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INFLUENCE OF MICROWAVE DRYING METHOD ON THE CHARACTERISTICS OF THE SWEET POTATO DICES

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ABSTRACT

Three different drying methods, microwave-spouted bed drying (MSBD), microwave-vacuum drying (MVD) and hot air drying (AD), were used to dry diced sweet potato. The drying characteristics and product quality are discussed in terms of the drying kinetics, rehydration ratio, expansion ratio, breaking force (crispness), product color and retention of β-carotene. As expected, the drying rates in MSBD and MVD were much faster than that obtained in hot AD; the largest drying rate was obtained in MSBD with 2.5 W/g microwave (MW) power level. The products dried using MSBD and MVD displayed good puffing: rehydration ratios were about 2.0 after 18 min, expansion ratio was close to 1.0, and the breaking force below 600 g. The color of MSBD product was uniform as well. Retention of β-carotene was about 80% in MSBD and MVD but only 40% in AD product compared with that present in the fresh produce.

PRACTICAL APPLICATIONS

MSBD can be used to produce dried sweet potato dices with good expansion ratio, low breaking force, high rehydration ratio and better color, compared with MVD and AD. Furthermore, MSBD overcomes the uneven characteristics observed when only MW drying is applied. MSBD could be regarded as a potentially new drying technology for production of high-quality snack foods in the form of puffed sweet potato dices.

INTRODUCTION

Sweet potato (*Ipomoea batatas*) is an important agricultural product in China. There is higher concentration of nutrients such as carotene, vitamin B_1, B_2, and iron, calcium mineral content, etc. in sweet potato than in rice and wheat flour (Van Hal 2000). Sweet potato can make significant nutritional contribution to the diet. It provides at least 90% of human requirements, except for protein and niacin (Bouwkamp 1985). Sweet potato is used widely in ready-to-eat foods such as noodles, Chinese-style French fries, canned foods, etc.

Fried sweet potato chips are common snacks in the tropics and Asia and its consumption is on the increase (Taiwo and Baik 2007). The traditional frying technology for sweet potato chips results in high oil content, which gives the product a unique texture and flavor to make them appealing to the consumer. However, during conventional deep-fat frying processes, acrylamide is formed in carbohydrate and asparagine-rich foods through the Maillard reaction when the temperature exceeds 120C (Granda and Moreira 2005; Baardseth *et al.* 2006). In recent years, increasing public concern over deep-oil fried snack foods has motivated the food industry and research community to explore new means for production of lower oil content or nonfat products. Much of the research has been concentrated on approaches to reduce oil absorption in fried products (Nourian and Ramaswamy 2003; Song *et al.* 2007a). Initial solids content in the product to be fried is a critical factor that influences the oil uptake during frying (Pinthus *et al.* 1993). Thus, drying of potato before frying using microwave (MW), hot air treatment and baking can result

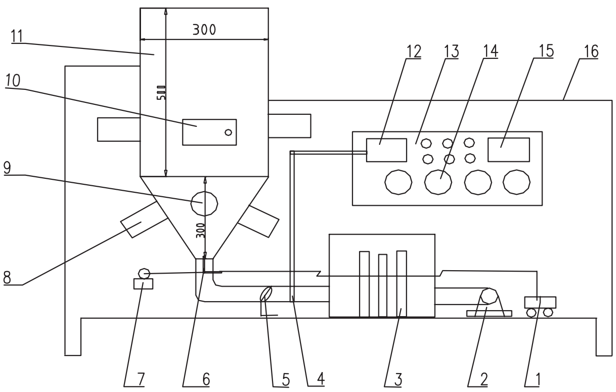

FIG. 1. SCHEMATIC OF THE MICROWAVE-SPOUTED DRYER (DIMENSION IN mm)
1. air compressor 2. blower 3. electric heating 4. pressure detector 5. valve 6. nozzle 7. peristaltic pump 8. magnetron 9. observation window 10. operation door 11. spouted bed 12. air flow detector 13. control box 14. power regulator 15. optical fiber measurement 16. equipment support.

in significant reduction in oil content of different products. In this research, MW drying was used to produce puffing snacks with high-quality and low-energy consumption, which will bring the new snack market.

MW drying has been studied as an alterative to improve the quality of dehydrated products. Positive vapor pressure from internal MW heating produces puffed products (Bouraoui *et al.* 1994; Boldor *et al.* 2005; Zhang *et al.* 2007). Yongsawatdigul and Gunasekaran (1996) have reported that MW vacuum-dried cranberries had softer texture compared with hot air-dried cranberries. A major drawback of MW vacuum drying is the nonuniformity of heating, which is caused by the inherently uneven spatial distribution of the electromagnetic field inside the drying cavity. Excessive localized heating leads to poor-quality products (Barrett *et al.* 1997; Wang and Sheng 2006; Gowen *et al.* 2007; Giri and Prasad 2009).

MW-enhanced spouted bed can yield more uniform drying. In spouted bed dryers, uniform exposure of product to MW energy is achieved by pneumatic agitation (Feng *et al.* 2001; Torringa *et al.* 2001; Boldor *et al.* 2005). Fluidization also facilitates heat and mass transfers because of a constant renewed boundary layer at the particle surface. Therefore, combined fluidized or spouted bed is considered as an effective way to solve the uneven problem of the MW drying. Nindo *et al.* (2003) used microwave-spouted bed drying (MSBD) to evaluate the retention of physical quality and antioxidants in sliced asparagus. The results showed that MSBD dried asparagus particles had good rehydration and color characteristics. In addition, the suitable MW power level (2 W/g) and heated air temperature (60C) resulted in the best retention of total antioxidant activity of asparagus.

Many researchers have concentrated their effort on study of the nutritional characteristics of products during MW-spouted drying and few reports on textural properties of puffed products from MSBD. The objective of this work is to investigate the comparative effects of three different drying methods (MSBD, microwave-vacuum drying [MVD] and air drying [AD]) on sweet potato dices. Crispness, rehydration, puffing degree, color, drying uniformity, drying rate and energy consumption were measured as indices for comparison. This study was conducted with one novel machine that we designed by ourselves, and this machine can be used as pilot scale experiment. So, this study is of great significance in promoting the MW application in food drying field.

MATERIALS AND METHODS

Yellow sweet potato (*I. batatas* Lam) was obtained from a local market at Wuxi, China. The samples were washed, peeled, sliced to 10 × 10 × 10 mm, then blanched in a water bath (90-95C, 2 min), and cooled in cold water (10-12C) for 60 s. The surface water of the slices was removed with handkerchief before each drying.

The lab-scale MW-spouted dryer (Fig. 1) used in this research was developed by the authors. The system consists of MW power sources, a cavity, a hot air source, a spouted bed and a control system. MW power was provided by four magnetrons, each having 1 kW maximum power capacity. The total MW power could be regulated continually from 0 to 4 kW. The temperature of the air for the spouted bed could be controlled from 20 to 150C through a feedback loop, and air velocity was maintained with an adjustable fan. The temperature in the drying cavity was detected by a fiber optic temperature sensor.

A lab-scale MW-vacuum dryer (Fig. 2) (Song *et al.* 2007b) was operated at 5 kPa (absolute pressure), the

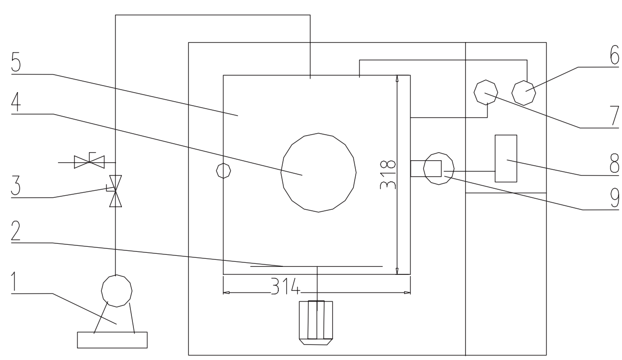

FIG. 2. SCHEMATIC OF THE MICROWAVE VACUUM DRYER
1. vacuum pump 2. rotating tray 3. valve 4. observation window 5. drying chamber 6. infrared thermometer 7. vacuum gauge 8. magnetron power control unit 9. magnetron.

output MW power was 146.5–488.5 W and the rotation speed of the turntable was 15 r/min.

Drying Experiments

Experiments were carried out using one of the three different drying methods, viz. MSBD, MVD and AD, until the final sample moisture content reached 6% (wet basis). The original weights of blanched sweet potato dices for MSBD, MVD and AD were 200, 300 and 100 g, respectively. All experiments were performed in duplicate. Experimental conditions were selected based on previous literature (Feng and Tang 1998; Nindo *et al.* 2003; Wang and Xi 2005; Duan *et al.* 2007; Song *et al.* 2007b) and drying parameters as follows.

Drying Test Program for MSBD. First, only hot air-spouted bed drying was applied (air temperature at 80 ± 2C) until the moisture content of sweet potato reached 60% (wet basis), then the spouted bed air temperature was reduced to 25C (room temperature) before starting application of the MW power; the MW power was set at 2.0 and 2.5 W/g, respectively. The twice finished product ratios were above 95% and there was no significance between the two experiments ($P > 0.05$).

Sweet potato was dried by MVD at a MW power level of 2.0 W/g (wet basis) at a vacuum pressure of 5 kPa. AD was used to dry sweet potato dices by placing them in a drying oven at an air temperature set at 80 ± 1C. The twice finished product ratios were about 90% and there was no significance between the two experiments ($P > 0.05$).

Moisture Content

The sweet potato dices were ground at the end of each vacuum frying operation. Moisture content was determined using approximately 5 g of the ground sweet potato dices after oven drying at 102 ± 3C until the weight stabilized. The tests were carried out in duplicate.

Rehydration Ratio

About 2 g was weighed and then poured into water. The sweet potato dices were taken out after a certain time of immersion at 50C. After vacuum filtration for 60 s, the sample was weighed. *R* (rehydration ratio) was obtained as the following formula:

$$R = \frac{M_2 - M_1}{M_1} \tag{1}$$

where M_1 is the initial weight of the products, and M_2 is the final weight of the products after immersion and vacuum filtration.

Crisp Degree

The crispness characteristics of the dried sweet potato dices were measured using a TA-XT2 texture analyzer (Stable Micro Systems, Surrey, UK). The sweet potato dice was placed over the end of a hollow cylinder. A stainless steel ball probe (P/0.25 s), moving at a speed of 5 mm/s over a distance of 5.0 mm, was used to break the dice. All the tests were repeated three times and the numerical results are expressed in grams.

Expansion Ratio

The volume of the sweet potato dices was measured with an exclusive method using millet as the filling material. The volume of sweet potato dices was calculated from:

$$V_m = V_1 - V_0 \tag{2}$$

where V_m is the volume of sweet potato dices, V_1 is the total volume of millet and sample, and V_0 is the volume of millet.

The expansion ratio was calculated from

$$\beta = \frac{V_b}{V_a} \tag{3}$$

where V_b is the final volume of the sample, and V_a is the initial volume of sweet potato dices.

Color

The color of dried dices was measured with a CR-400 model colorimeter (Konica Minolta Co., Tokyo, Japan). The experiment was replicated five times. The color values were expressed as *L* (whiteness/darkness), *a* (redness/greenness) and *b* (yellowness/blueness). Additionally, the total color difference from the freeze drying (FD) sweet potato dices ΔE, as defined below, was used to describe the color changes during the other combination drying process:

$$\Delta E = \sqrt{(L_o - L)^2 + (a_o - a)^2 + (b_o - b)^2} \tag{4}$$

where subscript "*o*" refers to the color reading of FD sample; and *L*, *a* and *b* indicate brightness, greenness and blueness of dried samples, respectively. FD sweet potato dices were used as the reference and a larger ΔE denotes greater color change from the reference material.

β-Carotene Content

The carotene content was determined following Prakash *et al.* (2004). Specifically, the dried sample (2 g) was placed in a 250-mL flask and 40 mL of acetone was added. A stirrer was used to aid extraction of the carotene and the process was continued until the residue became colorless. The

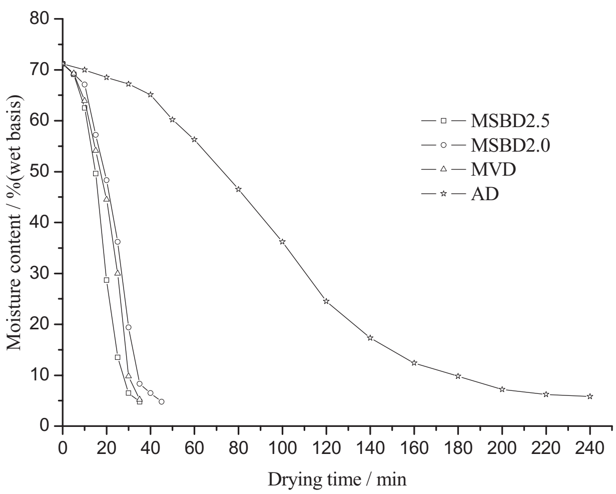

FIG. 3. THE EFFECT OF DIFFERENT DRYING METHOD ON THE MOISTURE CONTENT
MSBD, microwave-spouted bed drying; MVD, microwave-vacuum drying; AD, air drying.

acetone extract was filtered and placed in a separating funnel, then petroleum ether (100 mL) was added (to absorb any moisture) and the separating funnel was shaken for 1 min. Two distinct layers were formed of which the yellow upper layer was collected and the lower layer was drained off to another separating funnel. The lower layer solution was again extracted with petroleum ether (100 mL) and the upper yellow layer was collected. Combined, the petroleum ether extracts in a volumetric flask and the volume was made up to 250 mL by adding petroleum ether. An aliquot of this solution was placed in a cell of a spectrophotometer and the absorbance at 452 nm was measured for determination of the β-carotene content of the carrot sample. The curve was obtained within the range of 0–5 μg β-carotene per mL (Yen *et al.* 2008).

Statistical Analysis

The analysis of variance was analyzed by using Statistical Analysis System software. Least significance difference test was used to determine the difference between means. Significance was assumed at $P \leq 0.05$.

RESULTS AND DISCUSSION

Drying Characteristics

Typical drying curves for the three different methods are shown in Fig. 3. The drying time for AD was 6, 5.5 and 7 times longer than in MVD and MSBD at 2.0 and 2.5 W/g, respectively. In pure hot AD systems, heat at the surface has to be carried into the interior through a moisture-resistant dryer layer for evaporation of water at the receding waterfront. Thus, AD needs a longer drying time. For the MW drying, the MW penetrates the inert dry layers to be absorbed directly by the moisture at the waterfront. This rapid energy absorption causes rapid evaporation of water, creating an outward flux of rapidly escaping vapor. In addition, the high drying rate in MSBD can be attributed to a constant movement of sweet potato dices within the MW cavity. Also, the constant movement of dices allows different parts of the dices to receive relatively uniform MW radiation when averaged over a period of time. Moreover, heat and mass transfer at the particle surfaces of the dices is accelerated during fluidization; this results in a high drying rate. It is necessary to note that drying time will decrease with MW power increase under certain MW power of 2.5 W/g. In fact, several higher MW power levels were tested and the results showed that the total drying time changed little as the MW power levels were raised above 2.5 W/g. It could be explained that the drying intensity of lab-scale MW-spouted dryer at 2.5 W/g had reached the highest, just like the intensity of spray drying (Mujumdar 2001).

In Fig. 3, it can be observed that the drying process consists of three stages (Zhang *et al.* 2006). First, the drying rate is slow, and then becomes fast, and finally, the drying rate slows down again. In the first stage, MW energy is converted into thermal energy within the wet dices, and a part of MW energy is consumed to raise the temperature of the product. Therefore, the first drying rate is slow during the heating-up period. After the heating-up stage, a stable temperature profile is established and MW energy is utilized for vaporization of moisture. In porous food materials, rates of moisture vaporization at different locations, to a large extent, depend on the energy conversion rates from MW to thermal. So, the drying rate is very high in the second stage. The last drying stage is the falling rate drying period. The local moisture content is reduced to a low level. Low water content results in slow drying rates. However, in the same MW field, the higher MW power cannot accelerate the water vaporization when the moisture content was very low. Indeed, excessive MW input can cause charring (Lu *et al.* 1999). From Fig. 3, it can be seen that heating-up and falling rate drying periods are indeed relatively short relative to the entire drying process.

Effect of Different Drying Methods on Rehydration Ratio

The rehydration characteristics of dried products are commonly used as quality index because they indicate physical and chemical changes that may occur during drying. The effect of the three drying methods on rehydration ratio is shown in Fig. 4. It shows that sweet potato dices dried using

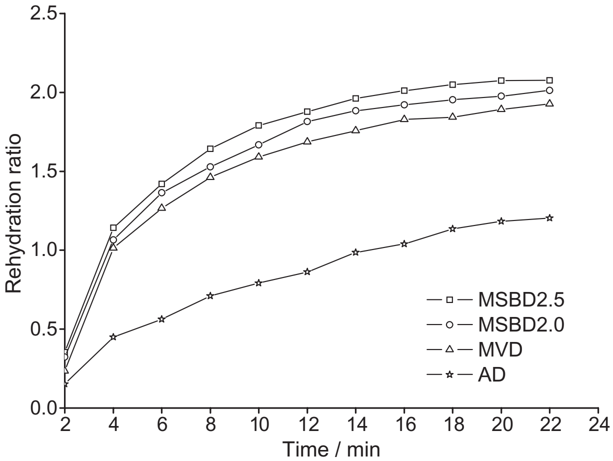

FIG. 4. REHYDRATION RATIO OF SWEET POTATO DICES DRIED BY DIFFERENT DRYING METHODS
MSBD, microwave-spouted bed drying; MVD, microwave-vacuum drying; AD, air drying.

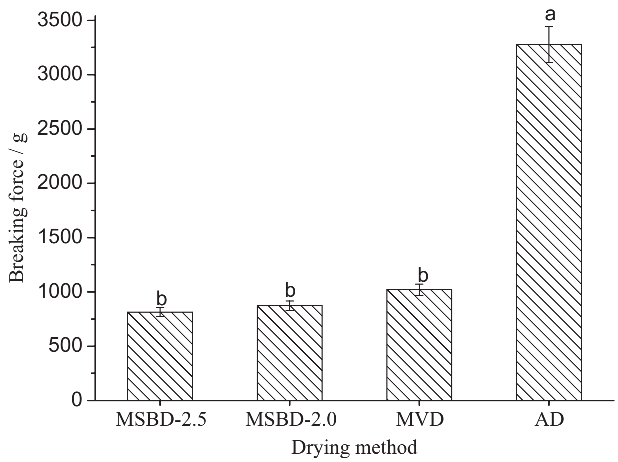

FIG. 5. BREAKING FORCE OF SWEET POTATO DICES DRIED BY DIFFERENT DRYING METHODS
MSBD, microwave-spouted bed drying; MVD, microwave-vacuum drying; AD, air drying.

MSBD-2.5 had the best rehydration capability compared with the product from the other two drying methods. Although the rehydration ratio of the sweet potato dices dried by MVD was lower than that of dices dried by MSBD, it was higher than that dried by AD. It is suggested that the rehydration capacity of sweet potato dices dried by combined MW drying methods is better than the one obtained without MW. The rapid evaporation of moisture during MVD and MSBD processes induces formation of a porous structure, which favors rapid rehydration of products. Feng and Tang (1998) have reported that apple cubes dried in MWSB have higher rehydration capacity compared with spout bed-dried and hot air-dried apples; this is in agreement with the results of this study. The rehydration ratio of sweet potato dices dried by AD is low; this is due to significant shrinkage and the formation of a compact internal structure during the long drying process. There is little difference between the rehydration ratios between MSBD and MVD after the rehydration time exceeds 18 min.

Crispness (Breaking Force)

The breaking force is an indicator of crispness as an important quality attribute of ready-to-eat puffed snack foods. A lower breaking force corresponds to higher crispness. Figure 5 shows that the crispness of product dried by MSBD and MVD is higher than that of the products dried by the AD. Note that the products were crispier when dried in MSBD at higher MW power levels than at lower MW levels.

Compared with the three drying methods, MW clearly has a significant effect on the crispness of sweet potato dices. Higher MW power level causes lower breaking force of puffed sweet potato dices. This is because the interior structure of puffed potato cubes was hollow and the shell is very thin when the dices puffed with MW, which leads to lower surface breaking force of sweet potato dices. On the other hand, hot AD can result in a thicker dry shell due to shrinkage, which increases the breaking force.

Expansion Ratio

Figure 6 gives results for the measured expansion ratios for sweet potato dices dried using the three methods tested. It

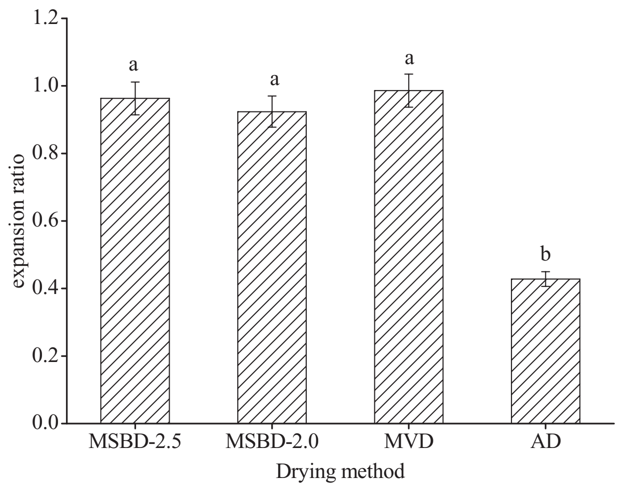

FIG. 6. EFFECT OF DIFFERENT DRYING METHOD ON EXPANSION RATIO OF SWEET POTATO DICES
MSBD, microwave-spouted bed drying; MVD, microwave-vacuum drying; AD, air drying.

can be seen that MSBD and MVD yield products with higher expansion ratio ($P < 0.05$) compared hot AD. However, there is no significant difference ($P > 0.05$) in expansion ratios among the dices dried using MSBD with 2.0 and 2.5 W/g and MVD with 2.0 W/g.

The removal of surface water of the sweet potato cubes during the initial hot air-spouted bed drying and subsequent cooling results in a relatively rigid surface layer when MSBD method is used. This layer holds back the vapor causing an increase in the internal pressure resulting in puffing during MW heating. Feng *et al.* (2001) have reported that the internal vapor pressure can be as high as 6 kPa during MSBD of apple dices ($12.5 \times 9.5 \times 6.4$ mm). In general, apple tissue is much more porous than sweet potato tissue. Therefore, during MSBD drying, as MW energy is applied volumetrically, the internal vapor generation will cause greater puffing as the vapor formed cannot escape fast enough through the lower porosity tissue structure of sweet potato.

On the other hand, during MVD drying, no rigid shell is formed prior to MW heating. At the early stage of drying, relatively cold product surface also causes partial condensation. The MW energy is absorbed faster and the interior temperature increases rapidly. The internal water in the material vaporizes and generates internal pressure as the vapor cannot escape fast enough to the surroundings, which results in higher expansion ratio (Feng *et al.* 1999). In hot AD, the long drying time resulting from poor heat transfer causes collapse and shrinkage of the tissue. AD heat transfer rates are too low to result in puffing.

Color

Table 1 shows the differences in color obtained with different drying techniques for sweet potato dices including FD. It can be observed that the difference in color among the MSBD, MVD and FD samples is small. This means that the MSBD and MVD products have good color ($P \leq 0.05$). AD drying results in high values of L ($P \leq 0.05$). In addition, in hot AD there is an increase not only in redness but also in yellowness. This is due to the combined effects of shrinkage and browning during AD. There were no significant differences in the L, a, b and ΔE values ($P > 0.05$) of not only dried but also rehydrated sweet potato dices for MSBD with different MW power level and MVD products. The result suggested that both MSBD and MVD methods can maintain the color of products well.

TABLE 1. COLOR OF DIFFERENT DRIED SWEET POTATO DICES

	L	a	b	ΔE
Drying method				
FD	18.2 ± 1.5^c	1.8 ± 0.1^b	13.2 ± 0.7^b	
MSBD-2.5	21.7 ± 1.3^b	2.1 ± 0.3^b	14.6 ± 2.4^b	3.7^b
MSBD-2.0	20.7 ± 2.5^b	1.9 ± 0.4^b	13.9 ± 1.8^b	2.6^b
MVD	23.2 ± 1.6^b	2.2 ± 0.7^b	14.3 ± 2.0^b	3.2^b
AD	13.6 ± 2.8^a	3.8 ± 0.9^a	20.5 ± 1.2^a	8.9^a
Rehydration				
FD	15.9 ± 1.1^c	1.2 ± 0.2^b	12.5 ± 1.4^b	
MSBD-2.5	18.6 ± 0.8^b	1.6 ± 0.4^b	13.7 ± 1.2^b	2.9^b
MSBD-2.0	17.4 ± 2.3^b	1.4 ± 0.3^b	12.4 ± 0.9^b	1.5^b
MVD	21.0 ± 1.7^b	1.5 ± 0.7^b	14.9 ± 1.7^b	3.2^b
AD	11.4 ± 2.3^a	3.7 ± 0.3^a	18.3 ± 1.3^a	7.8^a

[abc] different letters in the same column indicate a significant difference ($P \leq 0.05$).

MSBD, microwave-spouted bed drying; MVD, microwave-vacuum drying; AD, air drying; FD, freeze drying.

However, it should be noted that some evidence of charring appeared in the MVD experiments. This was also reported by Feng and Tang (1998). However, this phenomenon was not observed in MSBD. Drying uniformity was expressed as the number of charred dices per 100 randomly selected dried dices. For drying uniformity, the number for MVD is 8.2, while it is zero for MSBD, i.e., no charring occurred in MSBD. Dices dried in MSBD can absorb MW energy more evenly to the effect of fluidization.

β-Carotene Content

Carotenoids are widely known as provitamin A, and have many valuable physiological functions, such as anticancer activity, protection against cardiovascular disease, cataract prevention, etc. (Beveridge 2002). Research have indicated that the carotene depredated by heat, oxidation and light, and the degradation follow first-order or pseudo-first-order kinetics (Pesek and Warthesen 1987; Kalt *et al.* 1999). Therefore, carotene content was chosen as a quality index for evaluating the effect of MW-based drying.

The β-carotene content of sweet potato dices dried using different methods is shown in Fig. 7. It can be seen that the β-carotene content in MSBD and MVD sweet potato dices is the highest, and the value is about 80% of the vacuum FD product. For hot air-dried products, only about 40% retention is observed. This result can be explained such that the high-drying temperature and long-drying time have significant effects on β-carotene degradation. On the other hand, the retention rates are relativity high in MSBD and MVD because of the shorter drying time and lower drying temperatures.

CONCLUSIONS

Based on our experiments, MSBD is noted to be able to produce dried sweet potato dices with good expansion ratio, low breaking force, high rehydration ratio and good color. Although the drying rates in both MSBD and MVD are higher than those in conventional AD, nonuniformity of heating is the main disadvantage of the MVD method. In addition, the energy needed for production and mainte-

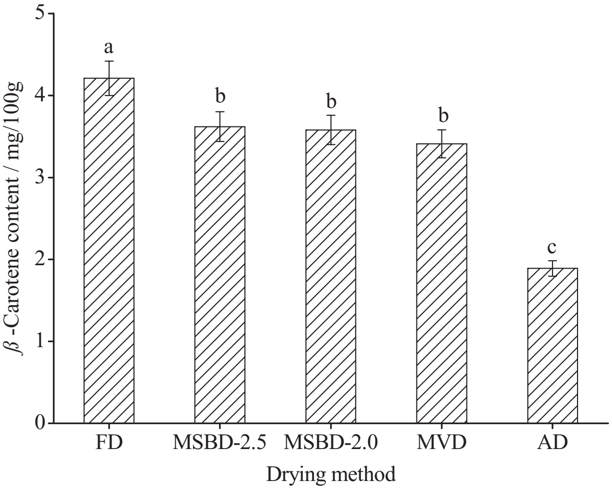

FIG. 7. EFFECT OF DIFFERENT DRYING METHODS ON B-CAROTENE CONTENT
MSBD, microwave-spouted bed drying; MVD, microwave-vacuum drying; AD, air drying; FD, freeze drying.

nance of vacuum is very high during MVD. MSBD can be regarded as a new technology for snack foods such as puffed sweet potato dices.

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