Optimization of high pressure processing parameters of Indian white prawn (*Fenneropenaeus indicus*)

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**ABSTRACT**

The effect of pressure (150, 250 and 350 MPa), ramp rate (200, 400 and 600 MPa/min) and holding time (3, 6 and 9 min) on the quality indices (dependent variable) of Indian white prawn (*Fenneropenaeus indicus*) was optimized using response surface methodology. Box–Behnken response surface design was used with 15 runs. Second-order response surface model was fitted to the experimental data and the model adequacy was measured by $R^2$ value. The linear and quadratic effect of pressure, ramp rate and holding time was significant for tri-methylamine, total volatile base nitrogen and total plate count. Based on the ridge analysis and response surface plots, the optimum combination obtained was 250 MPa pressure, 400 MPa/min ramp rate and 6 min holding time for high pressure (HP) processing of Indian white prawn. Validation of the experiment indicated that the developed model was appropriate to predict quality indices in Indian white prawn processed by HP processing.

**ARTICLE HISTORY**

Received 27 December 2016
Accepted 12 May 2017

**KEYWORDS**

Response surface methodology; high pressure processing; optimization; Indian white prawn

1. Introduction

High pressure (HP) processing, a novel non-thermal food processing technique is gaining attention of consumers, especially those who demand raw or minimally processed seafood with natural characteristics. Seafood processed by this technology retains natural flavour, taste, nutritional attributes and an extended shelf life. This could be due to the inactivation of enzymes responsible for spoilage and destruction of microflora. However, the overall quality of seafood under HP treatment is dependent on several response variables like physicochemical and microbiological attributes. These response variables are influenced by the direct and interaction effect of HP processing variables [1]. Pressure, ramp rate, holding time and temperature are the important independent variable for HP processing of seafood. Hence, obtaining a suitable combination of these process variables is highly necessary to improve the overall quality of the seafood under HP treatment [2]. Response surface methodology (RSM) plays an important role in designing the experiment and optimizing the process parameters in order to deliver large amount of information from a small number of experimental runs. Miriam and Pilar [3] applied RSM for optimizing HP
processing parameters such as pressure, time and temperature (process variables) for the production of blue whiting gel with better sensory characteristics.

Indian white prawn (*Fenneropenaeus indicus*) is one of the major seafood items that has good price and demand in the global market. However [4], prawns are highly perishable due to high water activity, amino acid content, pH, bacteria and autolytic enzymes. The content of tri-methylamine (TMA), total volatile base nitrogen (TVB-N) and free fatty acids (FFA), texture, colour and microbial load indicate the level of spoilage of prawn [5]. TMA is considered as one of the spoilage indices for seafood. TMA and non-protein nitrogenous content (NPN) in prawns are converted to TVB-N by enzymatic degradation [6]. Both TMA and TVB-N have been used to assess the spoilage of prawns [7]. HP processing has the ability to retard the formation of TMA by inactivating TMAOase and inhibiting the microbial growth. Similarly, reduction of TVB-N content in haddock muscle after HP treatment was reported by Karmin et al. [8]. Hydrolysis of lipid in seafoods leads to the accumulation of FFA, which has a vital role for the textural changes by accelerating denaturation of proteins and lipid oxidation [9]. HP treatment increases the release of FFA [9]; and it is directly proportional with pressurization time [10]. Generally, seafoods are more susceptible to post-mortem texture deterioration than animals. Harder texture and higher shear strength have been reported in many HP-treated seafood [11], whereas softening in fish muscle has also been evident in carp. However, Ashie and Simpson [12] found that HP treatment of seafood can control the enzymes responsible for texture deterioration thereby preserving the freshness of texture. Colour and appearance of seafood have a greater role for acceptability by consumers [13]. Changes in colour of shellfish due to HP processing have been reported with increasing pressure. Prawns are demersal and filter feeders which lead to the accumulation of several bacteria and viruses in their body [14]. Remarkable reduction of overall microflora by HP treatment is achievable by changing the morphology and internal organization of cells and alteration of genetic material. Lopez-Caballero et al. [15] suggested that a pressure level of 200–400 MPa at 7°C for 10 min is sufficient for the reduction of microflora of prawn.

Very little information has been reported for HP treatment on prawns, especially Indian white prawn. Moreover, HP processing has a significant role to change the spoilage indices of prawn. Hence, optimization of process variables such as pressure, ramp rate and holding time with respect to physicochemical and microbiological parameters of Indian white prawn by using RSM is highly relevant and it has been undertaken in this study.

2. Materials and methods

2.1. Raw material

Fresh prawns with an average length of 15 cm and weight 25 g were procured from the fish landing centre at Fort Cochin, Kerala, India, and transported to the laboratory in iced condition. The raw material was washed in potable water and the head was removed manually. The headless (HL) prawns were vacuum-packed in EVOH multilayer films for HP treatment.

2.2. HP treatment of samples

Pressure treatments were carried out in the HP processing machine (Stansted Fluid Power, Stansted, Essex, UK) FPG 9400:922 at DFRL. The dimension of the pressure
vessel was 570 mm height and 70 mm diameter with a two litre capacity and used 30% of propylene glycol in distilled water as the pressure transmitting fluid. Vacuum-packed prawns were subjected to 15 HP treatments comprising of three levels of pressure (150, 250 and 350 MPa), ramp rate (200, 400 and 600 MPa/min) and holding time (3, 6 and 9 min). Temperature of the process was set at 25 °C and it was measured by using a K-type thermocouple. However, a slight increase in temperature (i.e., 2–4 °C) in the pressure transmitting fluid has been noticed with the ramp rate, which was brought down to the set temperature by the cooling system of the machine (Ever Cool, Type EPIALT-7.5). This temperature variation was not corrected for any calculation of experimental data. Process variables such as pressure, ramp rate and holding time have a significant role to improve the microbial quality and sensory attributes of the prawn [16]. In the earlier study, authors identified a suitable level of process parameters for the pressurization of prawn to be 275 MPa pressure, 600 MPa/min ramp rate, 5 min holding time and 25°C temperature, so that a range nearer to this process variable was selected for the present experiment. Effect of process variables on the physicochemical and microbiological parameters of Indian white prawn was analysed immediately after the HP treatment and compared with unpressurized sample (control).

2.3. Chemical analysis

TVB-N and TMA were analysed by the micro diffusion method as per Conway [17] with slight modifications, and it expressed as mg 100 g⁻¹ of the sample. FFA was determined according to the method of AOCS [18] and it is expressed as % oleic acid.

2.4. Textural analysis

Texture profile analysis on prawn sample was determined by the method of Bourne [19] by using the Universal testing machine (Lloyd instruments LRX plus, UK) equipped with a load cell of 50 N.

2.5. Colour measurement

Colour of the sample was measured by Shah [20] using the Hunter lab colorimeter Model No. D/8-S (Miniscan XE Plus) with geometry of diffuse/8° (sphere 8 mm view) and an illuminant of D65/10°. The L*, a* and b* value or CIE Lab colour space is an international standard for colour measurement adopted by the Commission Internationale d’Eclairage (CIE) in 1976.

2.6. Enumeration of mesophilic aerobic count

Mesophilic aerobic count was enumerated as per Ryser and Schuman [21]. Duplicates of three consecutive homogenate dilutions were plated on plate count agar (Difco). Plates were incubated for 48 ± 2 h at 35 ± 2°C. Average counts were calculated and expressed as decimal logarithm of Log₁₀ CFU/g.
2.7. Statistical analysis

2.7.1. Experimental design

Box–Behnken central composite design with three process variables with three levels and three points at the centre was used for the experiment [22]. Pressure ($X_1$), ramp rate ($X_2$) and holding time ($X_3$) were considered as independent variables. Experimental data from 15 experimental units on response variables were measured. The detailed experimental set-up with original and coded values of the independent variables is presented in Table 1.

2.7.2. Statistical modelling

Second-order response surface regression model was used to predict and optimize the process parameters such as pressure, ramp rate and holding time with respect to quality indices of HP-treated prawn [22]. The quadratic model mentioned below was used to break up the total variability into variability due to linear, quadratic and interaction effect of process parameters and error on the dependent variables.

$$Y = \beta_0 + \sum_i \beta_i x_i + \sum_{ij} \beta_{ij} x_i^2 + \sum_{i<j} \beta_{ij} x_i x_j + e, \ i \neq j$$

(1)

where ‘$Y$’ is the response variable, ‘$\beta_0$’ is the intercept, ‘$\beta_i$’ is the linear regression coefficients, ‘$\beta_{ij}$’ is the quadratic regression coefficients, ‘$\beta_{ij}$’ is the interaction regression coefficients and ‘$e$’ is the error term. Ridge analysis was carried out to predict the response variable at different radiuses of the design region. The optimization of response variables was done based on the ridge score and response surface plot of the response variables. All the statistical analysis was carried out by using SAS 9.3.

3. Results and discussion

The effect of process parameters in terms of regression coefficients of the second-order response regression model on response variables is presented in Table 2. The model produced significant $R^2$ for all the response variables.

Table 1. Experimental design with original and coded values for the treatment of Indian white prawn.

<table>
<thead>
<tr>
<th>Sr. No</th>
<th>Pressure (MPa) $X_1$</th>
<th>Ramp rate (MPa/min) $X_2$</th>
<th>Holding time (min) $X_3$</th>
<th>Coded values$^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$x_1$ $x_2$ $x_3$</td>
</tr>
<tr>
<td>1</td>
<td>150</td>
<td>400</td>
<td>3</td>
<td>$-1$ $0$ $-1$</td>
</tr>
<tr>
<td>2</td>
<td>150</td>
<td>400</td>
<td>9</td>
<td>$-1$ $0$ $+1$</td>
</tr>
<tr>
<td>3</td>
<td>150</td>
<td>200</td>
<td>6</td>
<td>$-1$ $-1$ $0$</td>
</tr>
<tr>
<td>4</td>
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<td>6</td>
<td>$-1$ $+1$ $0$</td>
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<td>5</td>
<td>250</td>
<td>400</td>
<td>6</td>
<td>$0$ $0$ $0$</td>
</tr>
<tr>
<td>6</td>
<td>250</td>
<td>200</td>
<td>3</td>
<td>$0$ $-1$ $-1$</td>
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<td>7</td>
<td>250</td>
<td>600</td>
<td>3</td>
<td>$0$ $+1$ $-1$</td>
</tr>
<tr>
<td>8</td>
<td>250</td>
<td>400</td>
<td>6</td>
<td>$0$ $0$ $0$</td>
</tr>
<tr>
<td>9</td>
<td>250</td>
<td>200</td>
<td>9</td>
<td>$0$ $-1$ $+1$</td>
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<tr>
<td>10</td>
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<td>12</td>
<td>350</td>
<td>200</td>
<td>6</td>
<td>$+1$ $0$ $0$</td>
</tr>
<tr>
<td>13</td>
<td>350</td>
<td>400</td>
<td>3</td>
<td>$+1$ $0$ $-1$</td>
</tr>
<tr>
<td>14</td>
<td>350</td>
<td>600</td>
<td>6</td>
<td>$+1$ $+1$ $0$</td>
</tr>
<tr>
<td>15</td>
<td>350</td>
<td>400</td>
<td>9</td>
<td>$+1$ $0$ $+1$</td>
</tr>
</tbody>
</table>

$^a$Coded values $X_i = (\text{original values} - M)/S$, where ‘$M$’ is the average of the highest and lowest values for the variable in the design and ‘$S$’ is half their difference.
3.1. Effect of process parameters on TMA

Second-order response surface regression was found to be significant with an $R^2$ value of 0.83 to explain the total variability of TMA in terms of linear, quadratic and interaction effect of HP processing parameters (Table 2). The linear and quadratic effect of pressure, ramp rate and holding time were found to be significant ($p < .05$). Response surface plot of predicted values of TMA with respect to changes in the level of pressure and holding time at fixed ramp rate of 400 MPa/min is depicted in Figure 1(A). TMA content of the sample increased with holding time up to 6 min, and then it showed a declining trend with holding time. Whereas TMA content significantly reduced with pressure level up to 250 MPa, and then it revealed an increasing trend. Reduction of TMA content in vacuum-packed squid mantles (*Todaropsis eblanae*) treated with 150 and 200 MPa for 15 min at ambient temperature was reported by Paarup et al. [23]. TMA content in the prawn was reduced due to the linear effect of pressure and ramp rate. The interaction effect of pressure and ramp rate, similarly pressure and holding time revealed an

![Image](image_url)

**Figure 1.** (A) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) on TMA. (B) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) TVB-N. (C) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) free fatty acid. (D) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) hardness. (E1) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) on $L^*$ value. (E2) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) on $a^*$ value. (E3) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) on $b^*$ value. (F) Response surface plots for the effect of pressure and holding time at fixed ramp rate (400 MPa/min) on total plate count.
increasing trend of TMA, whereas interaction effect of ramp rate and holding time significantly reduced the TMA content of the sample. The stationary point of response variable was a saddle point. Based on the ridge analysis, the optimum combination range of process parameters was pressure treatment at 250–258 MPa, 400–433 MPa/min ramp rate and 3–6 min holding time.

3.2. Effect of process parameters on TVB-N

Second-order polynomial regression model was fitted with an $R^2$ value of 0.93 to predict the values of TVB-N with respect to changing level of pressure, holding time and ramp rate. Analysis of variance of total model and its linear, quadratic and cross product were found to be significant ($p < .01$) (Table 2). TVB-N gradually enhanced with pressure, ramp rate and holding time, whereas it reduced at higher levels of pressure and holding time. Similarly, the quadratic effect of process parameters and interaction effect of pressure and ramp rate as well as ramp rate and holding time also showed a decreasing trend of TVB-N content. The three-dimensional response surface plot of the predicted value of TVB-N with respect to changing the level of pressure and holding time at a constant ramp rate (400 MPa/min) is depicted in Figure 1(B) and it was clearly evident that a treatment of 250 MPa with 6 min holding time gave a better response on the dependent variable. The stationary point of TVB-N was maximum and the optimum (minimum) range of process parameters was 250–308 MPa pressure, 400–500 MPa/min ramp rate and 4–6 min holding time.

3.3. Effect of process parameters on free fatty acid (FFA)

Second-order polynomial regression model was fitted to predict the FFA values of the sample at different levels of the process parameters. Linear effect of pressure and holding time produced an increasing trend on FFA content, whereas it reduced with holding time. The response surface plot of predicted values of FFA is depicted in Figure 1(C) and it was clearly evident that the FFA content of the sample increased with
Table 2. The linear, quadratic and interaction regression coefficients of independent variables on response variables of HP-treated Indian white prawn.

<table>
<thead>
<tr>
<th>Response variables</th>
<th>TMA (mg N\textsubscript{2} 100 g\textsuperscript{-1})</th>
<th>TVB-N (mg N\textsubscript{2} 100 g\textsuperscript{-1})</th>
<th>FFA (mg % oleic acid)</th>
<th>Hardness (N)</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>TPC (Log\textsubscript{10} CFU/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intercept</td>
<td>44.15</td>
<td>0.076</td>
<td>−20.49</td>
<td>49.71</td>
<td>17.55</td>
<td>4.71</td>
<td>−9.353</td>
<td>8.14</td>
</tr>
<tr>
<td>X\textsubscript{1}</td>
<td>−0.19**</td>
<td>0.15**</td>
<td>0.4912</td>
<td>0.057</td>
<td>0.212**</td>
<td>−0.027*</td>
<td>0.038*</td>
<td>−0.013**</td>
</tr>
<tr>
<td>X\textsubscript{2}</td>
<td>−0.089**</td>
<td>0.022</td>
<td>−0.13015</td>
<td>0.037</td>
<td>−0.0025</td>
<td>−0.0075</td>
<td>0.021**</td>
<td>−0.00015</td>
</tr>
<tr>
<td>X\textsubscript{3}</td>
<td>4.406**</td>
<td>1.89*</td>
<td>10.66</td>
<td>−3.28</td>
<td>1.69</td>
<td>−0.322</td>
<td>0.445</td>
<td>−0.18**</td>
</tr>
<tr>
<td>X\textsubscript{1}\textsuperscript{2}</td>
<td>0.00022*</td>
<td>−0.00034**</td>
<td>−0.00018</td>
<td>0.000025</td>
<td>−0.00026**</td>
<td>0.000051</td>
<td>−0.0000014</td>
<td>0.0000044*</td>
</tr>
<tr>
<td>X\textsubscript{2}\textsuperscript{2}</td>
<td>0.000058**</td>
<td>−0.000034**</td>
<td>0.0003</td>
<td>0.0000069</td>
<td>0.0000059</td>
<td>0.0000093</td>
<td>−0.000013</td>
<td>−0.000002**</td>
</tr>
<tr>
<td>X\textsubscript{3}\textsuperscript{2}</td>
<td>−0.291**</td>
<td>−0.196**</td>
<td>−0.983</td>
<td>0.67</td>
<td>−0.14</td>
<td>0.017</td>
<td>0.045</td>
<td>0.008**</td>
</tr>
<tr>
<td>X\textsubscript{1}\texttimes X\textsubscript{2}</td>
<td>0.00016**</td>
<td>−0.000019</td>
<td>−0.00075**</td>
<td>0.000025</td>
<td>0.000013</td>
<td>0.0000014</td>
<td>−0.000038**</td>
<td>0.000005**</td>
</tr>
<tr>
<td>X\textsubscript{1}\texttimes X\textsubscript{3}</td>
<td>0.0015</td>
<td>0.0058**</td>
<td>−0.0189</td>
<td>0.0026</td>
<td>−0.00005</td>
<td>0.00047</td>
<td>−0.0014</td>
<td>0.0002**</td>
</tr>
<tr>
<td>X\textsubscript{2}\texttimes X\textsubscript{3}</td>
<td>−0.0023</td>
<td>−0.0006</td>
<td>0.0196</td>
<td>−0.011</td>
<td>0.00019</td>
<td>0.000029</td>
<td>−0.00072</td>
<td>0.000021</td>
</tr>
<tr>
<td>R\textsuperscript{2}</td>
<td>0.8300</td>
<td>0.93</td>
<td>0.53</td>
<td>0.57</td>
<td>0.94</td>
<td>0.53</td>
<td>0.86</td>
<td>0.99</td>
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</table>

*Indicates 5% level of significance of regression coefficients.
**Indicates 1% level of significance of regression coefficients.
holding time up to 8 min and then it slightly declined, whereas it decreased with pressure levels. Analysis of variance for the equation revealed a significant interaction effect of pressure and ramp rate ($p < .05$) on the FFA content of the sample (Table 2). Interaction effect of pressure and holding time as well as pressure and ramp rate revealed a decreasing trend of FFA content in the sample, but it increased with holding time and ramp rate. Sequeira-Munoz et al. [9] found that at a given pressure level, the FFA content released from the carp fillets increased with pressurization time. Based on the fitted model, optimum range of FFA value was noticed in the range of 199–250 MPa pressure, 252–400 MPa/min ramp rate and 6–7.3 min holding time.

### 3.4. Effect of process parameters on hardness

Texture is the sensory and functional manifestation of the structural and mechanical properties of foods [24]. Texture properties of seafood are mainly contributed by connective tissue and muscle fibres [25]. HP treatment improves the hardness and shear strength of seafood, however softening of muscle texture was also noticed in bluefish [10]. Modification of texture of seafood was due to proteolysis of oligomeric proteins [26] and aggregation of actomyosin [27]. Protein denaturation can be reversible or irreversible, depending upon the level of pressure and type of protein [28]. Hardness of the prawn increased with linear effect of pressure and ramp rate (Table 2), whereas it decreased with holding time up to 6 min and then it was found to show an increasing trend. Similarly, hardness was found to increase with pressure level and it is evident in the three-dimensional response plot (Figure 1(D)) of hardness at different levels of pressure and holding time at a fixed ramp rate (400 MPa/min). Hardness of the prawn increased with pressure and ramp rate. Quadratic effect of pressure, ramp rate and holding time produced an increasing trend of hardness in the sample. Interaction effect of pressure and ramp rate as well as ramp rate and holding time revealed a decreasing trend of hardness, while hardness was found to increase with interaction effect of pressure and holding time. Lopez-Caballero et al. [15] reported an increasing trend of hardness in prawn muscle treated at 200 and 400 MPa [29]. This could be due to the compacting of the muscle fibre, unfolding of actin and sarcoplasmic proteins and the formation of new hydrogen bonded networks during pressure treatment. The stationary point of hardness was a saddle point in the experimental region, but based on the ridge analysis the optimum combination range of process parameters were 200–250 MPa pressure, 400–572 MPa/min ramp rate and 6 min holding time.

### 3.5. Effect of process parameters on colour values

Response surface plots of lightness ($L^*$), redness ($a^*$) and yellowness ($b^*$) of the sample for varying levels of pressure and holding time at constant ramp rate of 400 MPa/min are depicted in Figure 1(E1–E3), respectively. Colour and appearance of crustaceans have a great role for consumer acceptability [30]. Colour changes of seafood after pressurization are due to the denaturation of myofibrillar and sarcoplasmic proteins [25], denaturation of myosin [24], the formation of metmyoglobin [31], oxidation of haemoprotein [32] and stabilization of ferrous nitrosomyoglobin [33]. According to Marshall et al. [34], cooked appearance of seafood was accentuated with pressure level. Authors also found an increased lightness and yellowness and decreased redness after HP treatment. Second-
order polynomial regression model fitted well with the experimental data for lightness \((R^2 0.94)\), redness \((R^2 0.53)\) and yellowness \((R^2 0.86)\) of the sample. The lightness of the sample slightly increased with holding time up to 6 min and then it showed a declining trend. Similarly, lightness of the sample enhanced with pressure level (Figure 1(E1)) [30]. Increasing trend of lightness in seafood was observed at a higher pressure level. Significant increases of lightness with an increase in the level of pressure and holding time in HP-treated carp muscle were reported by Yoshioka et al. [35]. Lightness of the sample decreased with quadratic terms of pressure and holding time, whereas it improved with ramp rate. The interaction effect of pressure and ramp rate as well as pressure and holding time significantly reduced the lightness of the sample, whereas an increasing trend was observed with ramp rate and holding time. Analysis of variance for the equation indicated a significant linear and quadratic effect of pressure \((p < .05)\) on lightness of the sample (Table 2). Redness was found to gradually reduce with pressure and holding time up to 250 MPa and 6 min, and then it increased with the level of pressure and holding time (Figure 1(E2)). Linear regression coefficient for pressure, ramp rate and holding time produced a significant reduction of redness in the sample, whereas it enhanced with quadratic terms of process parameters. Reduction of redness after HP processing of mackerel and cod fish was reported by Ohshima et al. [30]. Redness of the sample increased with interaction effect of pressure and holding time as well as ramp rate and holding time, whereas a slight reduction of redness was found for the effect of pressure and ramp rate. Yellowness of the sample was enhanced with the level of pressure and holding time (Figure 1(E3)). Increased yellowness in carp muscle with pressure level and holding time was reported by Yoshioka et al. [35]. Interaction regression coefficient for the process parameters produced a decreasing trend of yellowness. Reduction of yellowness was observed with quadratic effect of pressure and ramp rate, whereas it increased with holding time. Analysis of variance for the equation revealed the linear effect of pressure, and interaction effect pressure and ramp rate were significant \((p < .05)\) on yellowness of the sample (Table 2). The stationary point was a saddle point for the \(L^*\) and \(b^*\) value; and the same was a minimum for \(a^*\) value. Based on the ridge analysis, the best combination of process parameters for the colour response variables were 250 MPa pressure, 400 MPa/min ramp rate and 6 min holding time.

**3.6. Effect of process parameters on mesophilic aerobic count**

Second-order polynomial regression model was well fitted on the linear, quadratic and interaction effect of process parameters on the mesophilic count of the sample with an \(R^2\) value of 0.99. The linear, quadratic and interaction effects of HP processing parameters were found to be significant \((p < .01)\), except on the linear effect of ramp rate and interaction effect of ramp rate and holding time (Table 2). Pressure and holding time showed a significant effect on mesophilic count \((p < .01)\), whereas it was not significant for ramp rate \((p > .05)\). Similarly, a significant effect of quadratic and cross product of process parameters on the mesophilic count \((p < .05)\) of the sample was observed, except for cross product of ramp rate and holding time (Table 2). Figure 1(F) depicts the response surface plot of mesophilic count in terms of pressure and holding time by keeping ramp rate constant at 400 MPa/min and it indicated the reduction of mesophilic count of the sample with pressure and holding time. Büyükcan et al. [36] found the
reduction of mesophilic count in prawn (*Parapeneaus longirostris*) with increasing pressure, temperature and holding time. Ginson et al. [16] have reported that the reduction in mesophilic count of Indian white prawn was directly proportional to pressure level. Based on the fitted model, the optimum mesophilic count was obtained in the range for pressure 250–350 MPa, ramp rate 400 MPa/min and holding time 6 min.

### 3.7. Multiple response evaluation

Cross contour graphs of hardness vs mesophilic count, TVB-N content vs hardness, TVB-N vs mesophilic count and hardness vs lightness of HP-treated prawn are given in Figure 2.
(G–J), respectively. It is clearly evident that the increase in pressure and holding time significantly reduced the mesophilic count of the sample, whereas hardness showed an increasing trend with increasing pressure. Hardness increased with pressure and holding time, whereas TVB-N content increased at higher levels of pressure and holding time. There was a reduction of mesophilic count and increase in TVB-N content with increasing levels of pressure and holding time. Better hardness and lightness of HP-treated prawn were observed at lower levels of pressure and holding time. Ridge analysis was carried to see the effect of input variables on the response variable by drawing a radius that is equi-distant from the centre point of the design. Hardness of the sample revealed an increasing trend with increasing levels of pressure and holding time. Thus from the ridge, multiple response and desirability function analysis, the optimum combination of process variables was found to be 250 MPa pressure, 400 MPa/min ramp rate and 6 min holding time for HP-treated Indian white prawn. A validation study was conducted at the optimized condition and result indicated that the value of each response variable was in the range of predicted value of the response variables (Table 3).

4. Conclusions

Process parameters significantly altered the physicochemical and microbiological parameters of Indian white prawn. The second-order response surface regression model was significant enough to explain the total variability in terms of linear, quadratic and interaction effect of process parameters. Coefficient of determination ($R^2$) indicated the suitability of the model to explain the response variables with respect to processing parameters. Lightness, yellowness, hardness, TVB-N and FFA of the sample increased with pressure level, whereas redness, TMA and mesophilic count declined. Effect of holding time on lightness, yellowness, TMA, TVB-N and FFA of the sample showed an increasing trend, whereas the ramp rate significantly increased yellowness, hardness and TVB-N of the sample. Based on the ridge and multiple response analysis, 250 MPa pressure, 400 MPa/min ramp rate and 6 min holding time was found to be the optimum combination of process parameters for HP treatment of HL prawns with respect to the physicochemical and microbiological response variables.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

The authors acknowledge the financial assistance provided by the National Agricultural Innovation Project (NAIP), Indian Council of Agricultural Research [grant number: NAIP/C4/C-30027/2008-09] for carrying out this work.

Table 3. Response variable of validation study of Indian white prawn.

<table>
<thead>
<tr>
<th>TMA (mg N$_2$ 100 g$^{-1}$)</th>
<th>TVB-N (mg N$_2$ 100 g$^{-1}$)</th>
<th>FFA (mg % oleic acid)</th>
<th>Hardness (N)</th>
<th>L*</th>
<th>a*</th>
<th>b*</th>
<th>TPC (Log10 CFU/g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.5 ± 0.55</td>
<td>27.5 ± 0.92</td>
<td>26.5 ± 0.81</td>
<td>59.12 ± 0.73</td>
<td>57.10 ± 0.97</td>
<td>-1.3 ± 0.60</td>
<td>3.18 ± 0.85</td>
<td>4.5 ± 0.88</td>
</tr>
</tbody>
</table>
References


