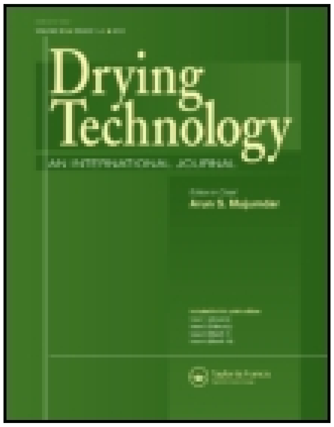

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In order to clarify the mechanism of influence of independent variables in terms of microwave power, vacuum degree, initial moisture content, and puffing time on the objective indexes, in terms of moisture ratio and expansion ratio, a series of single-factor experiments was performed during microwave vacuum puffing of raspberry leathers. The results showed that microwave power, vacuum, and initial moisture content had a significant influence on the dehydration and texture quality of raspberry snacks in terms of expansion ratio, hardness, and porosity. The change in both moisture content and volume obeyed a sigmoid function as microwave power, vacuum pressure, and initial moisture content, respectively. Both microwave power and initial moisture content had a positive influence on the puffing kinetics up to a certain value followed by negative trends, with the exception of vacuum pressure in the selected range of 15–45 kPa which was insignificant. Texture evolution, including hardness and porosity index processes, has three distinct stages during microwave vacuum puffing of raspberry leathers. But the change in temperature of raspberry leather lags behind that in the texture of hardness and porosity. Raspberry snacks with a high expansion ratio may be obtained under the following conditions: microwave intensity 28 $\mathrm{W g^{-1}}$, vacuum pressure 30 kPa, and initial moisture content 20.0% (wb).

Keywords Kinetics; Microwave vacuum; Puffing; Raspberry fruit; Snack

Raspberry fruit is produced widely in northern China, North America, and certain regions in Europe. Fresh raspberry fruit and its products are highly accepted by consumers due to their appearance, succulent taste, pleasant flavor, and nutrients, including anthocyanin and vitamins. However, the soft texture and high moisture content of fresh raspberry fruit and high climatic temperatures in the harvest season contribute to quality degradation. Raspberries have a short shelf life of 2–3 days at a temperature of 20–30°C. In addition to conventional foods such as juice, jam, and wine, raspberry snacks puffed using a microwave vacuum method are a crisp food with the original flavor and nutrients of fresh fruit.

Microwave vacuum processing has the obvious advantages of high production efficiency due to the rapid heating caused by the polar friction within the material at a high frequency of 24.5×10^9 times per second in a microwave field of 2,450 MHz frequency and superior quality of the final product due to the low processing temperature caused by the decreasing evaporating temperature of water within material in a vacuum condition, which weakens the degradation of nutritional ingredients of the materials.[1] A microwave vacuum puffing (MVP) method has been applied to process fruits and vegetables such as apple,[2] banana, carrot,[3] potato,[4] cranberry,[5] and Saskatoon berry.[6] Although the process of heat and mass (water) transfer in an MVP process is the same as that in a microwave vacuum drying process,[7] the quality of the final product with regard to volume expansion and crispy texture formations processed by the MVP method has been investigated.[8] In the conditions of microwave vacuum, microwave output power and vacuum pressure have pronounced effects on the moisture content and texture indexes of the final product. Understanding the puffing kinetics of fruit leather under microwave vacuum conditions helps to determine the effects of the parameters and explain the processing mechanism for quality improvement.[9–11] Figiel employed a sigmoid model to describe the change in moisture content of a garlic bulb under microwave powers in range of 240–720 W and found that pressure inside the garlic depended on the moisture content of the material, which caused its volume to expand.[12] Song et al. simulated the dehydration process for potato leathers as a function of microwave power and vacuum pressure and reported that the rate of dehydration had a positive correlation with microwave power and a negative correlation with vacuum level.[13] Ressing et al. suggested that the volume expansion of dough subjected to microwave vacuum conditions resulted from the pressure difference between air trapped in the dough and the chamber vacuum pressure and the generation of vapor caused by a

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temperature rise in the dough, according to the simulation results from a two-dimensional finite element model.[14] Microwave vacuum processing parameters contribute to the product process with premium quality and high yield, such as Saskatoon berry,[15] blackcurrant berry,[16] and button mushroom.[17]

According to the above-mentioned results, it was found that the drying (or puffing) kinetics result from the processing parameters, which have a pronounced effect on the desired quality of the final product. However, little information on microwave vacuum puffing raspberry leather is available in the literature. Thus, the objectives of the study were as follows:

1. To study the puffing characteristics of raspberry leathers subjected to microwave vacuum conditions.
2. To determine the effects of MVP conditions on the texture quality of raspberry snacks.

MATERIALS AND METHODS

Raw Materials

Fresh raspberry fruit was collected in July 2011 at the horticulture experimental station of Northeast Agricultural University, Harbin, China. Raw raspberries with the same maturity and free of impurities were picked out to store in a freezer at −18°C (BC/BD-272SC, Haier Group, Qingdao, China) for further experiments.

Preparation of Raspberry Leather

Frozen raspberries were thawed at 3–4°C for 12 h. The thawed raspberries were pureed using a blender at 600 rpm for 8–10 min (HR2027, Philips Domestic Appliance & Personal Care Co., Zhuhai, China). The raspberry puree was placed in a water bath to reduce the moisture content to desire level according to Eq. (1):

$$\Delta m_w = m_{re} - \frac{m_{re} \cdot (1 - M_{re})}{1 - M_p} \quad (1)$$

where Δm_w is the mass of evaporated water (g), m_{re} is the raw pulp mass before condensed processing (g), M_{re} is the moisture content of raw pulp before condensed processing (% wb), M_p is the moisture content after condensed processing (% wb), which was calculated using Eq. (2):

$$M_p = \left(1 - \frac{m_{ps}}{\frac{m_{ps}+m_{ms}}{1-M_0} - \frac{m_{ms}}{1-M_m}}\right) \times 100\% \quad (2)$$

where m_{ps} is the solids content of condensed raspberry pulp (g), m_{ms} is the solids content of maltodextrin (g), M_0 is initial moisture content of raspberry leather shown in Table 1 (% wb), and M_m is the moisture content of maltodextrin (% wb).

An already existing food-grade formulation of dextrin : gelatinized starch:material (provided by Liuzhou Food Co., Liuzhou, China) at a ratio of 1:1:1.06 was added into the conditioned puree.[8] A kneading operation was followed to produce raspberry leather with a weight of 4.00 ± 0.10 g, thickness of 3.75 ± 0.02 mm, and radius of 22.00 ± 0.10 mm. In this study, the raspberry sample used in the process of microwave vacuum puffing is referred to as *leather*, and the final raspberry sample obtained at the end of the microwave vacuum puffing process is referred to as a *snack*.

The prepared raspberry leathers were put into six microwave-safe boxes made of polytetrafluoroethylene (dimensions: 300 × 170 × 80 mm) and each box contained 8 equally spaced leathers. Thus, a total of 48 raspberry leathers with a total weight of 96 g were processed in each experiment. Six boxes containing leathers were then fixed on hanging baskets with a symmetrical distribution in the chamber of a microwave vacuum dryer (QW-4HV, Guangzhou Kewei Microwave Energy Co., Guangzhou, China). The temperature of each raspberry leather was measured using an optical fiber sensor. After the chamber door was tightly closed, experiments on microwave vacuum puffing raspberry leathers were performed according to the values shown in Table 1.

Actual microwave power levels were estimated as follows. One kilogram of deionized water was weighed using

TABLE 1
Parameters and values taken of microwave vacuum puffing raspberry leathers

Parameters of microwave vacuum puffing leathers	Unit (accuracy)	Value range		
Microwave output power	kW (±0.05)	1.34	2.68*	4.02
Vacuum pressure[a]	kPa (±2)	15.0	30.0*	45.0
Initial moisture content	% (wb) (±0.2)	17.0	20.0*	23.0
Puffing time	s (±0.1)		100.0*	Interval 10.0 s

In single experiments for microwave output power, puffing time depended on the final moisture content in the range of 5.00–9.00% (wb).

[a]Vacuum pressure is the gauge pressure.

*Values held constant when other parameters were tested.

an electrical balance (ARRW60, Ohaus Instrument Co., Shanghai, China) and poured into a flask, which was then sealed and sealed. The flask was put in a refrigerator (BCD-186KB, Haier Co., Qingdao, China) at 5°C for 12 h to reach the equilibrium temperature of 5°C. The cold deionized water was then poured into a loaded box and placed in the dryer chamber. The deionized water was heated under the set microwave power and ordinary pressure for 8 min. The heated deionized water was taken out and quickly stirred and its temperature was measured using a thermocouple (RH101, Extech Instruments Corporation, Waltham, MA). Each set of microwave output powers was measured three times following the above procedure and the average temperature was recorded. Assuming that the deionized water absorbed all of the microwave output energy without the consideration of thermal convection and conduction, the actual microwave output power was calculated using Eq. (3):

$$Q_{abs} = \frac{mC_p\Delta T}{t} = \frac{4.187 \times \Delta T}{t} \tag{3}$$

where Q_{abs} is the microwave energy of sample absorption in unit time, actual microwave output power (kW), m is the sample mass (kg), C_p is the specific heat at constant pressure with $C_p = 4.187$ kJ/kg·K, ΔT is the change in sample temperature (K), and t is the microwave heating time (s). Thus, the rated power and actual power (±SE) for the QW-4HV MV dryer were obtained as follows: 1.34 and 0.99(±0.04 kW), 2.68 and 1.76(±0.02 kW), and 4.02 and 2.48(±0.03 kW).

Experimental Design

A single experimental design method was employed to clearly show the influence of microwave power, vacuum degree, initial moisture content, and puffing time on the objective indexes in terms of moisture ratio and expansion ratio. The ranges of values are shown in Table 1. Before microwave vacuum puffing of raspberry leather, the boxes loaded with raspberry leathers were placed into a microwave vacuum chamber. For each set of microwave vacuum puffing experiments, parameters were set under the value shown in Table 1; for example, 1.34 kW microwave output power, 15 kPa vacuum pressure, and 17.0% (wb) initial moisture content (see Table 1). After 10 s of puffing time, samples were removed from the microwave vacuum chamber and indexes, including moisture content, expansion volume, and porosity of samples, were measured. Tested samples were discarded. A new batch of raspberry slices with the same initial moisture content were puffed for 20 s under the same conditions, sampled to measure indexes, and the new batch of raspberry slices were loaded. Subsequent experiments were conducted in additional 10-s increments up to 100 s. Microwave vacuum puffing experiments at the other chosen conditions were repeated according to the above-mentioned procedure.

Measurement of Moisture Ratio

The moisture content of raspberry samples was determined by using the direct oven method. The initial moisture content of raspberry fruit leather was determined by drying 10 samples of 10 g each in a convection oven at 100°C for 24 h and then measuring the masses of samples after cooling in desiccators with silica gel for 60 min to room temperature. The average initial moisture content of strawberry fruit leather was 83.35% (wb). This value was used to determine the moisture for all treatments and the relative error was within 0.2% compared to the AOAC method. Moisture losses were recorded using an electronic balance (ARRW60) with a sensitivity of 0.01 g at constant time intervals during drying for the determination of drying curves. Each drying test was replicated two times and averages were reported. Moisture ratio was calculated as follows:

$$\text{Moisture ratio} = \frac{M_i}{M_0} \tag{4}$$

where M_i is the moisture content at the ith sampling time and M_0 is the initial moisture content of raspberry leather.

Measurement of Expansion Ratio

The volumes of each sample were determined using a quartz sand volume replacement method. A suitable amount of quartz sand powder (diameter in range of 40–70 mesh) was poured into a measuring cylinder to measure the indicated volume V_1. Then a sample was put on the quartz sand, and quartz sand was poured into the sample until the sample was immersed, followed by an oscillating operation using as an oscillator (16700, Barnstead Thermolyne Co., Dubuque, IA) to compact the quartz sand around the sample and its indicated volume V_2 was recorded. Thus, the difference V between V_2 and V_1 was denoted as the real volume of sample. The volume of each sample was repeated twice and the average was taken as the final volume value. The expansion ratio (decimal) was calculated using Eq. (5):

$$\text{Expansion ratio} = \frac{V'}{V_0} \tag{5}$$

where V' is the puffing volume of the raspberry leather (mm^3) and V_0 is the original volume of material (mm^3).

Measurement of Hardness

A texture analyzer (TA.XT Plus, Texture Technologies Corp., Ltd., UK) was used to measure the hardness of the raspberry leathers and snacks. For the hardness measurement, a sample (leather or snack) was placed on the objective table fixed at bottom of the analyzer. A P/5 probe with a diameter of 5 mm fixed at the upper suspension arm was chosen to measure the hardness of sample at a set speed for pretesting, testing, and restored speed of 2, 1, and 10 mm/s (speed accuracy <0.1%), respectively. The maximum capacity was 5,000 g. The hardness value was presented as the highest value in a force–time curve obtained by the embedded software. The hardness value of each sample was measured 10 times and the average was used as the final hardness value.

Measurement of Porosity

The porosity of leather was calculated using Eq. (6):

$$\text{Porosity} = \frac{S2}{S1} \times 100\% \tag{6}$$

where $S2$ and $S1$ are the total area of pores and a magnification of the cross section parted in the middle of the leather, respectively. Images of $S2$ and $S1$ were captured by an image acquisition system consisted of a real-time image capture card (MV-VGA100, 9A/D processing, resolution 768×576, Frame Grabber, Microvision Digital Imaging Technology Co., Ltd., Shenzhen, China), a camera (WV-GP240, pixel 420×240, Panasonic Electric Works China Co., Ltd., Beijing, China), and the console, which was created by the authors.

The area calculation program was developed as shown in the flowchart in Fig. 1 using MATLAB software (ver. 7.5, The MathWorks, Inc., Natick, MA). All source images (as shown in step 1 in Fig. 1) were pretreated using a gray-scale and filter processing method to obtain a clear exterior margin and interior pores (as shown in step 2). The area of the whole section was calculated using the program code at step 2. The total pore areas distributed in the section were calculated using the program code at step 3, and then Wiener filtering and binary image treatment methods were applied to remove noise around images for the clear regions of the pores (as shown in step 3). The porostiy of raspberry materials was determined using the program code at step 4.

Measurement of Temperature

Temperatures of all samples in the conditions of microwave vacuum puffing were detected by an optical fiber system consisted of an optical fiber sensor (PIM type with sampling interval of 1 s, accuracy of ±1°C, and resolution of 0.1°C; Probing Technologies Co., Beijing, China) and a demodulator (PalmSens, sampling frequency 30 Hz and resolution of 0.01°C, Photo-Control Corp., Surrey, B.C., Canada). In order to thread the cable of the optical fiber sensor into the microwave vacuum chamber, a circular iron board with a thickness of 5 mm and diameter of 100 mm was selected to replace the original glass observation screen, in which a hole with a 2-mm diameter was drilled

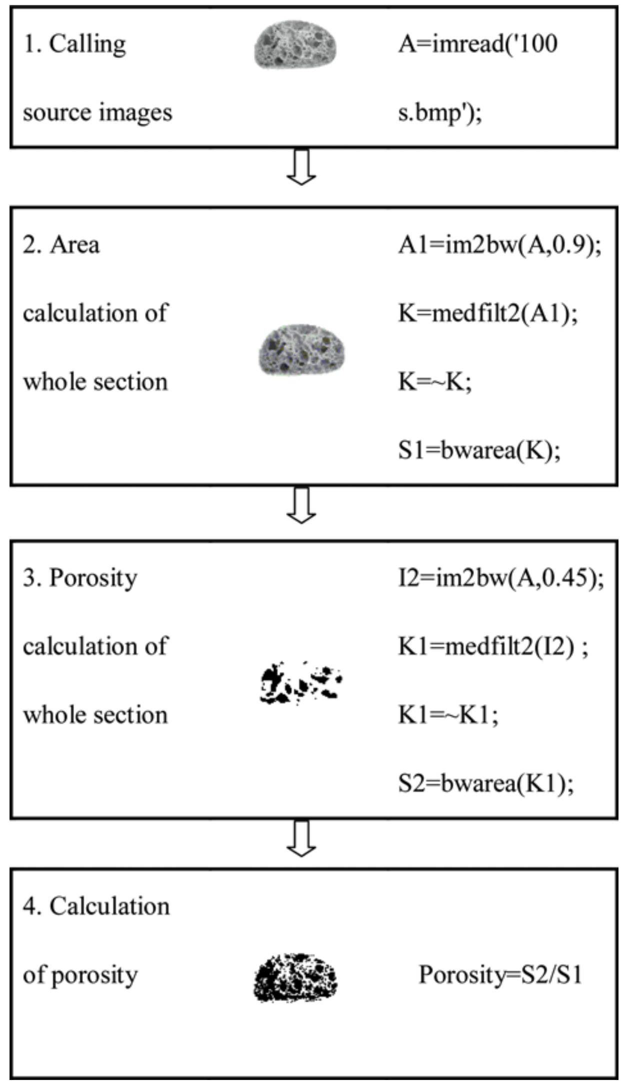

FIG. 1. Flowchart and images of treatment procedure for raspberry leather (or snack) (color figure available online).

as the path for the temperature sensor. The connection between the iron board and chamber wall, as well as between the outside of the sensor and inside of the hole, was sealed with sealing glue to avoid vacuum leakage and the interior of iron board was covered with a copper net to avoid microwave leakage.

Because it was not feasible to plug an optical fiber sensor into the raspberry leather in the revolving basket, a stable location on the bottom of microwave vacuum chamber was determined using a trial-and-error procedure, in which microwave irradiation had the same effect on the raspberry leathers as in the revolving basket. Thus, the tip of the optical fiber sensor was inserted into a raspberry sample in a microwaveable glass disk placed in the selected bottom position and temperature readings were recorded in the demodulator during the microwave vacuum puffing operation. Then the temperature data were transferred into a computer in synchronous mode for further data processing.

To determine whether a glass transition temperature T_g existed during microwave vacuum puffing raspberry leather, a differential scanning calorimeter (DSC; Q2000 DSC, Instrument Specialists, Inc., Twin Lakes, WI) was used to measure the change in temperature and heat flow associated with thermal transitions in a material. Samples of 2 mm diameter, 1-mm thick, and weighing 8 mg were loaded in aluminum crucibles. The rate of temperature increase of the raspberry leather was selected as 90°C/min, which was close to the average rate of temperature increase for material under microwave vacuum puffing conditions. An indirect resistance heating mode was adopted with inert nitrogen as the atmosphere.

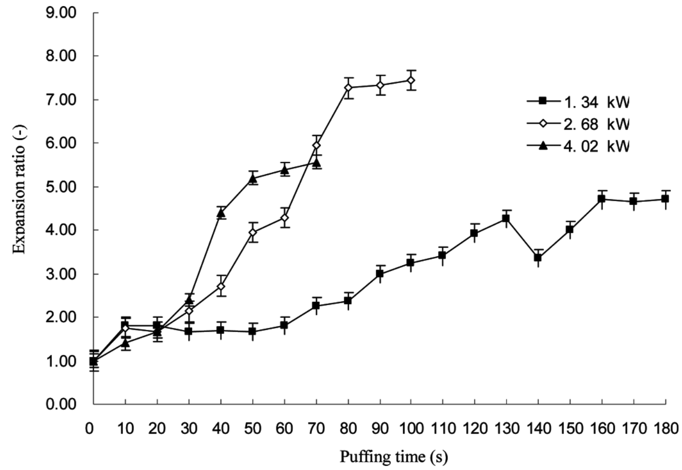

FIG. 3. Change in expansion ratio of raspberry leathers for three microwave powers during microwave vacuum puffing (vacuum pressure 30 kPa, initial moisture content 20% wb, mass 96 g).

Theoretical Consideration

From preliminary experiments, it was found that the evolution of moisture ratio and expansion ratio of raspberry leathers during MVP exhibited a progression from small beginnings that accelerated and reached a maximum over time. A sigmoid function of the general form shown in Eq. (7) is frequently used to describe an S-shaped curve.

$$y = y_0 + \frac{a}{1 + \exp\left(-k(t - t_{1/2})\right)} \tag{7}$$

$T_{1/2}$, called the half-time, is the time threshold when y achieves half of its highest value; a indicates an increment added to y_0 to obtain the highest y value;and k is the slope parameter of the sigmoid function, which shows a gentle trend with an increase in absolute k value. If k is positive, each slope is positive, and if k is negative, each slope is negative. In this study, k, called the kinetic coefficient, indicates the driving force of input parameters on the change in objective index (y value) whose absolute value has a positive correlation with the value of y. According to the shape of the curves in Figs. 2–7, the implication of each item in Eq. (7) was explained as follows. y_0 indicates the basic y value, denoting the moisture ratio or expansion ratio, at the starting point or lowest value at the end point of a specific process. This method requires some explanation in that the fitted curves involved in this research are only of part of whole S curve; thus, the values of parameters representing the highest and lowest position of whole S curve, a and y_0 shown in Tables 2–7, may exceed their theoretical significance relating to this study.

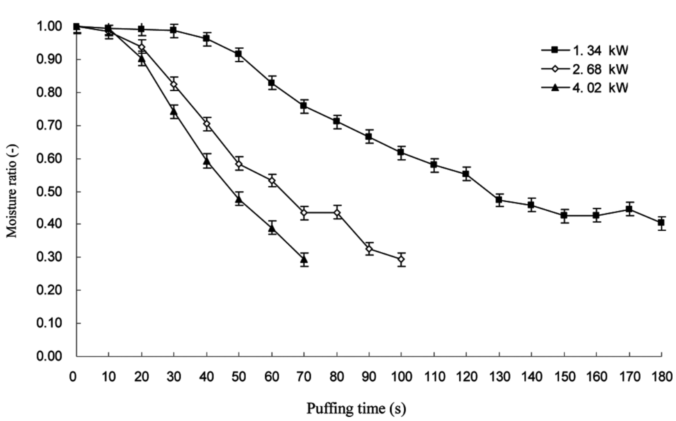

FIG. 2. Change in moisture ratio of raspberry leathers for three microwave powers during microwave vacuum puffing (vacuum pressure 30 kPa, initial moisture content 20% wb, mass 96 g).

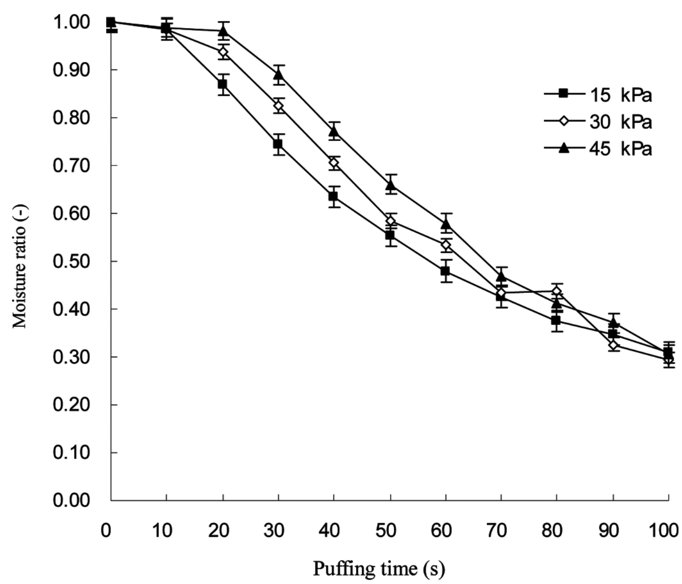

FIG. 4. Change in moisture ratio of raspberry leathers for three vacuum pressures during microwave vacuum puffing (microwave output power 2.68 kW, initial moisture content 20% wb, mass 96 g).

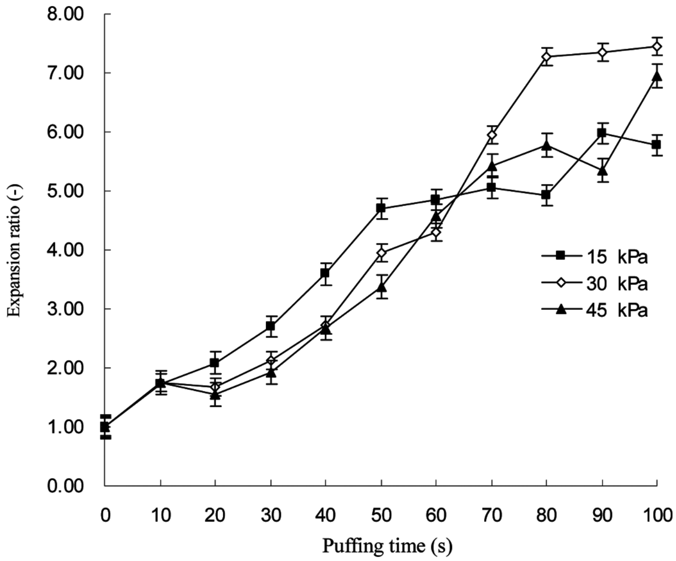

FIG. 5. Change in expansion ratio of raspberry leathers for three microwave powers during microwave vacuum puffing (microwave output power 2.68 kW, initial moisture content 20% wb, mass 96 g).

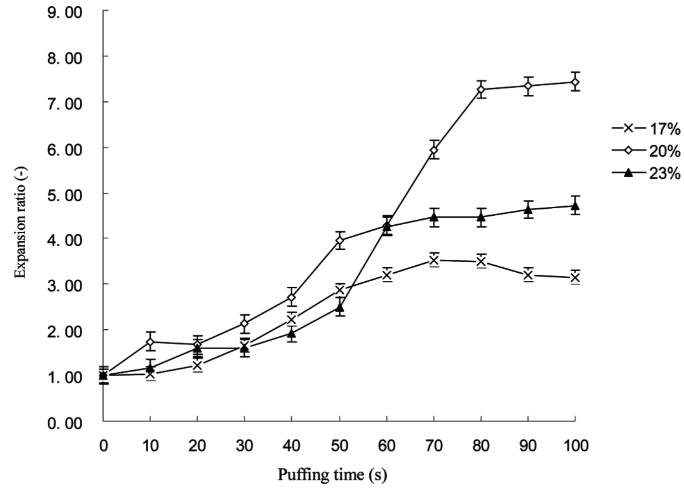

FIG. 7. Change in expansion ratio of raspberry leathers for three initial moisture contents during microwave vacuum puffing (microwave output power 2.68 kW, vacuum pressure 30 kPa, mass 96 g).

Data Processing

The experimental data were verified statistically using analysis of variance (ANOVA) (ver. 9.2, SAS Institute Inc., Cary, NC). The significance of the differences between treatments was determined by a one-factor analysis of variance using Duncan's multiple range test ($p < 0.05$). The parameter estimations of Eq. (7) for various microwave vacuum puffing conditions based on nonlinear regression technique were performed using SigmaPlot 11.0 (SPSS Inc., Chicago, IL) software. A high coefficient of determination (R^2 close to 1) and low standard error of estimate (*SEE*) are the basis for estimating the validity of each parameter.

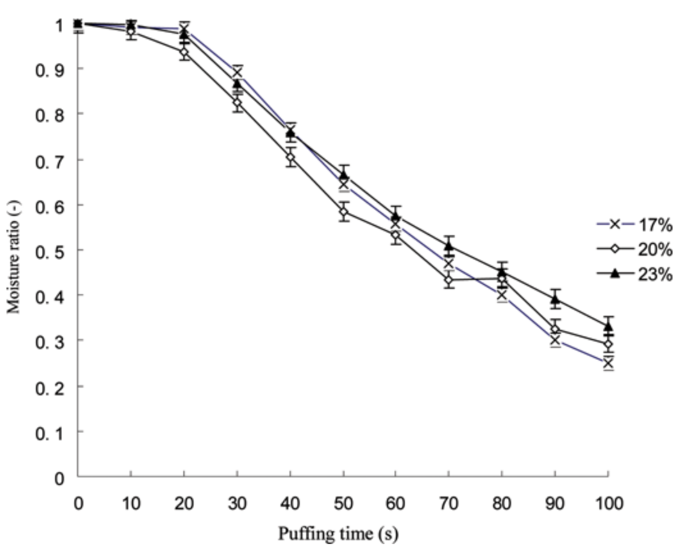

FIG. 6. Change in moisture ratio of raspberry leathers for three initial moisture contents during microwave vacuum puffing (microwave output power 2.68 kW, vacuum pressure 30 kPa, mass 96 g) (color figure available online).

RESULTS AND DISCUSSION

Puffing Kinetic of Raspberry Leathers Subjected to Three Microwave Powers

Figure 2 presents the effect of microwave power on the moisture content of raspberry leathers. The short constant drying stages are presented, which had a negative relationship to microwave output power. The moisture ratio of leather obviously decreased with an increase in microwave power. As shown in Table 2, the regression coefficients, in terms of y_0, a, $T_{1/2}$, and k, presented high statistical credibility due to the high R^2 (>0.99) and $SEE < 0.05$ with significance $p < 0.0001$. The results indicated that a sigmoid function can be used to describe the change in moisture ratio with time at three microwave powers (1.34, 2.68, and 4.02 kW). When the microwave output power was increased from 1.34 to 2.68 and 4.02 kW with the same other conditions, the kinetic coefficient was increased 30.95 and 54.14%, respectively, and the dehydration half-time ($T_{1/2}$) of raspberry leather was reduced 46.57 and 15.17%, respectively. The higher microwave output power caused absorption and conversion of microwave energy within the material to evaporate a large amount of water.

The volume of raspberry leathers expanded with puffing time under the three microwave powers, which had a positive influence on the expansion ratio (in Fig. 3). As shown in Table 3, when the microwave power was increased from 1.34 to 2.68 and 4.02 kW, the kinetic coefficient k increased in turn 1.03 and 1.48 times, respectively, and the half-time, $T_{1/2}$, decreased 43.77 and 37.17%, respectively.

TABLE 2
Regression coefficients of function (4) to represent the moisture ratio with time for the three microwave powers

Microwave power (kW)	y_0	a	$T_{1/2}$	k	R^2	SEE
1.34	0.4016	0.6475	80.3934	−0.0378	0.9904	0.0205
2.68	0.2656	0.8437	43.1021	−0.050	0.9918	0.0286
4.02	0.2503	0.8148	36.4389	−0.0763	0.9954	0.0247

Microwave power was set at 1.34, 2.68, and 4.02 kW, respectively, with initial moisture content of 20% (wb), vacuum pressure of 30 kPa, and load of 96 g. All regression coefficients were obtained at the significance level $p < 0.0001$.

TABLE 3
Regression coefficients of function (4) to represent the expansion ratio of raspberry leather with time for the three microwave powers

Microwave power (kW)	y_0	a	$T_{1/2}$	k	R^2	SEE
1.34	1.2979	3.5035	98.0236	0.0348	0.9940	0.3159
2.68	1.1185	5.9288	53.3284	0.0678	0.9845	0.3251
4.02	1.2052	4.3081	34.6291	0.1756	0.9953	0.1765

Initial moisture content of 20% (wb), vacuum pressure of 30 kPa, and load of 96 g. All regression coefficients were obtained at a significance level of $p < 0.0001$.

TABLE 4
Regression coefficients of function (4) to represent the moisture content of raspberry leather with time for the three vacuum pressures

Vacuum pressure (kPa)	y_0	a	$t_{1/2}$	k	R^2	SEE
15	0.2923	0.8817	32.2739	−0.0488	0.9961	0.0191
30	0.2656	0.8437	43.1021	−0.050	0.9918	0.0286
45	0.2900	0.7639	50.5379	−0.0599	0.9956	0.0211

Initial moisture content of 20% (wb), microwave power of 2.68 kW, and load of 96 g. All regression coefficients were obtained at a significance level of $p < 0.0001$.

TABLE 5
Regression coefficients of function (4) to represent the expansion ratio of raspberry leather with time for the three vacuum pressures

Vacuum pressure (kPa)	y_0	a	$t_{1/2}$	k	R^2	SEE
15	0.1814	5.6676	31.6544	0.0564	0.9772	0.3111
30	1.1185	5.9288	53.3284	0.0678	0.9845	0.3251
45	1.0517	5.6047	53.8256	0.0645	0.9686	0.4305

Initial moisture content of 20% (wb), microwave power of 2.68 kW, and load of 96 g. All regression coefficients were obtained at a significance level of $p < 0.0001$.

The regression coefficients of the sigmoid function (7), that is, y_0, a, $T_{1/2}$, and k, shown in Table 3 had a high R^2 (not less than 0.96) and acceptable SEE in the range 0.1765–0.5486. Thus, a sigmoid function can be employed to quantitatively indicate the change in expansion ratio of raspberry leather at microwave powers of 1.34, 2.68, and 4.02 kW. Figure 2 shows that the highest expansion ratio of raspberry snack was found at a microwave power of 2.68 kW. In fact, during microwave vacuum puffing of raspberry leather, the changes in leather volume resulted from two opposing trends: (1) the volume expansion caused by the water evaporating inside the leather due to the absorption of microwave energy and (2) the volume shrinkage caused by the dehydration that occurred on the exterior surface due to the microwave vacuum heating.[8] It was inferred a that microwave power of 2.68 kW evaporated water within the

TABLE 6
Regression coefficients of function (4) to represent the moisture content of raspberry leather with time for the three initial moisture contents

Initial moisture content (%)	y_0	a	$T_{1/2}$	k	R^2	SEE
17	0.2490	0.8123	51.2979	−0.0583	0.9923	0.0283
20	0.2656	0.8437	43.1021	−0.0500	0.9918	0.0286
23	0.3670	0.6905	46.1532	−0.0623	0.9946	0.0210

Vacuum pressure of 30 kPa, microwave power of 2.68 kW, and load of 96 g. All regression coefficients were obtained at a significance level of $p < 0.0001$.

TABLE 7
Regression coefficients of function (4) to represent the moisture content of raspberry leather with time for the three initial moisture contents

Initial moisture content (%)	y_0	a	$T_{1/2}$	k	R^2	SEE
17	0.9713	2.4573	38.9901	0.1139	0.9904	0.1247
20	1.1185	5.9288	53.3284	0.0678	0.9845	0.3251
23	1.3477	3.2602	51.5788	0.1812	0.9789	0.2697

Vacuum pressure of 20 kPa, microwave power of 2.68 kW, and load of 96 g. All regression coefficients were obtained at a significance level of $p < 0.001$.

leather into enough vapor to expand the volume to the highest level, which is greater than the volume shrinkage caused by dehydration on the leather surface.[18] However, at a microwave power of 1.34 kW, puffing force was decreased due to the low microwave power generating a small amount vapor, and at a microwave power of 4.02 kW high-intensity drying occurred, which resulted in excessive leather volume shrinkage. The volume expansion of raspberry leather under microwave vacuum puffing conditions depended on the microwave intensity defined as the ratio of microwave power to material mass, vacuum pressure, moisture content, and mass of material processed, in addition to the viscoelastic modulus of the material as the moisture content and temperature. A comparison of the microwave intensities of 4.02 and 2.68 kW/96 g showed that higher microwave intensities resulted in greater evaporation of moisture within the material, which resulted in volume expansion, and on the material surface, which resulted in volume shrinkage. In addition, rapid dehydration of the material improved its hardness to weakened the viscoelastic modulus, which is not conducive to volume expansion. of the volume expansion of the final snack was lower than that of 2.68 kW microwave power.

Puffing Kinetic of Raspberry Leathers Subjected to Three Vacuum Pressures

Figure 4 shows that the moisture ratio firstly keeps a short constant stage, depending on the vacuum pressure, and obviously decreased ($p < 0.001$) with puffing time. It was found that the extent of moisture removal had a negative ($p < 0.001$) correlation with vacuum pressure in the microwave vacuum chamber due to the increased evaporation of water within the leather at low pressure. The results in Table 4 indicate that when the vacuum pressure increased from 15 to 30 kPa, as well as from 30 to 45 kPa, the half-time $T_{1/2}$ is increased 33.09 and 17.66%, respectively, but the kinetic coefficient k showed a nonsignificant difference ($p > 0.05$) due to the same final moisture content.

Figure 5 shows that the expansion ratio of leather increased with puffing time at all three vacuum pressures. During microwave vacuum puffing of raspberry leather, the vacuum pressure in the puffing chamber had two effects on the volume expansion of leather: (1) the low environmental pressure around the material is in favor of the generation of vapor within the leather to expand its volume due to the improved activity kinetics of the water molecules with a decrease in pressure and (2) the low pressure accelerated the dehydration process on the surface layer of the material, resulting in volume shrinkage caused by the driving force from the difference between vapor pressure at the material surface and the partial pressure of vapor in the microwave vacuum puffing environment. Both expansion and shrinkage effects determined the final volume of puffed raspberry snack. From Fig. 5, it was found that expansion ratio of leather at 15 kPa vacuum pressure was slightly higher than that at 30 and 45 kPa for puffing times of 10–65 s ($p < 0.05$), which was attributed to the relatively greater volume expansion at 15 kPa than at other vacuum pressure levels. For puffing times of 65–100 s, the expansion ratio of leather puffed at 30 kPa vacuum pressure was higher than that at 15 and 45 kPa ($p < 0.05$), which was attributed to the pressure difference between the interior and exterior of the leather, which resulted in greater volume expansion compared to the other two vacuum pressures. However, compared to the volume expansion of raspberry leather puffed at 30 kPa in this puffing stage, excessive dehydration of the material puffed at a vacuum pressure of 15 kPa caused its volume to shrink due to the low puffing force from the less vapor generation at a vacuum pressure of 45 kPa. Thus, the regression coefficients of the sigmoid model (high R^2 and low *SEE*, shown in Table 5) were used to describe the expansion ratio of raspberry leather with time for the three vacuum pressures.

Puffing Kinetic of Raspberry Leathers Subjected to Three Initial Moisture Contents

At the beginning of puffing, the moisture content of leathers was invariable up to 20 s, followed by a marked decline ($p < 0.01$, Fig. 6). The dielectric properties, in terms of dielectric constant and dielectric loss factor, showed a positive relationship to moisture content of the material within certain moisture and temperature.[19] Thus, the absolute value of the kinetic coefficient k presented in Table 6 exhibits an increasing trend with an increase in initial moisture content. Both high R^2 and low *SEE* values proved that these regression coefficients, in terms of y_0, a, $t_{1/2}$, k, of sigmoid function (7), were suitable to characterize the change in moisture content of raspberry leather with time for the three initial moisture contents.

As shown in Fig. 7, the expansion ratio of raspberry leathers showed an increasing trend depending on the initial moisture content. When the other parameters were held constant (see Fig. 7), leathers with 20% initial moisture content had the highest final volume, followed by that with 23% initial moisture content, and the 17% initial moisture content had the lowest final volume. The moisture contents of final raspberry snacks produced from initial moisture contents of 23.0, 20.0, and 17.0% (wb) were 9.00, 5.86, and 6.82% (wb), respectively. To ensure the desired shape and expansion volume during microwave vacuum puffing raspberry snack, enough strength in the surface layer is needed to support pressure from the difference between the vapor pressure within the material and vacuum pressure in the chamber and avoid the interior vapor overflow. The strength of an agricultural material is responsible for its moisture content and temperature, as well as its textural properties, such as elasticity and viscoelasticity.The kinetic coefficient k was lowest and the expansion ratio was highest for the leather with a 20% initial moisture content. This was because a small portion of the water within the leather generates vapor and expands the volume and the major portion of water is dehydrated down to a low level (5.86% wb) with enough strength to bear pressure. Raspberry leathers with initial moisture contents of 17 and 23% had high kinetic coefficients k and low expansion ratios. This may be due to the 17% initial moisture content having insufficient vapor to expand the leathers' volume and high final moisture content without support interior pressure. According to the results in Table 7, the sigmoid model is also suitable for the expression of the expansion ratio of raspberry leathers at the three initial moisture contents.

Explanations of the Microwave Vacuum Puffing Process in Terms of Temperature and Texture

Temperature is an important index to evaluate the kinetics of the microwave vacuum conditions for the material.[20] In Fig. 8 four distinct stages can be seen in the temperature profile of raspberry leather during the microwave vacuum process. The leather temperature was lightly increased from 34.66 to 37.30°C within 10 s (from the starting point to point A, stage 1), followed by a rapid increase to 98.27°C for puffing times of 10–40 s at point B (from point A to point B, stage 2) and then a slow increase to119.55°C (from point B to point C, stage 3) for puffing times of 40–70 s, followed by a further elevation (from point C to end, stage 4) for puffing times of 70–100 s ($p < 0.001$). This temperature change during microwave vacuum puffing of raspberry leather may be presented by using a sigmoid function as shown in Fig. 8, which has relatively high credibility with R^2 of 0.9648 and *SEE* of 6.9921 at $p < 0.001$. In stage 1, it was inferred that the majority of thermal energy from microwave energy served as the latent heat to evaporate the moisture inside the leathers due to the microwave volumetric heating. In this stage, elevated temperature caused the expansion ratio of raspberry leathers to follow a distinct ascending trend (as shown in Figs. 3, 5, and 7 for puffing times of 0–10 s), and the moisture ratio of leathers to the unchanged state (as shown in Figs. 2, 4,

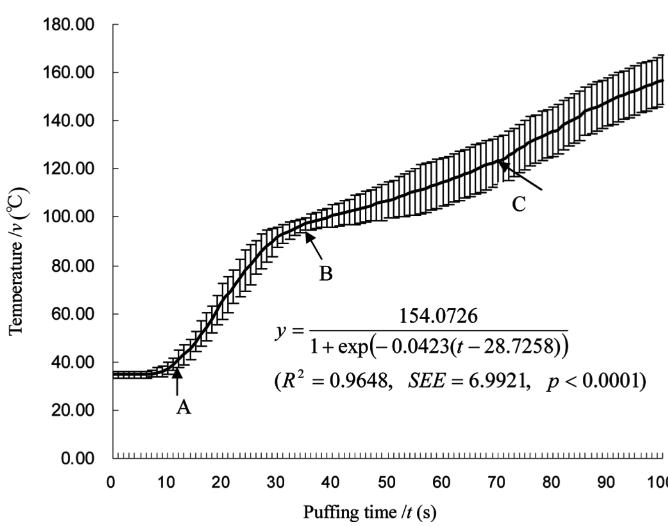

FIG. 8. Temperature profile inside raspberry leather during microwave vacuum puffing (microwave output power 2.68 kW, vacuum pressure 30 kPa, initial moisture content 20% wb, mass 96 g).

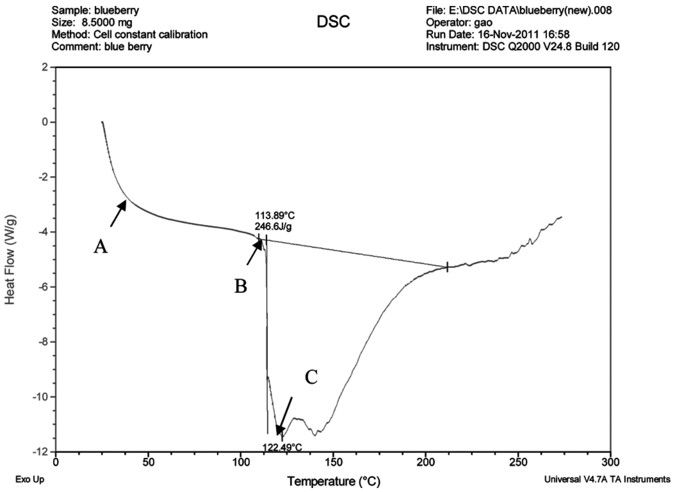

FIG. 9. Heat flow curve of dynamic transition for the raspberry leather during the heating process (initial moisture content 20% wb, temperature elevation rate 90°C/min).

and 6 for puffing times of 0–10 s). In stage 2, the rapid increase in the temperature of leathers caused by the microwaves continuously irradiating the leather had obviously negative effects on the change in hydration (as shown in Figs. 2, 4, 6) and positive effects on the change in volume expansion (as shown in Figs. 3, 5, 7 for puffing times of 10–40 s). In stages 3 and 4, the changes in moisture ratio (as shown in Figs. 2, 4, 6) and expansion ratios (as shown in Figs. 3, 5, 7) showed a continuous trend with stage 2 for puffing times of 40–100 s. As shown in Fig. 9, the occurrence of a turning temperature points A (38.5°C), B (113.89°C), C (122.49°C) was close to the corresponding temperature point shown in Fig. 8, which was attributed to the glass transition temperature of the mixture of raspberry puree, starch, and sugar in this research.This result exhibited a second-order phase transition of the molecular order inside the material from the amorphous state to the sequential rearrangement depending on the thermodynamics of the moisture content change.[21]

As shown in Fig. 10, the hardness value slowly increased to 676.89 g for a puffing time of 50 s, and the leather was in low porosity state in the range of 0–3.02%, called the *thermal absorbed stage*. Then hardness increased by 3.50 times in 10 s, called the *instantaneously porous stage*. The hardness is followed at a stable case in the statistical sense ($p = 0.9550 > 0.05$) and the porous structure with slim hole, evolutive process was presented by the porosity of samples E, F, G was formed, called the *shape formed stage*, during the remaining 40 s of puffing time. In the thermal absorbed stage, the microwave energies dispersing into the raspberry leathers caused the evaporation of moisture, which was responsible for the volume expansion and dehydration. In this stage, the volume of leather showed an increasing trend, but the porosity was lower, as shown for samples A, B, and C. According to the observable phenomena, the interior structure of leather was in a viscoelastic state with low hardness induced by the relatively low temperature and high moisture content. In the instantaneously porous stage, the porosity of the leather rapidly increased as much as nine times. It was explained that vapor enclosed within the leather dilated its volume, as well as diffused outward (dehydration process) when the low Young's modulus was arrived at due to the soft texture of the leather caused by the glass state transition. Thus, the pore structure was retained within leathers. Because the hardness of the leathers (Fig. 10) was measured at room temperature (28.5–31.2°C), the hardness values were much higher than those at high temperature in microwave vacuum puffing based on observation in

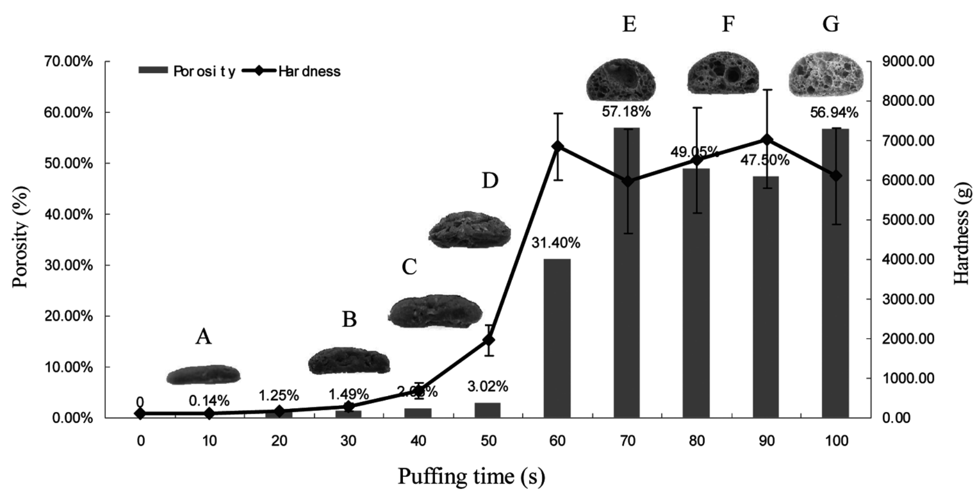

FIG. 10. Porosity and expansion ratio of raspberry leathers during microwave vacuum puffing (microwave power 2.68 kW, vacuum pressure 70 kPa, mass 96 g, and initial moisture content 20% wb). Sample A at 10 s, sample B at 30 s, sample C at 50 s, sample D at 60 s, sample E at 70 s, sample F at 80 s, and sample G at 100 s.

experiments. In this stage, the hardness of the puffed leathers with relative porosity was obviously raised at room temperature due to the decrease in moisture content improving the hardness. In the shape formed stage, continuous moisture evaporation changed the interior pores from the large sizes into uniform, slim sizes, as shown in samples E, F, and G. Although the leather matrix underwent a glass-phase transition in soft states, the tissue had enough strength to support the pores' structural network, when the space originally taken by the liquid water was continuously emptied and air-filled. At the same time, the surface layer became rigid and hardened to retain a stable shape due to their moisture removal and volume expanded from the leathers.

CONCLUSION

Microwave power, vacuum, and initial moisture content had significant influences on the dehydration and textural quality of final raspberry snacks in terms of expansion ratio, hardness, and porosity. The change in both moisture content and volume obeyed a sigmoid function as microwave power, vacuum pressure, and initial moisture content changed. During microwave vacuum puffing of raspberry leathers, the dehydration kinetics increased with an increase in microwave power and a decrease in vacuum pressure, as well as an increase in initial moisture content up to 20% (wb). Both microwave power and initial moisture content showed a positive influence on the puffing kinetics up to a certain value followed by negative trends, with the exception of the insignificance of vacuum pressure in the selected range of 15–45 kPa.

Texture evolution, including hardness and porosity indexes, has three distinct stages during microwave vacuum puffing of raspberry leathers: energy accumulated constant stage, rapid elevation stage, and fluctuating stability. Microwave heating in vacuum is the absolutely indispensable prerequisite for the microwave vacuum puffing raspberry snack. The change in temperature of raspberry leather lagged behind changes in hardness and porosity. The puffing quality of final raspberry product may be controlled based on the change in temperature, if the correlations of texture indexes including but not limited to hardness and porosity with temperature are developed in further research. Raspberry snacks with a high expansion ratio may be processed under the conditions of microwave intensity of 28 Wg^{-1} (from 2.68 kW/96 g), vacuum pressure of 30 kPa, and initial moisture content of 20.0% (wb).

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