetable samples after SV cooking. For instance, SV cooked carrots and Brussels sprouts had increased carotenoids concentrations compared to raw and steamed cooked samples [47]. The increased SV cooking may be responsible for the increase in carotenoid content in vegetable samples because it effectively releases carotenes that are typically contained in cellular crystals and bound by protein complexes or residual membranes [47,48]. Similarly, in this study, the increase in carotenoid content with increasing time-temperature can be attributed to the release of carotenoid which are normally bound to proteins in shrimp as carotenoprotein complex [45].

3.4. Textural properties

The textural changes of ready-to-eat shrimp as a result of varied temperature and time SV cooking treatments are shown in Table 7. SV cooking time-temperature significantly ($p < 0.05$) affected the textural attributes. The most important textural attribute in meat or seafood products, among all other characteristics, is hardness [49]. Samples cooked at higher temperatures for longer durations (T4, T6, T8, T9, T10, and T11) had considerably lower hardness than those cooked at lower temperatures for shorter durations (T1, T2, T3, T5, and T7). Comparatively, all the SV cooked samples had lower hardness in the range of 7654.74–10074.20 g than the initial raw material, which had a hardness of 11755.67 g. Our results are comparable to that of Ahmad and Traynor [35], where SV cooking resulted in a significant decrease in hardness of shrimp (*Litopenaeus setiferus*) compared to the raw sample. During heat treatment, the texture of fish meat undergoes remarkable changes giving rise to structures that are primarily stabilized by hydrophobic interactions and disulfide bonds [50,51]. Roldán et al. [52] showed that SV cooking of meat at high temperature of 80 °C for a long time shows less hardness than low-temperature SV cooking at 60 °C, which is in line with our results. SV cooking makes meat tender and reduces hardness due to solubilization of connective tissues [53]. Contrasting to hardness, the springiness and cohesiveness values in this experiment were noticeably higher in treatments with higher cooking time-temperature than initial raw material, with treatment T4 having highest springiness and cohesiveness values of 0.86 mm and 0.78, respectively, while raw material had springiness and cohesiveness values of 0.55 mm and 0.42, respectively. The increase in cohesiveness value is consistent with research conducted by Biyikli et al. [54] on the effects of various SV cooking temperature-time combinations on the characteristics of turkey cutlets.

3.5. Sensory properties

One of the crucial factors that customers take into account is sensory attributes [55]. The sensory scores of SV cooked shrimp product at different time-temperature treatments are shown in Table 8. The results indicate that all SV-cooked treatments were well accepted, with overall scores ≥7. Among the treatments, the overall acceptability of samples cooked at higher time-temperature (T4, T6, T8, T9, T10, and T11) were higher as compared to samples cooked at lower time-temperature (T1, T2, T3, T5, and T7). Based on the

Table 8
Sensory scores of sous vide cooked shrimp product at different time-temperature treatments.

Treatments	Appearance	Texture	Juiciness	Taste	Flavour	Odour	Colour	Overall Impression
T1	7.50 ± 0.53^{b}	7.40 ± 0.52^{b}	7.30 ± 0.67^{b}	6.90 ± 0.88^{b}	6.80 ± 0.42^{c}	6.80 ± 0.89^{b}	6.70 ± 0.67^{b}	7.20 ± 0.79^{b}
T2	7.60 ± 0.84^{b}	7.50 ± 0.71^{b}	7.40 ± 0.70^{b}	7.30 ± 048^{b}	7.20 ± 0.92^{b,c}	7.10 ± 0.55^{b}	7.00 ± 0.47^{b}	7.30 ± 0.48^{b}
T3	7.70 ± 0.48^{b}	7.50 ± 0.53^{b}	7.50 ± 0.53^{b}	7.40 ± 0.70^{b}	7.30 ± 0.82^{b,c}	7.20 ± 0.82^{b}	7.20 ± 0.42^{b}	7.50 ± 0.53^{b}
T4	8.90 ± 0.32^{a}	8.80 ± 0.42^{a}	8.70 ± 0.48^{a}	8.60 ± 0.70^{a}	8.50 ± 0.53^{a}	8.40 ± 0.52^{a}	8.30 ± 0.82^{a}	8.80 ± 0.42^{a}
T5	7.70 ± 0.48^{b}	7.60 ± 0.70^{b}	7.60 ± 0.52^{b}	7.50 ± 0.53^{b}	7.40 ± 0.52^{b}	7.30 ± 0.63^{b}	7.20 ± 0.63^{b}	7.50 ± 0.85^{b}
T6	8.70 ± 0.48^{a}	8.60 ± 0.52^{a}	8.50 ± 0.53^{a}	8.40 ± 0.52^{a}	8.30 ± 0.48^{a}	8.20 ± 0.75^{a}	8.10 ± 0.74^{a}	8.50 ± 0.53^{a}
T7	7.70 ± 0.82^{b}	7.60 ± 0.52^{b}	7.50 ± 0.71^{b}	7.40 ± 0.52^{b}	7.30 ± 0.48^{b,c}	7.30 ± 0.41^{b}	7.20 ± 0.42^{b}	7.50 ± 0.71^{b}
T8	8.70 ± 0.48^{a}	8.60 ± 0.52^{a}	8.50 ± 0.53^{a}	8.40 ± 0.70^{a}	8.30 ± 0.48^{a}	8.20 ± 0.63^{a}	8.10 ± 0.74^{a}	8.40 ± 0.52^{a}
T9	8.70 ± 0.48^{a}	8.60 ± 0.52^{a}	8.50 ± 0.53^{a}	8.40 ± 0.52^{a}	8.40 ± 0.52^{a}	8.20 ± 0.41^{a}	8.30 ± 0.48^{a}	8.50 ± 0.53^{a}
T10	8.90 ± 0.32^{a}	8.70 ± 0.48^{a}	8.60 ± 0.52^{a}	8.50 ± 0.53^{a}	8.40 ± 0.52^{a}	8.30 ± 0.55^{a}	8.20 ± 0.42^{a}	8.60 ± 0.52^{a}
T11	8.80 ± 0.42^{a}	8.70 ± 0.48^{a}	8.60 ± 0.52^{a}	8.50 ± 0.53^{a}	8.40 ± 0.52^{a}	8.30 ± 0.52^{a}	8.20 ± 0.42^{a}	8.50 ± 0.53^{a}

Data are expressed as the mean ± SD of three independent replications (n = 3), Mean values with different letters in the same column are significantly different ($p < 0.05$).

scores, treatment T4 (time: 15 min and temperature: 85 °C) fetched highest overall score of 8.80, while treatment T1 (time: 5 min and temperature: 75 °C) fetched the lowest overall score of 7.20. This indicated that with increasing SV cooking time and temperature, sensory attributes increased. Our results are comparable to previous studies by Biyikli et al. [54] and Naveena et al. [56]. According to Biyikli et al. [54], as SV cooking temperature and time are raised, the sensory qualities of turkey cutlets tend to get improved. Similarly, according to Naveena et al. [56], the flavour, juiciness, colour, and texture of SV cooked chicken increased after 30 and 60 min at 100 °C.

4. Conclusion

The research concludes that different SV cooking time-temperature combinations significantly altered the physicochemical, textural, and sensory characteristics of *Litopenaeus vannamei*. Maintaining optimal cooking conditions to obtain desired quality attributes is vital for better acceptability in terms of the overall quality of the SV-cooked shrimp product. Although the current time-temperature combination is suitable for shrimp, it might not be for other seafood products like finfish, cephalopods, and crab. Therefore, future research and the usage of SV-based procedures in diverse species are needed.

Author contribution statement

Rupali Das: Performed the experiments; Analyzed and interpreted the data; Wrote the paper. Naresh Kumar Mehta, Soibam Ngasotter: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper. Amjad K. Balange, Binaya Bhusan Nayak, Lakshmi Narasimha Murthy: Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data. K.A. Martin Xavier: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

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Data availability statement

Data will be made available on request.

Additional information

No additional information is available for this paper.

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.

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Appendix A. Supplementary data

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References

[1] C.O. Mohan, C.N. Ravishankar, T.K. Srinivasa Gopal, Effect of vacuum packaging and sous vide processing on the quality of Indian white shrimp (*Fenneropenaeus indicus*) during chilled storage, J. Aquat. Food Prod. Technol. 26 (10) (2017) 1280–1292.
[2] M. Salunke, A. Kalyankar, C.D. Khedkar, M. Shingare, G.D. Khedkar, A review on shrimp aquaculture in India: historical perspective, constraints, status and future implications for impacts on aquatic ecosystem and biodiversity, Rev. Fish. Sci. Aquac. 28 (3) (2020) 283–302.
[3] S.I. Shamshad, M. Riaz, R. Zuberi, R.B. Qadri, Shelf life of shrimp (*Penaeus merguiensis*) stored at different temperatures, J. Food Sci. 55 (5) (1990) 1201–1205.
[4] A. Imran, J. Chawalit, K. Somrote, Characterization of quality degradation during chilled shrimp (*Litopenaeus vannamei*) supply chain, Int. Food Res. J. 20 (4) (2013) 1833–1842.
[5] T. Tsironi, E. Dermesonlouoglou, M. Giannakourou, P. Taoukis, Shelf life modelling of frozen shrimp at variable temperature conditions, LWT - Food Sci. Technol. 42 (2) (2009) 664–671.
[6] B.P. Kaur, P.S. Rao, P.K. Nema, Effect of hydrostatic pressure and holding time on physicochemical quality and microbial inactivation kinetics of black tiger shrimp (Penaeus monodon), Innovat. Food Sci. Emerg. Technol. 33 (2016) 47–55.
[7] N. Kilibarda, I. Brdar, B. Baltić, V. Marković, H. Mahmutović, N. Karabasil, S. Stanišić, The safety and quality of sous vide food, Meat Technology 59 (1) (2018) 38–45.
[8] D.E. Baldwin, Sous vide cooking: a review, Int. J. Gastron. Food Sci. 1 (1) (2012) 15–30.
[9] F. Oz, E. Seyyar, Formation of heterocyclic aromatic amines and migration level of bisphenol-A in sous-vide-cooked trout fillets at different cooking temperatures and cooking levels, J. Agric. Food Chem. 64 (15) (2016) 3070–3082.
[10] B. Nieva-Echevarría, M.J. Manzanos, E. Goicoechea, M.D. Guillén, Changes provoked by boiling, steaming and sous-vide cooking in the lipid and volatile profile of European sea bass, Food Res. Int. 99 (2017) 630–640.
[11] J. Wan, A. Cao, L. Cai, Effects of vacuum or sous-vide cooking methods on the quality of largemouth bass (*Micropterus salmoides*), Int. J. Gastron. Food Sci. 18 (2019), 100181.
[12] H. Dogruyol, S. Mol, S. Cosansu, Increased thermal sensitivity of Listeria monocytogenes in sous-vide salmon by oregano essential oil and citric acid, Food Microbiol. 90 (2020), 103496.
[13] D. Kathuria, A.K. Dhiman, S. Attri, Sous vide, a culinary technique for improving quality of food products: a review, Trends Food Sci. Technol. 119 (2022) 57–68.
[14] S. Rodgers, N.W. Young, The potential role of latest technological developments including industrial gastronomy in functional meal design, J. Culin. Sci. Technol. 6 (2–3) (2008) 170–187.
[15] E. Gonzalez-Fandos, A. Villarino-Rodrıguez, M.C. Garcıa-Linares, M.T. Garcıa-Arias, M.C. Garcia-Fernandez, Microbiological safety and sensory characteristics of salmon slices processed by the sous vide method, Food Control 16 (1) (2005) 77–85.
[16] C.B. Singh, N. Kumari, S.R. Senapati, M. Lekshmi, K. Nagalakshmi, A.K. Balange, K.M. Xavier, Sous vide processed ready-to-cook seerfish steaks: process optimization by response surface methodology and its quality evaluation, LWT 74 (2016) 62–69.
[17] K. Chattopadhyay, K.A.M. Xavier, S. Ngasotter, S. Karmakar, A. Balange, B.B. Binaya Bhusan Nayak, Chitosan gel prepared with citric acid as food acidulant: effect of chitosan concentration and gel pH on physicochemical and functional properties of fish protein emulsion sausages, ACS Omega 8 (8) (2023) 7829–7837.
[18] M.A. Bezerra, R.E. Santelli, E.P. Oliveira, L.S. Villar, L.A. Escaleira, Response surface methodology (RSM) as a tool for optimization in analytical chemistry, Talanta 76 (5) (2008) 965–977.
[19] ACMSF, Report on vacuum packaging and associated processed, in: Advisory Committee on the Microbiological Safety of Food (ACMSF), HMSO, London, 1992.
[20] S. Bhattacharya, Central composite design for response surface methodology and its application in pharmacy, in: Response Surface Methodology in Engineering Science, IntechOpen, 2021.
[21] AOAC, Official Methods of Analysis, thirteenth ed., Association of Official Analytical Chemists. AOAC International Gaithersburg, Maryland, USA, 2005.
[22] R.S. Chaurasiya, P.Z. Sakhare, N. Bhaskar, H.U. Hebbar, Efficacy of reverse micellar extracted fruit bromelain in meat tenderization, J. Food Sci. Technol. 52 (6) (2015) 3870–3880.
[23] S. Remya, S. Basu, G. Venkateshwarlu, C.O. Mohan, Quality of shrimp analogue product as affected by addition of modified potato starch, J. Food Sci. Technol. 52 (7) (2015) 4432–4440.
[24] K.W. Young, K.J. Whittle, Colour measurement of fish minces using Hunter L, a, b values, J. Sci. Food Agric. 36 (5) (1985) 383–392.
[25] B. Dayakar, K.M. Xavier, S. Ngasotter, P. Layana, A.K. Balange, B. Priyadarshini, B.B. Nayak, Characterization of spray-dried carotenoprotein powder from Pacific white shrimp (*Litopenaeus vannamei*) shells and head waste extracted using papain: antioxidant, spectroscopic, and microstructural properties, LWT 159 (2022), 113188.
[26] J.A. Buege, S.D. Aust, Microsomal lipid peroxidation, in: Methods in Enzymology vol. 52, Academic press, 1978, pp. 302–310.
[27] M.C. Meilgaard, B.T. Carr, G.V. Civille, Sensory Evaluation Techniques, CRC press, 1999.
[28] A. Morales, B. Gullon, I. Davila, G. Eibes, J. Labidi, P. Gullon, Optimization of alkaline pretreatment for the co-production of biopolymer lignin and bioethanol from chestnut shells following a biorefinery approach, Ind. Crop. Prod. 124 (2018) 582–592.
[29] S. Jabbar, M. Abid, T. Wu, M.M. Hashim, M. Saeeduddin, B. Hu, X. Zeng, Ultrasound-assisted extraction of bioactive compounds and antioxidants from carrot pomace: a response surface approach, J. Food Process. Preserv. 39 (6) (2015) 1878–1888.
[30] H. Ayub, A. Ahmad, Physiochemical changes in sous-vide and conventionally cooked meat, Int. J. Gastron. Food Sci. 17 (2019), 100145.
[31] J. Cropotova, R. Mozuraityte, I.B. Standal, T. Rustad, The influence of cooking parameters and chilled storage time on quality of sous-vide Atlantic mackerel (*Scomber scombrus*), J. Aquat. Food Prod. Technol. 28 (5) (2019) 505–518.
[32] M. Roldan, T. Antequera, M. Armenteros, J. Ruiz, Effect of different temperature–time combinations on lipid and protein oxidation of sous-vide cooked lamb loins, Food Chem. 149 (2014) 129–136.
[33] J.S. Del Pulgar, A. Gázquez, J. Ruiz-Carrascal, Physico-chemical, textural and structural characteristics of sous-vide cooked pork cheeks as affected by vacuum, cooking temperature, and cooking time, Meat Sci. 90 (3) (2012) 828–835.
[34] S. Humaid, D. Nayyar, J. Bolton, D.I. Skonberg, Physicochemical properties and consumer acceptance of high-pressure processed, sous vide-cooked lobster tails, J. Food Sci. 84 (12) (2019) 3454–3462.
[35] I. Ahmad, M.P. Traynor, Impact of high-pressure processing and sous vide cooking on the physicochemical, sensorial, and textural properties of fresh whiteleg shrimp (*Litopenaeus setiferus*), J. Aquat. Food Prod. Technol. (2022) 1–17.

[36] S.I. Hwang, E.J. Lee, G.P. Hong, Effects of temperature and time on the cookery properties of sous-vide processed pork loin, Food Science of Animal Resources 39 (1) (2019) 65–72.

[37] C.H. Park, B. Lee, E. Oh, Y.S. Kim, Y.M. Choi, Combined effects of sous-vide cooking conditions on meat and sensory quality characteristics of chicken breast meat, Poultry Sci. 99 (6) (2020) 3286–3291.

[38] V.D. Bramblett, R.L. Hostetler, G.E. Vail, H.N. Draudt, Qualities of beef as affected by cooking at very low temperatures for long periods of time, Food Technol. 13 (1959) 707–711.

[39] E. Dominguez-Hernandez, A. Salaseviciene, P. Ertbjerg, Low-temperature long-time cooking of meat: eating quality and underlying mechanisms, Meat Sci. 143 (2018) 104–113.

[40] C. Botinestean, D.F. Keenan, J.P. Kerry, R.M. Hamill, 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 74 (2016) 154–159.

[41] O. Martínez-Alvarez, M.E. López-Caballero, M.D.C. Gómez-Guillén, P. Montero, The effect of several cooking treatments on subsequent chilled storage of thawed deepwater pink shrimp (*Parapenaeus longirostris*) treated with different melanosis-inhibiting formulas, LWT - Food Sci. Technol. 42 (8) (2009) 1335–1344.

[42] D.M. Affarin Tinku, K.M. Xavier, B.B. Nayak, V.H. Krishna, G. Krishna, A.K. Balange, Comparative evaluation of patties prepared from pacific white shrimps (*Litopenaeus vannamei*) grown in inland saline water and brackish water regimes during frozen storage, J. Aquat. Food Prod. Technol. 30 (7) (2021) 826–834.

[43] A. Głuchowski, E. Czarniecka-Skubina, G. Wasiak-Zys, D. Nowak, Effect of various cooking methods on technological and sensory quality of Atlantic salmon (*Salmo salar*), Foods 8 (8) (2019) 323.

[44] J. Kanner, E. Frankel, R. Granit, B. German, J.E. Kinsella, Natural antioxidants in grapes and wines, J. Agric. Food Chem. 42 (1) (1994) 64–69.

[45] S.S. Pattanaik, P.B. Sawant, K.M. Xavier, K. Dube, P.P. Srivastava, V. Dhanabalan, et al., Characterization of carotenoprotein from different shrimp shell waste for possible use as supplementary nutritive feed ingredient in animal diets, Aquaculture 515 (2020), 734594.

[46] S. Ngasotter, L. Sampath, K.M. Xavier, Nanochitin: an update review on advances in preparation methods and food applications, Carbohydr. Polym. 291 (2022), 119627.

[47] E. Chiavaro, T. Mazzeo, A. Visconti, C. Manzi, V. Fogliano, N. Pellegrini, Nutritional quality of sous vide cooked carrots and brussels sprouts, J. Agric. Food Chem. 60 (23) (2012) 6019–6025.

[48] W. Kalt, Effects of production and processing factors on major fruit and vegetable antioxidants, J. Food Sci. 70 (1) (2005) R11–R19.

[49] F. Erdoğdu, M.O. Balaban, Thermal processing effects on the textural attributes of previously frozen shrimp, J. Aquat. Food Prod. Technol. 9 (4) (2008) 61–84.

[50] A. Sequeira-Munoz, D. Chevalier, A. LeBail, H.S. Ramaswamy, B.K. Simpson, Physicochemical changes induced in carp (Cyprinus carpio) fillets by high pressure processing at low temperature, Innovat. Food Sci. Emerg. Technol. 7 (1–2) (2006) 13–18.

[51] K. Angsupanich, M. Edde, D.A. Ledward, Effects of high pressure on the myofibrillar proteins of cod and Turkey muscle, J. Agric. Food Chem. 47 (1) (1999) 92–99.

[52] M. Roldán, T. Antequera, A. Hernández, J. Ruiz, Physicochemical and microbiological changes during the refrigerated storage of lamb loins sous-vide cooked at different combinations of time and temperature, Food Sci. Technol. Int. 21 (7) (2015) 512–522.

[53] M. Rinaldi, C. Dall Asta, M. Paciulli, M. Cirlini, C. Manzi, E. Chiavaro, A novel time/temperature approach to sous vide cooking of beef muscle, Food Bioprocess Technol. 7 (10) (2014) 2969–2977.

[54] M. Bıyıklı, A. Akoğlu, S. Kurhan, İ.T. Akoğlu, Effect of different Sous Vide cooking temperature-time combinations on the physicochemical, microbiological, and sensory properties of Turkey cutlet, Int. J. Gastron. Food Sci. 20 (2020), 100204.

[55] M. Cullere, G. Tasoniero, G. Secci, G. Parisi, P. Smit, L.C. Hoffman, A. Dalle Zotte, Effect of the incorporation of a fermented rooibos (*Aspalathus linearis*) extract in the manufacturing of rabbit meat patties on their physical, chemical, and sensory quality during refrigerated storage, LWT 108 (2019) 31–38.

[56] B.M. Naveena, P.S. Khansole, M. Shashi Kumar, N. Krishnaiah, V.V. Kulkarni, S.J. Deepak, Effect of sous vide processing on physicochemical, ultrastructural, microbial and sensory changes in vacuum packaged chicken sausages, Food Sci. Technol. Int. 23 (1) (2017) 75–85.