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Research article

Production method and optimization of puffing tofu skin snack using home microwave oven

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Abstract

Importance of the work: The microwave puffing method can produce a non-fried tofu skin snack to replace the fried snack.

Objectives: To investigate the production method and optimization of puffing a tofu skin snack using response surface methodology (Box-Behnken technique).

Materials & Methods: The sample conditions were optimized based on the initial moisture content (IMC), microwave power (MWP) and puffing time (PT). The tofu skin samples were pre-dried at 40 °C using a hot-air oven to have different initial moisture content conditions. Then, the samples were puffed in a home microwave oven.

Results: The results indicated that the IMC and MWP were the most important parameters affecting all responses, followed by the PT. The optimum conditions for puffing tofu skin in a microwave oven were an IMC of 55%, an MWP of 1,071 W and a PT of 111 s, producing a 0.836 desirability index value. Conditions involving an IMC value outside the range 56.5–57%, an MWP value that lower than 1,200 W or a PT value that lower than 120 s resulted in a reduced expansion ratio and reduced the crispness but increased the hardness. However, lower IMC and higher MWP values resulted in decreased lightness, whereas the redness and yellowness increased. In addition, the moisture content after puffing was inversely proportional to the expansion ratio.

Main finding: This knowledge can be used to produce healthy snacks based on a novel method with rapid heating, high temperature and a short processing time that did not cause a loss of nutritional food value.

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Introduction

Tofu skin, known as yuba in Japanese (Yue et al., 2019), and fupí in Chinese (Yan and Kai, 2020), is a kind of protein-lipid film generated on the top of soymilk that has been continuously heated; it is one of the most famous traditional foods, having a history of over 2,000 years in China (Shurtleff and Aoyagi, 2012). Tofu skin can be divided into three main types: fresh, semi-dry and dry. The form and characteristics of tofu skin products vary depending on different types of cooking. Tofu skin is popular with vegetarians around the world and people in Asian countries, such as Japan, China, Korea and Thailand, because of its high nutritional value, fine taste and unique texture; it has been developed as various types, such as fried, baked and sticks, and can be stored for 3–6 mth in the dry state at room temperature when the tofu skin has been dried to 8% moisture content (Zaigui et al., 2008). The tofu skin contains about 52–57% protein, 24–26% lipid, 12–19% carbohydrate and 3% ash (dry basis) and contains many vitamins and minerals, such as niacin, magnesium, calcium, iron and zinc (Wu and Bates, 1972; Chen and Ono, 2010). Furthermore, the skin contains isoflavones that are antioxidants and phytoestrogens; therefore, they contribute to reducing certain chronic diseases, such as osteoporosis and hormone-dependent cancers (Yeung and Yu, 2003). Tofu skin contains good fat, little saturated fat and no cholesterol and it is good for the heart, while its fiber plays a role in digestive health (König et al., 2012).

Snack production is a rapidly growing food sector and one of the most important areas of the food industry, with snack products being highly appreciated and consumed globally (Monaco et al., 2010), particularly today when consumers are looking for healthier alternatives with pro-health properties (high energy, no trans-fat, high protein) to replace traditional snack foods (Wójtowicz et al., 2018). The healthy snack food market continues to increase and globally is projected to reach USD 32.88 billion by 2025, recording a compound annual growth rate of 5.2% (Grand View Research, 2019). This phenomenon has resulted in the design and production of more complex snack foods to meet variant consumer demands (Mishra et al., 2014). Desirable attributes of products can be achieved by selecting an appropriate food processing technique and optimizing the associated parameters. One novel preparation method for crispy snacks is microwave puffing.

Microwave puffing offers unique opportunities for creating an expanded snack product as it is a novel method involving rapid heating, high temperature and a short processing time; therefore, it does not cause a loss of flavor and nutritional value (Moraru and Kokini, 2006; Sagar and Kumar, 2010; Gulati and Datta, 2016). In addition, it is oil-free, provides a texture similar to that of deep-fried foods and can be stored safely under atmospheric conditions for a longer period (Dhumal et al., 2014). Therefore, microwave puffing is an alternative method for a new snack in the present market that can also benefit the health of consumers. The critical factors in a microwave puffing process are the initial moisture content, microwave power, puffing time and some other parameters, such as adding salt to increase the dielectric properties of cereal grains (Chanlat and Songsermpong, 2015; Van der Sman and Bows, 2017; Mom et al., 2020). An outer snack layer, such as starch gel, a bran layer or rice husk, can help to collect the steam and generate a strong steam burst and a higher expansion ratio than for brown or white rice (Maisont and Narkrugsa, 2009). Packaging also plays a role in collecting the steam and helping to increase expansion (Bhatt and Joshi, 2014; Dash and Das, 2021). Microwave puffing generates intense heat using a high microwave power to ensure rapid evaporation of the optimum water content for the optimum puffing time, thus helping to build internal pressure as steam. The phase change from glass to rubber makes the product soft and easy to expand (Gulati and Datta, 2016). The internal pressure leading to puffing is governed by the evaporation rate, with the reduced permeability layer at the surface acting as a container for the superheated steam (Pompe et al., 2020). Once the superheated steam has left the outer layers, the product becomes fully puffed and the product cools quickly with a reduced moisture content. This is accompanied by a phase change from rubber to glass (Boischot et al., 2003).

Very few studies have been conducted regarding puffing, usually involving proteinaceous products, such as egg white, pork rinds and imitation cheese (Froning et al., 1981; Truong et al., 2014; Zhang et al., 2017). To date, there has been no published report on microwave puffing of tofu skin. The determination of the optimal conditions for microwave puffing process for tofu skin is needed to progress the development of a healthy snack. Therefore, this research aimed to apply response surface methodology to study the production method of puffing a tofu skin snack using a home microwave oven based on the initial moisture content, the microwave power and the puffing time. Optimization of the processing conditions was done and the resultant product quality was compared with the commercial fried tofu skin product.

Materials and Methods

Tofu skin formation

Tofu skin production was carried out in a continuous system to produce a tofu skin sheet of the desired length. The machine was designed by Dr. Sirichai Songsermpong and three of his undergraduate students (Miss Anchuda Tatiyanuntaporn, Miss Nuttita Chuboonlert and Miss Vipasinee Rattanapornmongkol) at Kasetsart University, Bangkok, Thailand. The machine consisted of a soymilk storage tank with a valve to control the soymilk flow. The soymilk was discharged into the film-forming tray through a pipe placed in position below the film level so that it did not interfere with film formation. The film-forming tray was made of stainless steel (width 20 cm, length 30 cm, height 4.5 cm). A cooling tray using tap water was the same size as the film-forming tray. A set of stainless-steel rollers pressed the Teflon perforated belt below the water level. The Teflon belt was fixed by two storage rolls with stainless-steel rollers between the film-forming tray and the cooling tray. The belt movement was rotated by hand. The thickness of the tofu skin was controlled based on the soymilk concentration, the film-forming time and the soymilk temperature.

Sample preparation and pretreatment processes

Shelled soybeans (Raitip brand) were purchased from a local market in Bangkok, Thailand. The shelled soybeans (500 g) were washed with tap water 3–4 times and subsequently soaked in water for 4–5 hr before draining. Then, the soybeans were ground with water in a blender using a water-to-soybean ratio of 3:1. The ground mixture was filtered through a straining cloth to separate the soybean residue and soymilk. The soymilk was poured into a pot and heated at 80 °C for about 20 min. The heated soymilk was fed into the storage tank for the machine designed for tofu skin production in a continuous system.

The rate of soymilk added was controlled using an on-off valve on the inlet to the film-forming tray that was maintained at 80 °C using a gas stove below the film-forming tray. When the soymilk film had formed for 20 min, the Teflon belt rotating the tofu skin sheet was moved to the cooling tray and a new sheet of soymilk film was formed that was connected to the previous sheet. Once heated for 20 min, each tofu skin sheet was rolled along the Teflon belt. This machine could produce tofu skin sheets continuously as needed that were stored at 4 °C in a refrigerator before further use. The thickness of the tofu skin film was 0.2 mm.

Tofu skin sheets were placed on top of one another and pressed all over by hand and then cut into rectangular-shaped pieces (each 4 cm × 5 cm). The initial moisture content of the tofu skin was 61.88% on a wet basis. Then, tofu skin samples were pre-dried at 40 °C using a hot-air oven (Binder, FD-115; Germany) until the initial moisture content was 59%, 57% or 55% on a wet basis. The moisture content was determined based on Association of Official Analytical Chemists (2005).

Microwave puffing

After pre-drying under the different initial moisture content conditions, the tofu skin samples (six pieces approximately 0.5 g each) were heated at microwave power intensities of 320 W/g, 360 W/g or 400 W/g. Each sample was placed in the middle of a plastic bowl with a microwavable plastic cover and then puffed in a home microwave oven (Sharp model R-380I; Thailand) with power outputs of 960 W, 1,080 W or 1,200 W at a frequency of 2,450 MHz. After cooling at room temperature for 30 min, the puffed tofu skin samples were kept in sealed aluminum foil pouches until analysis.

Expansion ratio measurement

The expansion ratio (ER) of the tofu skin snack was determined using the sesame seed displacement method (modified from Segnini et al., 2004). The sesame seeds were poured into a flat-mouthed glass cup to fill the cup. Then, a ruler was passed across the top of the cup to smooth the surface evenly around the edge of the cup. The volume of sesame seeds was measured using a measuring cylinder and recorded as V_1. Six pieces of tofu skin before puffing were placed in the same cup and then filled with sesame seeds until the cup was filled. The cup was tapped to compress the sesame seeds until they had completely penetrated the gaps between the samples and a ruler was again used to smooth the surface. The tofu skin samples were separated from the sesame seeds. The volume of sesame seeds was recorded as V_2. The six pieces of tofu skins were puffed in the microwave oven. Then, their volume was measured using the same method and was recorded as V_3. ER was calculated using Equation 1. Each experiment was replicated three times.

$$ER = (V_1-V_3) / (V_1-V_2) \quad (1)$$

where ER is the expansion ratio of tofu skin, V_1–V_3 is the volume of tofu skin after puffing and V_1–V_2 is the volume of tofu skin before puffing.

Texture measurement

The hardness (HD) and crispness (CP) of the puffed tofu skin samples were measured using a texture analyzer TA-XT Plus (Stable Micro Systems; UK) with a 25 kg load cell, 0.635 cm diameter spherical probe (P/0.25S) and each sample was put on the crisp fracture support rig (HDP/CFS). Samples were tested using a penetration of 10 mm into the sample, a trigger force of 5 g, a test speed of 1 mm/s and a post-test speed of 10 mm/s. The peak (maximum force) was recorded and represented the hardness measured in newtons (N). Crispness was determined from the number of peaks during the penetration cycle. The testing conditions were modified from Thao et al. (2013). Each experiment was replicated five times.

Color measurement

The color of the puffed tofu skin was measured using a colorimeter (Hunter Lab, Ultra Scan Pro; USA) based on the CIELAB system (L*, a*, b*), where the parameter L* is a measure of the lightness and darkness, a* describes greenness (-) and redness (+) and b* describes blueness (-) and yellowness (+). Each experiment was replicated five times.

Moisture content after puffing

The moisture content after puffing (MCAP) of the puffed tofu skin was determined using the hot-air oven method (Association of Official Analytical Chemists, 2005). The samples were dried in an oven at 135°C for 2 hr or until a constant weight was achieved. The moisture content was measured in triplicate on a wet basis and calculated using Equation 2. Each experiment was replicated three times.

$$M = ((W_1 - W_2) / W) \times 100 \quad (2)$$

where M is the moisture content of the puffed tofu skin as a percentage, W is the weight in grams of the sample, W_1 is the weight in grams of the sample before drying and W_2 is the weight in grams of the sample after drying.

Experimental design

The weight of the tofu skins was assigned as a control variable. In the experimental design, three variables were studied at three levels: initial moisture content (IMP; 55%, 57%, 59%), microwave power (MWP; 960 W, 1,080 W, 1,200 W), and puffing time (PT; 80 s, 100 s, 120 s) using response surface methodology (RSM) based on a Box-Behnken design using the Design-Expert version 11 software package (Stat-East, Inc, 2018). The process responses consisted of ER, texture, color and moisture content after puffing. The design consisted of 15 experimental conditions. Three replications were carried out for the experimental conditions at the center point (0, 0, 0) and the code values used for the factors are shown in Table 1. Response surfaces were built using the second-order polynomial regression model containing the coefficients of linear, quadratic and interaction effects. Equation 3 shows the response variable (Y) as a function of three independent process variables (X_1, X_2, X_3):

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_{11} X_1^2 + \beta_{22} X_2^2 + \beta_{33} X_3^2 + \beta_{12} X_1 X_2 + \beta_{13} X_1 X_3 + \beta_{23} X_2 X_3 \quad (3)$$

Table 1 Code values and actual values of independent variables applied in Box-Behnken design

Independent variable	Code	Coded levels		
		-1	0	1
Initial moisture content (%)	X_1	55	57	59
Microwave power (W)	X_2	960	1,080	1,200
Puffing time (s)	X_3	80	100	120

where β_0 is the constant coefficient, β_1, β_2 and β_3 are linear coefficients), β_{11}, β_{22} and β_{33} are quadratic coefficients and β_{12}, β_{13} and β_{23} are interaction coefficients. The model adequacy was checked based on the adjusted co-efficient of determination (R^2), the predicted R^2, the coefficient of variation (CV%) and adequate precision values. The CV% values should be less than 10 and the adequate precision values should be above 4 for acceptability of the models (Mohapatra and Bal, 2010).

Optimization

The optimized condition was chosen based on the desirability function value on a scale of 0–1 (Le and Jittanit, 2015). The desirability of each response depends on the objective type such as the maximum, minimum or target. This study used several critical responses regarding commercial fried tofu skin product purchased from a supermarket in Bangkok, Thailand to identify the optimization process of puffed tofu skin by microwave, considering ER, HD and CP, because such parameters are more important in microwave puffing than the other quality parameters. The overall desirability of the response values was calculated using Equation 4:

$$D = \{d_1(\hat{Y}_1) \times d_2(\hat{Y}_2) \times d_3(\hat{Y}_3) \times ... \times d_k(\hat{Y}_k)\}^{1/k} \quad (4)$$

where D is the desirability index, $d(\hat{Y})$ is the desirability of each response and k is the number of responses.

Statistical analyses

Regression analyses were performed between IMC (X_1), MWP (X_2) and PT (X_3) as independent variables and the following dependent variables, ER, HD, CP, L*, a*, b* and MCAP. The significance of all terms in the regression equation was statistically analyzed based on analysis of variance at the 95% confidence interval to observe the effect on qualities of puffed tofu skin. Non-significant ($p > 0.05$) terms of the process variables were eliminated without damaging model accuracy.

Results and Discussion

Modeling and statistical analysis

The experimental results of puffed tofu skin by microwave are shown in Table 2. (Table 3). The regression equations obtained after eliminating the non-significant terms were shown in Table 4. From the results of the analysis, the adjusted R^2 and predicted R^2 values showed reasonably good agreement. Furthermore, the adequate precision values were more than 4 and the CV% was under 10, indicating a good fit for the models, as shown in Table 4.

Table 2 Conditions used for Box-Behnken experimental designs (15 runs) and quality of microwave-puffed tofu skin compared with commercial fried tofu skin products

Run	Independent variable			Microwave puffing quality						
	IMC (%)	MWP (W)	PT (s)	ER	HD (N)	CP	L*	a*	b*	MCAP
1	55	960	100	3.33±0.17	4.80±0.29	3.60±0.26	62.85±0.18	-1.04±0.14	20.05±0.17	3.14±0.05
2	59	960	100	2.00±0.12	5.40±0.21	3.20±0.16	69.56±0.22	-1.64±0.18	17.05±0.09	5.23±0.14
3	55	1,200	100	5.17±0.26	4.30±0.31	4.10±0.27	60.37±0.12	-0.92±0.12	21.78±0.19	3.04±0.06
4	59	1,200	100	2.67±0.09	4.86±0.18	3.50±0.14	68.06±0.29	-1.39±0.14	17.61±0.15	4.52±0.15
5	55	1,080	80	4.00±0.11	4.55±0.12	3.70±0.29	62.41±0.08	-0.94±0.03	20.83±0.17	3.11±0.07
6	59	1,080	80	2.17±0.05	5.24±0.19	3.30±0.26	69.17±0.27	-1.56±0.17	17.33±0.06	4.82±0.16
7	55	1,080	120	4.33±0.19	4.40±0.12	4.00±0.21	61.35±0.10	-0.93±0.03	21.26±0.16	3.05±0.02
8	59	1,080	120	2.50±0.16	5.12±0.17	3.40±0.25	68.70±0.21	-1.47±0.16	17.47±0.06	4.60±0.18
9	57	960	80	7.50±0.21	4.11±0.28	4.20±0.19	67.24±0.07	-1.37±0.15	18.79±0.15	4.12±0.09
10	57	1,200	80	9.17±0.21	3.44±0.34	4.70±0.23	64.32±0.07	-1.10±0.19	19.46±0.28	3.53±0.06
11	57	960	120	7.83±0.18	3.98±0.22	4.30±0.25	65.77±0.11	-1.27±0.17	18.96±0.05	3.95±0.07
12	57	1,200	120	9.50±0.24	3.18±0.35	4.90±0.37	63.03±0.08	-1.02±0.05	19.77±0.19	3.26±0.14
13	57	1,080	100	8.00±0.17	3.70±0.23	4.60±0.29	65.72±0.13	-1.19±0.06	19.12±0.17	3.78±0.13
14	57	1,080	100	8.17±0.15	3.76±0.24	4.60±0.21	65.49±0.12	-1.18±0.13	19.10±0.19	3.86±0.14
15	57	1,080	100	8.17±0.17	3.73±0.21	4.50±0.28	65.60±0.16	-1.22±0.13	19.04±0.17	3.80±0.13
				Commercial product quality						
				ER	HD (N)	CP	L*	a*	b*	MCAP
				4.00±0.17	4.78±0.33	4.20±0.28	59.27±0.23	0.49±0.16	27.09±0.15	3.31±0.14

IMC = initial moisture content; MWP = microwave power; PT = puffing time; ER = expansion ratio; HD = hardness; CP = crispness; L* = lightness; a* = greenness-redness; b* = blueness-yellowness; MCAP = moisture content after puffing;
Values are shown as mean ± SD of five replicates.

Table 3 *F* values and regression equations of different response variables

Source of variable	*F* value						
	ER	HD	CP	L*	a*	b*	MCAP
Model	549.54***	104.21***	126.29***	111.69***	75.31***	179.22***	104.64***
X_1	321.70***	119.57***	130.43***	877.56***	565.96***	1480.12***	776.24***
X_2	196.24***	114.05***	117.72***	100.33***	90.15***	100.61***	97.38***
X_3	9.99*	7.89*	15.98*	19.87**	8.92*	7.80*	8.14*
X_1X_2	15.70*	0.0579^{ns}	2.61^{ns}	2.07^{ns}	3.85^{ns}	19.38**	32.05**
X_1X_3	0.0001^{ns}	0.0326^{ns}	2.61^{ns}	0.7517^{ns}	1.46^{ns}	1.19^{ns}	0.8042^{ns}
X_2X_3	0.0001^{ns}	0.6119^{ns}	0.6522^{ns}	0.0700^{ns}	0.0910^{ns}	0.2775^{ns}	0.3141^{ns}
X_1^2	4294.82***	682.80***	861.69***	0.0458^{ns}	6.19^{ns}	0.0093^{ns}	18.48*
X_2^2	7.80*	0.2139^{ns}	0.4181^{ns}	4.03^{ns}	0.2107^{ns}	0.1779^{ns}	0.1779^{ns}
X_3^2	5.02^{ns}	0.5648^{ns}	0.4181^{ns}	0.7953^{ns}	0.7150^{ns}	3.49^{ns}	6.45^{ns}

X_1 = initial moisture content; X_2 = microwave power; X_3 = puffing time; ER = expansion ratio; HD = hardness; CP = crispness; L* = lightness; a* = greenness-redness; b* = blueness-yellowness; MCAP = moisture content after puffing

* = $p < 0.05$; ** = $p < 0.01$; *** = $p < 0.001$; ns = non-significant

Table 4 Regression equations for responses of puffed tofu skin

Equation	Adjusted R^2	Predicted R^2	CV%	Adequate precision
ER = 8.113-0.936×IMC+0.731×MWP+ 0.165×PT-0.293×IMC×MWP-5.04× IMC^2+0.215×MWP_2	0.997	0.986	2.62	62.039
HD = 3.73+0.321×IMC-0.314×MWP- 0.083×PT+1.13×IMC^2	0.985	0.919	1.93	32.960
CP = 4.567-0.25×IMC+0.238×MWP+ 0.088×PT-0.946×IMC^2	0.988	0.951	1.53	33.876
L* = 65.603+3.56×IMC-1.21×MWP- 0.54×PT	0.986	0.924	0.52	34.330
a* = -1.197-0.279×IMC+0.111×MWP+ 0.035×PT	0.980	0.899	2.73	28.825
b* = 19.087-1.808×IMC+0.471×MWP- 0.131×PT-0.293×IMC×MWP	0.991	0.952	0.69	42.005
MCAP = 3.813+0.879×IMC-0.311×MWP - 0.09×PT-0.253×IMC×MWP+0.2×IMC^2	0.985	0.922	2.31	34.442

R = coefficient of determination; CV = coefficient of variation; ER = expansion ratio; HD = hardness; CP = crispness; L* = lightness; a* = greenness-redness; b* = blueness-yellowness; MCAP = moisture content after puffing

Effect on expansion ratio

Table 2 shows that the ER of the puffed tofu skin was in the range 2.00–9.50. Comparing the F value of the process variables in Table 3, the greater F value of IMC (X_1) indicated that it was the most influential factor followed by MWP (X_2) and PT (X_3), respectively. The higher values of MWP and PT resulted in an increase in the ER, as shown in the positive model coefficients for MWP and PT. IMC had a negative correlation because of the conversion of moisture present in the structure into steam that consequently increased the pressure gradient for greater expansion, as evident from the equation given in Table 4. The moisture content affected deformability and was important for vapor formation because the higher moisture content reduced the physical strength and made puffing easier. Reduced surface permeability was critical to build up the internal pressure. Deformability or the mechanical property of the product structure before puffing must be flexible and this was dependent on the moisture content. If there were less or too much moisture, it was harder to puff. Intense heat and internal pressure were dependent on the applied wattage and time; therefore, intense heat was needed to ensure rapid evaporation of water within the product and to help build internal pressure that in turn led to puffing controlled by the evaporation rate and the reduced permeability of the surface (Pompe et al., 2020). This correspondence was evident in the negative correlation of IMC^2 and the positive correlation of MWP^2 (Table 4). Fig. 1A shows that the values of IMC in the range 56.5–57%, an MWP of 1,200 W and a PT of 120 s were optimal for the puffing conditions because the raw material had suitable moisture and was subjected to microwave energy so that heat would be generated inside the raw material. When the temperature was higher than the boiling point of water, the water became superheated steam. This increased the internal pressure and there was a phase transition from glass to rubber and more water vapor accumulated in the product resulting in greater product expansion, like a pressure vessel storing steam (Boischot et al., 2003). Furthermore, Nath et al. (2007) reported that temperature was an important factor affecting the ER, as a rise in temperature helped puffing by increasing the rate of vaporization. Though the PT had a comparatively smaller effect on the ER, it played an important role in determining the quality of snacks. A short PT produced less expansion due to insufficient vapor pressure being developed, while a longer PT caused discoloration of the product surface.

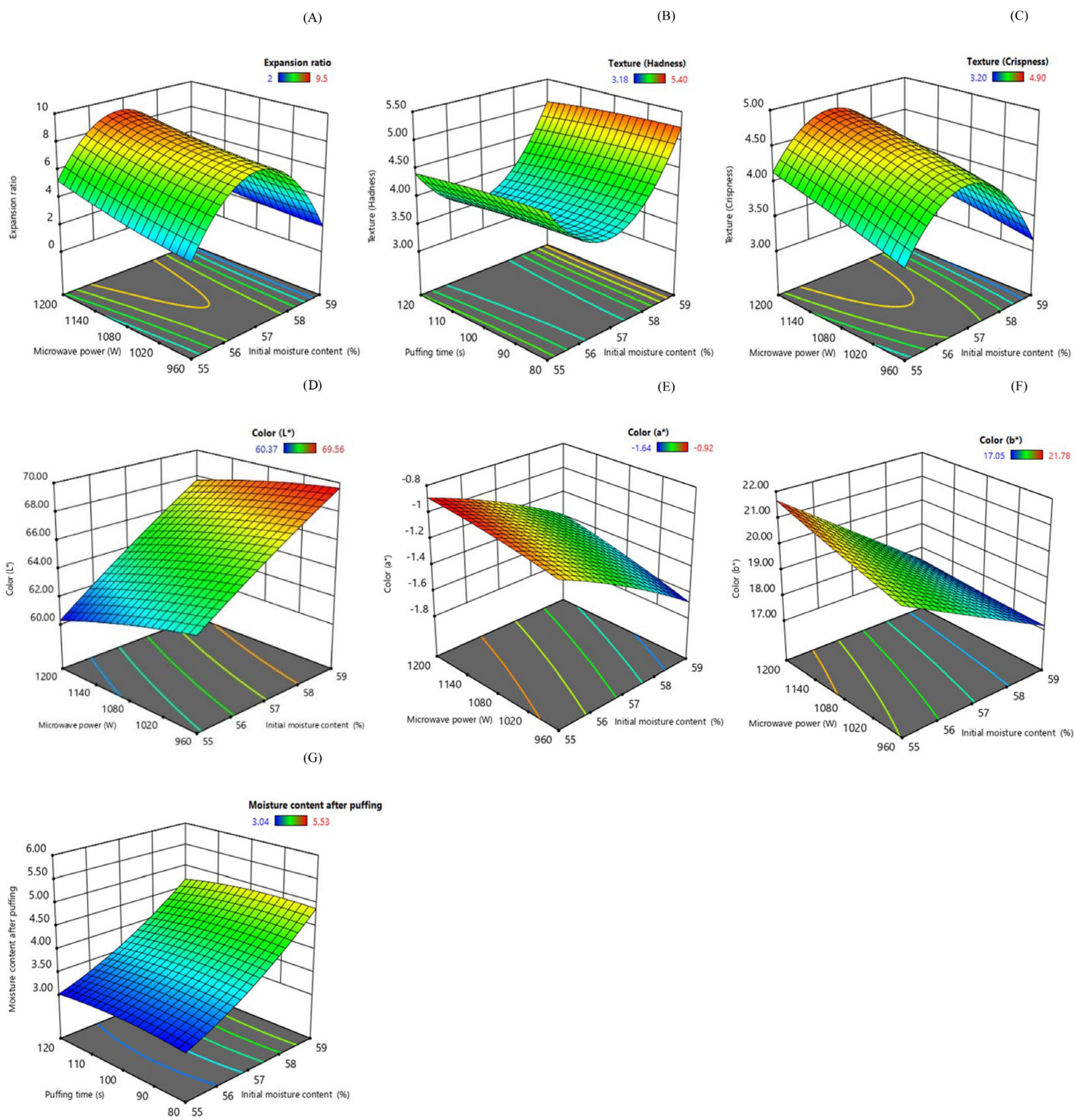

Fig. 1 Surface-contour plot showing effect of initial moisture content (X_1), microwave power (X_2) and puffing time (X_3) on: (A) expansion ratio; (B) hardness; (C) crispness; (D) lightness; (E) greenness; (F) yellowness; (G) moisture content after puffing

Effect on textural properties

The hardness and crispness data of puffed tofu skin were in the ranges 3.18–5.40 N and 3.20–4.90, respectively (Table 2). The F values in Table 3 indicated that the hardness and crispness were greatly affected by IMC (X_1) followed by MWP (X_2) and PT (X_3). The results indicated that the IMC at 57%, the MWP at 1,200 W and the PT at 120 s resulted in the lowest hardness and the highest crispness, as shown in Figs. 1B and 1C, respectively. When MWP and PT increased, the water inside the product rapidly evaporated. The internal structure expanded like a large bubble resulting in a thin and crisp surface layer on the puffed tofu skin, as shown by the positive correlation of MWP and PT, while IMC was negatively correlated (Table 4). On the other hand, the hardness increased when MWP and PT decreased because the internal vapor pressure was less, causing the internal structure to form smaller bubbles, resulting in a thick surface layer of the puffed tofu skin and little expansion. This was evident in the negative correlation with MWP and PT, while IMC had a positive correlation, as shown in Table 4. Furthermore, the quadratic term of (IMC^2) resulted in increasing hardness and lowering crispness. Similar results were reported by Kongngoen (2017) and Nath et al. (2007) who found that when MWP and PT increased, there was a tendency for greater expansion that caused a large porous structure, expelling more of the water contained within the product. This resulted in surface dryness of the product. Therefore, the measured hardness values decreased with increased PT. Mom et al. (2020) observed similar results in rice snack puffing using microwaves.

Effect on color

The color values of puffed tofu skin (Table 2) indicated lightness (L*) was in the range 60.37–69.56, greenness-redness (a*) was in the range -1.64 to -0.92, and blueness-yellowness (b*) was in the range 17.05–21.78. The effect of IMC and MWP was more than for PT based on the F values (Table 3). L* decreased when IMC decreased and when MWP and PT increased, whereas a* and b* increased, as illustrated in Figs. 1D, 1E, and 1F, respectively. Heating the tofu skin using 1,200 W compared to the other levels (1,080 W and 960 W) caused water molecules to evaporate and resulted in further heat build-up inside the product. As a result, there was a higher temperature, causing an increased non-enzymatic browning reaction and resulting in a darker product (Nath and Chattopadhyay, 2007; Argyropoulos et al., 2008; Kantrong et al., 2014). Varnalis et al. (2004) reported similar results in puffed potato cubes, where an increase in PT led to a decrease in L* but an increase in a*. Maisont and Narkrugsa (2010) observed the same results for a puffed rice product, where the browning reaction of the puffed rice products significantly increased, which also seemed to affect the L*, a*, and b* values. Furthermore, in the current study, the negative interactions term of IMC×MWP affected the b* value, whereas the interactions term of IMC×MWP was not affected regarding the L* and a* values (Table 4).

Effect on moisture content after puffing

The data on MCAP ranged from 3.04–5.23% (Table 2). Fig. 1G shows that the increases in both MWP and PT decreased the MCAP of the tofu skin and was inversely proportional to the ER. A higher MWP resulted in an increase in evaporated moisture (Keskin et al., 2005; Rakesh and Datta, 2011), as a consequence of mass transfer on the surface and inside the sample (Chang and Chen, 2013), with the water molecules on the surface of the product absorbing energy from the microwaves and causing vibrations of water and ionic molecules and heat diffusion to occur simultaneously. The heat generated rapidly in the material would have accelerated the rate of water movement and caused increased evaporation. Finally, the moisture content would be lower, as shown by the negative interaction term of IMP×MWP (Table 4). Likewise, If the PT were longer, the water contained in the product would evaporate for a longer period as well (Hebbar et al., 2004; Shi et al., 2008). A similar result was reported by Arimi et al. (2008) who studied the microwave expansion of imitated cheese containing resistant starch, where the puffing time was 10–100 s. They found that as the puffing time increased, the moisture loss increased, which corresponded to Nath and Chattopadhyay (2007) who reported moisture loss in puffed potato-soy snack products as a result of increases in temperature and the time required to heat the product.

Optimization

Optimization was performed on the process variables to obtain puffed tofu skin with qualities in terms of expansion ratio, hardness and crispness that were most similar to a commercial fried tofu skin product by setting the target of expansion ratio at 4.00, hardness at 4.78 and crispness at 4.20, according to Table 2, while the targets for color (L*, a*, b*), and moisture content after puffing were set within the range of the experimental results. Optimum conditions were chosen based on the highest overall desirability. Out of 28 solutions generated by the software, the highest overall desirability value for puffed tofu skin using microwave cooking was 0.836. The optimum process variables were an IMC of 55%, MWP of 1,071 W and PT of 111 s.

Validation

Validation of the model was conducted using the optimal condition of the three factors (expansion ratio, hardness and crispness) with three replications. The actual and predicted responses were found to be within acceptable limits, which confirmed the suitability of the produced model, as shown in Table 5.

Images of puffed tofu skin snack

The images of tofu skin after puffing in a microwave oven based on 15 experimental conditions are shown in Fig. 2. Three replications were carried out for the experimental condition at the center point (0, 0, 0). The condition that resulted in the maximum expansion of tofu skin was IMC 57%, MWP 1,200 W and PT 120 s.

Notably, for proteinaceous products, the IMC, MWP and PT values were higher than for grain products that contain more carbohydrate contents, for example, egg white (50%, 625 W, 2 min; Froning et al., 1981), pork rinds (13.15%, 1,200 W, 3 min; Truong et al., 2014) and imitation cheese (59.14%, 1,000 W, 90 s; Zhang et al., 2017) compared to paddy rice (13%, 800 W, 80 s; Chanlat and Songsermpong, 2015), maize (13%, 900 W, 60 s; Solanki et al., 2018), quinoa (18%, 100 W, 135 s; Mandhare et al., 2020) and sorghum (16.62%, 900 W, 140 s; Mishra et al., 2015). Because proteinaceous products have a higher moisture content than grains, the protein gel layer formed in the pretreatment processes is stronger than for the starch-protein gel layer of grains, making it more difficult to puff. Therefore, a higher MWP and longer PT are required to induce puffing (Chandrasekhar and Chattopadhyay, 1990).

Conflict of Interest

The authors declare that there are no conflicts of interest.

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Table 5 Validation of optimized conditioning process

Quality parameter	Predicted value	Actual value ± SD	Mean difference
Expansion ratio	4.08	4.20±0.31	0.12
Hardness	4.50	4.61±0.27	0.11
Crispness	3.92	3.83±0.33	0.09
L*	61.68	62.01±0.12	0.33
a*	-0.95	-0.93±0.15	0.02
b*	20.99	21.07±0.18	0.08
Moisture content after puffing	3.09	3.07±0.03	0.02

L* = lightness; a* = greenness-redness; b* = blueness-yellowness

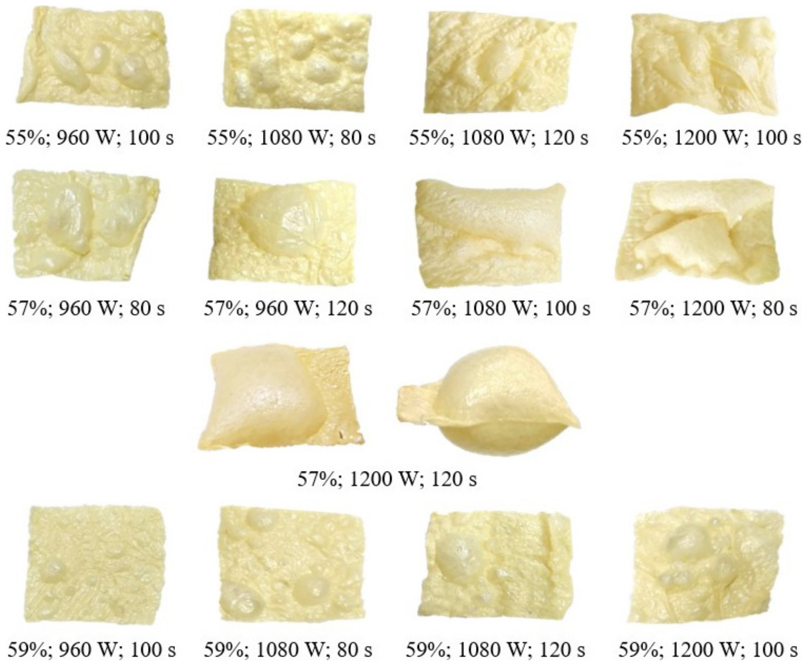

Fig. 2 Images of tofu skin after puffing using a home microwave oven, where values are initial moisture content, microwave power and puffing time, based on three replications

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