Research Article

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Study of the optimisation of puffing characteristics of potato cubes by spouted bed drying enhanced with microwave

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Abstract

BACKGROUND: In commercial deep-fat frying of potato chips, the oil content of the final products ranges from 35 to 45 g 100 g^{-1} (wet basis). High-temperature frying may cause the formation of acrylamide, making the products unhealthy to the consumer. The aim of this research was to explore a new method, spouted bed microwave drying, to produce healthier puffed snack potato cubes as possible alternatives to oil-fried potato chips. The influence of drying conditions of the spouted bed microwave drying on puffing characteristics of potato cubes were studied and compared with the direct microwave and hot air drying method.

RESULTS: Tandem combination drying of microwave-enhanced spouted bed drying (MWSB) could achieve a good expansion ratio, breaking force and rehydration ratio. The puffing characteristics of potato cubes were significantly affected ($P < 0.05$) by moisture content before starting microwave power in spouted bed microwave drying, by microwave (MW) power, and by the original size of potato cubes.

CONCLUSION: The optimum processing parameters were the moisture content at the start of microwave power (60%), the size of potato cubes (10–12 mm), and microwave power (2–2.5 W g^{-1})

Keywords: microwave-enhanced spouted bed drying; potato cubes; expansion ratio; breaking force; conversion point; puffing characteristics

INTRODUCTION

Traditional potato chips have a high oil content that ranges from 35 to 45 g 100 g^{-1} (wet basis), which gives the product a unique texture and flavor to make them appeal to the consumer.[1] The retail sales of potato chips in the United States are about $6 billion/year.[2] However, during conventional deep-fat frying processes acrylamide is formed in carbohydrate- and asparagine-rich foods through Maillard reactions when the temperature exceeds 120 °C.[3,4] Studies have shown that acrylamide could cause damage to the nervous system in both humans and animals.[5]

In recent years, increasing public concern over deep-oil-fried snack foods has motivated the food industry and research communities to explore new means for the production of lower oil content or non-fat products. Much of the research has been concentrated on approaches to reduce oil absorption in fried products.[6–8] The initial solids content in the product to be fried is a critical factor that influences oil uptake during frying.[9] Drying of potato before frying using microwave, hot-air treatment and baking can result in a significant reduction in oil content of different products.[10]

Microwave drying has been studied as an alternative method for improving the quality of dehydrated products.[11,12] Positive vapour pressure from internal microwave heating produces puffed products.[13–15] Yongsawatdigal *et al.*[16] reported that microwave vacuum dried (MWVD) cranberries had a softer texture compared to hot-air-dried cranberries. A major drawback of microwave vacuum drying is the non-uniform heating, caused by uneven spatial distribution of the electromagnetic field inside the drying cavity. Excessive localised heating leads to poor-quality products.[11,17]

A microwave-enhanced spouted bed can produce more uniform drying. In spouted bed dryers, uniform exposure of the product to microwave (MW) energy is achieved by pneumatic agitation.[15,18,19] Fluidisation also facilitates heat and mass transfers due to a constant renewed boundary layer at the particle surface. Therefore, a combined fluidised or spouted bed is considered as an effective way to solve the uneven problem of microwave drying. Nindo

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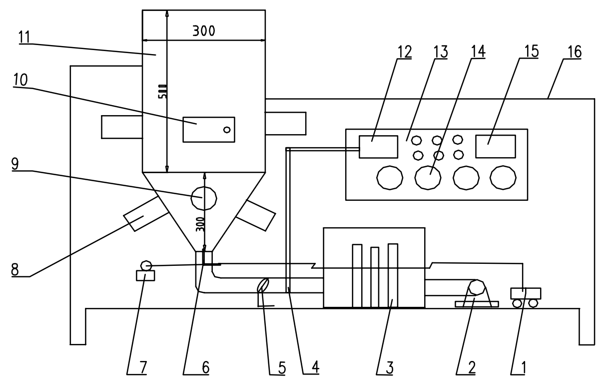

Figure 1. Schematic of the microwave spouted dryer (dimension in mm). 1. Air compressor (used for atomization and cleaning); 2. blower; 3. electric heating; 4. pressure detector; 5. valve; 6. nozzle; 7. peristaltic pump (used for atomisation); 8. 2450 MHz magnetron; 9. observation window; 10. operation door; 11. spouted bed; 12. air detector (a digital display detector of air velocity for detecting pressure, velocity and flowing of inlet air); 13. control box; 14. microwave power regulator; 15. optical fibre measurement; 16. equipment support.

et al.[20] used MWSB to evaluate the retention of physical quality and antioxidants in sliced asparagus. The results showed that MWSB-dried asparagus particles had good rehydration and colour characteristics. In addition, the suitable MW power level (2 W g^{-1}) and heated air temperature (60 °C) resulted in the best retention of total antioxidant activity of asparagus.

Many researchers concentrated on the nutritional characteristics of products during microwave-spouted drying. Few reported on textural properties of puffed products from microwave-spouted bed drying. The objectives of this study were to study the effects of MWSB drying on textural properties of puffed potato cubes in an effort to optimise drying conditions for combined MWSB processes.

MATERIALS AND METHODS

Materials and equipment

Fresh potatoes were purchased from a local supermarket in Wuxi, China. The samples were washed, peeled, sliced to cubes of different sizes (8, 10 and 12 mm), blanched in a water bath (90 °C, 5 min), and cooled in cold water (about 10–12 °C) for 60 s. The surface water of the cubes was removed with dry paper towels before each drying test.

The pilot-scale microwave spouted bed dryer (Fig. 1) used in this research was developed by the authors. The system consisted of 2450 MHz microwave power sources, a cavity, a hot-air source, a spouted bed, and a control system. Microwave power was provided by four magnetrons, each having 1 kW maximum power capacity. The total microwave power could be regulated between 0 and 4 kW. The temperature of the air for the spouted bed could be controlled between 30 and 150 °C through a feed-back loop, and air velocity was maintained with an adjustable fan. A fibre optic temperature sensor detected the temperature in the drying cavity.

Drying methods

Experiments were carried out by using one of the three different drying methods.[15,19–21] Method A was single microwave drying in spouted bed with ambient air temperature (MD). The microwave output power was set at 2.0 W g^{-1} (wet basis), and the spouted air temperature was at 25 °C (room temperature). Method B was simultaneous microwave and hot-air spouted drying (or parallel drying). The microwave output power was set at 2.0 W g^{-1} (wet basis), and the spouted air temperature was controlled at 60 ± 2 °C. Method C was a combination of microwave drying and spouted drying (or tandem drying). First, only hot air spouted bed drying was applied (air temperature at 60 ± 2 °C) until the moisture content of the potato reached 60% (wet basis), then the spouted bed air temperature was reduced to 25 °C (room temperature) before starting microwave power.

Five hundred grams of sample were dried in each test to a final moisture content under 5% (wet basis).

Table 1. The coded values of the independent variables used for response surface design

Variable	Symbol	Codes −1.68	−1	0	+1	+1.68
Conversion point (%)	X_1	43	50	60	70	76.8
Size of potato cubes (mm)	X_2	6.5	8	10	12	13.5
Microwave power (W g^{-1})	X_3	1.16	1.5	2	2.5	2.8

Optimisation of MWSB puffing potato cubes by response surface analysis

Based on the results of preliminary testing, the drying process was carried out by Method C, and a five-level, central composite experimental design of three factors was used to optimise the MWSB drying process C for puffed potato cubes.[22] The three independent variables were the moisture content after the initial hot air drying (conversion point, X_1), size of potato cubes (X_2) and microwave power (X_3). Five levels of each of the three independent variables were chosen for this study: −1.68, −1, 0, +1, +1.68. The coded values of the three independent variables are summarised in Table 1. The expansion ratio (ER) and breaking force (BF) of the final products were measured as the texture indices. All experiments were repeated three times and the averages of the results were used for statistic analyses. Dependent variables were represented mathematically by models using the regression equation as follows:

$$Y = a_0 + a_1X_1 + a_2X_2 + a_3X_3 + a_{11}{X_1}^2 + a_{22}{X_2}^2 + a_{33}{X_3}^2 + a_{12}X_1X_2 + a_{13}X_1X^3 + a_{23}X_2X_3 \quad (1)$$

Moisture content

Moisture content was determined by the oven method (AACC 44-16). At regular time (10 min) intervals during the drying experiments, sub-samples of 10 g were removed from the microwave spouted bed dryer, and dried in an air oven for 2–3 h at 105 °C until constant weight. Those samples were weighed on a digital balance, and moisture contents (wet basis) were calculated from the weights before and after oven drying. The tests were performed in duplicate.

Expansion ratio

The volume of the potato cubes was measured with an exclusive method using millet as the filling material.[23] The volume of potato cubes was calculated from:

$$V_m = V_1 - V_0 \quad (2)$$

where V_m is the volume of potato cubes, V_1 is the total volume of millet and potato cube samples, and V_0 is the volume of millet.

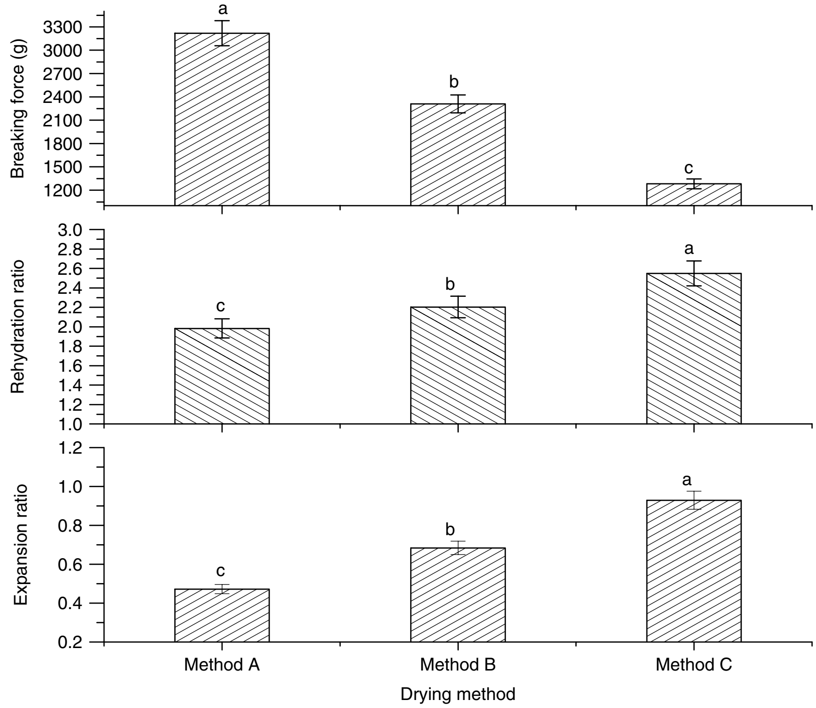

Figure 2. Breaking forces, rehydration ratio and expansion ratio for puffed potato cubes dried by three different methods. Method A: single stage microwave drying; method B: AD+MD parellel; method C: AD and MD tandem drying. [a,b]Different letters indicate a significant difference ($P < 0.05$).

The expansion ratio, β, was calculated from:

$$\beta = \frac{V_b}{V_a} \quad (3)$$

where V_b is the final volume of the puffed potato cubes, and V_a is the initial volume of potato cubes.

Rehydration ratio

Dried potato cubes were weighed and then poured into water. The samples were removed after 2 min immersion at 50 °C. After vacuum filtration for 10 s, the samples were weighed.[24] The rehydration ratio, R, was obtained from:

$$R = \frac{M_2 - M_1}{M_1} \quad (4)$$

where M_1 is the initial weight of a potato sample and M_2 is the final weight after immersion and vacuum filtration.

Texture

The texture characteristics of the potato cubes were determined using a TA-XT2 texture analyser (Stable Micro Systems, Guildford, UK) fitted with a spherical probe (P/0.25 s; Surrey, UK). The breaking force of the potato cubes was determined at room temperature in a puncture test. The probe speed was set at 5.0 mm s^{-1} to travel over a distance of 5 mm. The parameter maximum force was obtained from the force versus distance curves using the software Texture Expert (6.06) of the texture analyser. All numerical results were expressed in grams. To maintain consistency, all the tests were conducted on the day the puffed potato cubes were processed. Three replicates were performed for each batch of samples.

Statistical analysis

ANOVA was conducted using Statistical Analysis System software (SAS Institute Inc., 1996). The least significance difference test was used to determine difference between means at a significance level of $P < 0.05$.

RESULTS AND DISCUSSION

Effects of drying methods on quality attributes of dried potato cubes

The influence of three drying methods on the texture attributes of the dried potato cubes is shown in Fig. 2 The tandem method (method C) produced puffed potato cubes with the highest expansion ratio, while methods A and B resulted in low expansion ratios (Fig. 2). These are clearly shown in the appearance and the shape of puffed potato cubes (Fig. 3).

The rehydration ratio of products dried by method C was also higher than the products produced with the other two methods.

The breaking force is an indicator of crispness as an important quality attribute of ready-to-eat puffed snack foods.[6] The lower breaking force corresponded to higher crispness. Figure 2 shows that the product dried by method A is harder than the products produced by the other two methods, while method C produced a product with the best crispness among the three methods.

It can be concluded from the above experimental results that drying methods used in this study had a significant effect on puffing characteristics (expansion ratio, rehydration ratio, crispness) of potato cubes, and method C (AD+MD tandem method) produced the best products, expansion ratio of 0.929, rehydration ratio of 2.549, breaking force of 1282 g. It is possible that when using method C, the removal of surface water of the potato cubes during the initial hot air spouted drying and consequent cooling

Figure 3. The picture of puffing potato cubes dried with three different drying methods. Method A: single stage microwave drying; method B: AD+MD parallel drying; method C: AD+MD tandem drying.

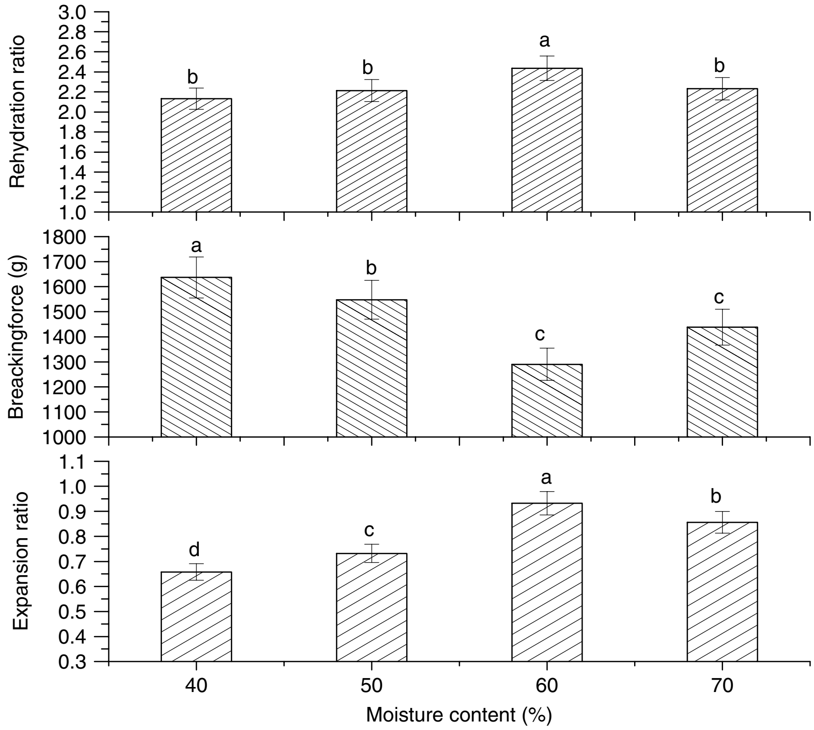

Figure 4. Effect of moisture content after hot-air spouted bed drying (conversion points) on quality attributes of puffed potato cubes. [a,b]Different letters indicate significant difference ($P < 0.05$).

resulted in the formation of a relatively rigid and sealed surface layer. This layer holds back the vapour pressure during microwave heating and results in a puffed product. Feng *et al.*[15] recorded up to 6 kPa internal vapour pressure in microwave spouted bed drying of apple dices of similar sizes (12.5 × 9.5 × 6.4 mm) to those used in our study. In general, apple tissues are more porous than potato tissues. Therefore, we expected similar or even high internal vapour pressure in potato cubes in hot-air spouted bed tandem drying in this study.

On the other hand, in method A, the microwave heats the inner water in products to generate internal vapour pressure. The volume of potato cubes increased rapidly, but since no rigid shell was formed prior to microwave heating, the structure collapsed as the water was removed. At the early stage of drying, the relatively cold product surface also caused partial condensation as the internal vapour moves from the interior to the surface, which further reduced product quality. With method B, external water and inner water evaporate simultaneously. As with method A, no dry shell was formed prior to microwave heating, and shrinkage took place in the final dried products. Therefore, we focused further optimisation studies only on method C.

Effects of moisture content after hot-air spouted drying

As shown above, it is critical to form a desirable hard shell in potato cubes using a hot-air spouted bed before applying microwave energy to produce puffed products. The moisture content after hot-air spouted drying was, therefore, considered as an important parameter of the drying process. For convenience, we will refer to this moisture content as the conversion point. Experiments were carried out with four conversion points (70%, 60%, 50%, 40% moisture content) using 2.0 W g^{-1} (wet basis) microwave drying power.

The effects of different moisture conversion points on puffing characteristics of potato cubes are shown in Fig. 4. It can be seen that moisture content at the conversion point had a significant effect on the expansion ratio of the puffed potato cubes. The expansion ratio of products was 0.932 when the moisture content was 60%. It was the highest expansion ratio among the results of four moisture contents. We observed that a higher conversion

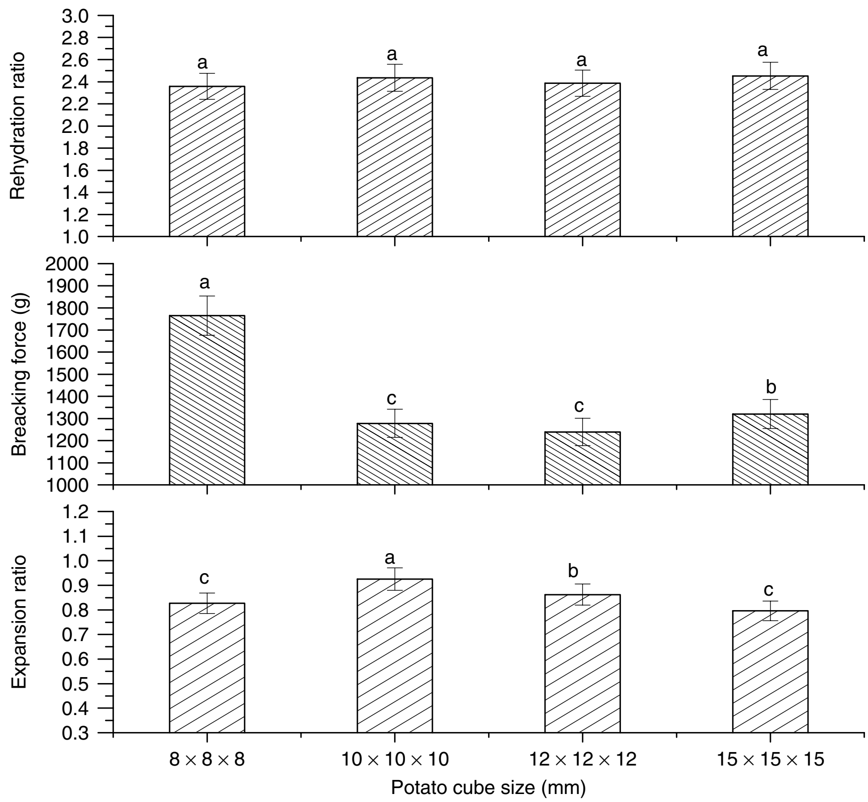

Figure 5. Effect of original potato cube size on quality attributes of puffed potato cubes. [a,b]Different letters indicate a significant difference ($P < 0.05$).

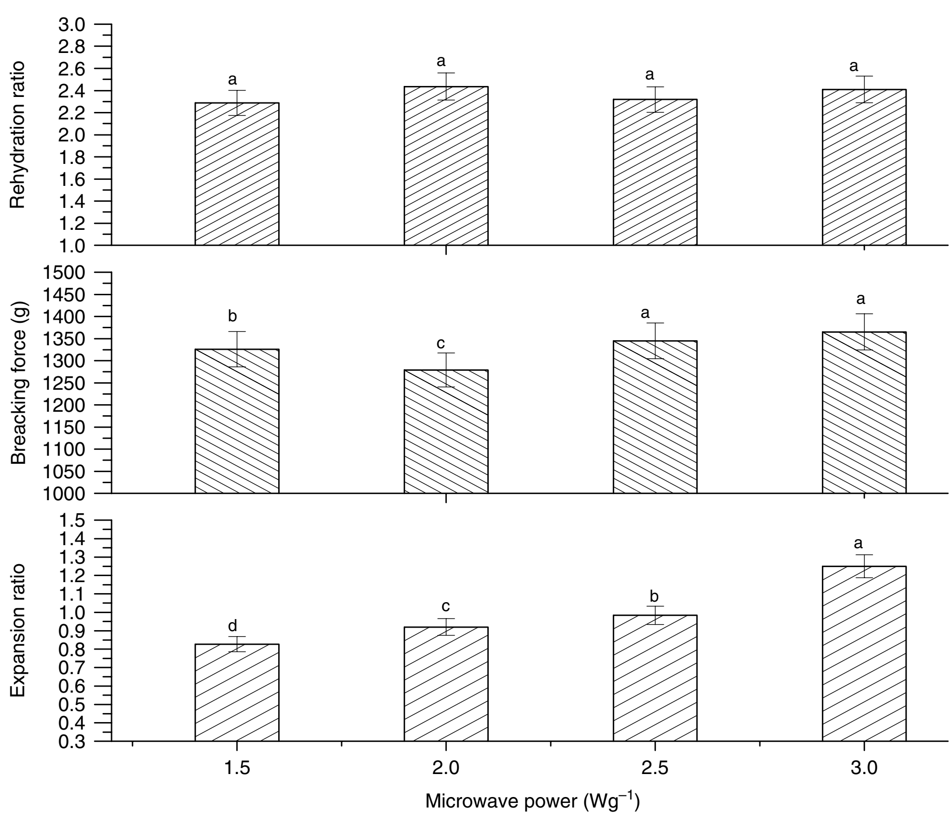

Figure 6. Effect of microwave power on quality attributes of puffed potato cubes. [a,b]Different letters indicate a significant difference ($P < 0.05$).

point required a longer microwave drying time, and longer drying time resulted in product shrinkage after puffing. The texture of the final products is stiff. On the other hand, a lower conversion point caused potato cubes to undergo significant shrinkage during hot-air spouted drying before puffing with microwave-spouted drying. Similar results were reported by Zhang *et al*.[14] and Mudahar *et al*.[25]

The conversion point also has an effect on the crispness of the puffed potato cubes as shown in Fig. 4. The crispness was the best at the conversion point, corresponding to 60% moisture content. A lower or higher conversion point caused a higher breaking force of puffed potato cubes. Song *et al*.[26] reported similar results on potato chips with vacuum frying. There was little difference in the rehydration ratio value among different conversion points. This is because similar porous structure in dried potato cubes with MWSB.[21] Therefore, the 60% moisture content was the optimal conversion point level for the following microwave-spouted drying processing.

Effects of sample size on puffing characteristics of potato cubes

During initial studies, it was observed that some potato cubes could not be puffed when cubes of size 8 mm × 8 mm × 8 mm were used. So a series of sizes of potato cubes was investigated. The effects of different size on puffing characteristics of potato cubes are shown in Fig. 5. Increasing cube size improved the expansion ratio and a size of 10–12 mm achieved the best expansion ratio. It is possible that a good balance between an appropriate internal vapour pressure was held back by a desirable size of hard shell so that, after drying, the products retain the porous structure after drying. Particles of too large a size contain more interior moisture and require a longer microwave drying time, which would upset the balance and cause shrinkage in puffing potato cubes upon cooling.

As for texture, when the size of the potato cubes exceeded 10 mm, the breaking force of the cubes decreased, which means that the crispness of puffed products was improved. This is because the interior structure of puffed potato cubes is hollow and the shell is very thin when the expansion ratio was close to 1, which leads to a reduced surface breaking force of potato cubes. The results were in agreement with a previous study on puffed potato chips with vacuum frying.[6] Therefore, it was appropriate to choose 10–12 mm as the size of potato cubes for puff experiments.

Effects of microwave power on puffing characteristics of potato cubes

Figure 6 presents the effects of microwave power on puffed potato cubes. It can be seen that higher power level achieved a higher expansion ratio ($P < 0.05$) when compared with 1.5, 3.0 W g^{-1} and 2.0, 2.5 W g^{-1}. It is certain that a lower power output increased the time of drying puffed potato cubes and reduced the overall generation of internal pressure, causing more shrinkage of potato cubes. However, according to Fig. 6, a power output at 2.0 W g^{-1} is the best for crispness of potato cubes compared to other power levels because a lower breaking force means higher crispness. Greater microwave intensity can result in a thicker dry shell. Although the expansion ratios increase with microwave intensity, the highest microwave intensity could not result in the smallest breaking force because of a relatively thick shell.

Figure 6 also illustrates that there is no significant difference ($P > 0.05$) in rehydration ratios of samples dried by different microwave power levels, which could be explain why dried products with MWSB have a similar inner structure. Similar results have been reported for dried asparagus with MWSB.[20]

Table 2. The results of RSA of the variation of expansion ratio and breaking force with conversion point (X_1), size of potato cubes (X_2) and microwave power (X_3)

	Coded variables				
Run	X_1	X_2	X_3	Expansion ratio	Breaking force (g)
1	0	1.68	0	0.835	1320.0
2	1	−1	1	1.029	1407.5
3	0	0	0	0.920	1293.0
4	0	0	−1.68	0.779	1863.0
5	−1.68	0	0	0.660	1636.0
6	0	0	0	0.916	1274.0
7	0	0	0	0.918	1293.0
8	0	0	0	0.924	1289.0
9	1	1	−1	0.834	1588.6
10	0	0	1.68	1.246	1341.5
11	1.68	0	0	0.884	1282.0
12	0	0	0	0.938	1276.0
13	1	−1	−1	0.725	1749.8
14	0	0	0	0.930	1283.0
15	−1	1	1	1.115	1301.3
16	−1	−1	−1	0.702	1749.2
17	−1	−1	1	1.006	1407.4
18	0	−1.68	0	0.821	1422.8
19	1	1	1	0.944	1245.0
20	−1	1	−1	0.811	1588.7

Table 3. Regression and analysis of variance for dependent variables of MWSB drying potato cubes

Coefficient	Expansion ratio	Breaking force (g)
a_0	0.92	1284.17
X_1	0.020*	−47.719*
X_2	0.019	−55.903**
X_3	0.132***	−160.536***
X_1X_2	−0.024	−7.038
X_1X_3	−0.023*	−7.038*
X_2X_3	−0.022*	6.695*
${X_1}^2$	−0.048**	64.885**
${X_2}^2$	−0.028	33.930*
${X_3}^2$	0.037***	115.584***
R^2	0.914	0.943

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

Optimisation of MWSB procedures by response surface analysis

The variable design and experiment results are shown in Tables 1 and 2. Regression coefficients for ER and BF are shown in Table 3. The high R^2 values (0.914 and 0.943) indicate that the independent variables fitted well to a regression equation. Figure 7 shows the surface plots of expansion ratio (ER) and breaking force (BF) of MWSB drying puffing potato cubes as affected by size of potato cubes (X_2) and microwave power (X_3) for a fixed conversion point ($X_1 = 0$).

As shown in Table 3, the expansion ratio of puffed potato cubes was significantly ($P < 0.05$) affected by conversion point (X_1) and microwave power (X_3), and size of potato cubes (X_2) affected the

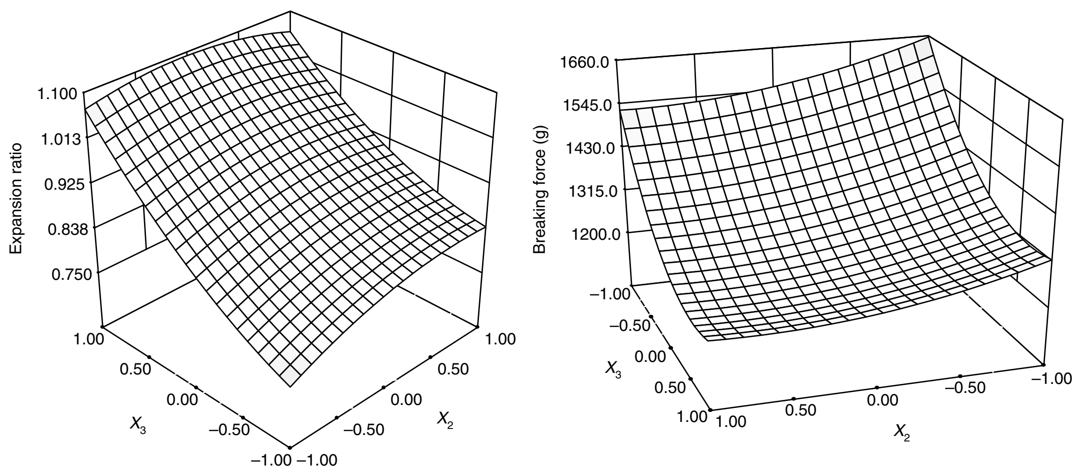

Figure 7. Surface plots of expansion ratio (ER) and breaking force (BF, in grams) of MWSB drying puffing potato cubes as affected by conversion point (X_1), size of potato cubes (X_2) and microwave power (X_3).

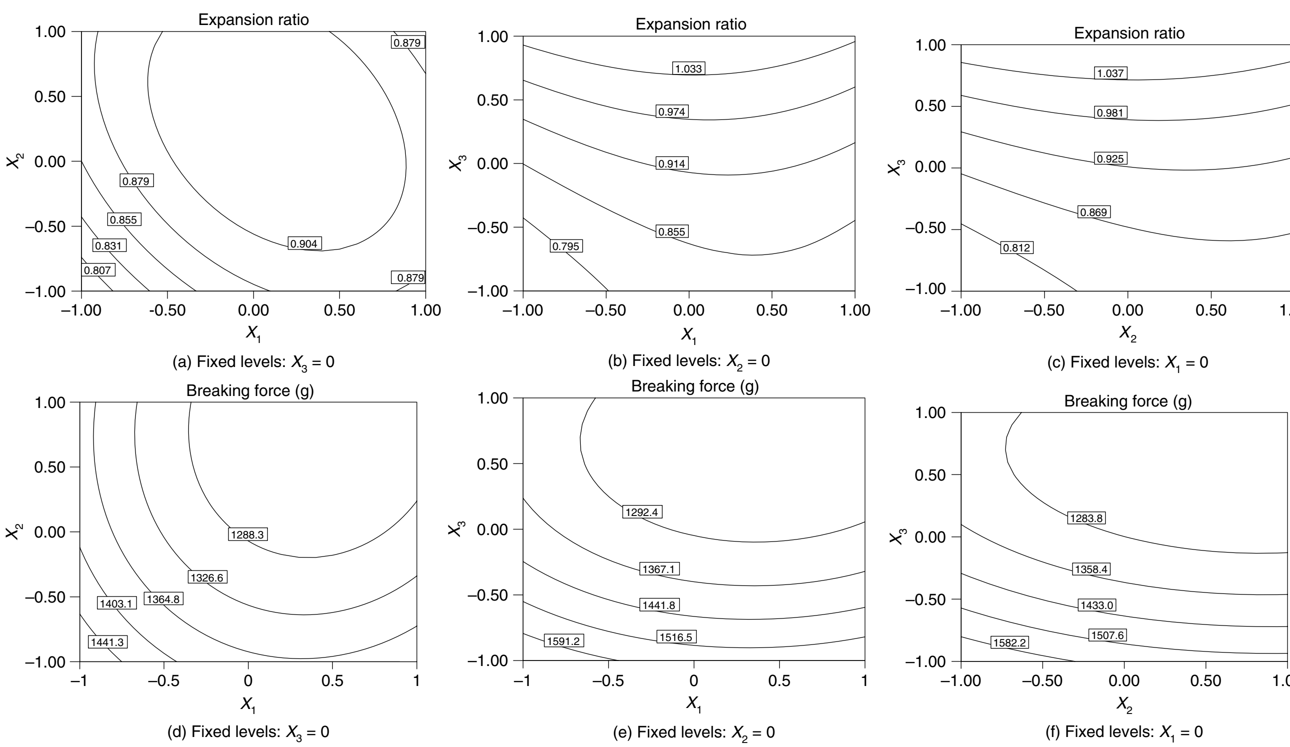

Figure 8. The contour plots of expansion ratio (ER) and breaking force (BF, in grams) of MWSB drying puffing potato cubes as affected by size of potato cubes (X_2) and microwave power (X_3).

ER insignificantly ($P > 0.05$). From Fig. 8a–c, when X_3 was fixed at 2 W g^{-1} ($X_3 = 0$), cubes size was about 10 mm and conversion point was from 55 to 70%, the ER value was above 0.9%. When X_2 was fixed at 10 mm ($X_2 = 0$), or X_1 was fixed at 60% ($X_1 = 0$), the ER values increased as the microwave power increased. Evidently, a high expansion ratio of puffed potato could be obtained when the microwave power exceeded 2.0 W g^{-1}, the moisture content of conversion point was about 50–70%, and the size of potato cubes was 10 mm.

As shown in Table 3, conversion point (X_1), size of potato cubes (X_2) and microwave power (X_3) had a significant effect ($P < 0.05$) on the breaking force. From Fig. 8d–f, the breaking force of puffed potato cubes was less than 1300 g when the moisture content of conversion point was about 60%, microwave power was above 2 W g^{-1}, and size of potato cubes was at 10–12 mm. The constraints were met in the region of moisture content of conversion point of about 60%, size of potato cubes of 10–12 mm, and microwave power at 2–2.5 W g^{-1} (because too high power would easily lead to charring in puffed potato cubes).

CONCLUSIONS

Different drying methods had significant effects on texture attributes of puffed potato cubes; a tandem drying combination of MWSB could achieve a good expansion ratio, breaking force, and rehydration ratio. The factors which affected the puffing characteristics were conversion point, size of potato cubes, and microwave power. Results of response surface analysis showed that expansion ratio and breaking force were significantly ($P < 0.05$) affected by conversion point, size of potato cubes, and microwave power, only the size of potato size had a non-significant effect ($P > 0.05$) on expansion ratio. Using expansion ratio and breaking force as indicators of puffing characteristics, the optimum conditions were moisture content of conversion point of about 60%, size of potato cubes of 10–12 mm, and microwave power at 2–2.5 W g^{-1}.

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