Application of Response Surface Methodology in Scallop Shelling

Cunzhuang Lu
Shandong University
Chenxu Cai
Shandong University
Jianhua Zhang (jhzhang@sdu.edu.cn)
Shandong University
Aiquan Wang
Shandong Provincial Institute of Mechanical Design
Fuqian Li
Shandong Golden Scoop Food Machinery Co., LTD.

Research Article

Keywords: Scallop shelling, Mechanization scallop processing, Response surface methodology, Binding force, Mathematical regression model

Posted Date: March 2nd, 2021

DOI: https://doi.org/10.21203/rs.3.rs-255330/v1

Application of response surface methodology in scallop shelling

Cunzhuang Lu[1,2] • Chenxu Cai[1,2] • Jianhua Zhang[1,2*] • Aiquan Wang[3] • Fuqian Li[4]

1 School of Mechanical Engineering, Shandong University, Jinan 250061, China

2 Key Laboratory of High Efficiency and Clean Mechanical Manufacture of MOE/Key National Demonstration Center for Experimental Mechanical Engineering Education, Jinan 250061, China

3 Shandong Provincial Institute of Mechanical Design, Jinan 250031, China

4 Shandong Golden Scoop Food Machinery Co., LTD., Weihai 264300, China

*Corresponding author

School of Mechanical Engineering, Shandong University, Jinan 250061, China.

E-mail addresses: jhzhang@sdu.edu.cn (J.H. Zhang)

Running title: Regression model of scallop shelling

Abstract

Shelling is a central and crucial step in the mechanized processing of scallops. However, current research on the peeling mechanism is insufficient, and a relatively complete theoretical system has not been established so far. This paper proposes an application of response surface methodology and the design of an experiment to provide and stimulate further research on the automation of scallop shucking. Effective factors on the binding force of scallops are evaluated and discussed in this paper. The relationship between responses with significant factors is established. By employing response surface methodology, mathematical regression model can be efficiently performed. This response model is applied to analyze the response surface contours and surface plots to estimate shelling performance by developing a better shucking process. At the same time, quadric model proposed is used not only for predicted optimal process parameters but also for process optimization, and enrich the theoretical system of shellfish shelling.

Keywords Scallop shelling · Mechanization scallop processing · Response surface methodology · Binding force · Mathematical regression model

Introduction

Scallops, as one of the most essential economic shellfish, are widely distributed in coastal countries and regions [1-3]. Scallops are extremely popular among consumers because of fresh and tender meat, rich nutrients [4]. Besides, it also plays a crucially important role in improving blood lipids, fighting fatigue, and enhancing immunity. Adductor muscle, the main edible part of scallop, which could be made into massive delicious dishes after being dried, which is highly sought after by some food lovers [5-8]. The Scallop Skirt could be made into delicious seafood soy sauce, a good helper for stir-fry seasoning, and could also serve as processed into raw materials for bait. Using biochemical technology to prepare medicinal value of scallop extract from scallop viscera mass could be utilized to treat certain diseases. The variety of colors of the shells, which are crushed and ground to make powder, could be applied to decorate walls [9].

In short, no matter what products are processed, most of them need to be shelled first. In view of this, it is extremely important to deal with the problem for the separation of shellfish shell and meat. In the prior period, it has been one of the tough and challenging problems in this field. The traditional shucking way is by hand, with low efficiency and requires adequate physical strength [10]. Since the 19th century, shellfish shelling has applied mechanics, thermal, and pressure other technologies [11]. A steam shelling machine was proposed by Zhang et al. [12] to address scallop shelling. High pressure (HP) [13-18] technology is applied to scallops or oysters processing, after applying HP technology, scallops or oysters could be effectively detached from shells, peeled the scallops or oysters. High hydrostatic pressure (HHP) [19] also has potential in solving shelling problems. Yi et al. [20] proposed HHP is an alternative for shellfish detaching, experiment reveals that HHP peeling at 200MPa for 3 minutes can make the adductor muscle 100% shucked. Besides, Martin et al. [21, 22] presented a heat-cool process to promote the separation of oysters, which could make the separation rate higher than 85%. Other classic methods are also applied to enrich this field. For example, Little et al. [23] presented laser added shellfish shelling. Due to the high energy of laser beam, it is irradiated on the adductor muscle, so that the adductor muscle falls off from the inner surface of shell. Because laser added shelling method is limited to the range of shellfish species, it has not been commonly used. So far, although there have been many methods to work around this issue. However, many studies only have focused on shellfish shelling methods. By contrast, less attention has been focused on the establishment and optimization of shellfish shelling model.

The research of this paper describes areas where further research is required that will advance the technology of shellfish shucking. Water bath thermal shelling technology is adopted in order to study shellfish shucking. By researching under what conditions the binding force of scallop is the smallest and to improve the degree of scallop shelling. Under the design environment in Design-Expert 10.0, analysis of variance (ANOVA) is proposed for this paper to select the most significant factors level range and further analyze in a response surface model. Built on the experimental data and contour graphs, an approximate functional relationship was provided. According to the result of the smaller lack of fit of the model, it can be determined that the reliability of the model is high, which could be accepted to analyze and predict the binding force of scallops. This method enriches the theory for scallop shelling and builds a solid foundation in other shellfish shelling.

Materials and methods

Equipment and sample preparation

Bay scallops used in the experiment were purchased from the Qipan Street Comprehensive Market, Lixia District, Jinan City, Shandong Province, and 50 fresh active bay scallops with no parasites, good appearance, and different sizes (death and destruction have been excluded) were selected random. The electronic balance was bought from Shanghai Hengji Scientific Instrument Co., Ltd. (China). Vernier caliper was purchased from Guilin Guiliang Tools Co., Ltd. (China). The timer was bought from Shenzhen Yuanguanghao Electronics Co., Ltd. (China). Digital force gauge (HP-10N) was bought from Yueqing Aidebao Instrument Co., Ltd. (China). Digital display constant temperature oil bath was bought from Jintan District Xicheng Xinrui Instrument Factory (China).

Measuring method of binding force

In the experiment, V-shaped probe of the digital force gauge was employed for measuring the binding force of scallop. The process was recorded when reaching the peak of the binding force, and the values were processed by Origin 2018 software so that the value on the digital force gauge could be read as shown in Figure 1.

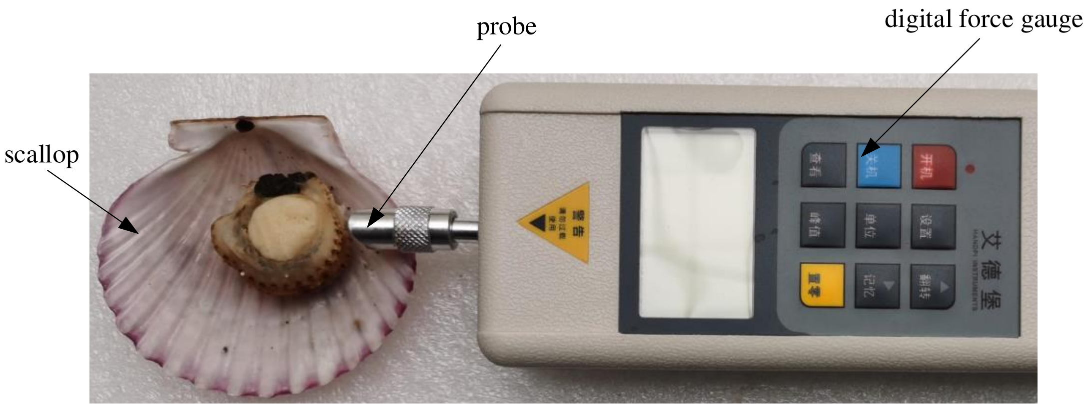


Fig. 1 Binding force measurement experiment figure

Structural characteristics of bay scallop

The interior of the bay scallop is mainly consisted of five parts: shell, ligament, adductor muscle (scallop pillar), viscera mass, and Scallop Skirt (mantle). Among them, ligament, adductor muscle, viscera mass, and Scallop Skirt are soft biological tissues with complex and easily deformable characteristics. Shell, as the outermost layer of scallop, has a relatively hard texture and is mainly used to protect the soft tissues of the body. The internal structure of the bay scallop is shown in Figure 2.

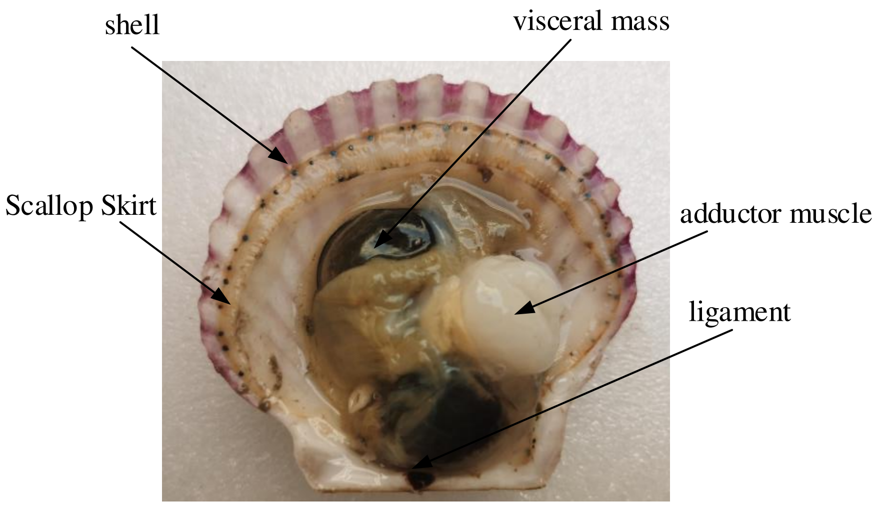


Fig. 2 The internal structure of bay scallop

The biological binding force of bay scallop

The biological binding force is a collective term for a series of intermolecular forces in organisms, including the ubiquitous van der Waals forces, hydrophobic bonds formed by the interaction of polar genes in molecules, and hydrogen bonds formed by the interaction of hydrogen atoms [24, 25]. In the shucking process, the adductor muscles that are glued to the shell are cut off or released. In essence, the process of processing scallops is the process of overcoming these biological binding forces (hereinafter referred to as the binding force), and the process of overcoming these intermolecular forces.

Measurement of scallop dimensions

When measuring, clean and wipe the soil on the surface of the scallops. Next, using a vernier caliper (measurement accuracy: 0.02mm) to measure the dimensions of the selected scallops (see Figure 3), and the three morphological characteristics of the scallop shell length, shell width, and shell height were measured. Particularly to point out that the shell length refers to the maximum straight line distance between the left and right edges of the shell, the shell width refers to the maximum straight line distance between the two shells, and the shell height refers to the maximum straight line distance from the top of the shell to the ventral edge. Furthermore, the seawater on each surface absorbing dry with filter paper, and electronic balance (measurement accuracy: 0.01g) was employed to measure the quality of live scallops one by one, and the measurement data are presented in Table 1.

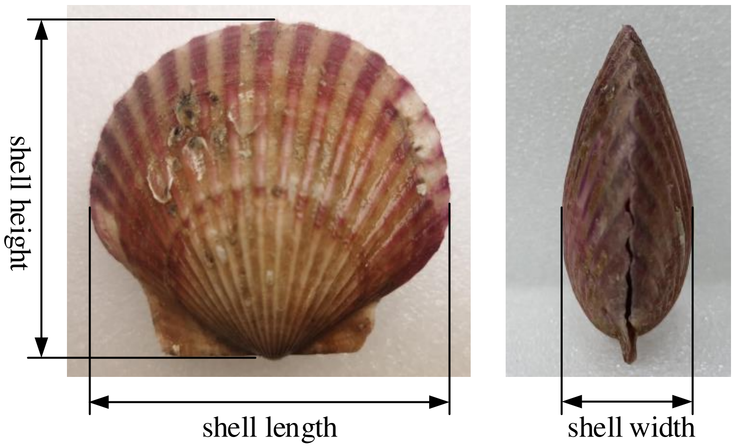


Fig. 3 Dimensional distribution of scallop

Table 1 Statistics of basic scallop shapes

Serial number	Quality /g	Shell length /mm	Shell width /mm	Shell height /mm
1	46.48	70.70	28.60	68.40
2	42.89	74.58	24.36	71.88
3	34.20	69.40	27.04	61.00
4	38.45	65.84	27.46	59.72
5	33.63	63.86	25.10	60.46
6	38.40	66.88	24.44	66.00
7	45.38	67.66	28.48	67.66

Table 1 (Continued)

Serial number	Quality /g	Shell length /mm	Shell width /mm	Shell height /mm
8	31.67	66.44	27.26	64.56
9	45.64	71.58	27.10	64.62
10	43.46	70.18	27.20	67.50
11	48.44	72.46	26.82	70.04
12	40.27	68.58	26.78	60.30
13	43.07	66.32	27.22	65.18
14	40.30	73.68	28.92	66.90
15	43.54	69.76	29.14	62.34
16	37.36	68.12	27.00	62.78
17	44.24	71.26	29.34	63.10
18	44.40	69.06	27.28	62.36
19	33.25	64.18	26.86	58.58
20	40.97	69.96	26.64	63.46
21	55.36	70.60	30.08	69.22
22	53.18	71.00	26.64	65.12
23	41.28	66.88	27.46	66.88
24	40.43	72.00	29.14	66.00
25	42.70	68.14	29.10	62.34
26	35.71	67.76	27.06	60.78
27	38.12	69.04	25.60	64.64
28	46.96	71.28	28.00	68.84
29	42.38	71.00	30.00	64.04
30	36.81	62.76	30.00	58.82
31	35.71	66.42	25.54	63.76
32	35.15	69.24	30.14	66.00
33	34.05	67.72	26.78	66.00
34	37.82	65.16	26.12	63.26

Table 1 (Continued)

Serial number	Quality /g	Shell length /mm	Shell width /mm	Shell height /mm
35	46.53	72.70	28.18	66.54
36	36.27	70.64	26.68	68.20
37	44.38	67.42	25.56	63.80
38	45.31	67.80	27.92	64.90
39	45.62	73.16	28.94	69.00
40	50.72	71.06	28.24	65.82
41	52.81	69.74	29.54	63.12
42	35.32	67.14	25.60	63.32
43	41.89	69.04	28.92	64.06
44	58.57	72.00	30.06	65.82
45	40.14	66.92	27.18	63.14
46	46.43	69.82	27.46	65.96
47	46.44	71.00	26.20	65.82
48	59.29	74.24	27.28	65.18
49	53.22	70.00	29.02	64.72
50	29.78	69.00	27.12	65.00

Note: When the data is equal to the boundary value, it is divided into larger groups.

Statistical analysis

After sorting out the quality and dimensions of the measure scallops, Excel 2016 and Origin 2018 software are employed to analyze and process, and distribution histograms were drawn. Figure 4 displays the distribution histograms of the quality, shell length, shell width, and shell height of 50 experimental scallops. The abscissa represents the experiment grouping situation and the ordinate represents the number of traits. From the distribution histograms, it can be noted that the quality and shape of scallops content the normal distribution. The measurement results provide data support for subsequent experiments and sample selection.

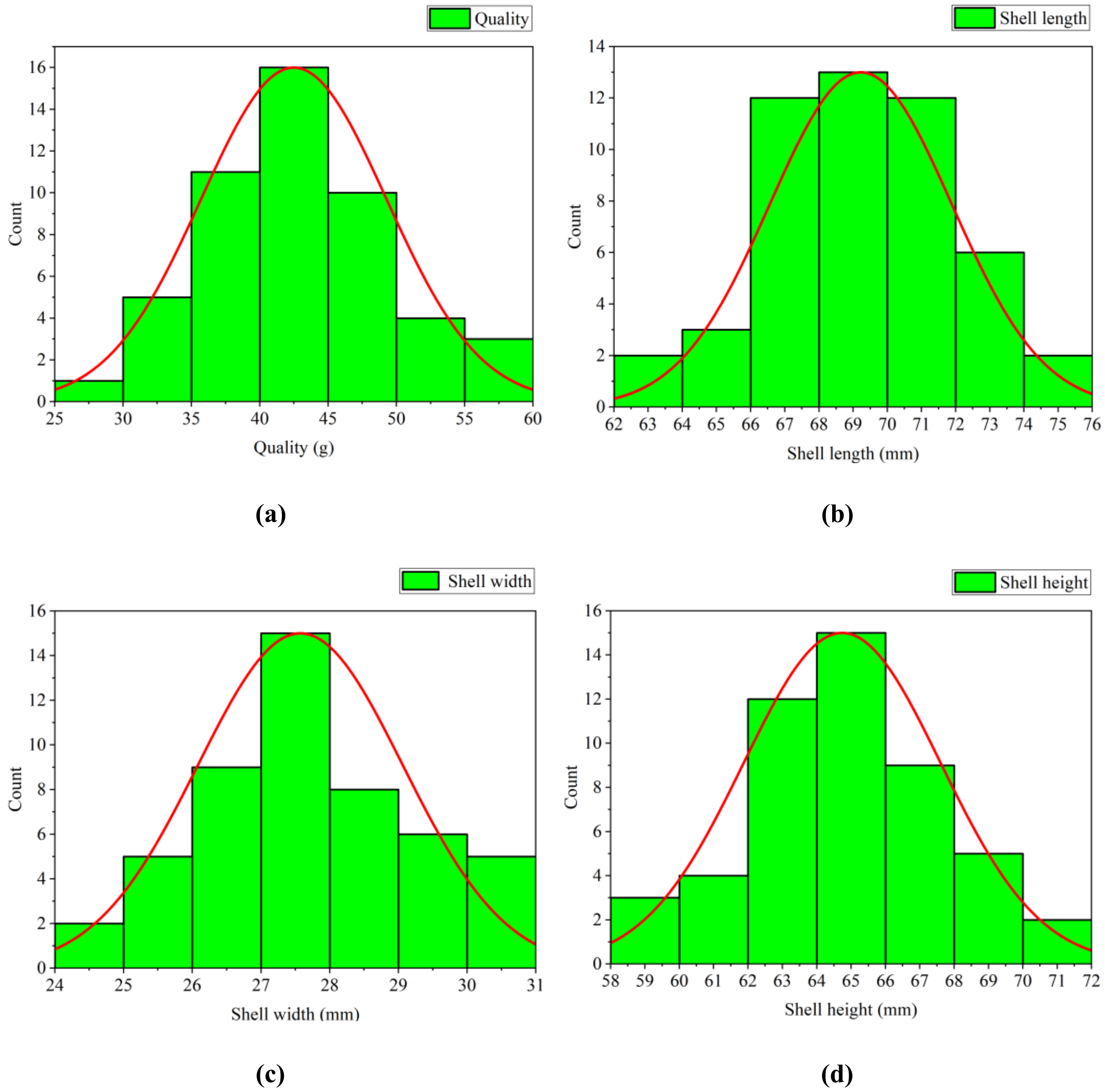


Fig. 4 Histogram of scallop characteristics distributions; quality **(a)**, shell length **(b)**, shell width **(c)**, and shell height **(d)**

Binding force experiments design for scallop shelling process

Experimental procedure and design

In this paper, fresh bay scallops are employed as the research object, and three factors of water temperature, heating time, and scallop quality are studied to analyze the law of influence on the binding force and provide positive guidance for subsequent automated shelling production. On this basis, first of all, based on the single factor tests, the optimal level range of the influence of parameters on the binding force was screened out, which reduced variance and established a good foundation for the later response surface methodology. On second thoughts, the Box-Behnken response surface methodology was utilized to optimize and test the selected optimal parameter range to obtain the response surface methodology model and optimal match of the working parameters of scallop shell meat separation.

The factors range of selection for tests

In this experiment, in terms of the size level, bay scallops with shell length of 66-72mm were selected as the experimental research object.

In the single factor test process, three parameters (water temperature, heating time, and scallop quality) were determined as the factors of tests, and the binding force is chosen as the test index. Under single factor test process, other factors are fixed, the influence of a certain factor on its binding force is analyzed. Under each test factor level, 20 bay scallops were selected for repeating tests. The test conditions are given in Table 2.

Table 2 Single factor tests table

Factors	Initial condition	Changing conditions
Water temperature (°C)	60	70、80、90、100
Heating time (min)	2	3、4、5、6
Scallop quality (g)	31-	36-、41-、46-、51-、

The influence of water temperature on binding force

As the water temperature increases, the temperature inside the scallop shell gradually increases, and the binding force between the shell and the adductor muscle gradually decreases. The effect of water temperature on the binding force is shown in Figure 5.

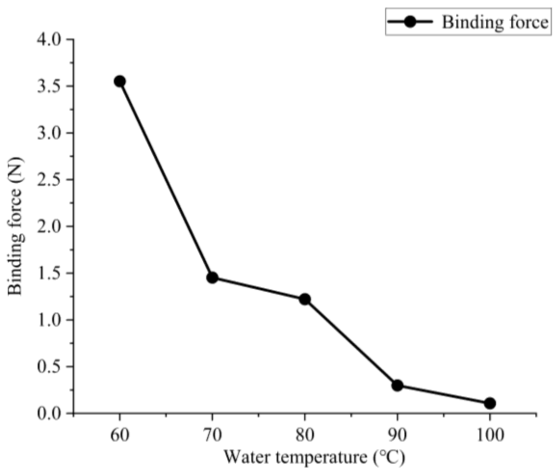


Fig. 5 The relationship between water temperature and binding force

Because the scallop adductor muscle is fibrous tissue, rich in protein, has a certain toughness, and is exceedingly sensitive to temperature changes. When the water temperature gradually increases and arrives at a certain level, the actomyosin in the fibrous tissue will continuously shrink. When the maximum temperature exceeds its tolerance, actomyosin will experience relative dislocation, slip and rupture, and even lose its original biological activity [26]. At this time, the adductor muscle gradually loosens and falls off until it is separate. Therefore, within a certain water temperature range, the higher the water temperature, the more distinct the decrease in binding force, and the better the separation effect of scallop adductor muscle from the shell.

The influence of heating time on binding force

As the heating time increases, the heat absorbed in the scallop will increase, and the binding force between the shell and the adductor muscle gradually decreases. The effect of heating time on the binding force is shown in Figure 6.

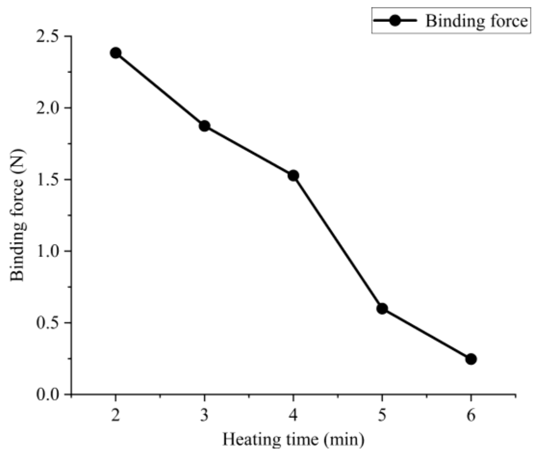


Fig. 6 The relationship between heating time and binding force

In the heating process, heat is transferred from the outside to the inside of shell, only when the junction between the adductor muscle and the shell reaches a certain temperature could be detached. However, it takes a certain period of time to come to the temperature at which the shell flesh falls off and separates. If the heating time is too short, the temperature at the junction of the adductor muscle and the shell will not reach the shedding temperature, and the binding force between them will be too late to weaken or weaken very little. The degree of shedding of the adductor muscle and the shell is not distinct. As the heating time increases, the heat transferred to the shell increases, and the heat absorbed by the adductor muscle also increases, which enormously undermine the binding force between the adductor muscle and the shell, and enhanced the effect of scallops shucking. Therefore, within 5 minutes, the longer the heating time, the smaller the binding force, and the better the shelling effect.

The influence of scallop quality on binding force

As the quality of scallop increases, the quality of other scallop structures such as adductor muscle also gradually increases, and the binding force between the shell and the adductor muscle gradually increases. The effect of scallop quality on the binding force is shown in Figure 7.

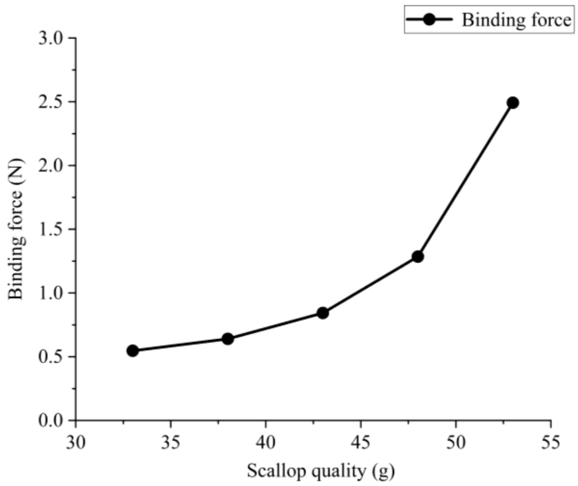


Fig. 7 The relationship between scallop quality and binding force

It is particularly emphasized that compared with smaller scallops, the mass and diameter of the adductor muscle of larger scallops increase accordingly. When heated, larger scallops require higher temperature and longer time to make adductor muscle fall off and separate. Similarly, for larger scallops, the binding force is greater than smaller scallops, and the degree of shedding is not distinct or even more difficult to fall off. Thus, when scallop quality gradually increases, the binding force is large, the shelling effect of scallop is poor, and the shucking rate is low.

Response surface methodology

The response surface methodology (RSM) was first presented by Box and Wilson (1951) and has been a powerful technique in many different application areas [27-30]. The objective is to solve the relationship between the input (several experimental variables) and outputs (responses or test index) [31-33]. In addition, the RSM model is used to determine the levels of experimental parameters and to optimize the responses [34].

Characteristics and advantages of the RSM are to provide a mathematical model including the first-order term, the square term of each significant factor, and the first-order interaction term between any two factors through a reasonably designed limited number of an experiment, to fit these factors [35]. Thus, the RSM is useful for quickly modeling, shortening optimization time, and improving application credibility. Through the analysis of the function response surface and contour lines, the level of various factors affecting the response value and their interaction is optimized and evaluated, and the optimal conditions of the multi-factor system are quickly and effectively determined. The response surface function expression is generally shown in Equation (1).

$$y = \beta_o + \sum_{i=1}^{n} \beta_i X_i + \sum_{i=1}^{n} \beta_{ii} X^2 + \sum_{i<j} \sum \beta_{ij} X_i Y_j + \varepsilon \quad (1)$$

Where β_o, β_i, β_{ii}, β_{ij} are the coefficient to be determined, and ε represents the error of y. This is a second-order polynomial that can approximately replace the actual function within a certain range. After obtaining experimental data, least squares method was employed to gain the response surface function.

Response surface methodology design

Single factor test results were carried out to pick out the independent variables levels which affect the chosen response variables. Next, the best level range of the three factors of water temperature (A), heating time (B), and scallop quality (C) were determined, designing a three-factor three-level response surface methodology with the binding force (Y) as the response value. This paper uses the Design-Expert 10.0 software and the Box-Behnken experimental to design RSM model. The experimental factors and levels design are given in Table 3.

Table 3 Factors and levels of response surface methodology

Levels	Factors		
	A Water temperature	B Heating time	C Scallop quality
-1	60	2	33
0	80	4	38
1	100	6	43

Experimental results and discussion

Estimated binding force characteristics

Table 4 shows the results of the response surface methodology experiment.

Table 4 Experimental design and results of response surface methodology

Test number	Water temperature ℃	Heating time min	Scallop quality g	Binding force N
1	100	60	38	0.035
2	60	2	38	4.530
3	80	6	33	0.047
4	80	4	38	0.848
5	80	4	38	0.881
6	100	4	43	0.891
7	60	4	33	1.898
8	80	4	38	0.601
9	80	2	43	4.129
10	80	4	38	0.741
11	100	2	38	0.694
12	80	6	43	1.551
13	80	2	33	1.871
14	60	6	38	1.991
15	100	4	33	0.039
16	80	4	38	0.999
17	60	4	43	3.901

Estimating the effects of each factor

Table 5 shows the ANOVA for the experimental results. The ANOVA analysis was performed based on the RSM for various factors characteristics, and was employed to efficiently explore the important factors that affect scallop shelling process. From Table 5, it can be readily seen that the F value $F_A > F_B > F_C$, in the ANOVA table indicates that the larger the F value, the more significant the influence of this factor on the test results. Therefore, it can be further concluded that factors A and B are the most important factor, whereas, C is less significant, that is, water temperature and heating time have the greatest influence on the binding force, which is the main factor, followed by scallop quality.

Response surface methodology analysis

The regression types of model for the RSM were selected according to the results of the ANOVA. The ANOVA results present the fitting linear in the experiments. The ANOVA table reveals that the model $P < 0.0001$, indicating that the corresponding quadratic model obtained by fitting has a high degree of significance, which has an extremely significant impact on the response value Y. In order to evaluate each influential factors in the quadratic RSM, Design-Expert 10.0 software was used to perform multiple regression fitting on the experimental data of binding force obtained in the experiment in Table 5.

Furthermore, from the ANOVA Table 5, it can be observed that single factors, quadratic term and pairwise interactions are significant. Among them, factors A, B, and C in the first term have $P < 0.0001$, indicating that the water temperature, heating time and scallop quality of each factor have a significant influence on the response. Compared with BC, the pairwise interactions of AB and AC are more significant, indicating that the interaction terms of water temperature and heating time and the interaction terms of water temperature and scallop quality have significant impact on the binding force. The model lack of fit item reflects the inconsistency between the experimental data and the model, $P = 0.39$, indicating that the lack of fit is smaller. Therefore, it is believed that the model fits well with the actual, and unknown factors have little interference with the experimental results. The multiple regression model obtained by fitting can better analyze and predict the change law of scallop binding force and various factors. The quadratic regression model equation of the binding force is obtained according to each ANOVA table with significant factors. That is, $Y = 0.81 - 1.33A - 0.95B + 0.83C + 0.47AB - 0.29AC - 0.19BC + 0.39A^2 + 0.61B^2 + 0.48C^2$.

Table 5 ANOVA for various factor types

	Sum of square	Degree of freedom	Mean square	F value	P value
Model	31.77	9	3.53	51.36	<0.0001
A	14.21	1	14.21	206.72	<0.0001
B	7.22	1	7.22	105.05	<0.0001
C	5.47	1	5.47	79.63	<0.0001
AB	0.88	1	0.88	12.86	0.0089
AC	0.33	1	0.33	4.82	0.0642

BC	0.14	1	0.14	2.07	0.1936
A^2	0.64	1	0.64	9.35	0.0184
B^2	1.56	1	1.56	22.64	0.0021
C^2	0.96	1	0.96	13.98	0.0073
Residual	0.48	7	0.069		
Lack of fit	0.39	3	0.13	5.75	0.0621
Pure error	0.091	4	0.023		
Cor total	32.25	16			

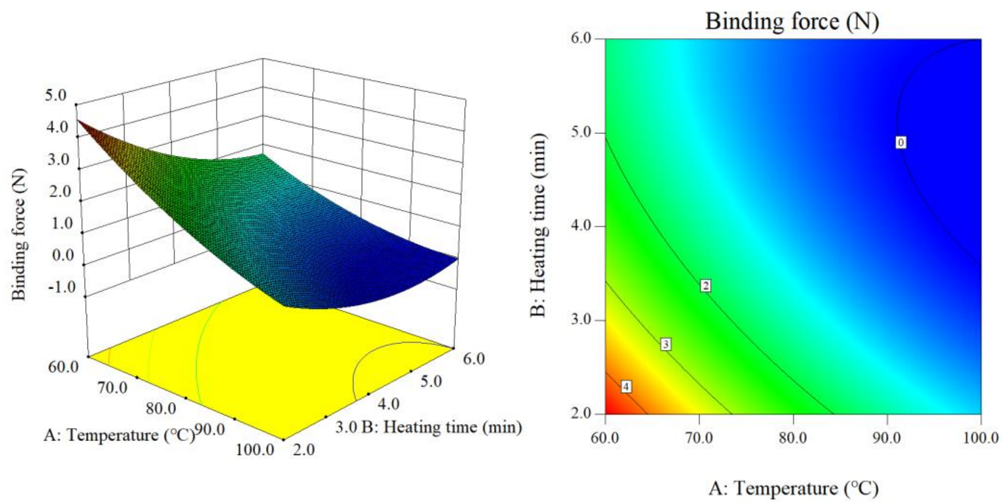
The relative importance of the parameters and their interaction between the parameters can be observed from the values of the above polynomial coefficients. Table 6 implies that the correlation coefficient R^2 and correction coefficient R_{Adj} for quadratic regression model were 0.9851 and 0.9659. This means that 96% of the total variance of the binding force percentage could be explained through the regression model. CV value is 17.38%, suggesting that the model can work well reflect the true test value, and the reliability of the test is higher. Therefore, we can conclude that the performance of the quadratic regression model is satisfactory and can be applicable to actual production.

Table 6 Regression coefficient of the responses model

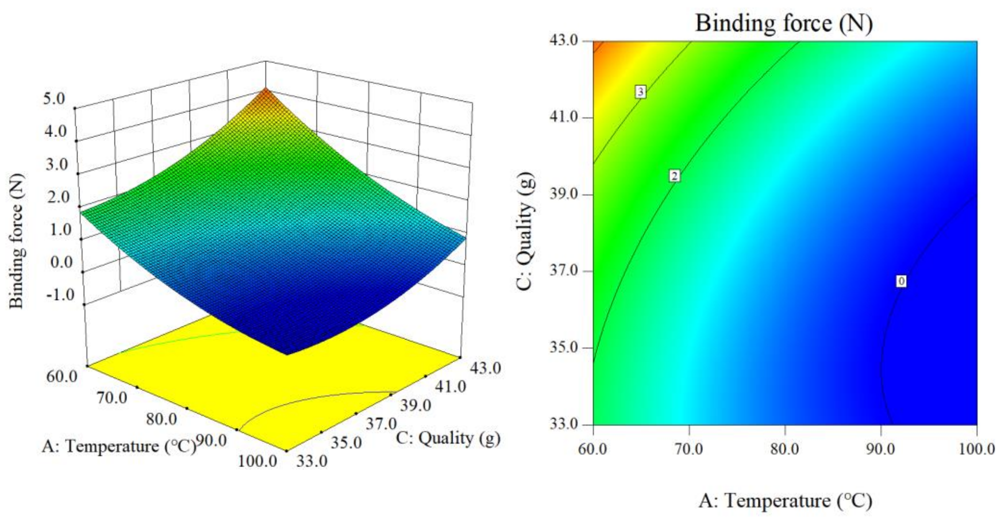
Std. Dev.	0.26	R-Squared	0.9851
Mean	1.51	Adj R-Squared	0.9659
C. V. %	17.38	Pred R-Square	0.8019
PRESS	6.39	Adeq Precision	23.648

Response surface contour analysis

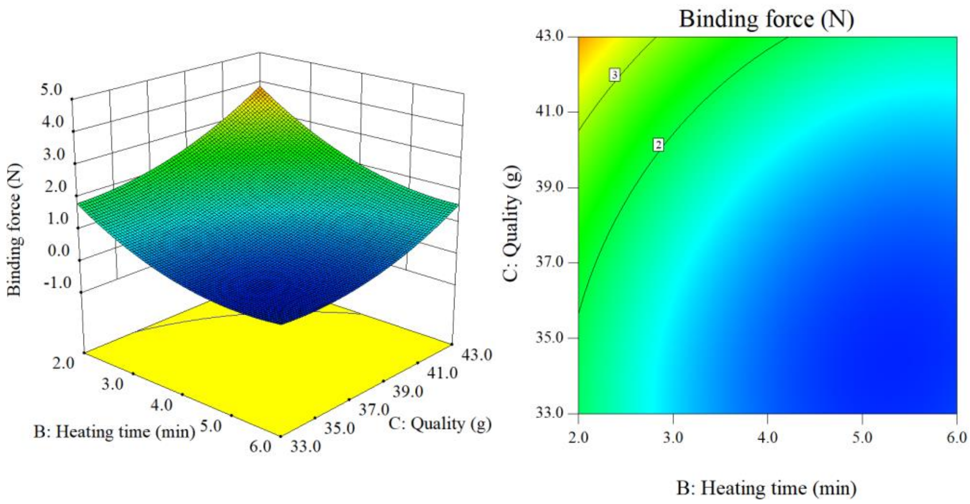
To further study the interaction between related factors and determine the best point, based on Design-Expert 10.0 software, from quadratic regression model equation, a series of corresponding response surface contours of all possible factor pairs and their interactions are obtained in Figure 8. Figure 8(a) and (b) reveal the response surface contour effect of the temperature and heating time and temperature and scallop quality, respectively. It is obvious that the binding force tends to decrease with the increase of water temperature. Analysis of the reasons is primarily because the temperature is too high, which reduces the elasticity of the adductor muscle and even causes its maturation. Under the action of high temperature, the actomyosin (main functional protein in the adductor muscle) will unwind, and some tissues will be eroded and deform, which will cause the adductor muscle fall off. As can be seen in Figure 8(a) and (c) show the response surface contour between temperature and heating time and heating time and scallop quality of the interaction influence on the binding force. For the binding force tends to decrease with the increase of heating time. Analysis of the causes is chiefly because as the heating time increases, the heat absorbed in the scallop shell will increase. At the same time, the fibrous tissue structure of the adductor muscle shows a gradual breaking trend. Figure 8(b) and (c) present the response surface contour between temperature and scallop quality and heating time and scallop quality of the interactive influence on the binding force. As the increase of scallop quality, the binding force is increasing. The reason is that the larger the scallop, the quality of the scallop structure such as the adductor muscle also has increase accordingly. Therefore, the higher the quality of the scallop, the less likely it is to fall off the adductor muscle.



(a)



(b)



(c)

Fig.8 Response surface contour plot for the binding force; changing control factors were temperature and heating time **(a)**, temperature and quality **(b)**, and heating time and quality **(c)**

Optimization of shelling process conditions

To obtain the best solution, it is necessary to optimize the generated quadratic mode under constraints. It can be seen from the response surface graphs in Figures 8 that the response value Y has a minimum value and the shell and flesh are completely separated, that is, the smaller the binding force Y or zero, the more significant the separation effect of scallop shell flesh. In the optimization standard, target=0 can be selected for the Y term, and click on the optimization results (solutions). At the same time, generated optimization results are presented in Figure 9.

As shown in Figure 9, it is obvious that the optimization results of response surface methodology that the state parameters for realizing shell and meat separation are not unique, and the excellent state parameters can be freely selected according to economic benefits and actual conditions. At the same time, the optimization results provide a certain theoretical basis for a better selection of shells and meat separation parameters.

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:temperature	is in range	60	100	1	1	3
B:time	is in range	2	6	1	1	3
C:quality	is in range	33	43	1	1	3
force	is target = 0	0	4.53	1	1	3

Solutions

Number	temperature	time	quality	force	Desirability	
1	89.570	5.377	37.462	0.000	1.000	Selected
2	96.093	3.662	36.972	0.000	1.000	
3	98.181	4.722	39.448	0.000	1.000	
4	88.910	4.223	33.486	0.000	1.000	
5	99.648	5.539	39.283	0.000	1.000	
6	86.360	4.669	35.076	0.000	1.000	
7	92.827	4.731	38.298	0.000	1.000	
8	92.487	4.677	38.153	0.000	1.000	
9	87.292	5.527	33.616	0.000	1.000	
10	99.710	3.146	34.216	0.000	1.000	
11	86.093	5.445	34.054	0.000	1.000	
12	99.334	5.247	39.566	0.000	1.000	
13	92.545	4.138	37.197	0.000	1.000	
14	98.620	3.366	36.604	0.000	1.000	
15	85.902	5.473	34.406	0.000	1.000	
16	98.706	5.713	38.857	0.000	1.000	
17	97.721	3.736	37.820	0.000	1.000	
18	87.754	4.442	33.407	0.000	1.000	
19	96.389	3.444	33.406	0.000	1.000	
20	98.231	5.231	39.426	0.000	1.000	
21	87.645	4.419	35.291	0.000	1.000	
22	90.427	4.250	36.584	0.000	1.000	
23	91.220	5.658	37.595	0.000	1.000	
24	98.397	3.359	36.453	0.000	1.000	
25	97.998	4.698	39.404	0.000	1.000	
26	98.636	4.064	38.826	0.000	1.000	
27	91.494	4.670	37.849	0.000	1.000	
28	85.651	4.956	33.916	0.000	1.000	
29	99.750	3.164	35.604	0.000	1.000	
30	87.101	4.830	33.011	0.000	1.000	
31	89.609	5.293	37.523	0.000	1.000	
32	88.532	4.340	33.232	0.000	1.000	
33	93.489	5.857	37.655	0.000	1.000	
34	90.186	5.263	37.717	0.000	1.000	
35	94.146	5.972	34.071	0.000	1.000	
36	93.814	3.656	33.439	0.000	1.000	
37	99.043	4.825	39.623	0.000	1.000	
38	91.789	5.576	37.885	0.000	1.000	
39	98.327	3.517	37.238	0.000	1.000	
40	99.526	3.637	38.046	0.000	1.000	
41	91.541	5.832	37.238	0.000	1.000	
42	97.144	3.432	33.108	0.000	1.000	
43	98.730	5.490	39.248	0.000	1.000	
44	96.157	5.407	38.973	0.000	1.000	
45	90.519	4.055	33.176	0.000	1.000	
46	85.904	5.424	35.475	0.000	1.000	
47	88.641	4.361	35.911	0.000	1.000	
48	86.221	5.105	35.964	0.000	1.000	
49	91.511	5.258	38.095	0.000	1.000	
50	91.115	3.894	33.819	0.000	1.000	
51	88.124	5.574	33.458	0.000	1.000	
52	98.661	5.414	39.331	0.000	1.000	
53	88.714	5.872	35.555	0.000	1.000	
54	85.911	4.948	33.650	0.000	1.000	
55	87.190	5.204	33.043	0.000	1.000	
56	98.888	4.411	39.351	0.000	1.000	
57	98.605	5.298	39.433	0.000	1.000	
58	98.567	5.485	39.234	0.000	1.000	
59	98.482	5.835	38.517	0.000	1.000	
60	93.598	4.824	38.560	0.000	1.000	
61	86.948	5.420	33.479	0.000	1.000	
62	95.124	3.722	36.811	0.000	1.000	
63	87.733	5.712	36.015	0.000	1.000	
64	88.577	5.853	34.785	0.000	1.000	
65	89.845	5.711	37.045	0.000	1.000	
66	88.619	5.593	33.370	0.000	1.000	
67	97.269	3.305	34.659	0.000	1.000	
68	87.930	5.651	36.372	0.000	1.000	
69	88.935	4.162	33.986	0.000	1.000	
70	89.616	5.703	36.982	0.000	1.000	
71	98.826	3.710	38.067	0.000	1.000	
72	86.365	5.587	35.310	0.000	1.000	
73	98.725	3.319	36.354	0.000	1.000	
74	95.229	5.721	38.351	0.000	1.000	
75	87.816	5.718	34.171	0.000	1.000	
76	97.438	4.400	39.053	0.000	1.000	
77	87.321	4.483	35.297	0.000	1.000	
78	99.283	3.828	38.494	0.000	1.000	
79	92.101	5.758	37.609	0.000	1.000	
80	93.890	5.438	38.527	0.000	1.000	
81	85.944	5.412	35.557	0.000	1.000	
82	97.058	4.620	39.181	0.000	1.000	
83	97.912	3.994	38.520	0.000	1.000	
84	90.639	3.927	34.237	0.000	1.000	
85	88.018	5.253	36.945	0.000	1.000	
86	90.736	5.228	37.890	0.000	1.000	
87	88.952	4.158	34.847	0.000	1.000	
88	91.253	4.214	36.870	0.000	1.000	
89	93.249	4.837	38.482	0.000	1.000	
90	87.538	5.596	33.744	0.000	1.000	
91	92.025	4.556	37.869	0.000	1.000	
92	87.134	5.373	33.307	0.000	1.000	
93	98.139	5.041	39.486	0.000	1.000	
94	92.398	3.732	34.297	0.000	1.000	
95	88.746	4.232	33.595	0.000	1.000	
96	91.437	4.641	37.796	0.000	1.000	
97	85.715	5.315	34.016	0.000	1.000	
98	86.576	5.305	33.425	0.000	1.000	
99	88.274	4.276	33.841	0.000	1.000	
100	85.343	5.171	34.269	0.000	1.000	

Fig.9 Response surface methodology optimization results

Conclusions

This paper puts forward a general method to obtain and optimize water bath thermal shelling solutions for scallops based on RSM. It is experimentally revealed that the RSM with designed experiments is a simple and intensely method for improving high efficiency shelling rate of scallops. Higher shelling rate with lower binding force and optimal conditions on the scallop thermal shelling has been achieved. Based on the experimental results, the main contributions of this paper are described as follows.

(1) In order to design an experiment plan for measuring the binding force of scallops, the bay scallop was used as the experimental object. The most significant factors identified by ANOVA affecting the binding force process are the factors A (water temperature) and B (heating time) for scallop shelling, and the factor C (scallop quality) less important.

(2) In this paper, a quadratic model with interaction terms was fitted to the data, and the correlation coefficient R^2 and correction coefficient R_{Adj} for quadratic regression model was 0.9851 and 0.9659, respectively. This implies that 96% of the total variance of the binding force percentage could be explained through the regression model. It is clear that the quadratic response surface model provides a new direction for scallop shelling field, which established a good foundation for subsequent other shellfish shelling technology. This method enriches the field of shellfish shelling and suitable for the research of the shellfish shelling.

(3) In addition, the concept of optimization is introduced to further enrich the theory in the field of shellfish shelling. The RSM is extremely effective in determining the most influential parameters and the optimal conditions in scallop shelling process. The optimized results obtained provide a theoretical basis for better application to actual production in the future.

Acknowledgements

This work was financially supported by the Key Research and Development Plan of Shandong Province, China [grant number 2019JZZY020709].

Disclosure Statement

No potential conflict of interest was reported by the authors.

References

[1] M. Chen, B. Liu, B. Ma, G. Liu, W. Cao, X. Liu, X. Yan, B. Yang, C. Wang, Aquac. **528**, 735513 (2020). https://doi.org/10.1016/j.aquaculture.2020.735513

[2] T. Ye, K. Tan, H. Zhang, H. Zheng, Sci. Total Environ. **751**, 142268 (2021). https://10.1016/j.scitotenv.2020.142268

[3] J. Yan, Y. Wang, X. Jiang, J. Han, Y. Du, J. Pan, H. Wu, Food Chem. **336**, 127687 (2021). https://doi.org/10.1016/j.foodchem.2020.127687

[4] B. Liu, Z. Liu, D. Li, M. Yu, Y. Liu, L. Qin, D. Zhou, F. Shahidi, B. Zhu, Food Chem. **323**, 126790 (2020). https://doi.org/10.1016/j.foodchem.2020.126790

[5] H. Wei, Y. Tian, T. Yamashita, G. Ishimura, K. Sasaki, Y. Niu, C. Yuan, Food Chem. **319**, 126559 (2020). https://doi.org/10.1016/j.foodchem.2020.126559

[6] H. K. Xie, G. H. Zhao, Z. X. Wu, D. Y. Li, M. T. Zhao, A. Li, H. L. Liu, D. Y. Zhou, B. W. Zhu, J. Sci. Food Agric. **101**(4), 1554-1561 (2020). https://doi.org/10.1002/jsfa.10774

[7] L. Zhao, S. Lian, Q. Ren, Z. Yang, Z. Guo, J. Lou, X. Kong, M. Li, Z. Bao, X. Hu, Aquac. **530**, 735817 (2021). https://doi.org/10.1016/j.aquaculture.2020.735817

[8] H. Xie, A. Li, M. Zhao, M. Zhang, Z. Liu, F. Yin, X. Liu, D. Zhou, F. Shahidi, B. Zhu, LWT-Food Sci. Technol. **134**, 110214 (2020). https://doi.org/10.1016/j.lwt.2020.110214

[9] S. Her, T. Park, E. Zalnezhad, S. Bae, J. Cleaner Prod. **278**, 123987 (2021). https://doi.org/10.1016/j.jclepro.2020.123987

[10] F. Wheaton, S. Hall, Aquacult. Eng. **37**(1), 67-72 (2007). https://doi.org/10.1016/j.aquaeng.2007.02.002

[11] D. E. Martin, S. G. Hall, Int. J. Food Sci. Technol. **41**(3), 223-232 (2006). https://doi.org/10.1111/j.1365-2621.2005.01052.x

[12] J. Zhang, J. G. Yi, H. Y. Jiang, J. Z. Wang, J. T. Liu, Applied Mech. Mater. **441**, 879-882 (2013). https://doi.org/10.4028/www.scientific.net/AMM.441.879

[13] M. Cruz-Romero, M. Smiddy, C. Hill, J. P. Kerry, A. L. Kelly, Innov. Food Sci. Emerg. Technol. **5**(2), 161-169 (2004). https://doi.org/10.1016/j.ifset.2004.01.002

[14] H. He, R. M. Adams, D. F. Farkas, M. T. Morrissey, J. Food Sci. **67**(2), 640-645 (2002). https://doi.org/10.1111/j.1365-2621.2002.tb10652.x

[15] K. Hsu, J. Hwang, H. Chi, K. Lai, J. Sci. Food Agric. **90**(3), 530-535 (2010). https://doi.org/10.1002/jsfa.3854

[16] D. H. Kingsley, K. Calci, S. Holliman, B. Dancho, G. Flick, Food Environ. Virol. **1**(3-4), 137-140 (2009). https://doi.org/10.1007/s12560-009-9018-5

[17] L. W. Murchie, M. Cruz-Romero, J. P. Kerry, M. Linton, M. F. Patterson, M. Smiddy, A. L. Kelly, Innov. Food Sci. Emerg. Technol. **6**(3), 257-270 (2005). https://doi.org/10.1016/j.ifset.2005.04.001

[18] R. Cao, L. Zhao, Q. Liu, Oceanic Coast. Sea Research. **16**, 351-355 (2017). https://doi.org

/10.1007/s11802-017-3087-0

[19] M. F. Patterson, J. Applied Microb. **98**(6), 1400-1409 (2005). https://doi.org/10.1111/j.1365-2672.2005.02564.x

[20] J. Yi, Q. Xu, X. Hu, P. Dong, X. Liao, Y. Zhang, Innov. Food Sci. Emerg. Technol. **18**, 57-64 (2013). https://doi.org/10.1016/j.ifset.2013.02.010

[21] D. E. Martin, J. Supan, J. Theriot, S. G. Hall, Aquacult. Eng. **37**(1), 53-60 (2007). https: //doi.org/10.1016/j.aquaeng.2006.12.006

[22] D. E. Martin, J. Supan, U. Nadimpalli, S. G. Hall, Aquacult. Eng. **37**(1), 61-66 (2007). https://doi.org/10.1016/j.aquaeng.2006.12.008

[23] N. E. Little, O. H. Smith, F. W. Wheaton, M. A. Little, Aquacult. Eng. **37**(1), 35-43 (2007). https://doi.org/10.1016/j.aquaeng.2006.12.007

[24] I. Anapolitanos, I. M. Sigal, Commun. Pure Applied Mathematics. **70**(9), 1633-1671 (2017). https://doi.org/10.1002/cpa.21695

[25] W. E. Thomas, Curr. Nanosci. **3**(1), 63-83(2007). https://doi.org/10.2174/157341307779940544

[26] K. Namba, M. Kabayashi, S. Aida, K. Uematsu, M. Yoshida, Y. Kondo, Y. Miyata, Fish. Sci. **61**(2), 241-244 (1995). https://doi.org/10.2331/fishsci.61.241

[27] T. Ahmad, S. G. Gilmour, J. Stat. Plan. Inference. **140**(1), 92-103 (2010). https://doi.org/ 10.1016/j.jspi.2009.06.011

[28] T. Chien, M. Jean, M. Lu, W. Huang, J. Chin. Inst. Ind. Eng. **27**(2), 90-102 (2010). https://doi.org/10.1080/10170660903522617

[29] P. Li, H. Li, Y. Huang, K. Wang, N. Xia, Adv. Eng. Softw. **114**, 325-336 (2017). https://doi.org/10.1016/j.advengsoft.2017.07.014

[30] N. Yang, P. K. Das, X. Yao, Ships Offshore Struct. **10**(6), 653-659 (2015). https://doi.org/ 10.1080/17445302.2014.943388

[31] Y. R. Lee, M. Tian, K. H. Row, Asian J. Chem. **26**(18), 6189-6193 (2014). https://doi.org /10.14233/ajchem.2014.17114

[32] T. Banerjee, R. S. Sen, B. Oraon, G. Majumdar, Int. J. Adv. Manuf. Technol. **64**(9-12), 1729-1736 (2013). https://doi.org/10.1007/s00170-012-4136-x

[33] S. D. Balkin, D. K. J. Lin, Commun. Stat.-Theory Methods. **29**(9-10), 2215-2227 (2000).

https://doi.org/10.1080/03610920008832604

[34] J. Kwak, Int. J. Mach. Tools Manuf. **45**(3), 327-334 (2005). https://doi.org/10.1016/j.ijmachtools.2004.08.007

[35] G. R. Kress, P. Ermanni, Struct. Multidiscip. Optim. **30**(5), 368-380 (2005). https://doi.org/10.1007/s00158-004-0458-0

Figures

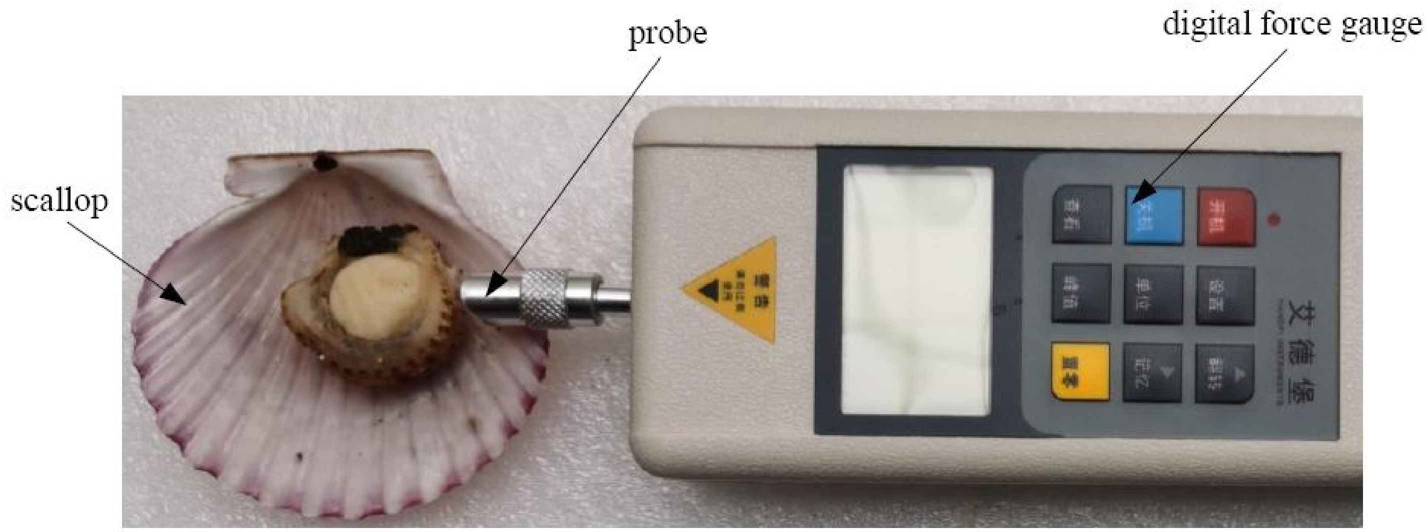


Figure 1

Binding force measurement experiment figure

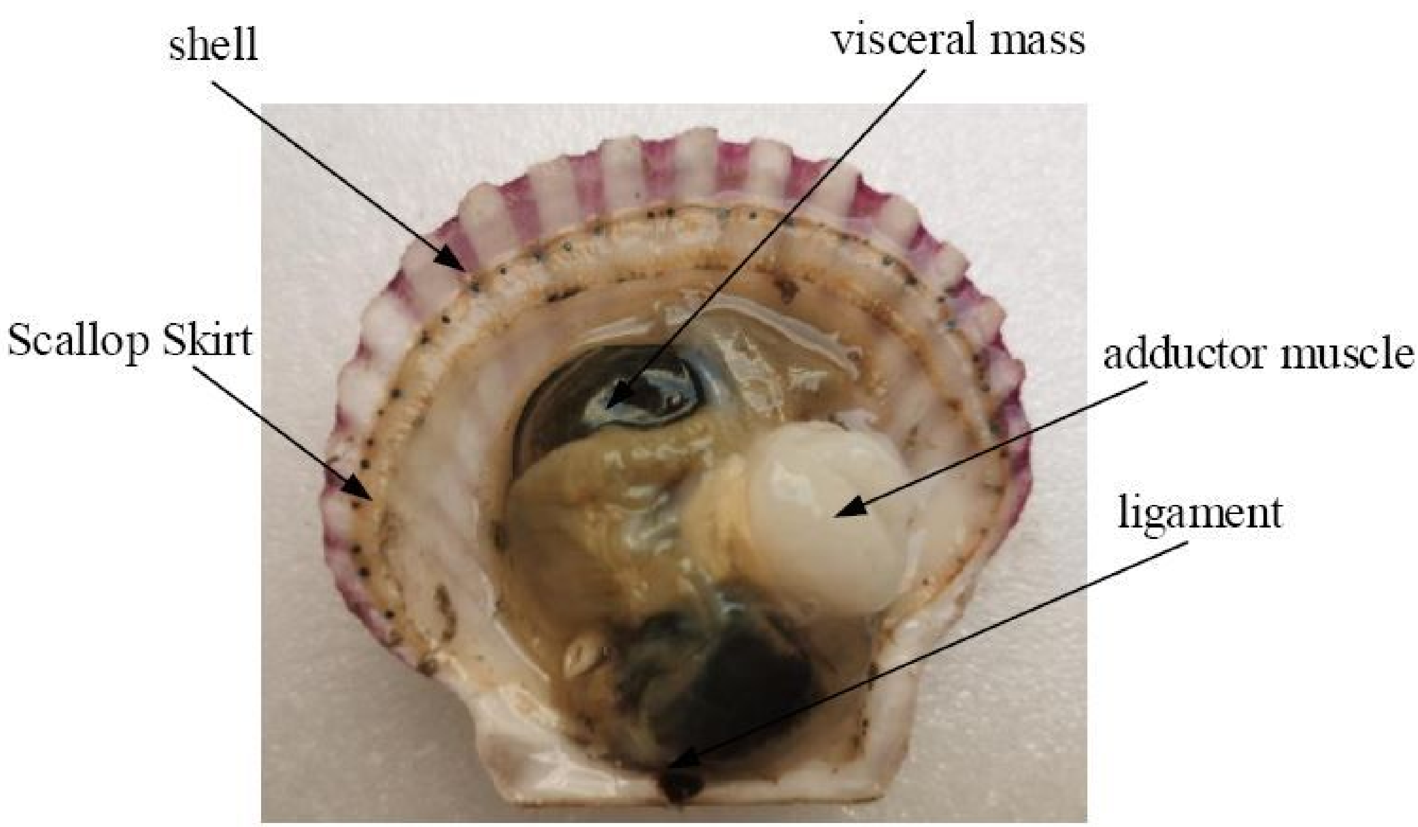


Figure 2

The internal structure of bay scallop

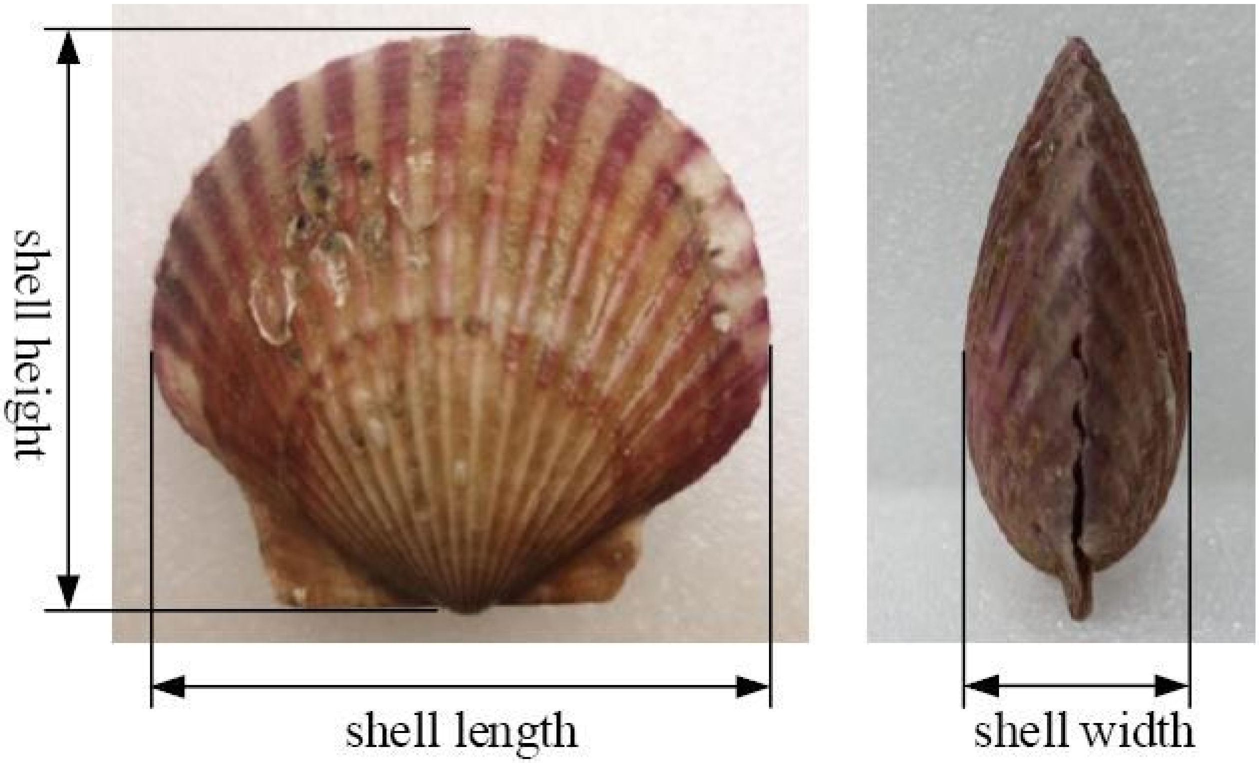


Figure 3

Dimensional distribution of scallop

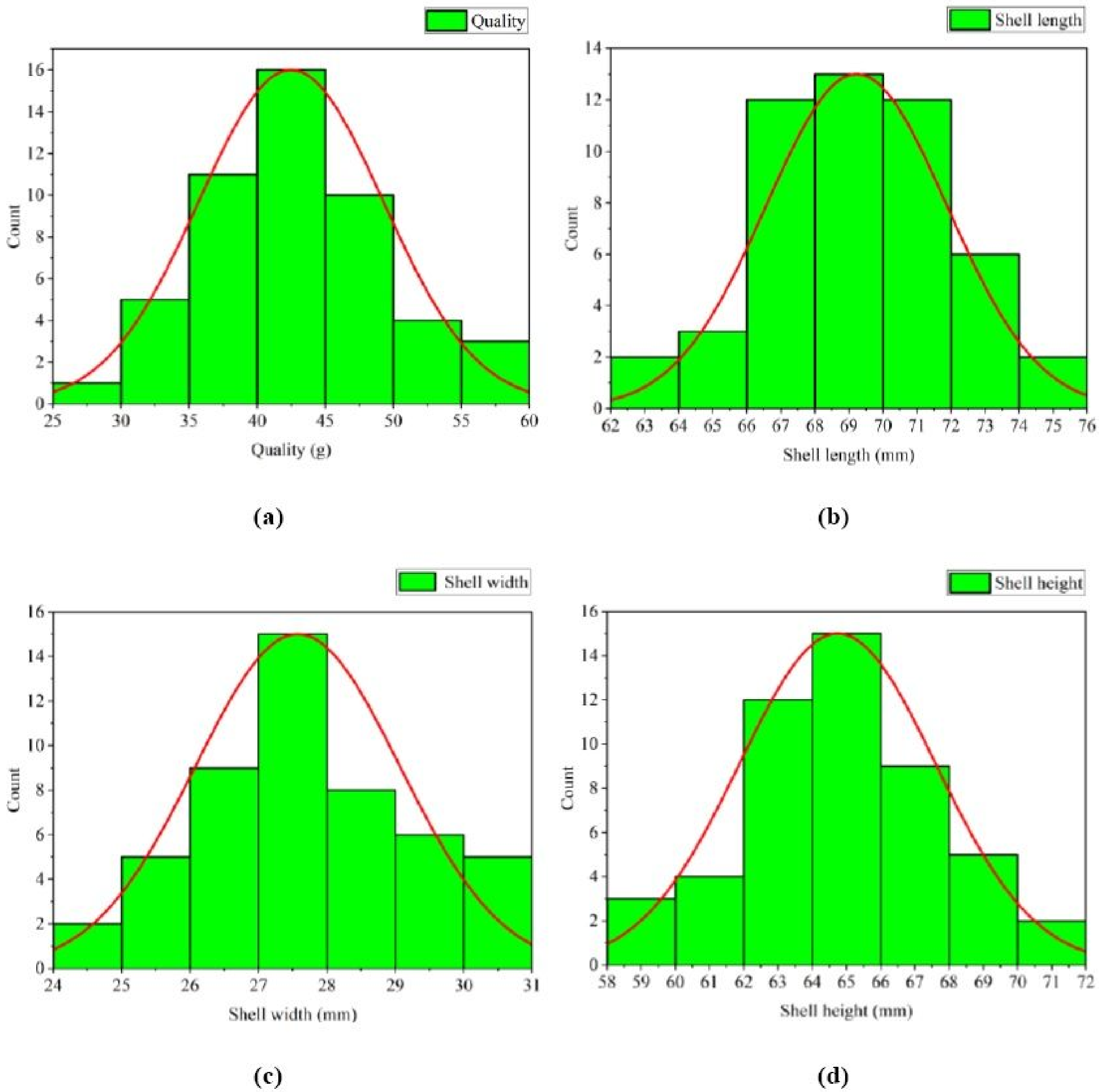


Figure 4

Histogram of scallop characteristics distributions; quality (a), shell length (b), shell width (c), and shell height (d)

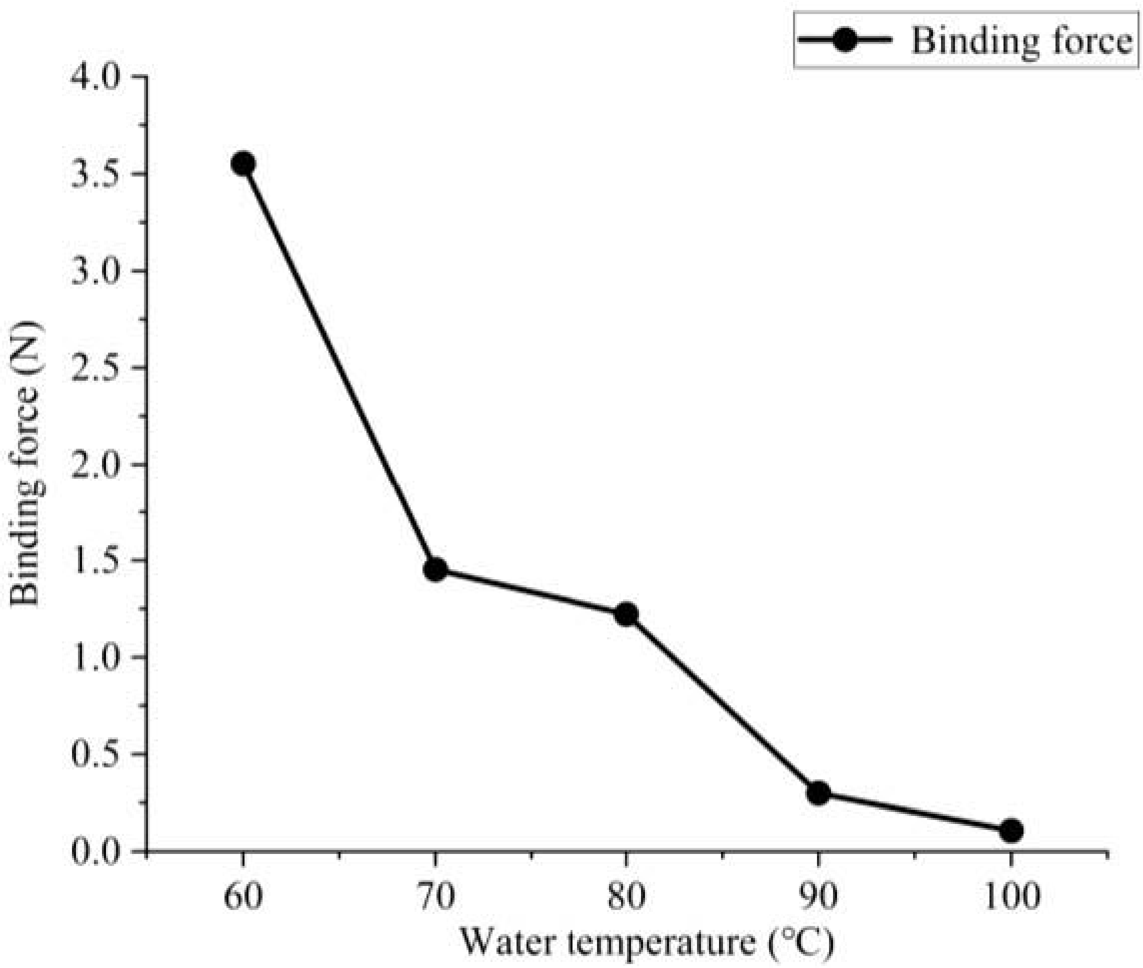


Figure 5

The relationship between water temperature and binding force

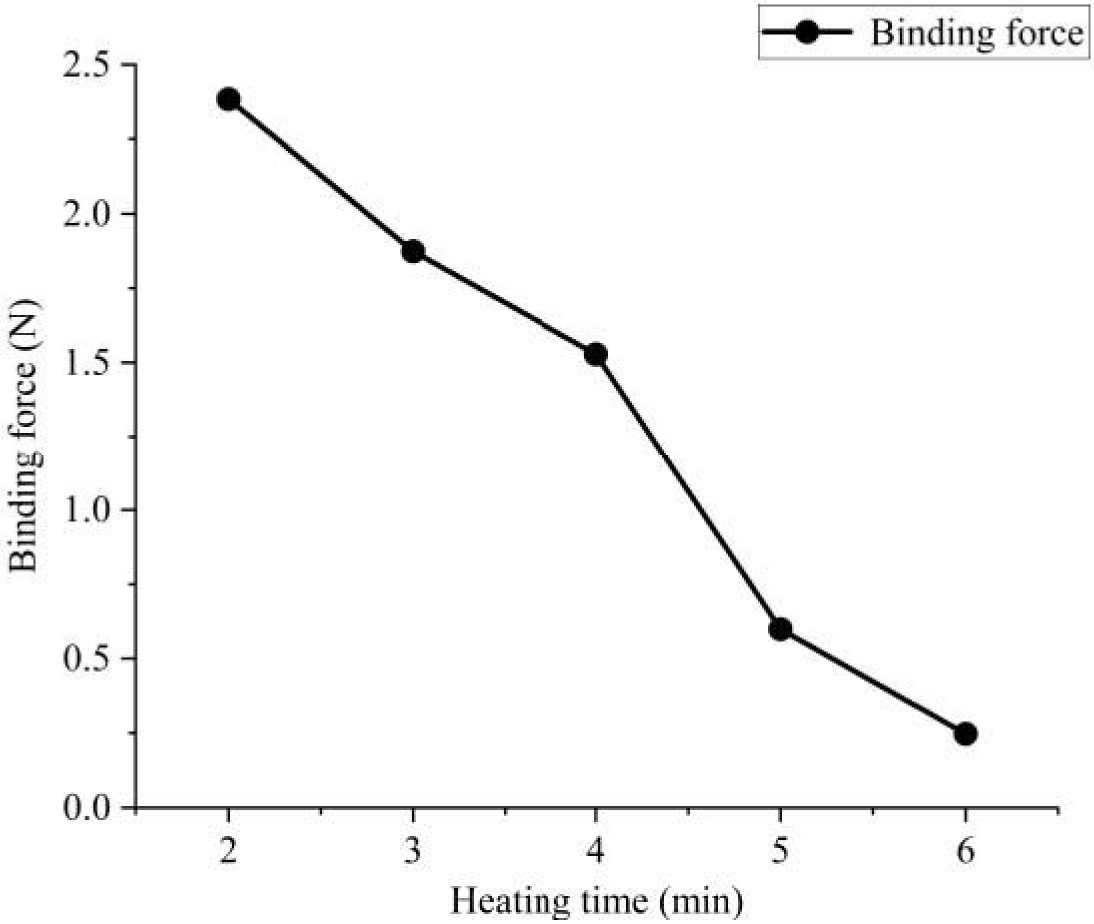


Figure 6

The relationship between heating time and binding force

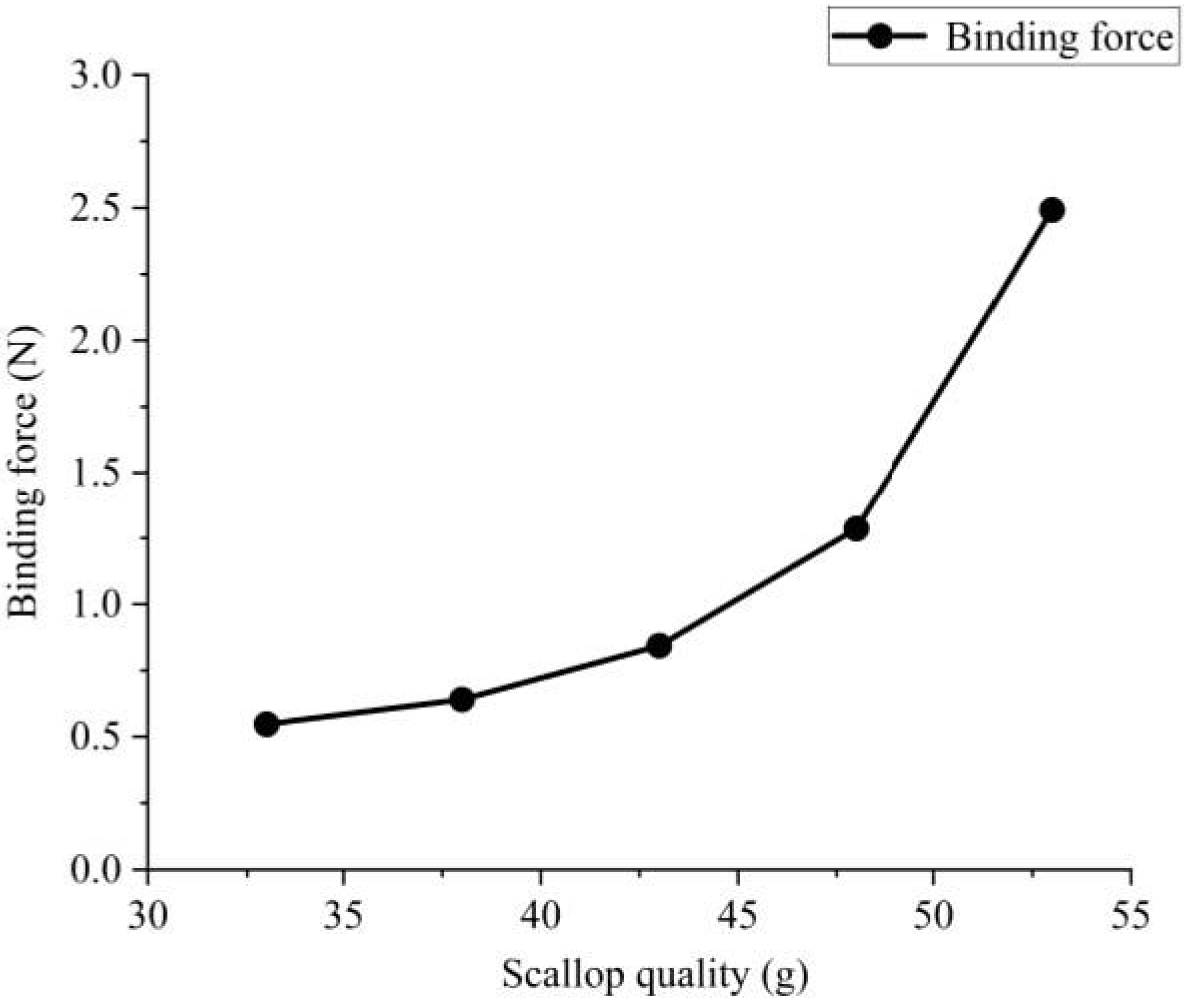


Figure 7

The relationship between scallop quality and binding force

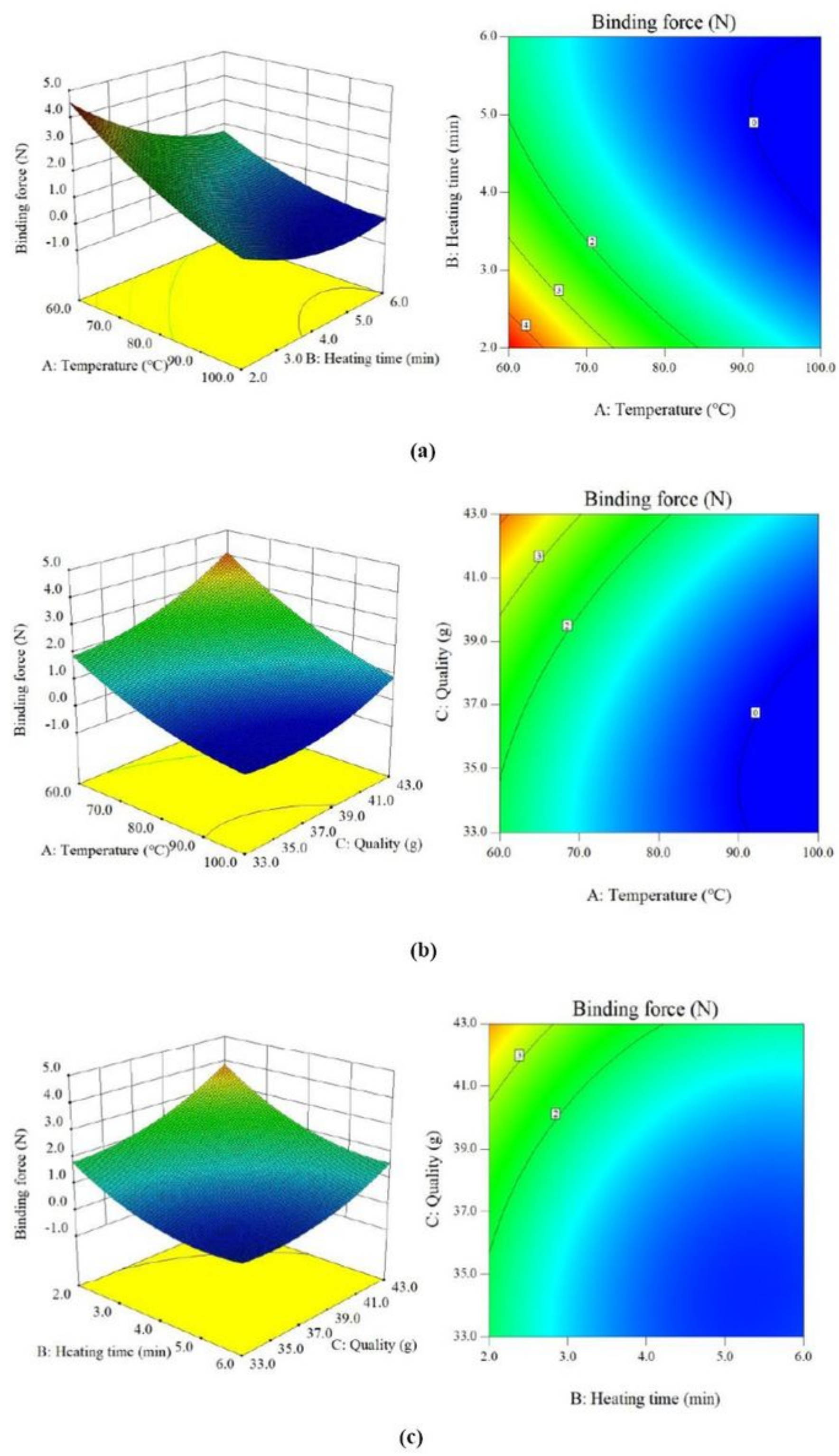


Figure 8

Response surface contour plot for the binding force; changing control factors were temperature and heating time (a), temperature and quality (b), and heating time and quality (c)

Constraints

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A:temperature	is in range	60	100	1	1	3
B:time	is in range	2	6	1	1	3
C:quality	is in range	33	43	1	1	3
force	is target = 0	0	4.53	1	1	3

Solutions

Number	temperature	time	quality	force	Desirability	
1	89.570	5.377	37.462	0.000	1.000	Selected
2	96.093	3.662	36.972	0.000	1.000	
3	98.181	4.722	39.448	0.000	1.000	
4	88.910	4.223	33.486	0.000	1.000	
5	99.648	5.539	39.283	0.000	1.000	
6	86.360	4.669	35.076	0.000	1.000	
7	92.827	4.731	38.298	0.000	1.000	
8	92.487	4.677	38.153	0.000	1.000	
9	87.292	5.527	33.616	0.000	1.000	
10	99.710	3.146	34.216	0.000	1.000	
11	86.093	5.445	34.054	0.000	1.000	
12	99.334	5.247	39.566	0.000	1.000	
13	92.545	4.138	37.197	0.000	1.000	
14	98.620	3.366	36.604	0.000	1.000	
15	85.902	5.473	34.406	0.000	1.000	
16	98.706	5.713	38.857	0.000	1.000	
17	97.721	3.736	37.820	0.000	1.000	
18	87.754	4.442	33.407	0.000	1.000	
19	96.389	3.444	33.406	0.000	1.000	
20	98.231	5.231	39.426	0.000	1.000	
21	87.645	4.419	35.291	0.000	1.000	
22	90.427	4.250	36.584	0.000	1.000	
23	91.220	5.658	37.595	0.000	1.000	
24	98.397	3.359	36.453	0.000	1.000	
25	97.998	4.698	39.404	0.000	1.000	
26	98.636	4.064	38.826	0.000	1.000	
27	91.494	4.670	37.849	0.000	1.000	
28	85.651	4.956	33.916	0.000	1.000	
29	99.750	3.164	35.604	0.000	1.000	
30	87.101	4.830	33.011	0.000	1.000	
31	89.609	5.293	37.523	0.000	1.000	
32	88.532	4.340	33.232	0.000	1.000	
33	93.489	5.857	37.655	0.000	1.000	
34	90.186	5.263	37.717	0.000	1.000	
35	94.146	5.972	34.071	0.000	1.000	
36	93.814	3.656	33.439	0.000	1.000	
37	99.043	4.825	39.623	0.000	1.000	
38	91.789	5.576	37.885	0.000	1.000	
39	98.327	3.517	37.238	0.000	1.000	
40	99.526	3.637	38.046	0.000	1.000	
41	91.541	5.832	37.238	0.000	1.000	
42	97.144	3.432	33.108	0.000	1.000	
43	98.730	5.490	39.248	0.000	1.000	
44	96.157	5.407	38.973	0.000	1.000	
45	90.519	4.055	33.176	0.000	1.000	
46	85.904	5.424	35.475	0.000	1.000	
47	88.641	4.361	35.911	0.000	1.000	
48	86.221	5.105	35.964	0.000	1.000	
49	91.511	5.258	38.095	0.000	1.000	
50	91.115	3.894	33.819	0.000	1.000	
51	88.124	5.574	33.458	0.000	1.000	
52	98.661	5.414	39.331	0.000	1.000	
53	88.714	5.872	35.555	0.000	1.000	
54	85.911	4.948	33.650	0.000	1.000	
55	87.190	5.204	33.043	0.000	1.000	
56	98.888	4.411	39.351	0.000	1.000	
57	98.605	5.298	39.433	0.000	1.000	
58	98.567	5.485	39.234	0.000	1.000	
59	98.482	5.835	38.517	0.000	1.000	
60	93.598	4.824	38.560	0.000	1.000	
61	86.948	5.420	33.479	0.000	1.000	
62	95.124	3.722	36.811	0.000	1.000	
63	87.733	5.712	36.015	0.000	1.000	
64	88.577	5.853	34.785	0.000	1.000	
65	89.845	5.711	37.045	0.000	1.000	
66	88.619	5.593	33.370	0.000	1.000	
67	97.269	3.305	34.659	0.000	1.000	
68	87.930	5.651	36.372	0.000	1.000	
69	88.935	4.162	33.986	0.000	1.000	
70	89.616	5.703	36.982	0.000	1.000	
71	98.826	3.710	38.067	0.000	1.000	
72	86.365	5.587	35.310	0.000	1.000	
73	98.725	3.319	36.354	0.000	1.000	
74	95.229	5.721	38.351	0.000	1.000	
75	87.816	5.718	34.171	0.000	1.000	
76	97.438	4.400	39.053	0.000	1.000	
77	87.321	4.483	35.297	0.000	1.000	
78	99.283	3.828	38.494	0.000	1.000	
79	92.101	5.758	37.609	0.000	1.000	
80	93.890	5.438	38.527	0.000	1.000	
81	85.944	5.412	35.557	0.000	1.000	
82	97.058	4.620	39.181	0.000	1.000	
83	97.912	3.994	38.520	0.000	1.000	
84	90.639	3.927	34.237	0.000	1.000	
85	88.018	5.253	36.945	0.000	1.000	
86	90.736	5.228	37.890	0.000	1.000	
87	88.952	4.158	34.847	0.000	1.000	
88	91.253	4.214	36.870	0.000	1.000	
89	93.249	4.837	38.482	0.000	1.000	
90	87.538	5.596	33.744	0.000	1.000	
91	92.025	4.556	37.869	0.000	1.000	
92	87.134	5.373	33.307	0.000	1.000	
93	98.139	5.041	39.486	0.000	1.000	
94	92.398	3.732	34.297	0.000	1.000	
95	88.746	4.232	33.595	0.000	1.000	
96	91.437	4.641	37.796	0.000	1.000	
97	85.715	5.315	34.016	0.000	1.000	
98	86.576	5.305	33.425	0.000	1.000	
99	88.274	4.276	33.841	0.000	1.000	
100	85.343	5.171	34.269	0.000	1.000	

Figure 9

Response surface methodology optimization results