Drying Technology, 31: 726–739, 2013

ISSN: 0737-3937 print/1532-2300 online
DOI: 10.1080/07373937.2013.776071

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Optimum Conditions of Fluidized Bed Puffing for Producing Crispy Banana

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Oil-free snacks have been increasingly demanded by health-conscious consumers. Bananas, which are among the world's leading fruit crops, can be served as a snack. Because a porous structure is an important requirement for crispy banana, a high-temperature short-time treatment were chosen in this study. The effect of operating parameters—that is, intermediate moisture content, puffing temperature, and puffing time—on the volumetric shrinkage and quality attributes of banana were studied. The experimental results showed that the puffing temperature, puffing time, and intermediate moisture content significantly affected the shrinkage, hardness, and crispiness properties as well as color. The intermediate moisture content provided higher or lower shrinkage depending on its level and this factor subsequently affected the textural properties. The higher puffing temperature and longer puffing time resulted in less shrinkage, better texture, and a browner color. A second-order polynomial equation explained the quality parameters reasonably well. All quality parameters, except for volumetric shrinkage, were optimized by means of response surface methodology and the results showed that anintermediate moisture content of 26% db, puffing temperature of 163°C, and puffing time of 1 min should be established for puffed banana using a fluidized bed technique. Another experiment was conducted under the optimum condition to validate the quality parameters with predictions and the differences between experimental data and predictions were insignificantly different at $p < 0.05$.

Keywords Crispiness; Fluidization; Optimization; Quality; Snack

INTRODUCTION

Bananas contain vitamins A, B, and C and high potassium, mineral, and dietary fiber contents, all of which are health benefits to help prevent high blood pressure, normal the heartbeat, calm the nervous system, and cure intestinal disorders.[1] Bananas are mostly consumed as fresh fruit or as processed fruit. The banana chip is a common product that can be produced by frying. Fried bananas have a short shelf life due to rancidity caused by lipid oxidation, although proper packaging is utilized. Drying is a possible method to alleviate the rancidity problem. Freeze drying can minimize the quality changes associated with dried products.[2] During freeze drying, the structure of the product is stiffened and subsequently the solid state of water during freezing protects the primary structure with minimal reductions in volume and shape.[3] Hence, freeze-dried products have less structural collapse than hot air–dried products. However, utilization of this technique in food-related industries is rather limited because of high investment and high operating costs. Thus, the application of freeze drying to foods is restricted to high-value products.[3] An alternative method to produce foods with almost the same texture quality as freeze-dried products is a puffing technique. A puffing process involves the release or expansion of vapor inside the raw material while it is subjected to intensive heating for a short period of time. This technique can produce or expand an internal structure and rupture an original structure.[4,5] There are several puffing methods, such as fluidized bed puffing,[6–9] low-pressure superheated steam drying,[10] microwave,[11] and controlled sudden decompression.[12] The fluidized bed technique seems to be an appropriate method because this method has high heat and mass transfer coefficients as well as good mixing properties,[13] all factors that encourage the moisture inside the food product to be vaporized rapidly and resulting in high volume expansion of products.

Many works have studied the effect of puffing conditions on the volume expansion of puffed products such as rice,[14] potato,[6–9] and amaranth seeds.[15] From these studies, it can be concluded that the puffing temperature, puffing time, and intermediate moisture content have a strong impact on the volume expansion of product. The

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suitability of puffing conditions for maximum volume expansion depends on many factors, such as genotype, size, and the aforementioned factors.

The qualities of snack products such as color and textural properties are influential in consumer acceptability and such qualities are strongly affected by the puffing conditions. The suitable condition for each quality—that is, texture and color—may be obtained under different operating conditions. Hence, it is difficult to obtain optimum qualities by experiment due to the interrelated effects of different process variables. The full-factorial design is one method used for determining optimum conditions for many processes.[16,17] Full-factorial parametric designs provide more complete information about the exact relationship among all main and interaction effects tested. Todetermine the optimum condition, optimization is frequently used. Response surface methodology (RSM) is a statistical technique used to optimize complex processes.[18] This method is an effective statistical technique that uses quantitative data from an appropriate experimental design to determine and simultaneously solve multiple equations.[19] The basic theoretical and fundamental aspects of RSM are to reduce the number of experimental trials needed to evaluate multiple parameters and their interactions. Because RSM is a black-box-type tool, it may lead to the wrong conclusions. To ensure the correct answer, the optimum condition obtained from RSM should be verified experimentally.

The objective of this study was to investigate the effect of operating parameters—that is, intermediate moisture content, puffing temperature, and puffing time—on banana qualities such as texture, color, and volume expansion. Response surface methodology was applied to find the optimum condition that provided a product with appropriate qualities regarding color and textural properties.

MATERIALS AND METHODS

Materials

Gros Michel bananas (*Musasapientum* L.) were purchased from a local market and had a soluble solids content in the range of 17 to 18 Brix. Before processing, the bananas were peeled and sliced into a 3.5-mm thickness using a cutting machine and dipped in a sodium metabisulfite solution. From the preliminary study, the sodium metabisulfite solution at a concentration of 700 ppm and treatment time of 5 min was enough to prevent enzymatic browning reactions. After treatment, the samples were gently blotted with tissue paper to eliminate the excess water on the sample surface. The initial banana moisture content prior to experiments ranged between 300 and 400% (db).

Puffing Process

The puffing process used in this study consisted of three main steps. The fresh bananas were predried in a tray dryer at a drying temperature of 90°C and superficial velocity of 2 m/s. This temperature is the maximum temperature that can prevent brown color development in banana.[20] The banana samples were dried to intermediate moisture contents of 15, 25, and 35% (db) and puffed in a hot air–fluidized bed dryer. A diagram of the fluidized bed drying system consisting of three major components—a cylindrical drying chamber with an inner diameter of 20 cm and a height of 140 cm, 12-kW electrical heaters with a temperature controller, and a backward-curved-blade centrifugal fan driven by a 1.5 kW motor—is shown in Fig. 1. A 30-g sample was puffed in the fluidized bed dryer. If the sample mass was greater than 30 g, the banana sample was not fluidized during puffing. The samples were puffed at temperatures of 140, 160, and 180°C for 1, 1.5, and 2 min at a superficial velocity of 3.5 m/s. The superficial velocity used was 1.4 times the minimum fluidization velocity. The minimum fluidization velocity was 2.4 m/s for 3.5-mm-thick banana slices. After puffing, the samples were further dried to a final moisture content of 4% (db) using a tray dryer operated under the same drying condition as in the first step. Experiments were repeated twice for each experimental condition.

Measurement of Moisture Content

The moisture content of fruits is traditionally determined by the standard vacuum oven method (method 934.06).[21] In this work, however, the moisture content of banana slices was determined by drying at temperature of 103°C for 3 h in a hot air oven (model no. ULE 500, Memmert, Schwabach, Germany). A 3- to 5-g mashed sample was used. Moisture content determination at such a condition was within an error of approximately 0.4–0.6% compared to

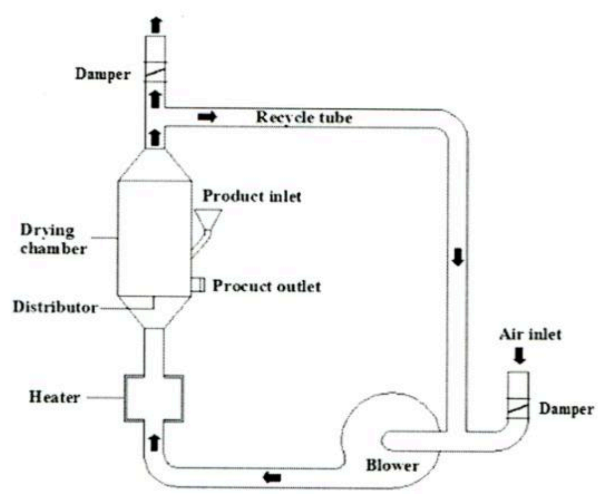


FIG. 1. Schematic diagram of hot air–fluidized bed dryer.

the vacuum oven method. A similar small moisture content determination error (0.4%) was also reported by Thuwapanichayanan et al.[20] using the oven method.

Quality Evaluation

Shrinkage Measurement

Ten samples obtained from each experimental condition were used to determine their shrinkage. The shrinkage of each sample was determined by a solid displacement method using glass beads with a diameter in the range of 0.106–0.012 mm.[22] The percentage of shrinkage was calculated using Eq. (1):

$$\% \text{ shrinkage} = \left(\frac{V_0 - V}{V_0}\right) \times 100, \tag{1}$$

where V_0 is the volume of fresh banana slices and V is the volume of dried banana slices.

For each measurement, one sample was used and the average value of 10 samples was reported. The samples were weighed and transferred to an aluminum can and glass beads were poured over the banana sample until the aluminum can was full. The volume of banana sample (V) was calculated using Eq. (2):

$$V = \frac{M_b - [M_{S+b} - M_v - M_S]}{\rho_b} \tag{2}$$

where M_b is the mass of the aluminum can filled with beads, M_v is the mass of the empty can, M_{S+b} is the mass of the can plus the sample and the beads, M_s is the mass of the sample, and ρ_b is the bulk density of the glass beads.

Color Evaluation

The color of the sample was measured at its surface using colorimeter (Color Flex, Hunter Lab, Buckinghamshire, UK) with D65 illuminant and view angle of 10°. The colorimeter was calibrated with standard white and black plates before testing. For each banana slice, five different positions around the banana surface were measured. Ten banana samples were used to represent the color of the sample under each experimental condition. The mean values of L (brightness/darkness), a (redness/greenness), and b (yellowness/blueness) were reported. In addition, the overall color of puffed banana slices was presented using the hue angle (ϕ), which was calculated as $\phi = \arctan\ (b/a)$. The hue angles at 0, 60, 120, 180, and 240 correspond to the red, yellow, green, cyan, and blue colors, respectively.

Texture Analysis

Fifteen samples were used to determine the textural properties. The hardness and crispiness properties of the dried samples were measured using a texture analyzer (TA.XT. Plus, Stable Micro System, Haslemere, UK) equipped with a cutting probe (HDP-BSK type; Instron Ltd., High Wycombe, UK) connected to a 5 N load cell. The cutting probe was set to travel at a crosshead speed of 2 mm/s. The maximum force was considered as hardness in the force deformation curveandthe crispness of banana slices was characterized by the number of peaks and initial slope of the first peak.[5,20,23] The number of peaks was counted when the peak had a value higher than the threshold value, which was set at 30 *g* force.

Experimental Design and Statistical Analysis

In this study, the independent variables considered to evaluate the effect of puffing conditions on the crisp banana qualities were the intermediate moisture content (*Mc*, coded X_1), puffing temperature (PT, coded X_2), and puffing time (Pt, coded X_3). Based on the preliminary study, the range of independent variables and their levels were established and are presented in Table 1. A total of 27 experimental runs were performed according to the full factorial design with three variables and three levels, and each experimental condition was repeated twice. The experiments were run in random order to minimize the effects of unexplained variability in the observed responses due to extraneous factors. Table 2 shows the experimental data obtained from the operating conditions. The quality of banana snack was evaluated in terms of shrinkage (Y_1) and textural properties; that is, hardness (Y_2), initial slope (Y_3) and number of peaks (Y_4), and color presented by L value (Y_5) and hue angle (Y_6). A second-order polynomial response model (Eq. (3)) was fitted to each of the response variables (Y_k).

TABLE 1
Independent variables of the process and their levels in the three-factor, three-level response surface design

Independent variables	Symbols		Levels	
	Coded	Uncoded	Coded	Uncoded
Intermediate moisture content (% db)	X_1	Mc	−1	15
			0	25
			1	35
Puffing temperature (°C)	X_2	PT	−1	140
			0	160
			1	180
Puffing time (min)	X_3	Pt	−1	1
			0	1.5
			1	2

TABLE 2
Experimental design and experimental results

Experiment no.	Code levels			Experimental result					
	X_1	X_2	X_3	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
1	0	−1	0	13.4	23.1	40.6	12	41.3	64.1
2	0	0	1	6.1	20.1	46.8	23	41.5	59.9
3	0	0	−1	10.6	20.4	45.4	18	45.2	66.0
4	−1	1	0	7.1	22.2	37.9	13	32.8	48.9
5	−1	−1	0	21.5	23.5	35.4	11	43.5	67.4
6	1	1	1	9.6	20.9	40.9	18	37.5	57.2
7	0	0	0	8.2	20.6	47.2	20	43.8	64.1
8	−1	−1	−1	21.4	24.4	31.3	9	43.8	67.8
9	1	0	−1	19.5	26.4	33.1	12	42.4	65.1
10	−1	0	1	12.9	20.8	36.5	15	36.1	54.7
11	−1	−1	1	16.9	24.1	33.5	10	44.1	64.1
12	1	−1	0	22.9	32.1	32.7	9	45.2	65.3
13	1	0	0	16.5	24.8	37.2	13	41.4	65.6
14	0	−1	0	14.1	24.5	41.2	11	42.1	63.3
15	1	1	0	8.5	23.0	39.4	17	39.2	61.3
16	−1	1	−1	6.4	20.9	40.7	16	33.9	54.1
17	−1	−1	0	18.9	24.6	32.8	13	44.9	67.8
18	1	0	1	14.2	26.3	35.9	12	42.9	63.7
19	0	−1	1	11.9	22.5	43.4	13	41.9	64.1
20	1	0	0	18.3	24.8	37.2	13	41.0	65.6
21	1	−1	−1	24.6	32.6	31.6	8	47.1	68.3
22	1	−1	1	20.8	30.8	33.3	8	42.8	35.8
23	−1	1	1	6.4	19.7	40.2	15	31.2	47.9
24	0	−1	−1	15.5	23.3	40.9	7	41.6	65.5
25	−1	1	−1	7.5	21.1	37.4	15	33.7	53.6
26	1	−1	1	18.4	30.8	33.3	8	45.2	35.8
27	0	0	1	5.1	19.8	48.5	25	42.3	60.9
28	0	1	0	2.1	18.4	47.5	24	36.8	56.5
29	1	1	−1	14.5	22.2	36.0	16	40.2	63.5
30	0	1	1	3.5	17.4	51.2	27	32.4	53.6
31	0	−1	−1	14.9	23.3	40.9	7	42.2	65.5
32	−1	1	1	7.5	19.2	35.4	17	31.8	47.7
33	−1	0	0	14.2	22.6	34.2	12	34.2	55.4
34	−1	1	0	8.3	23.6	42.1	15	32.4	49.1
35	1	−1	−1	26.2	33.2	32.4	7	47.1	68.8
36	1	0	1	15.8	25.4	36.4	11	43.5	65.8
37	0	0	0	7.5	21.1	47.5	21	44.0	63.9
38	1	0	−1	18.6	27.5	32.4	11	43.2	66.3
39	−1	−1	1	17.5	23.5	36.7	10	44.3	63.7
40	−1	0	0	13.6	23.4	35.6	11	35.4	55.6
41	0	−1	1	12.8	22.9	42.3	12	41.5	64.4
42	0	0	−1	9.3	21.2	44.8	17	44.8	65.9
43	1	1	0	10.9	24.1	36.5	15	37.4	63.9
44	1	1	1	10	19.8	38.4	19	36.7	62.0
45	0	1	1	2.6	17.6	52.4	28	33.2	53.6
46	−1	0	−1	17.4	21.3	36.3	14	35.4	56.9

(*Continued*)

TABLE 2
Continued

Experiment no.	Code levels X_1	X_2	X_3	Experimental result Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
47	1	−1	0	24.7	33.4	33.6	8	46.0	69.1
48	−1	−1	−1	23.8	22.8	32.5	10	44.2	68.3
49	0	1	−1	4.1	19.8	46.2	25	37.9	60.3
50	−1	0	1	14.2	19.7	33.5	16	33.1	54.7
51	0	1	−1	5.5	18.4	49.1	25	38.5	62.0
52	0	1	0	2.8	19.5	46.8	26	36.0	56.7
53	1	1	−1	12.4	23.8	35.7	11	41.2	64.0
54	−1	0	−1	15.8	19.5	34.2	15	37.6	57.4

Y_1 = shrinkage, Y_2 = hardness (N), Y_3 = initial slope (N/mm), Y_4 = number of peaks, Y_5 = color (L), Y_6 = hue angle.

$$Y_k = b_o + \sum_{i=1}^{3} b_i X_i + \sum_{i=1}^{3} b_{ii} X_i^2 + \sum_{\substack{i=1 \\ i<j}}^{3} b_{ij} X_i X_j, \quad (3)$$

where Y_k is the response variable; X_i represents the coded independent variables; b_o is a constant; b_i, b_{ii}, and b_{ij} represent the linear, quadratic, and interaction coefficients, respectively; and X_i, X_i^2, and X_iX_j represent the linear, quadratic, and interaction terms effects of the independent variables.

Analysis of variance (ANOVA) was used to determine the effects of linear, quadratic, and interaction coefficients of the independent variables. The significance of all terms in the polynomial was evaluatedstatistically by computing the F-value and the significance was set at $p < 0.05$.

Optimization Procedure

Minitab software Ver. 16[26] was used to optimize the multiple responses or multiple qualities. In order to determine the optimal condition, the possible desired goal for each response was considered under suitability for each response. In this study, the goal of hardness was minimized and the goals of initial slope and number of peaks were maximized. The quality in terms of shrinkage was not considered because the textural properties are related to the volumetric shrinkage of the sample. Because the response values were different, it was necessary to normalize them to the same scale. The normalized value (d_k) is called the *desirability*, which ranges between 0 and 1.[24–26] To maximize the response, the dependent variable was normalized by the following equation:

$$d_k = \frac{Y_k - Y_{min}}{Y_{max} - Y_{min}}. \quad (4)$$

To minimize the response, it was defined as

$$d_k = \frac{Y_{max} - Y_k}{Y_{max} - Y_{min}}, \quad (5)$$

where Y_{max} and Y_{min} are the maximum and minimum values of responses, respectively. In order to find an appropriate solution of multiple responses, the individual desirability values were combined into an overall desirability function, D, which is defined as[26]

$$D = \left(d_1^{w_1} \times d_2^{w_2} \times \cdots\cdots \times d_k^{w_k}\right)^{1/(I_1+I_2+\cdots+I_k)}, \quad (6)$$

where w_k and I_k are the weight and importance of k response, respectively. The $w$can be chosen from 0.1 to 10. If the selected value of w is 10, more emphasis is on the goal and thus a response value that is very close to the goal has a high desirability. In this case, it should be applied for the material with a very sensitive quality. On the other hand, if the selected value of w is 0.1, less emphasis is on the goal and thus a response value far from the goal may have high desirability. In this case, it should be applied for the material with a very insensitive quality. In this study, $w = 1$ was chosen. F value of I indicates the importance of each response; a higher value implies a more important response and smaller value indicates less importance. In this study, the textural characteristics and color of banana snacks were equally important and thus the selected values of I for both qualities were identical. The sum of I values must be 10. The optimization technique was used to find a point that maximizes the overall desirability function. A reduced gradient method was used to determine the optimum condition.

RESULTS AND DISCUSSION

Statistical Analysis

The effects of the three independent variables—that is, intermediate moisture content, puffing temperature, and puffing time—on the six response functions—that is, hardness, initial slope, number of peaks, shrinkage, L value, and hue angle—are shown in Table 2. The independent and dependent variables were fitted to Eq. (3) and the regression coefficients were calculated to dictate how the responses were changed with the independent variables. Several indicators—that is, R^2 value, coefficient of variation (CV), and lack of fit—were utilized to evaluate the validity of the fitted models for the aforementioned qualities. R^2 is defined as the ratio of the explained variation to the total variation and is a measure of degree of fit.[27] The coefficient of variation (CV) indicates the relative dispersion of experimental points from the model prediction.

Table 3 shows the ANOVA of responses and their significance at a 95% confidence level as well as R^2, CV, and lack of fit. The lack of fit was examined statistically by F-test.

The lack of fit is a measure of the failure of a model to represent data in the experimental domain at which points were not included in the regression and variations in the models cannot be accounted for by random error.[28] The statistical analysis showed insignificance lack of fit for the initial slope, indicating the validity of the model to explain the data. On the other hand, the lack of fit was significant for shrinkage, hardness, number of peaks, L value, and hue angle. The significant lack of fit for those quantifies was due to small pure errors in the experiment.

Although the lacks of fit forshrinkage, hardness, number of peaks, L value, and hue angle were significant, it was found that the CV values of those qualities wererelatively small, in the range of 2–12%, implying less dispersion between experimental data and predictions. In addition, the R^2 values were higher than 0.8, except for hue angle, which had an R^2 value of 0.62. This low R^2 value could still be used to present the data, as suggested by Malcolmson et al.[29]

As mentioned above, the disagreement among statistical indicators for some particular quality parameters did not mean that those models could not be used for the optimization; they could still be used and validation of the models should be performed. The agreement between experiment and calculation should be achieved using the interesting condition.[30,31]

Shrinkage

The result of coefficients for the empirical equation and the ANOVA for percentage of shrinkage of banana slices are shown in Tables 3 and 4, respectively. The regression coefficients of the shrinkage model indicated that intermediate moisture content, puffing temperature, and puffing time were significant for the linear terms, intermediate moisture content was significant for quadratic terms, and puffing temperature and puffing time were significant for interaction terms. A suitable equation, taking into account only significant terms, was expressed by

$$\% \text{ Shrinkage: } Y_1 = 8.33 + 1.53X_1 - 5.84X_2 - 1.71X_3 + 7.15X_1^2 + 0.72X_2X_3; (R^2 = 0.96) \quad (7)$$

TABLE 3
ANOVA on the effect of puffing conditions (X_i) as linear, quadratic, and interaction terms on each of the response variables (Y_i)

Sum of squares							
Source of variation	Degrees of freedom	Y_1	Y_2	Y_3	Y_4	Y_5	Y_6
Regression	9	2,054.75*	775.76*	1,581.47*	1,381.19*	899.81*	1,944.00*
Linear	3	1,421.26*	512.00*	350.96*	859.39*	845.38*	967.23*
Square	3	615.68*	182.11*	1,222.71*	502.72*	10.13	133.75
Interaction	3	17.80*	81.65*	7.81	19.08	44.29*	843.02*
Residual error	44	66.06	40.91	128.11	300.06	188.25	1,055.92
Lack of fit	17	37.08*	27.49*	69.33	268.06*	171.21*	1,027.67*
Pure error	27	28.97	13.42	58.79	32.00	17.04	28.24
CV (%)		4.93	2.56	2.51	12.40	3.81	5.00
R^2		0.96	0.94	0.92	0.82	0.82	0.64

*Significant at $p < 0.05$.

TABLE 4
Regression coefficients (based on coded data) of the polynomial equations showing the relationship between response variables (Y_i) and independent variables (X_i)

Coefficients	Shrinkage Y_1	Hardness Y_2	Initial slope Y_3	Number of peaks Y_4	L value Y_5	Hue angle Y_6
Constant	8.305*	20.764*	45.974*	19.703*	40.700*	64.059*
X_1	1.530*	2.361*	−0.283	−0.583	2.433*	2.000*
X_2	−5.847*	−2.883*	2.927*	4.694*	−4.055*	−3.144*
X_3	−1.716*	−0.577*	1.047*	1.222*	−1.055*	−3.603*
$(X_1)^2$	7.158*	3.638*	−10.088*	−6.361*	−0.600	−2.178
$(X_2)^2$	−0.158	0.988*	−0.088	−1.194	−0.666	−1.944
$(X_3)^2$	0.200	−0.977*	−0.313	0.055	0.200	−1.619
X_1X_2	0.212	−1.787*	−0.062	0.833	1.158*	5.275*
X_1X_3	−0.420	−0.362	0.566	0.291	−0.191	−2.100*
X_2X_3	0.720*	−0.275	0.020	0.125	−0.683	1.700

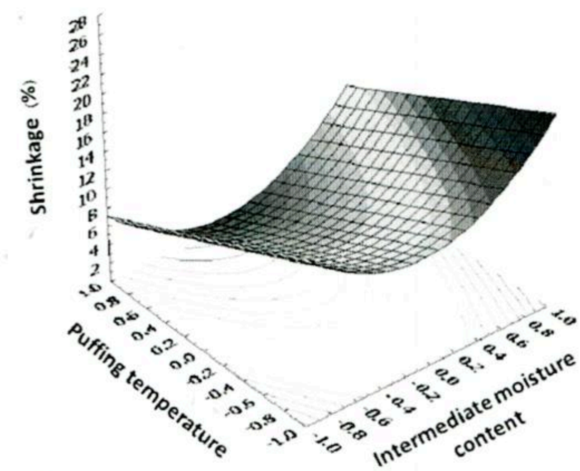
*Significant at $p < 0.05$.

From the above equation, when plotting the percentage of shrinkage as functions of either puffing temperature and intermediate moisture content or puffing temperature and puffing time, it can be seen in Fig. 2b that a higher puffing temperature or longer puffing time provided a lower percentage of shrinkage. A higher puffing temperature or longer puffing time resulted in a higher moisture evaporation rate and subsequently higher vapor pressure inside the product, both factors that allow for expansion or reduced shrinkage of the sample.

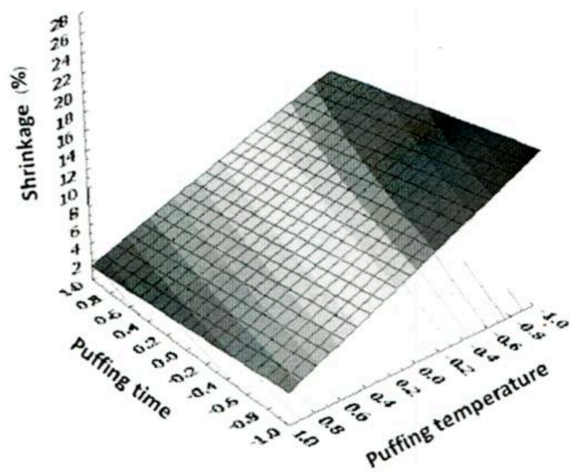
In addition, the intermediate moisture content affected the shrinkage, but its importance was less than that of puffing temperature. As shown in Fig. 2a, this factor exhibited a negative or positive effect on the shrinkage; a low or high intermediate moisture content resulted in higher shrinkage. A low intermediate moisture content of 15% db generated a low vapor pressure inside the sample and subsequently resulted in low expansion during the puffing step or the large shrinkage at the end of the process. On the other hand, the high intermediate moisture content—that is, 35% db—could generate high vapor pressure, but the shrinkage of the sample was still high. This was probably because the sample still retained sufficiently high moisture content (about 20–22% db) after puffing and was rather soft, so that the puffed structure collapsed immediately, thus largely reducing the sample volume. Moreover, a decrease in sample volume also took place during the last drying stage. As measured from the experiment, the sample volume was decreased approximately 10%, which was related to the sample volume after puffing. This decrease was due to stress formation. When moisture is removed, it causes an unbalance of pressure between the inside and outside, which yields contracting stresses that lead to product shrinkage.[32]

When the intermediate moisture content was below 35% db—for example, 15 and 25% (db) in this study—the shrinkage of the sample after puffing and drying in the last stage did not occur because the samples after the puffing stage had relatively low moisture content and the surface of the sample was rather stiff. These data indicate that the suitable intermediate moisture content for puffing banana should be around 25% (db). A suitable intermediate moisture content can vary from material to material. For the naked barley, the appropriate intermediate moisture content to achieve the maximum volume expansion was about 20% (db).[14] The expansion was not successful for potato at an intermediate moisture content lower than 51% (db) and the volume expansion was higher at higher intermediate moisture contents.[33]

Figure 3 illustrates the morphological features of banana slices at the end of the process. The banana morphology obtained from single-stage drying contained fewer small-sized cavities, indicating the compact structure of the banana sample. When the banana samples were puffed at a temperature of 160°C for 2 min, the samples were expanded, leading to a distinct change in morphology compared to Fig. 3a. As shown in Figs. 3b–3d, it appears a very big cavity at inner area and the dense layer near the surface of these samples and their morphologies were not clearly different amongst the samples at intermediate moisture contents of 15–35% (db). However, when considering the volumetric shrinkage result, it was found that the intermediate moisture content had a strong effect on the degree of shrinkage. Compared to the freeze-dried banana, the banana morphologies found in this study were distinctly different; the freeze-dried banana had a uniform and small porous structure.[34] The banana volume after



(a)



(b)

FIG. 2. Effects of puffing temperature, puffing time, and intermediate moisture content on the shrinkage of banana slices (refer to Table 1 for coding): (a) 2-min puffing time and (b) 25% (db) intermediate moisture content (color figure available online).

freeze drying was reduced by 5.9%,[34] which was very close to that found in this study under optimum puffing conditions.

Textural Properties

Hardness

Table 4 shows the regression coefficients of Eq. (3) for the hardness. The puffing temperature, puffing time, and intermediate moisture content were significantly affected on the hardness at $p < 0.05$ for the linear and quadratic terms. The intermediate moisture content and puffing temperature were significantfor theinteraction terms. The regression equation describing the effect of process variables on hardness in terms of coded values of variables, neglecting the insignificant terms, was expressed by

$$\text{Hardness: } Y_2 = 20.76 + 2.36X_1 - 2.88X_2 - 0.55X_3 + 3.63X_1^2 + 0.98X_2^2 - 0.97X_3^2 - 1.78X_1X_2; (R^2 = 0.94) \quad (8)$$

The results shown in Fig. 4 demonstrate the effects of puffing temperatures and intermediate moisture contents on the hardness property of banana slices using Eq. (8). As shown in Fig. 4a, the hardness of banana slices at a given puffing temperature was rather high at the low intermediate moisture content and decreased with increasing intermediate moisture content up to a certain moisture content beyond which the hardness increased again. The lower value of hardness for all puffing temperatures was found at an intermediate moisture content of around 25% (db). The high hardness at high (35% db) or low intermediate (15% db) moisture content was possibly related to the shrinkage, as shown in Fig. 2a. The higher shrinkage at both intermediate moisture contents implicitly showed the lower porosity or dense banana structure and this factor responded to the higher hardness of banana slices. Similarly, a higher puffing temperature provided lower shrinkage and the corresponding hardness became lower. The lower hardness can be attributed to the fact that the interaction between solid matrixes in the banana was weaker at lower shrinkage. For the effect of puffing times shown in Fig. 4b, the hardness changed slightly at puffing times between 1 and 2 min.

The experimental results indicated that the puffing time was less important to hardness than puffing temperature and intermediate moisture content.

Initial Slope and Number of Peaks

Crispiness is associated with a rapid drop in force during mastication. When the force is applied to brittle foods, collapse of the cellular structure occurs and generates a typical sound, contributing to the sensation of crispiness. The puffed banana product consisted of brittle walls surrounding the cavities and its crispness was characterized by the number of peaks and the initial slope of the first peak of the force deformation curve. The slope and number of

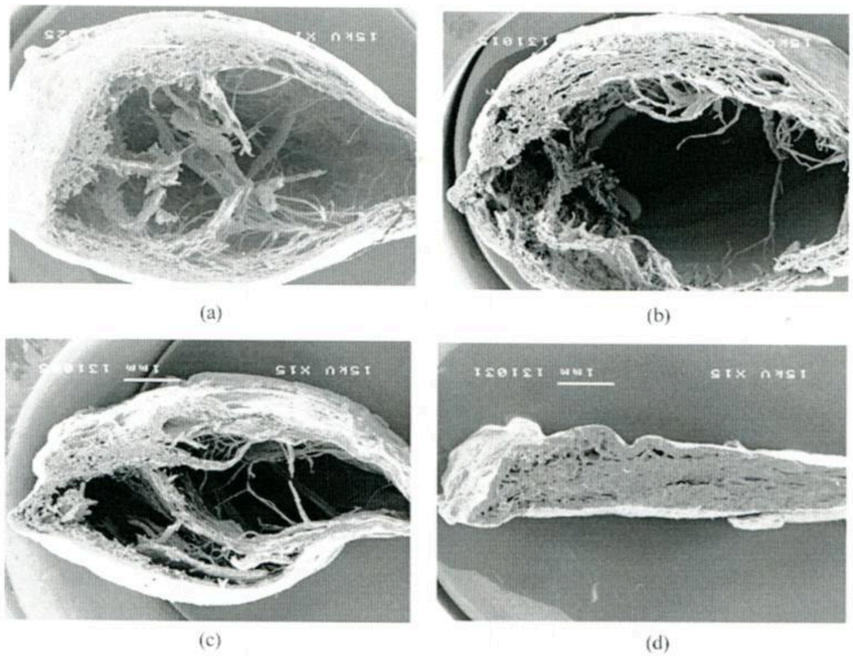


FIG. 3. Scanning electron micrographs of banana slice obtained from different intermediate moisture contents, puffing temperature of 160°C, and puffing time of 2 min: (a) single-stage drying (90°C), (b) 15% db, (c) 25% db, and (d) 35% db (color figure available online).

peaks were related to the large voids in the food material and expansion. The effects of intermediate moisture content, puffing temperature, and puffing time on the initial slope and numbers of peak are presented in Table 4. The puffing temperature and puffing time were significant for the linear terms and the intermediate moisture content was significant for the quadratic terms for the initial slope and number of peaks. The regression equations describing the effect of process variables on the initial slope and number of peaks are given as:

$$\text{Initialslope: } Y_3 = 45.70 + 2.92X_2 + 1.04X_3 - 10.08X_1^2; (R^2 = 0.91) \quad (9)$$

$$\text{Number of peaks: } Y_4 = 18.94 + 4.69X_2 + 1.22X_3 - 6.36X_1^2; (R^2 = 0.80) \quad (10)$$

The variations in initial slope and number of peaks with puffing temperature, puffing time, and intermediate moisture content were determined using Eqs. (9) and (10), respectively, and are presented in the 3D surface plots. As shown in Figs. 5a and 6a, the puffing temperature and puffing time had a positive effect on the crispiness of puffed banana. Increases in both puffing temperature and puffing time provided the increased initial slope and larger number of peaks due to the smaller volumetric shrinkage and more voids, leading to a physically weaker interaction between the solid matrixes. For the intermediate moisture content as shown in Figs. 5b and 6b, this factor exhibited a negative or positive effect on the crispiness property. The highest crispiness at each puffing temperature, corresponding to the largest number of peaks and highest initial slope, was found near the intermediate moisture content of 25% (db).

The texture results revealed that using a high temperature and long puffing time could improve the texture of banana, with more crispiness and less hardness, and the intermediate moisture content impacted positively or negatively on the hardness and crispiness properties, depending on the moisture level prior to puffing. A suitable intermediate moisture content for banana slices with a good texture, with less hardness and more crispiness, was around 25% (db), which corresponded to the lowest shrinkage. In the case of potato, however, the effect of intermediate moisture content on shrinkage and texture was not similar to that found in this study; the increasing intermediate moisture content of potato caused a monotonic increase in hardness and a monotonic decrease in product volume.[7] Similarly, the hardness of okara/rice blends after puffing increased with increasing intermediate moisture content.[35]

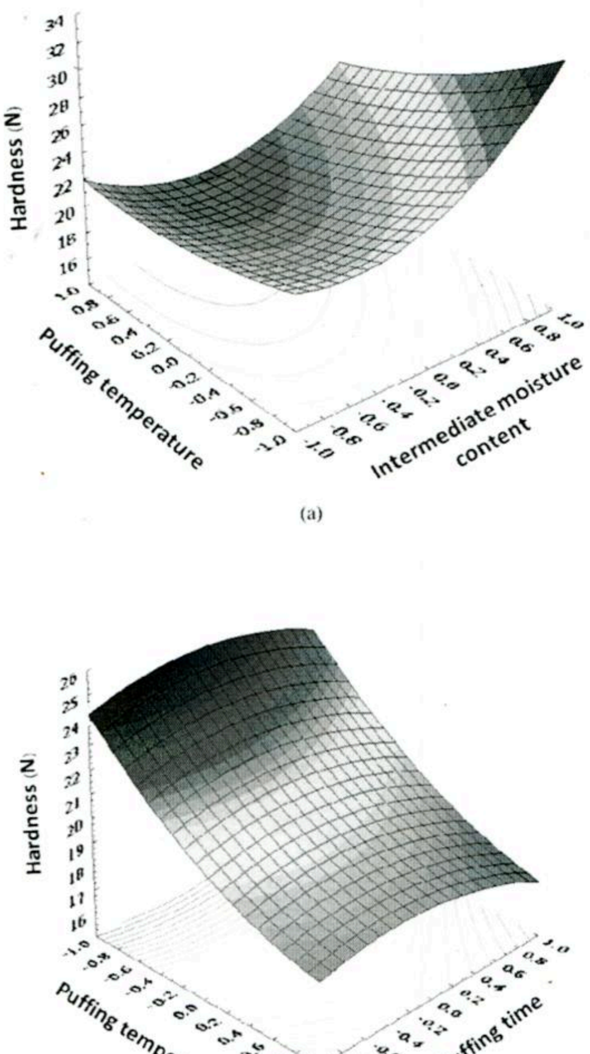


FIG. 4. Effects of puffing temperature, puffing time, and intermediate moisture content on the hardness of banana slices (refer to Table 1 for coding): (a) 2-min puffing time and (b) 25% (db) intermediate moisture content (color figure available online).

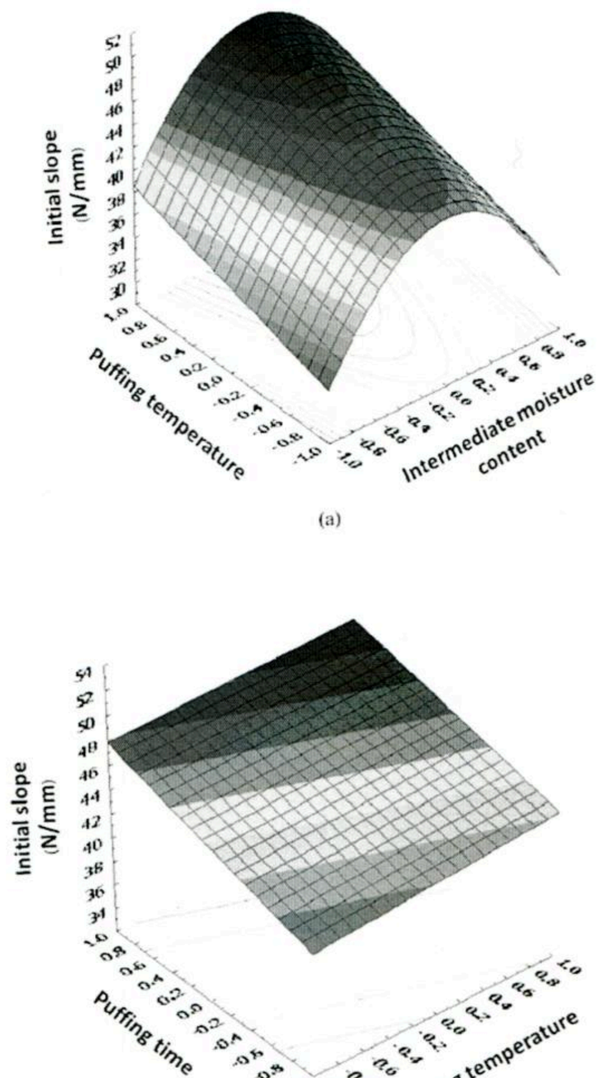


FIG. 5. Effects of puffing temperature, puffing time, and intermediate moisture content on initial slope of banana slices (refer to Table 1 for coding): (a) 2-min puffing time and (b) 25% (db) intermediate moisture content (color figure available online).

Color

The *L* value is an indication of the brightness of a sample and the hue angle is a parameter used to characterize color in food products. Changes in the color parameters of puffed banana slices are associated with the nonenzymatic browning reactions. A decrease in *L* value, *b* value, and hue angle and an increase in *a* value indicates a browner color. The regression coefficients of color

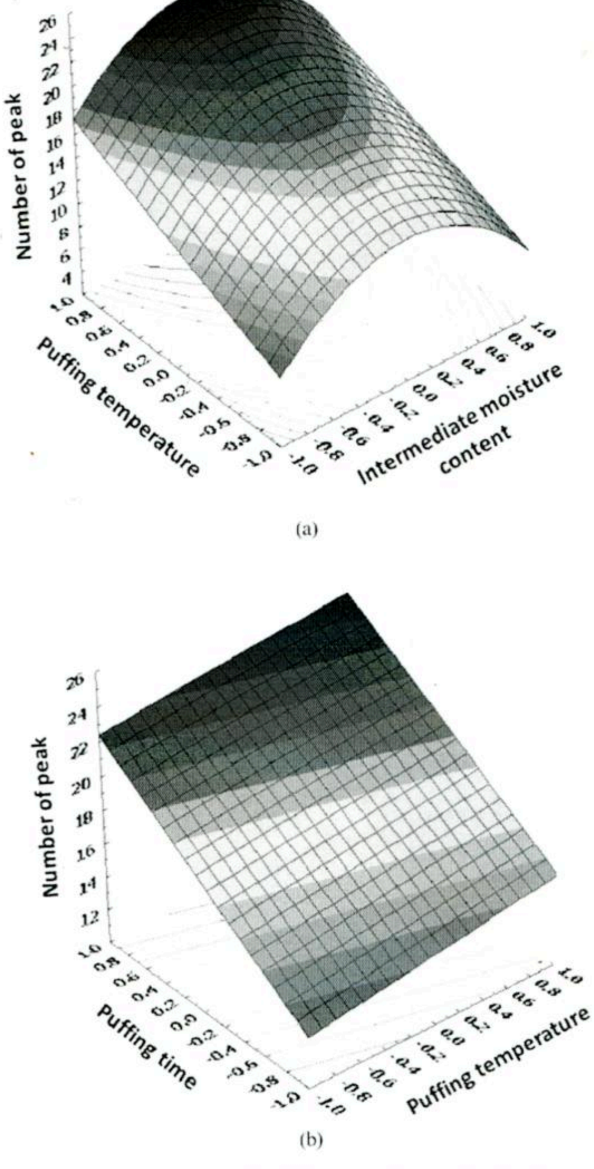


FIG. 6. Effects of puffing temperature, puffing time and intermediate moisture content on number of peaks of banana slices (refer to Table 1 for coding): (a) 2-min puffing time and (b) 25% (db) intermediate moisture content (color figure available online).

equations for L value and hue angle are shown in Table 4. The L value and hue angle were significant for the linear terms intermediate moisture content, puffing temperature, and puffing time and interaction terms intermediate moisture content and puffing temperature. Moreover, the interactions of intermediate moisture content and puffing temperature and intermediate moisture content and puffing time were significant for the hue angle model. The expressions of L value and hue angle are represented by the following equations:

$$L\text{ value: } Y_5 = 39.98 + 2.43X_1 - 4.05X_2 - 1.05X_3 + 1.15X_1X_2; (R^2 = 0.80) \quad (11)$$

$$\text{Hue angle: } Y_6 = 60.23 + 2.00X_1 - 3.14X_2 - 3.60X_3 + 5.27X_1X_2 - 2.10X_1X_3; (R^2 = 0.58) \quad (12)$$

Figures 7 and 8 show the effect of puffing temperature, puffing time, and intermediate moisture content on the L value and hue angle, respectively. A lower intermediate moisture content, higher puffing temperature, and longer puffing time resulted in a final product with lower lightness (L value) and lower hue angle because puffing at such conditions increased the product temperature, which accelerated the nonenzymatic browning reactions.[6,36] The banana product had a light goldenrod yellow color when puffed at a temperature of 140°C, intermediate moisture content of 35% (db), and puffing time of 1 min and was mud-colored at operating conditions of 180°C, 2-min puffing time, and 15% (db) intermediate moisture content.

From the texture and color results, it can be seen that high-temperature and long puffing time provided banana slices with a good texture but detrimentally affected the product color. The trade-off between both qualities was difficult to determine from the experiment, and optimization can help to determine the appropriate operating condition.

Optimization of Puffing Conditions for Banana Slice

Determination of the optimum conditions of puffing banana can be done by setting the objective functions and weights for each of the responses. The settings are shown in Table 5. The result from the optimization showed that the optimum condition for puffing banana was a puffing temperature of 163°C, puffing time of 1 min, and intermediate moisture content of 26% (db). Under the optimum condition, the overall composite desirability as depicted in Table 6 was 0.72. To verify the optimum condition, the experiment was carried out and the quality attributes of the banana product were determined. The observed and calculated values are presented in Table 6. A t-test was used to compare the mean experimental values of responses with the predicted values. Statistical analysis showed the

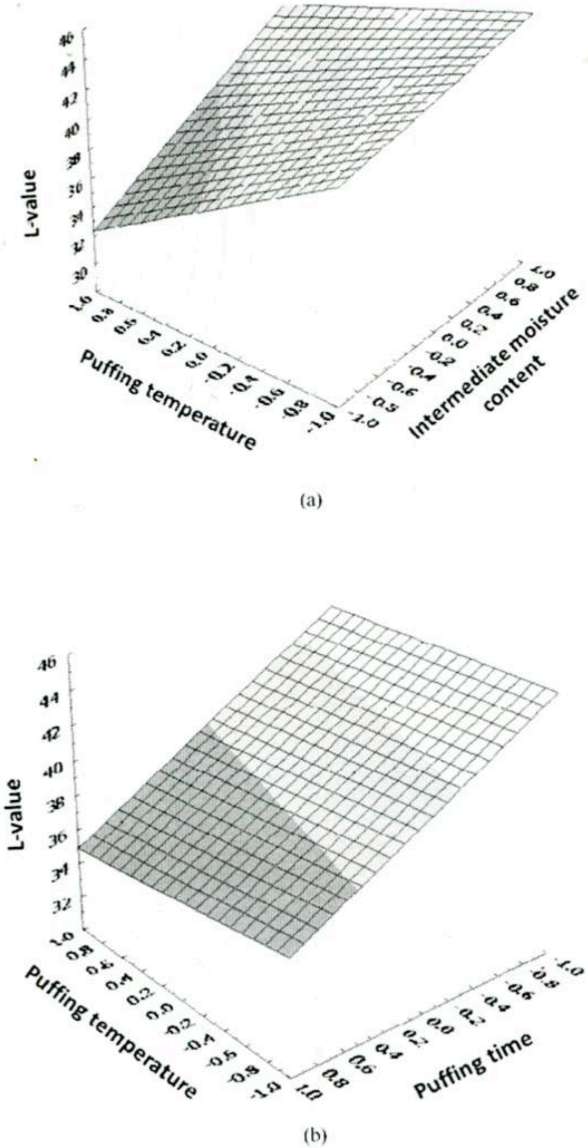


FIG. 7. Effects of puffing temperature, puffing time and intermediate moisture content on *L* value of banana slices (refer to Table 1 for coding): (a) 2-min puffing time and (b) 25% (db) intermediate moisture content (color figure available online).

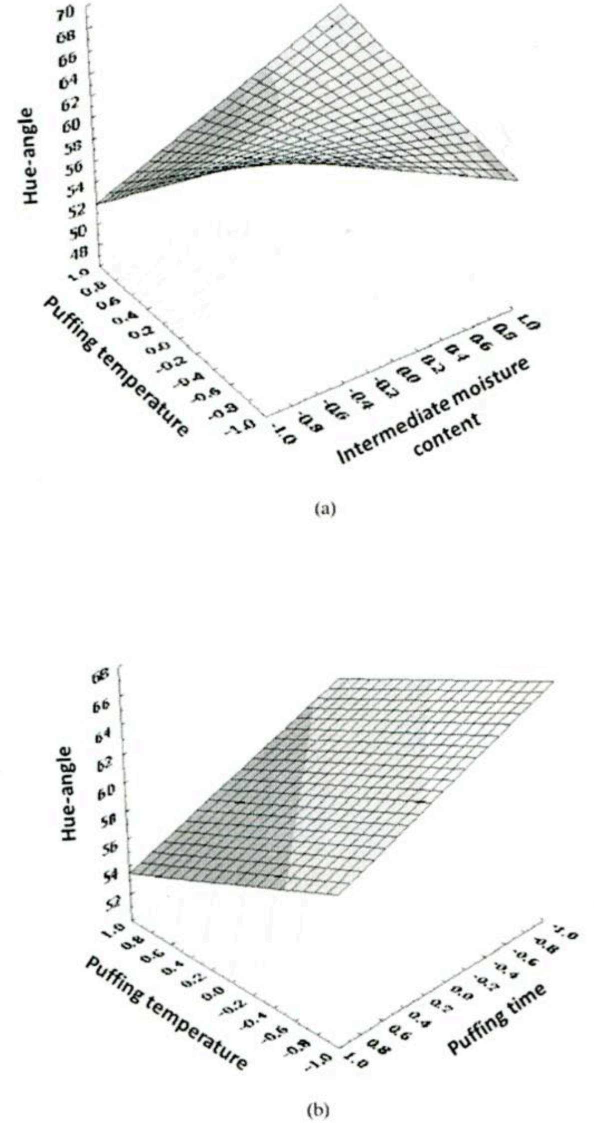


FIG. 8. Effects of puffing time, puffing temperature, and intermediate moisture content on hue angle of banana slices (refer to Table 1 for coding): (a) 2-min puffing time and (b) 25% (db) intermediate moisture content (color figure available online).

insignificant difference between the actual and predicted valuesat $p < 0.05$.

Compared to the textures of commercial freeze-dried banana or fried banana, the texture of banana puffed under optimum condition was crisper than the freeze-dried banana but similar to the crisp texture of fried banana. The hardness of puffed banana was insignificantly different from the commercial products. However, an improvement in the puffed banana color

TABLE 5
Optimization criteria and the value of importance for different responses

Quality	Objective	Lower	Upper	Importance
Hardness (N)	Minimum	17.4	33.4	4
Initial slope (N/mm)	Maximum	31.3	52.4	4
Number of peaks	Maximum	7	28	4
Hue angle	Maximum	35.8	69.1	6
L value	Maximum	31.2	47.1	6

TABLE 6
Quality of the puffed banana slices obtained experimentally under optimum puffing condition compared to predicted values and the quality of commercial products

Quality	Predicted value	Experimental value	Significance (two-tailed)	Desirability	Commercial product	
					Freeze drying	Vacuum frying
Hardness (N)	20.24	22.3 ± 5.6	0.776	0.822	37.5 ± 8.3	26.4 ± 6.7
Initial slope (N/mm)	44.88	43.5 ± 4.8	0.832	0.644	16.7 ± 7.5	34.6 ± 8.8
Number of peaks	19.08	16 ± 4.0	0.582	0.575	12 ± 8	10 ± 8
Hue angle	65.69	66.2 ± 1.4	0.778	0.897	60.5 ± 1.1	76.2 ± 3.1
L value	41.67	44.3 ± 0.9	0.210	0.659	83.7 ± 2.1	46.5 ± 2.6
Overall composite desirability				0.72		

is necessary. The pretreatment method for bananas at a less ripe stage may reduce the browning rate. Such factors will be pursued and reported in future work.

CONCLUSIONS

The effect of operating parameters—that is, intermediate moisture content, puffing temperature, and puffing time—on quality attributesof crispy banana such as texture and color were determined quantitatively. The experimental results showed that a higher puffing temperature and longer puffing time provided a lower percentage of shrinkage and the intermediate moisture content exhibited a negative or positive effect on the degree of shrinkage. The shrinkage directly affected the textural properties of puffed banana in such a way that the low shrinkage provided less hardness and more crispiness, as indicated by the initial slope and number of peaks. This was because large voids were created during fluidized bed puffing, which led to a weak interaction between the solid matrixes. Though a good texture was achieved at high puffing temperature, the banana color was brown. To obtain appropriate quality attributes, the optimization technique was used to tradeoff between texture and color, and the result showed that an intermediate moisture content of 26% (db), puffing temperature of 163°C, and puffing time of 1 min is recommended.

ACKNOWLEDGMENTS

The authors express their sincere appreciation to the National Science and Technology Development Agency (NSTDA), Thailand Research Fund, and King Mongkut's University of Technology Thonburi for supporting the project financially.

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