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Research Article

Novel Combined Freeze-Drying and Instant Controlled Pressure Drop Drying for Restructured Carrot-Potato Chips: Optimized by Response Surface Method

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Combined freeze-drying and instant controlled pressure drop process (FD-DIC) for restructured carrot-potato chips was developed and its processing conditions were optimized using response surface methodology (RSM) with the purpose of improving the quality of products and reducing energy consumption. Three critical variables including the amount of carrot, the moisture content of the partially dried product before DIC treatment, and equilibrium temperature of DIC for the restructured chips were considered. Response parameters such as the final moisture content, color value (L, a, and b), and texture properties of restructured carrot-potato chips were investigated. The results showed that the graphical optimal ranges of FD-DIC drying process were as follows: the amount of carrot was 46–54% w/w, the moisture content of the partially dried product before DIC treatment was 0.20–0.35 g/g, and the equilibrium temperature of DIC was 85–95°C. Furthermore, the numerical optimization suggested that conditions were 47.43% w/w, 0.29 g/g, and 90.57°C, respectively. It could be concluded that the combined drying method of FD-DIC provided the restructured carrot-potato chips with higher quality, as compared to the freeze-dried chips. Considering the relatively high production cost of FD, this novel FD-DIC could be an alternative method for obtaining desirable restructured fruit and vegetable chips.

1. Introduction

Carrot and potato are both prolific and common vegetables, which have been widely cultivated and consumed around the world. According to FAO, the production of carrot and potato was 40 million and 3 billion tons in 2015. Carrot is highly nutritious as it contains appreciable amount of vitamins B1, B2, B6, and B12 besides being rich in β-carotene [1]. It is well known that carrots are beneficial for eyesight and could prevent cardiovascular disease [2]. Potatoes are the second staple food in Europe and United States, since they are rich in vitamins, calcium, and potassium and suitable for all ages [3].

Recently, a rapid increase in the consumption of snack food has been witnessed, especially the snack food derived from fruits and vegetables. On the one hand, among these plant-based snack foods, potato and carrot chips are still the most popular products in Chinese market. Many drying technologies have been employed to dry carrots and potatoes with the goal of maintaining their appearance and their nutrients [4]. The fruit and vegetable chips could be simply separated into two categories according to processing methods: fried chips and nonfried chips. In Chinese market, the fried chips which are mainly produced by deep-frying have been mainstream since 1980s. It is generally recognized that the unique texture-flavor combination of fried chips is attributed to the complicated chemical reaction during frying, for example, Maillard reaction and lipid oxidation; meanwhile, frying often leads to a residual oil content ranging from 35.3% to 44.5% wet basis (w.b.) [5]. Due to the possibility of intake of excessive energy during consumption of fried chips, consumers are becoming more and more interested in healthy products with low amount of fat as well as good taste [6]. On the other hand, restructured chips are recognized as a type of healthier products, which often were mixed together with several different fruits and vegetables followed by remodeling and finally drying through various means. According to the "The Dietary Guidelines for Chinese Residents" published in 2016, it is recommended for Chinese residents to take 200–300 g of fruits and 300–500 g of vegetables daily, and it is suggested that at least 25 different types of food should be consumed every day. Nevertheless, few citizens in China could achieve balanced diet according to the guidelines due to the fast pace of city-life, excessive consumption of animal foods, and abuse of fast foods with simple ingredients. From the view of diet balance, restructured chips derived from various fruits and vegetables could not only guarantee the amount and type of plant foods consumed, but also provide a variety of nutrients, including vitamins, minerals, and dietary fiber, with obvious advantages of meeting the daily nutritional demand of human beings.

Currently, a variety of technologies were developed for producing restructured chips, like extrusion, vacuum frying, freeze-drying, and so on. In Chinese market, restructured chips are often produced by extrusion which has been increasingly popular as a remodeled method, while vacuum frying is mainly applied in restructured potato chips. Generally, in order to enhance the adhesive property of mixture puree, total amount of more than 50%–70% of starch, flour, corn powder, and/or other ingredients were added, leading to a decline of the proportion of fruit and vegetable materials for restructured chips [7]. Moreover, the extruded products have to experience high temperature and high pressure treatments during remodeling, possibly resulting in significant degradation of beneficial nutrients [8]. In contrast, freeze-dried foods were characterized with high qualities such as super crispness, high retention of nutrients, and minimum shrinkage [9], which might be suitable for processing restructured chips. Though the advantages of FD are obvious, one major problem for this technology is the relative long drying time, which in turn leads to high energy consumption and production cost [10]. Fortunately, the high production cost for FD process could be reduced by combining it with some of other drying technologies [11]. Huang et al. [12] found that the restructured chips containing potato and apple dried by combined microwave and freeze-drying (MFD) obtained the best quality, and the drying time of MFD was shorter than that of FD. In addition, the combination of FD and hot-air-drying for apple cubes was confirmed to be a good alternative instead of mere FD treatment [13]. According to these previous reports, the drying time and energy consumption for FD could be significantly reduced through applying several combination methods, with the products comparatively superior to hot-air-dried products and nearer in quality to FD products [14].

Instant controlled pressure drop process (French term: détente instantannée controlee, DIC), also known as explosion puffing drying [15], was defined in 1988 by a French scientist named Allaf and his colleagues as a high-temperature short-time treatment followed by an abrupt pressure drop towards a vacuum (pressure drop rate higher than 0.5 MPa/s) [16]. DIC has been perfectly adapted to texture-sensitive products such as apple and onion and could significantly expand the volume of materials, thus generating porous microstructure and improving crispness, which pointed to superior quality for fruit and vegetable chips [17]. According to the study of Professors T. Allaf and K. Allaf [18], DIC technology requires relatively a low moisture content for materials (around 10–30% d.b.) before using DIC process, which indicates that the fresh materials need predrying first. Due to this unique principle, DIC is not suitable for drying of raw agroproducts with high moisture content such as fresh fruits and vegetables. Consequently, many drying methods have been introduced prior to the DIC treatment with the aim of reducing the moisture content of raw materials, among which the combination of hot-air-drying and DIC is wildly practiced in industry. However, this combination does not scale well to the production of restructured fruit and vegetable chips due to the fact that remarkable shrinkage could occur during hot-air-predrying, which significantly compromises the expansion effects of DIC treatment and yields products with high hardness. Therefore, our previous study on jackfruit chips provides clue for solving this problem by combining FD with DIC treatment, which yields jackfruit chips with comparative overall quality to FD-dried products [19]. However, the feasibility of this combination on restructured chips remains unknown.

The objective of this work was to validate the feasibility and optimize the processing conditions of combined freeze-drying and instant controlled pressure drop process (FD-DIC) on restructured carrot-potato chips by using response surface methodology (RSM). In terms of this, simple formula was adopted which only contained two representative materials, that is, carrots containing high content of dietary fibers and potatoes containing high amount of starch, for preparing restructured chips, because it is easy to develop series of products by adding more types of fruits and vegetables based on the simple formula.

2. Materials and Methods

2.1. Sample Preparation. Fresh carrots (*Daucus carota L.* CV. Heitianwucun) and potatoes (*Solanum tuberosum L.* CV. Dabaihua) were purchased from a local market (Beijing, China) and kept in a refrigerator at $4 \pm 0.5^{\circ}$C. The carrots and potatoes were washed with tap water then peeled and uniformly cut into sticks (4 mm × 4 mm × 50 mm) by an automatic cutter (CL50, Robot Coupe, France) before being used. The initial moisture content of carrot and potato was 10.61 g/g and 4.62 g/g on dry basis (d.b.), respectively. All of the carrot and potato sticks were steamed for 30 minutes and then blended (JYL-C022, Mixer, Joyoung Co., Ltd. Shandong, China) with different mixed ratio according to the experimental design (Table 2). At last, the mixed puree was poured into molds (5 cm × 5 cm × 5 mm) and frozen at -40°C overnight.

2.2. Freeze-Drying Combined with Instant Controlled Pressure Drop Drying. The mixed purees together with the molds were placed into the chamber of a freeze-drying machine (Alpha 1-4 Lplus, Marin Christ Co., Ltd., Osterode, Germany). The pressure of the treatment chamber was set at 0.37 mbar and the chamber was equipped with a condensate collector set at −50°C. Samples were taken out from the chamber when they reached the certain moisture content according to the experimental design (Table 2). Besides, a batch of samples were dried to final state by FD, which was used as control sample for the comparison of microstructure with FD-DIC finished samples.

Partially FD-dried samples were then treated by a DIC reactor (QDPH10-1, Tianjin Qin De Co., Ltd., Tianjin, China). Detailed information of the mechanism and system of DIC reactor were available in a previous publication [19, 20]. Firstly, the treatment chamber was heated to different equilibrium temperature according to the experimental design (Table 2) by heat exchanger. Then the samples were placed into the treatment chamber and kept for a certain time (10 min) at atmospheric pressure. An instant pressure drop towards vacuum (3–5 kPa) was carried out by opening the decompression valve which connected with the vacuum tank. Finally, the samples were dried at 60°C and under continuous vacuum for 1.5 h. Final products were taken out and stored in a desiccator before analysis. The drying process was performed in triplicate.

2.3. Experimental Design and Statistical Analysis. Response surface methodology (RSM) was applied for evaluation of the effects of drying parameters and their optimization for various responses. Central composite experimental design (CCD) with three numeric factors on three levels was used. Factors and levels of the CCD were obtained by single factor experiments. Fourteen different combinations with six replicates at the central point were constituted to run the experiment. Various parameters could affect the FD-DIC process, but the mixed ratio and the moisture content of the partially dried products to be DIC-treated could be distinguished as the most influencing factor. Therefore, the independent variables used in experimental design were the amount of carrot (or mixed ratio), the moisture content of the partially dried product before DIC treatment, and equilibrium temperature of DIC. To affect the response surfaces more evenly, drying parameters were normalized as coded variables according to Table 1.

The response variables were fitted to a second-order polynomial model (see (1)) which is generally able to describe relationship between the responses and the independent variables [21].

$$Y = \beta_0 + \sum_{i=1}^{2} \beta_i X_i + \sum_{i \neq j=1}^{2} \beta_{ij} X_i X_j + \sum_{i=1}^{2} \beta_{ii} {X_i}^2, \quad (1)$$

where Y represents the response variable, X_i and X_j are the independent variables affecting the response, and β_0, β_i, β_{ii}, and β_{ij} are the regression coefficients for intercept, linear, quadratic, and interaction terms, respectively. Analysis of variance (ANOVA) was used in order to evaluate model adequacy and determine regression coefficients and statistical significance. The results were statistically tested at significance level of $P = 0.05$. The adequacy of the model was evaluated by the coefficient of determination (R^2), model P value, and lack-of-fit testing. A mathematical model was established to describe the influence of single process parameter and/or interaction of multiple parameters on each investigated response. Three-dimensional (3D) response surface plots were generated using a software Design-Expert v.8.0 Trial (Stat-Ease, Minneapolis, MN, USA) and drawn by using the function of two factors while keeping the others constant.

Table 1: The factors and levels of central composite design of response surface methodology.

Coded levels	X_1 (the amount of carrot, %)	X_2 (the moisture content of the partially dried product before DIC treatment, g/g)	X_3 (equilibrium temperature of DIC, °C)
−1.68	16.4	0.132	73.2
−1	30.0	0.200	80.0
0	50.0	0.300	90.0
1	70.0	0.400	100
1.68	83.6	0.468	107

2.4. Moisture Content. Moisture content was determined by drying the samples at 105°C until reaching constant weight [22]. The weights were measured in triplicate and the results were shown as the averages.

2.5. Texture. Texture of the samples were analyzed by using a Texture Analyzer (TA.XT 2i/50, Stable Micro System Ltd., Surry, UK), which was loaded with a ball probe. The measurements were operating at a test speed of 1.0 mm/s over a distance of 5.0 mm. The pretest and posttest speeds for compression were set at 1.0 mm/s and 10.0 mm/s, respectively [23]. Data obtained from force-deformation curve were used for the analysis of hardness and crispness of the samples. Hardness is expressed as the maximum force (N) drawn from the highest compression peak, while crispness is the distance (mm) from origin of coordinate to abscissa of the first fracture point [24].

2.6. Color. The CIE Lab color coordinates were measured by using a colorimeter (MINOLTA Chroma Meter, CM-700d, Konica Minolta Ltd, Tokyo, Japan). The apparent (surface) color of the samples was measured in terms of L (degree of lightness and darkness), a (degree of redness and greenness), and b (degree of yellowness and blueness) [25]. Samples were placed on the measure head of the colorimeter and measurements of color were performed for all the prepared samples. Standard white and black colors were used for calibration. Experiments were replicated five times for statistical purpose.

Table 2: The results of central composite design of response surface methodology.

Run	Coded levels			Responses					
	X_1	X_2	X_3	Y_1 (final moisture content, g/g)	Y_2 (hardness, N)	Y_3 (crispness, mm)	Y_4 (L)	Y_5 (a)	Y_6 (b)
(1)	−1	−1	−1	0.046 ± 0.001	7.26 ± 0.25	0.34 ± 0.03	72.27 ± 0.57	22.15 ± 0.54	30.27 ± 0.54
(2)	1	−1	−1	0.054 ± 0.002	6.33 ± 0.14	0.68 ± 0.06	66.64 ± 0.97	28.13 ± 1.46	33.61 ± 0.89
(3)	−1	1	−1	0.041 ± 0.002	5.41 ± 0.30	0.24 ± 0.02	71.63 ± 0.86	22.46 ± 0.55	33.34 ± 0.54
(4)	1	1	−1	0.052 ± 0.005	6.50 ± 0.20	0.61 ± 0.01	65.86 ± 0.79	29.85 ± 1.07	38.42 ± 0.58
(5)	−1	−1	1	0.041 ± 0.001	5.30 ± 0.30	0.76 ± 0.05	74.02 ± 0.55	21.14 ± 0.84	29.21 ± 0.73
(6)	1	−1	1	0.050 ± 0.003	6.41 ± 0.28	1.24 ± 0.27	65.32 ± 0.79	26.18 ± 2.15	34.08 ± 0.84
(7)	−1	1	1	0.032 ± 0.017	5.69 ± 0.13	0.42 ± 0.02	72.69 ± 0.48	23.45 ± 1.51	32.71 ± 0.31
(8)	1	1	1	0.058 ± 0.004	8.57 ± 0.40	1.32 ± 0.21	64.95 ± 0.76	28.51 ± 0.84	34.62 ± 0.88
(9)	−1.68	0	0	0.044 ± 0.005	7.17 ± 1.16	0.27 ± 0.03	72.63 ± 0.48	21.50 ± 0.65	28.81 ± 0.78
(10)	1.68	0	0	0.060 ± 0.002	6.08 ± 0.47	0.57 ± 0.05	62.02 ± 0.38	26.55 ± 1.06	30.96 ± 1.05
(11)	0	−1.68	0	0.041 ± 0.004	9.21 ± 0.79	0.26 ± 0.03	70.40 ± 0.75	24.40 ± 0.68	35.88 ± 2.02
(12)	0	1.68	0	0.047 ± 0.007	6.84 ± 0.44	0.31 ± 0.09	68.34 ± 0.70	27.98 ± 0.25	37.29 ± 1.91
(13)	0	0	−1.68	0.044 ± 0.002	7.90 ± 0.69	0.37 ± 0.04	72.49 ± 0.37	24.83 ± 0.39	32.39 ± 0.76
(14)	0	0	1.68	0.033 ± 0.005	6.84 ± 0.54	0.56 ± 0.08	71.59 ± 0.48	22.13 ± 0.87	35.86 ± 2.14
(15)	0	0	0	0.028 ± 0.002	10.46 ± 0.31	0.36 ± 0.03	69.89 ± 0.72	24.10 ± 0.83	36.63 ± 3.02
(16)	0	0	0	0.025 ± 0.001	9.53 ± 0.26	0.45 ± 0.02	70.07 ± 1.01	24.48 ± 0.23	35.88 ± 0.36
(17)	0	0	0	0.030 ± 0.004	10.37 ± 0.17	0.25 ± 0.03	70.43 ± 0.94	24.52 ± 0.77	35.07 ± 0.93
(18)	0	0	0	0.028 ± 0.002	11.36 ± 0.25	0.18 ± 0.04	70.38 ± 0.41	25.76 ± 1.19	37.89 ± 1.36
(19)	0	0	0	0.031 ± 0.002	10.12 ± 0.21	0.27 ± 0.02	70.06 ± 1.51	25.02 ± 1.34	36.32 ± 1.04
(20)	0	0	0	0.028 ± 0.002	10.05 ± 0.23	0.31 ± 0.03	70.70 ± 1.05	24.99 ± 0.52	35.21 ± 1.01

2.7. Scanning Electron Microscopy. Microstructural analysis of the restructured chips was carried out using a scanning electron microscope (SU8010, Hitachi Co., Ltd., Tokyo, Japan) at an accelerating voltage of 20.0 kV. The samples were fixed on the scanning stub using double sided adhesive tapes and then sputter-coated with gold by ion sputtering apparatus (MCI000, Hitachi Co., Ltd, Tokyo, Japan) for 10 min under low vacuum with argon gas to provide a reflective surface for electron beam. Image analysis was conducted at magnification of 80x.

2.8. Data Analysis. Statistical analysis was performed using RSM software Design-Expert v.8.0 Trial (Stat-Ease, Minneapolis, MN, USA). Analysis of variance (ANOVA) and the coefficient of determination (R^2) were used to assess the validity of the model. Comparison of the mean was considered to be defined at $P < 0.05$.

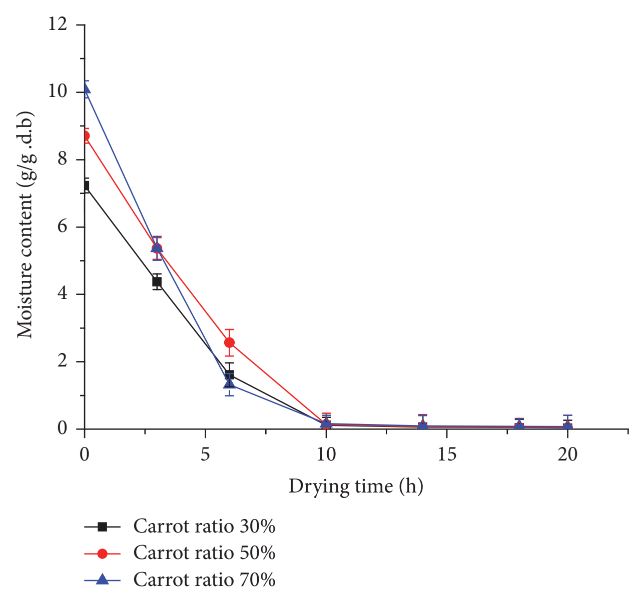

Figure 1: Freeze-drying curves of the restructured carrot-potato chips.

3. Results and Discussion

3.1. Effect of Amount of Carrot on the Freeze-Drying Characteristic of the Restructured Chips. The evolution of the moisture content of the restructured carrot-potato chips during FD is shown in Figure 1. Due to the differences in mixed ratio, the initial moisture contents of the restructured chips were varied from 10.08 g/g to 7.23 g/g with reducing of the amount of carrot from 70% to 30%. In other words, higher initial moisture content of the mixture was found by increasing the amount of carrot in the formula of restructured chips. This was attributed to the fact that the moisture content of the raw carrots was higher (10.61 g/g d.b.) than that of potatoes.

Table 3: Estimated coefficients of the fitted second-order polynomial models for the final moisture content, hardness, and color of the restructured chips.

Regression coefficient	Response				
	Final moisture content	Hardness	L	a	b
β_0	0.028	10.340	70.270	24.800	36.170
Linear					
β_1	$5.924 \cdot 10^{-3**}$	0.170	-3.350^{**}	2.570^{**}	1.380^{*}
β_2	$1.531 \cdot 10^{-4}$	−0.230	-0.480^{**}	0.930^{**}	1.050^{*}
β_3	$-2.233 \cdot 10^{-3*}$	−0.096	−0.068	-0.570^{*}	0.060
Interaction					
β_{12}	$2.500 \cdot 10^{-3*}$	0.470	0.100	0.180	−0.150
β_{13}	$2.000 \cdot 10^{-3}$	0.480	-0.630^{**}	−0.410	−0.200
β_{23}	$7.500 \cdot 10^{-4}$	0.530	−0.035	0.330	−0.480
Quadratic					
β_{11}	$8.561 \cdot 10^{-3**}$	-1.460^{**}	-1.110^{**}	0.130	-2.240^{**}
β_{22}	$5.732 \cdot 10^{-3**}$	-0.960^{**}	-0.390^{**}	0.560^{*}	0.130
β_{33}	$3.788 \cdot 10^{-3**}$	-1.190^{**}	0.550^{**}	−0.400	−0.740
R^2	0.956	0.900	0.989	0.955	0.830

*Significant at the 5% level, **significant at the 1% level.

Notably, it could be seen that the restructured chips with 70% carrot exhibited the fastest trend of water removing in the first 10 h during the FD process among all the samples. This might be due to the lower bulk density of the chips containing 70% carrot, which tend to form large pores and porous structure during FD, and this in turn helped in moisture diffusion [26]. In addition, though the moisture content of all the samples decreased quickly in the first 10 h, a plateau was observed in further drying process, indicating that the samples entered secondary drying stage in which the desorbed water vapor was transported through the pores of the material. Generally, the basic energy used to remove one kilogram of water is almost double for freeze-drying than for conventional drying [27]. In this study, considering the relatively long drying time and high energy cost, DIC drying was applied combined with FD process instead of single FD process in order to improve the efficiency of dehydration for the restructured carrot-potato chips.

3.2. Diagnostic Checking of Predictive Models and Response Surfaces. RSM was used to determine the experimental conditions for optimal response parameters including moisture content, hardness, crispness, and color of the final products. The experimental design and results of the responses for the restructured chips are presented in Table 2. All the response parameters except for the crispness of the samples were fitted well to a second-order polynomial model (see (1)) according to the multiple regression coefficients which were analyzed using the method of least square approach (MLS). In addition, the relationships between the process conditions and the moisture content, hardness, and color of the final products were depicted by means of quadratic polynomial models. The regression coefficients and corresponding statistical significance for each investigated response are summarized in Table 3. The results showed that the models representing the moisture content, hardness, and L and a value of the final products were of high adequacy to the experimental results ($R^2 \geq 0.90$), while the b value of the products was of moderate adequacy ($R^2 = 0.83$). The analysis of variance (ANOVA) of the fitted second-order polynomial models for the moisture content, hardness, and L, a, and b value of the final products are presented in Table 4. According to statistically significant values of P value (<0.05) for the investigated responses of the moisture content, hardness, and L, a, and b value of the samples, it could be concluded that the applied mathematical model provided proper simulation of the experimental results [28]. Additionally, the nonsignificant ($P > 0.05$) effects of lack-of-fit test implied that the prediction of the constant variance was satisfied for all the responses [29]. To sum up, the predictive models selected in this study could be satisfactorily applied to describe the experimental data for the majority of the responses.

3.3. Effect of Processing Variables on the Final Moisture Content of the Restructured Chips. The equation of second-order polynomial model of the final moisture content of products was obtained through RSM and showed as follows:

$$\begin{aligned} Y_1 = 0.028 &+ 0.0059X_1 + 0.00015X_2 - 0.0022X_3 \\ &+ 0.0025X_1X_2 + 0.002X_1X_3 + 0.00075X_2X_3 \\ &+ 0.0086{X_1}^2 + 0.0057{X_2}^2 + 0.0038{X_3}^2, \end{aligned} \quad (2)$$

where Y_1 is final moisture content (g/g d.b.); X_1 is the amount of carrot (%); X_2 is the moisture content of the partially dried product before DIC treatment (g/g d.b.); X_3 is equilibrium temperature of DIC (°C).

As shown in Table 2, the final moisture content of the restructured chips in response to the experimental variables was varied from 0.025 g/g to 0.060 g/g d.b. In addition, the results showed in Table 3 suggested that the final moisture content was highly significant ($P < 0.01$) on the linear

Table 4: The results of analysis of variance (ANOVA) of the fitted second-order polynomial models for the moisture content, hardness, and color of the restructured chips.

Source	Sum of squares	DF	Mean square	F value	P value
Moisture content					
Model	$2.129 \cdot 10^{-3}$	9	$2.365 \cdot 10^{-4}$	24.200	<0.0001
Residual	$9.774 \cdot 10^{-5}$	10	$9.774 \cdot 10^{-6}$		
Lack of fit	$7.641 \cdot 10^{-5}$	5	$1.528 \cdot 10^{-5}$	3.580	0.0939
Pure error	$2.133 \cdot 10^{-5}$	5	$4.267 \cdot 10^{-6}$		
Cor total	$2.227 \cdot 10^{-5}$	19			
Hardness					
Model	61.430	9	6.830	7.990	0.0016
Residual	8.540	10	0.850		
Lack of fit	6.700	5	1.340	3.640	0.0913
Pure error	1.840	5	0.370		
Cor total	69.970	19			
L					
Model	185.290	9	20.590	106.890	<0.0001
Residual	1.920	10	0.190		
Lack of fit	1.470	5	0.290	3.280	0.1092
Pure error	0.450	5	0.090		
Cor total	187.220	19			
a					
Model	116.89	9	12.99	23.63	<0.0001
Residual	5.50	10	0.55		
Lack of fit	3.82	5	0.76	2.28	0.1935
Pure error	1.68	5	0.34		
Cor total	122.39	10			
b					
Model	121.82	9	13.54	5.13	0.0087
Residual	26.83	10	2.64		
Lack of fit	20.98	5	4.20	3.88	0.0816
Pure error	5.41	5	1.08		
Cor total	148.21	19			

terms of the mixed ratio of the sample (β_1), as well as on the quadratic terms of the mixed ratio (β_{11}), the moisture content of the partially dried product before DIC treatment (β_{22}), and equilibrium temperature of DIC (β_{33}); meanwhile the moisture content of the final product was significant ($P < 0.05$) on the linear term of the equilibrium temperature of DIC (β_2) and the interaction term of "the amount of carrot and the moisture content of the partially dried product before DIC treatment" (β_{12}). Moreover, positive coefficients were found in the linear terms of the amount of carrot and the moisture content of the partially dried product before DIC treatment and negative linear coefficients were obtained in the equilibrium temperature of DIC (see (2)), as demonstrated by the three-dimensional response surfaces of mixed ratio, the moisture content of the partially dried product before DIC treatment, and equilibrium temperature of DIC on the final moisture content of the restructured chips (Figures 2(a) and 2(b)). The moisture content of the products was slowly raised with increasing the amount of carrot when the equilibrium temperature was fixed (90°C), while it sharply increased with increasing the amount of carrot when the moisture content of the partially dried product before DIC treatment was in the range of 0.35–0.40 g/g d.b. (Figure 2(a)). This might be attributed to the fact that the moisture content of the partially dried product before DIC treatment was increased with adding more amount of carrot in the mixture, which in turn led to the high moisture content of the final products. Additionally, the final moisture content slowly decreased with increasing of the equilibrium temperature of DIC when the amount of carrot was constant (30%) (Figure 2(b)). This could be explained by the fact that the rate of water diffusion is proportional to the material temperature and time of heat during drying process [13]. The R^2 of the regression model of the final moisture content of products was 0.956, which indicated that 95.6% of the total variability in the final moisture content of the restructured carrot-potato chips could be explained by this model (Table 3). The maximum (0.060 g/g d.b.) and minimum (0.025 g/g d.b.) of the final moisture content were observed in the samples mixed with approximately 83.6% and 50.0%

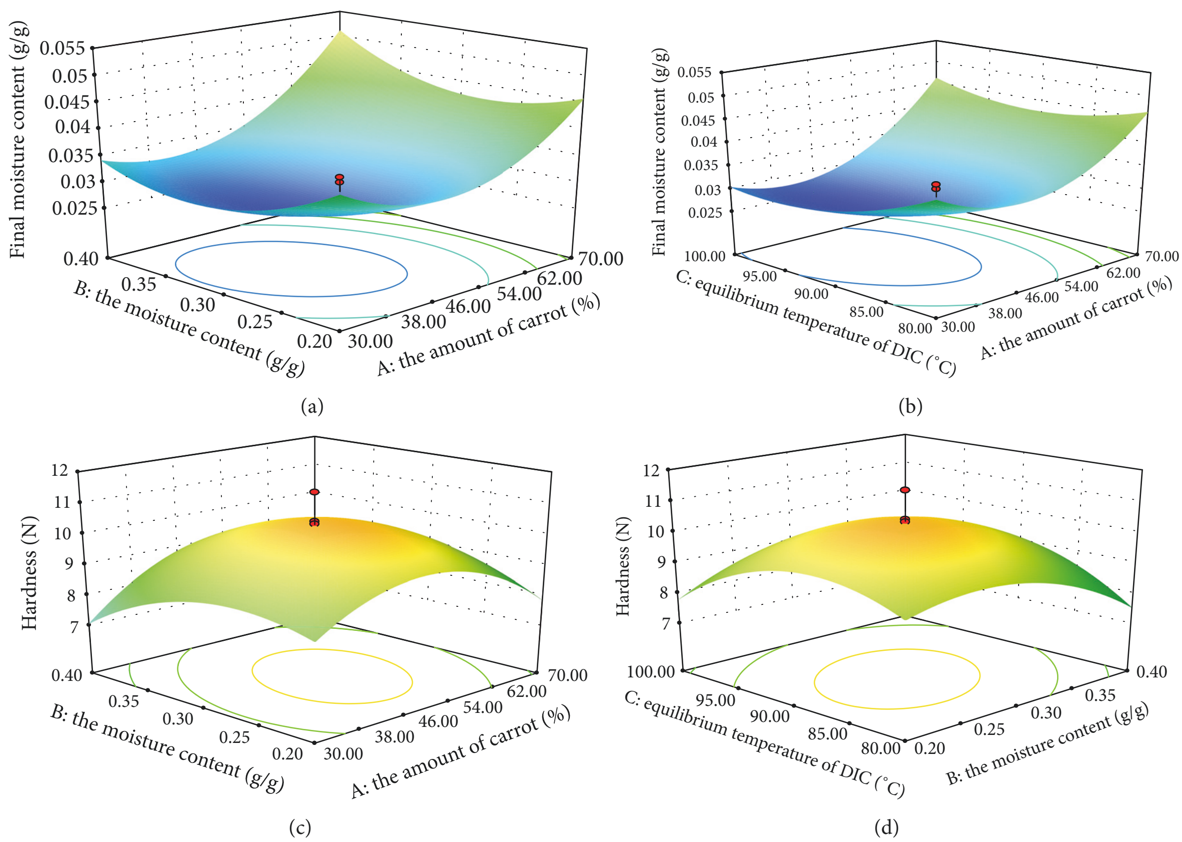

FIGURE 2: Response surfaces for the effects of the amount of carrot, the moisture content of the partially dried product before DIC treatment, and equilibrium temperature of DIC on the moisture content (a-b) and hardness (c-d) of the restructured carrot-potato chips dried by FD-DIC.

carrot, respectively, the moisture content of 0.30 g/g d.b. of the partially dried product, and the equilibrium temperature of 90°C. Considering the hygroscopicity of the restructured chips and with the aim of extending storage time, the lowest final moisture content was chosen as the optimum moisture content of the restructured chips.

3.4. Effect of Processing Variables on the Hardness and Crispness of the Restructured Chips. The equation of the second-order polynomial model for the hardness of the products was obtained through RSM and showed as follows:

$$Y_2 = 10.34 + 0.17X_1 - 0.23X_2 - 0.096X_3 + 0.47X_1X_2 + 0.48X_1X_3 + 0.53X_2X_3 - 1.46{X_1}^2 - 0.96{X_2}^2 - 1.19{X_3}^2, \quad (3)$$

where Y_2 is hardness (N); X_1 is the amount of carrot (%); X_2 is the moisture content of the partially dried product before DIC treatment (g/g d.b.); X_3 is equilibrium temperature of DIC (°C).

The observation for hardness was varied from 11.36 N to 5.30 N and the crispness was from 0.18 mm to 1.32 mm, as shown in Table 2. It is illustrated that the restructured chips with the highest hardness and crispness could be obtained under the condition that the amount of carrot was 50%, the moisture content of the partially dried product before DIC treatment was 0.30 g/g d.b., and the equilibrium temperature of DIC was 90°C. The results in Table 3 suggested that the second-order polynomial model explained 90% of the total variability in hardness; however, it only represented 69% of the total variability in crispness. Therefore, the 3D response surfaces concerning crispness were not shown, except for the experimental results in Table 2. The increase in the amount of carrot, the moisture content of the partially dried product before DIC treatment, and equilibrium temperature of DIC firstly resulted in the increase of crispness of the final products, and subsequently led to a decrease when these parameters exceed certain limits, that is, 50% carrot, the moisture content of 0.30 g/g d.b. of the partially dried product, and equilibrium temperature of 90°C, respectively. This was in accordance with the results of Jiang et al. [30] who reported that higher crispness of the dried products was obtained by adding higher amount of potato in the sample. In Table 3, the interaction terms of all the process parameters showed significantly negative effects ($P < 0.01$), while the linear terms and quadratic terms of all the process parameters exhibited no significance on hardness. However, the linear terms of the moisture content of the partially dried product before DIC treatment (β_2) and the equilibrium temperature of DIC (β_3) showed negative coefficients with hardness of the products, whereas the linear term of the amount of carrot (β_1) exhibited positive coefficient (see (3)). In Figure 2(c), the hardness of the chips was firstly enhanced by an increase in the amount of carrot and equilibrium temperature of DIC and subsequently decreased after the two parameters reached certain level, that is, 50% carrots and equilibrium temperature of 90°C. Moreover, Figure 2(d) suggested that the hardness slightly increased with decreasing of the moisture content of the partially dried product before DIC treatment. Though Chien et al. [31] claimed that higher quality of the dried product could be featured with relatively low hardness, the maximum of hardness was chosen as the optimum parameter in this study considering that the final products could be crispier when it obtained harder texture after FD-DIC process [12].

3.5. Effect of Processing Variables on the Color Value of the Restructured Chips. The equations of the second-order polynomial model for the L, a, and b value of the products were obtained through RSM and showed as follows:

$$Y_4 = 70.27 - 3.35X_1 - 0.48X_2 - 0.068X_3 + 0.1X_1X_2 - 0.63X_1X_3 - 0.035X_2X_3 - 1.11X_1^2 - 0.39X_2^2 + 0.55X_3^2, \quad (4)$$

$$Y_5 = 24.8 + 2.57X_1 + 0.93X_2 - 0.57X_3 + 0.18X_1X_2 - 0.41X_1X_3 + 0.33X_2X_3 + 0.13X_1^2 + 0.56X_2^2 - 0.4X_3^2, \quad (5)$$

$$Y_6 = 36.17 + 1.38X_1 + 1.05X_2 + 0.06X_3 - 0.15X_1X_2 - 0.2X_1X_3 - 0.48X_2X_3 - 2.24X_1^2 + 0.13X_2^2 - 0.74X_3^2, \quad (6)$$

where Y_4 is L value; Y_5 is a value; Y_6 is b value; X_1 is the amount of carrot (%); X_2 is the moisture content of the partially dried product before DIC treatment (g/g d.b.); X_3 is equilibrium temperature of DIC (°C).

As shown in Table 2, the L, a, and b value of the restructured carrot-potato chips was varied from 62.02 to 74.02, from 21.14 to 28.51, and from 28.81 to 38.42, respectively. According to the P-statistics in Table 3, the L value exhibited significant ($P < 0.01$) negative relationship with the linear terms of the amount of carrot (β_1) and the moisture content of the partially dried product before DIC treatment (β_2), and the interaction terms of "the amount of carrot and equilibrium temperature of DIC" (β_{13}), as well as all the quadratic terms. However, the equilibrium temperature of DIC showed no significant influence on L value. Similarly, Figures 3(a) and 3(b) also depicted that the L value sharply increased with decreasing the amount of carrot and slowly increased with decreasing the moisture content of the partially dried product before DIC treatment at high amount of carrot (62%–70%). This might be attributed to the increase of the amount of potato which contributed to the lightness of the products [12]. Table 3 showed that the linear terms of the amount of carrot (β_1) and the moisture content of the partially dried product before DIC treatment (β_2) exhibited significantly ($P < 0.01$) positive influences on the a value of the restructured chips, while the linear term of the equilibrium temperature of DIC (β_3) showed negative significance ($P < 0.05$). As shown in Figures 3(c) and 3(d), the a value, presenting redness in this case, was improved with increasing the amount of carrot and the moisture content of the partially dried product before DIC treatment. However, the a value slowly decreased with increasing the equilibrium temperature of DIC. A possible reason was that the high temperature adopted during DIC process might cause degradation of carotenoids thus leading to the disappearing of redness (a) and yellowness (b), and this was in accordance with the research of Hornero-Méndez and Mínguez-Mosquera [32] who found that the thermal effects during cooking might bring negative impacts on the stability of carotenoids. According to (6), positive coefficients were found in the linear terms of the amount of carrot and the moisture content of the partially dried product before DIC treatment concerning the b value, and negative coefficients were obtained in the quadratic terms of the amount of carrot. In addition, Figures 3(e) and 3(f) also demonstrated that the increase of the amount of carrot resulted in increase of b value when the amount of carrot was below 50%, while the increase of the moisture content of the partially dried product before DIC treatment slightly enhances the b value. However, the equilibrium temperature of DIC showed no significant impacts on the b value. Similarly, Zhang et al. (2011) put forward a point of view that the color of raw materials (especially carrots) might fade and tend to become white during prefreezing of the mixed puree, which suggested that the color of the restructured carrot-potato chips after FD would be lighter and tend to become yellow instead of orange.

3.6. Effect of the Amount of Carrot on the Microstructure of the Restructured Chips. Based on the data obtained from response surface methodology, it was found that the mixed ratios of potato and carrot significantly affected the qualities (especially hardness and crispness) of the restructured carrot-potato chips after the above analysis of qualities. Therefore, the effect of the amount of carrot on the microstructure of the products was investigated. The microstructure of the restructured chips of the FD-DIC dried products is shown in Figure 4. As seen in Figure 4(a), the FD-DIC dried restructured chips with 30% carrot obtained several large pores and the size of these pores was inhomogeneous. Moreover, these samples are easy to collapse, which could be explained by the high proportion of potato. This phenomenon was similar to the microscopic image taken by Gao et al. [33] who revealed that the starch gelatinization during blanching resulted in partially collapsed or broken cell walls in the cross-section of fried sweet potato chips. In Figure 4(b), the FD-DIC restructured chips with 50% carrot obtained more pores, and the distribution of pore size was more uniform than the other mixed ratios. This homogeneous microstructure might be the reason why the FD-DIC dried restructured chips with 50% carrot obtained the highest hardness and crispness among all the samples [34], which are indicated in the 3D surface contour (Figure 2(b)). In addition, more numbers of pores were

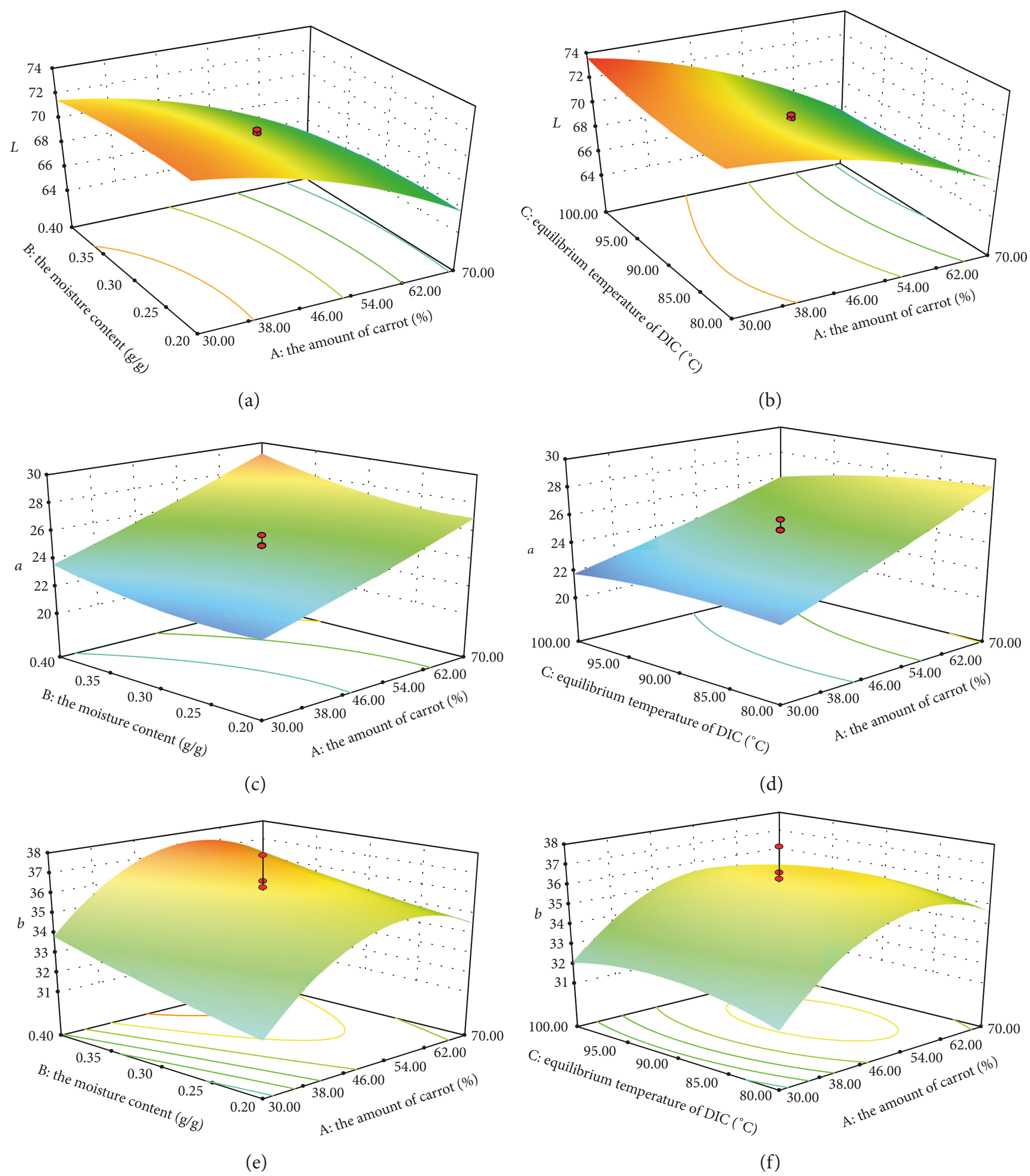

FIGURE 3: Response surfaces for the effect of the amount of carrot, the moisture content of the partially dried product before DIC treatment, and equilibrium temperature of DIC on the color values of *L* (a-b), *a* (c-d), and *b* (e-f) of the restructured carrot-potato chips dried by FD-DIC.

found in the FD-dried restructured chips with 50% carrot (Figure 4(d)), and the distribution of pores was much more regular in comparison to the restructured chips with the same amount of carrot but dried by FD-DIC (Figure 4(b)). During the freeze-drying process, the shrinkage of the sample was limited and the integrity of the microstructure of the raw material could be well maintained [35]. However, the homogenous porous microstructure found in FD-dried samples often pointed to a soft taste or mouth-feel. In contrast, the pores of FD-DIC dried restructured chips expanded and became inhomogeneous after DIC process, which could bring super crispness during masticating. From this point of view, DIC was defined as a texturing operation [17]. Overall, the optimum hardness and crispness of the restructured carrot-potato chips could be obtained by FD-DIC drying when the amount of carrot was 50%.

3.7. Process Optimization and Validation of Predicted Models. Numerical and graphical optimization techniques were adopted to optimize the different drying variables for the production of restructured chips. The main criterion for constraints optimization was the minimum moisture content and the maximum hardness and crispness, with the *L*, *a*, and *b* value of color being in an appropriate range [24]. The results of numerical optimization were listed in Table 5 and verified by experiments. The results showed that the actual values

Table 5: Validation of predicted values for the qualities of the restructured chips.

Variables response	Optimized solutions	Predicted value	Experimental value
Amount of carrot, %	47.43	-	-
The moisture content of the partially dried product before DIC treatment, g/g	0.29	-	-
Equilibrium temperature of DIC, °C	90.57	-	-
Moisture content, g/g	-	0.0275	0.028 ± 0.002
Hardness, N	-	10.30	11.30 ± 0.25
Crispness, mm	-	0.28	0.31 ± 0.01
L	-	70.72	70.05 ± 0.64
a	-	24.37	25.62 ± 0.78
b	-	35.88	36.54 ± 0.82

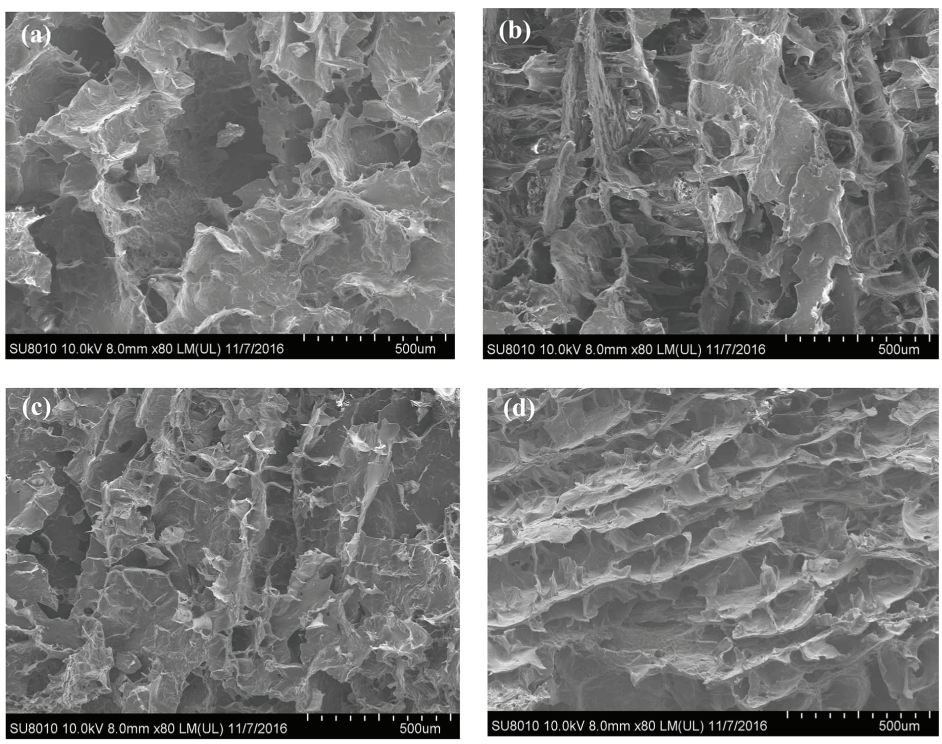

Figure 4: Scanning electron microscopy (SEM) of the restructured carrot-potato chips with different amount of carrot. (a) FD-DIC dried restructured carrot-potato chips with 30% carrot; (b) FD-DIC dried restructured carrot-potato chips with 50% carrot; (c) FD-DIC dried restructured carrot-potato chips with 70% carrot; (d) FD-dried restructured carrot-potato chips with 50% carrot.

for the qualities of the restructured chips were close to the predicted values. For any two given sets of variables, the third one was kept constant, and overlaid contours were obtained between the other two variables in graphical optimization. Figure 5(a) described the overlay plots for the amount of carrot and the moisture content of the partially dried product before DIC treatment when the equilibrium temperature of DIC was set at 90°C. Similarly, Figure 5(b) described the overlay plots for the moisture content of the partially dried product before DIC treatment and the equilibrium temperature of DIC when the constant amount of carrot was 50%. The yellow area within the overlay plots highlighted the most advantageous range for a given set of variables. The most favorable ranges drawn from the overlay plot were found to be between 46% and 54% for the amount of carrot, from 0.20 to 0.35 g/g for the moisture content of the partially dried product before DIC treatment, and from 85 to 95°C for the equilibrium temperature of DIC, respectively. Based on the quality parameters, the optimized process parameters could be helpful in manufacturing the restructured carrot-potato chips with superior texture and color, indicating that the combined drying method of FD-DIC might be practicable for industry.

4. Conclusions

RSM was used to optimize the process parameters of FD-DIC for producing restructured carrot-potato chips. All the three

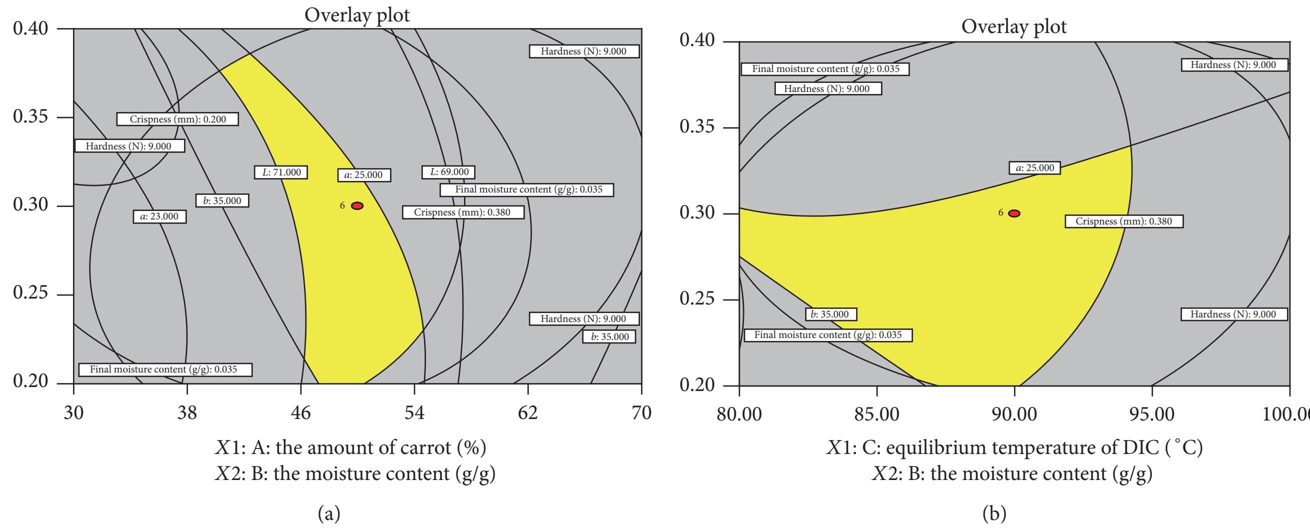

Figure 5: Overlaid contours for (a) the amount of carrot and the moisture content of the partially dried product before DIC treatment to optimize the qualities of the restructured carrot-potato chips at 90°C equilibrium temperature of DIC and (b) for the moisture content of the partially dried product before DIC treatment and equilibrium temperature of DIC to optimize the qualities of the restructured carrot-potato chips at 50% carrot.

targeted parameters, that is, the amount of carrot (mixed ratio), the moisture content of the partially dried product to be DIC-treated, and the equilibrium temperature of DIC, were found to significantly affect the final moisture content, color (L, a, and b), and texture (hardness and crispness) of the restructured chips. For restructured carrot-potato chips, the graphical ranges of the optimized conditions for FD-DIC process were derived as 46–54% w/w for the amount of carrot, 0.20–0.35 g/g for the moisture content of the partially dried product before DIC treatment, and 85–95°C for the equilibrium temperature of DIC, respectively. In addition, the numerical optimization suggested that the optimal solution for the amount of carrot, the moisture content of the partially dried product before DIC treatment, and the equilibrium temperature of DIC were 47.43%, 0.29 g/g, and 90.57°C, respectively, which could yield products with the minimum moisture content, the maximum hardness and crispness, and desirable color. Moreover, the combined drying method was confirmed to have benefits on yielding restructured chips with comparatively superior texture due to the well expanded porous microstructure, as compared to the FD-dried restructured chips. Besides, it is reasonable to speculate that the energy consumption could be significantly reduced due to the reduced drying time during the final stage of drying, and these benefits should be validated in further research and commercial practice. In conclusion, data from the parameter optimization and product quality suggested that instant controlled pressure drop combined with freeze-drying (FD-DIC) could be an alternative method for obtaining high-quality restructured fruit and vegetable chips or processing valuable agroproducts.

Additional Points

Practical Applications. Instant controlled pressure drop (DIC) drying, an emerging drying technology, has been used for a variety of fruit and vegetables, which featured the advantages of yielding products with pleasant crispness and flavor. However, the hot-air-drying combined with DIC drying is not suitable for restructured fruit and vegetable chips owing to the shrinkage of the mixture puree during drying. This problem can be solved by using freeze-drying (FD) which can remove the moisture by sublimation and disadsorption and keep the shape of the samples which were previously frozen in the mold, thus avoiding significant shrinkage. Nevertheless, the application of FD is limited by the relative high consumption of energy and low efficiency of water removing. Considering both the quality of products and energy consumption, the novel combination of FD and DIC with optimized processing conditions could be a practical solution to manufacture restructured fruit and vegetable chips.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Authors' Contributions

Jianyong Yi and Chunhui Hou contributed equally to the present paper.

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