QUALITY OF FROZEN FRUIT BARS MANUFACTURED THROUGH INFRARED PARTIAL DEHYDRATION

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ABSTRACT

In this study, frozen restructured whole apple and strawberry bars were manufactured by partial dehydration, using infrared (IR) heating, followed by restructuring and freezing. The objective of this investigation was to determine the effect of IR partial dehydration on the quality of restructured frozen apple and strawberry bars. Apples and strawberries were cut into 6-mm-thick slices before being dried at 50C to various moisture levels: from 89.0 to 75.3% for apples and from 92.7 to 75.3% (wet basis) for strawberries. IR drying reduced the moisture in the fruits quickly and caused partial degradation of total phenolic and vitamin C. However, the concentration of total phenolic and vitamin C significantly increased in the finished fruit bars due to the moisture removal. Both frozen apple and strawberry bars had desirable appearance and hardness when their water activities were below 0.97.

PRACTICAL APPLICATIONS

This research demonstrated a new processing method for manufacturing healthful frozen fruit bars by using infrared partial dehydration of sliced fruit slices, followed by restructuring and freezing.

INTRODUCTION

Consumption of frozen desserts has risen steadily since the 1990s. Americans are the leading consumers of ice cream and frozen desserts, consuming 20 L per capita per year (Anon 2011a). Fruity popsicles are one popular choice, especially among children. The targeted market has been on those who want all-natural and fresh-fruit taste products (Walsh 2011). Most fruity popsicles – made from water, fruit juice, sugar and/or artificial sweetener, colorant and flavor – are poor sources of vitamins, fiber, minerals and other micronutrients. The increased intake of added sugars from soft drinks and sugar-based sweeteners in U.S. diets raises concerns about displacement of vital nutrients such as vitamins and minerals and increases in overall caloric intake (Alok and Aliaksandr 2007). The potential adverse consequences of increased sugar consumption include coronary heart disease, obesity and dental caries (Kranz *et al.* 2005).

Fruits and vegetables are rich sources of many vitamins, minerals, fiber and phytochemicals. Numerous studies report the importance of consuming more servings of fruits and vegetables due to their health benefits, which include preventing cardiovascular disease, diabetes and stroke (Willett 1994, 1995; Temple 2000; Lydia *et al.* 2002).

There is much evidence suggesting that nutrition is best acquired through consuming whole foods, not through taking pills or extracts (Rui 2005). Though the United States Department of Agriculture (USDA) has suggested five to nine servings of fruits and vegetables daily for each adult, most Americans do not meet this standard (Guenther *et al.* 2006). Frozen whole-fruit bars represent one kind of new product to promote fruit consumption and improve human health.

Fresh fruits or vegetables have high-moisture content, usually 80–90%. This moisture content presents a significant challenge, as consuming frozen whole fruits or vegetables or reformed frozen products without removing moisture may result in a final product too hard to bite. The

other challenge is taste. Fruits after being frozen are less sweet than most consumers like. Our preliminary test showed that fruits partially dehydrated using infrared (IR) could be reconstructed and frozen to form fruit bars with the characteristics of whole fruits – reasonable hardness, good taste and natural flavor.

Typical hot-air dehydration may not be usable for partial dehydration of fruits to produce reformed frozen bars because it is a slow drying process and can cause significant quality deterioration, such as browning. By contrast, IR heating is a much faster processing method and also can achieve simultaneous dehydration and blanching to preserve fruit quality (Ponne *et al*. 1994; Pan *et al*. 2005). It has been reported that IR heating has many advantages over conventional heating methods. These include high energy and processing efficiencies, improved product quality and environmental friendliness (Ginzburg 1969; Navarri and Andrieu 1993; Hashimoto and Kameoka 1999; Menshutina *et al*. 2004; Kumar *et al*. 2005). IR heating energy can be generated by a catalytic IR (CIR) emitter that uses natural or propane gas. When the gas passes through a mesh catalyst pad, it is converted to thermal radiation energy through a catalytic reaction occurring below ignition temperature. The emitted radiation energy falls in the spectrum of medium and far IR, with peak wavelengths from 3 to 6 μm. As water is very efficient in absorbing heat energy in this range (Siegel and Howell 1992), the peak power region of CIR energy well matches the absorption peaks of water. For this reason, IR heating results in rapid heating and removal of water in high-moisture foods such as fruits and vegetables (Pan and Atungulu 2011). The energy transfer of IR is also highly efficient because air does not absorb IR radiation; thus, the surrounding air is not heated during the process. Its efficient energy absorption and transfer make IR heating very energy efficient.

Our preliminary tests showed that CIR heating could be used to remove a certain amount of moisture from sliced fresh apples very quickly, resulting in concentration of solids. Frozen bars made from partially dehydrated apples had acceptable levels of hardness. However, the relationship between the moisture content and the final product quality is not clear. The objective of this study was to investigate the effect of CIR partial dehydration on the quality of frozen fruit bars. The studied quality indicators were color, hardness, moisture content, water activity, soluble solid content, vitamin C content and total phenolic levels.

MATERIALS AND METHODS

Chemicals

Folin-Ciocalteu reagent and ascorbic acid were purchased from Sigma Chemical Co. (St. Louis, MO). Gallic acid was obtained from MP Biomedicals, LLC (Solon, OH). Anhydrous sodium carbonate, metaphosphoric acid, 2, 6-dichloroindophenol sodium salt and sodium bicarbonate were obtained from Fisher Scientific (Houston, TX). Kaolin was purchased from Hochberg and Company, Inc. (Chester, NJ). Ethanol and acetic acid were obtained from Gold Shield Chemical Co. (Hayward, CA).

Fruit Materials

Apples and strawberries were chosen for this study because of their many health-promoting attributes, especially anticancer, antiradical and antioxidant properties, due to their high polyphenolic, vitamin and fiber content (Cheng and Breen 1991; Eberhardt *et al*. 2000; Proteggente *et al*. 2002; Boyer and Liu 2004). Therefore, they could satisfactorily serve the purpose of producing healthy frozen fruit bars. Fresh apples (*Malus domesticus* Borkh variety Golden delicious) and strawberries (*Fragaria* variety Aromas CN209) were obtained from a local grocery store (Davis, CA).

Frozen Bar Manufacturing Method

Apples were peeled, cored and sliced into about 6-mm slices with an apple peeler (Back to Basics Products, Inc., Draper, UT). The slices were dipped in a dipping solution containing 0.5% ascorbic acid and 0.5% calcium chloride for 5 min to prevent enzymatic browning (Lin *et al*. 2009; Zhu and Pan 2009; Zhu *et al*. 2010). Dipped apple slices were then drained on a screen for 5 min and excessive surface moisture was removed by blotting with paper towels before drying. Strawberries were washed and the peduncles were removed before slicing into 6-mm-thick slices using a hand-operated slicer (Hobart Corporation, Troy, OH).

A single layer of fruit slices was distributed evenly on a sample tray for partial dehydration using an IR dehydrator equipped with two CIR emitters powered by natural gas (Catalytic Infrared Drying Technologies LLC, Independence, KS) (Pan and Atungulu 2010). The samples were heated from both top and bottom (Fig. 1). Our preliminary test showed that when the center temperature of the sample slices was kept at 50C, using an automatic data acquisition system to turn the gas on and off, samples had the best quality after CIR drying. Therefore, sample slices with a center temperature of 50C were used in the partial dehydration process. The apple and strawberry slices were heated for up to 25 min to achieve different moisture levels: 89.0–75.3% for apples and 92.7–75.3% (wet basis [w.b.]) for strawberries. The sample tray was placed on a balance to measure the sample weight in-line during the partial dehydration. After drying, the partially dehydrated samples were kept in a closed container at room temperature for about 10 min for the moisture to equilibrate between the strawberry surface and interior for

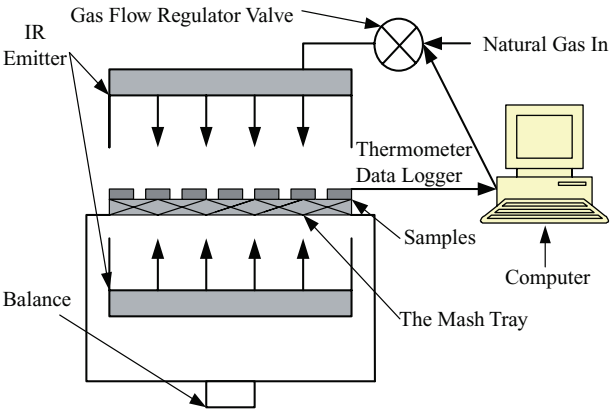

FIG. 1. SCHEMATIC DIAGRAM AND SET-UP OF INFRARED DEHYDRATOR
IR, infrared.

easy grinding. Then, the partially dehydrated slices were ground into a homogeneous mash with particle size less 1 mm using a minichopper (Betty Crocker, Minneapolis, MN). The mash was placed in a $110 \times 30 \times 20$ mm plastic mold and frozen for 72 h at a temperature of −18C. Three replications were conducted for each test.

The frozen bars were removed from the freezer and thawed for 30 min at room temperature before determining their vitamin C content, total phenolic content, water activity and soluble solids. The hardness and color of frozen bars were measured right after the samples were removed from freezer, using methods mentioned below.

Measurement of Moisture Content

The moisture contents of the samples before and after partial dehydration were determined using 2-g samples dried for 12 h at 70 ± 1C under pressure 20 in. Hg in Lindberg/Blue vacuum oven (Waltham, MA) (Association of Analytical Communities [AOAC] 934.06).

Measurement of Vitamin C Content

The vitamin C content of frozen bars and raw apples and strawberries was determined using the 2, 6-dichloroindophenol titration method (AOAC 967.21). Kaolin was added to the strawberry solution to absorb the color before the vitamin C content was determined by titration.

Measurement of Total Phenolic Content

The total phenolic content was measured using the Folin-Ciocalteu method (Slinkard and Singleton 1977). A 10-g sample was first weighed and mixed with 5 mL ethanol. The extract was centrifuged at 13,000 rpm for 4 min; then, the supernatant was collected. The 20 μL supernatant was mixed with 1.58 mL distilled water. Then, 100 μL Folin-Ciocalteu reagent (Sigma Chemical Co.) was added and mixed well. After waiting for 1 min, a 300 μL of sodium carbonate solution was added and shaken to mix. The solution was kept at 40C for 30 min before the absorbance was measured at 765 nm by the Beckman DU 7500 spectrophotometer (Corona, CA). Gallic acid monohydrate was used as a standard, and the total phenolic content was expressed as gallic acid equivalents (Waterhouse 2011).

Measurement of Water Activity

The water activity of thawed fruit bars was determined by using Aqualab CX-2, a water activity meter (Decagon Devices, Pullman, WA).

Measurement of Soluble Solid Content

Thawed samples were filtered by double-layer cheese cloth to obtain juice for measuring soluble solids with Abbe Refractometer (American Optical Corporations, Buffalo, NY). The soluble solid is reported as °Brix.

Measurement of Color

The color of the frozen fruit bar was determined using a Minolta colorimeter CR-200 (Osaka, Japan) to measure Hunter *L*, *a* and *b* values. The color measurement was conducted at three surface locations, two close to the ends and one at the middle. The measurement was repeated three times at each location.

Measurement of Hardness

The hardness of the frozen bars was determined using Instron (Norwood, MA) with a custom-designed probe within 1 min after they were removed from the freezer (Fig. 2). The probe is 2 mm in width and 50 mm in length. The measuring speed of the probe was 15 mm/min. The peak force was used to quantify the hardness of the bars.

Statistical Analysis

The SAS 9.1.3 software (SAS Institute, Inc., Cary, NC) was used for data analysis. Differences between variables were tested at a level of significance of $P < 0.05$.

RESULTS AND DISCUSSION

When the sliced apples were dipped in the ascorbic acid and calcium chloride solutions, their moisture content was slightly increased to 90.1% from 89.0% (w.b.) due to water

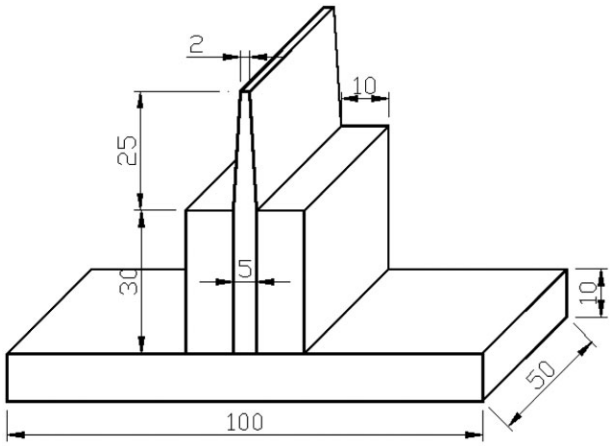

FIG. 2. PROBE USED FOR MEASURING HARDNESS OF FROZEN FRUIT BARS (UNIT IN MM)

absorption. When the slices of apple and strawberry were dried with IR, the moisture contents were reduced quickly (Fig. 3a). The strawberry slices had a much higher drying rate than the apple slices. In 18 min, the moisture content of strawberries was reduced from 92.7 to 70.8%; for apples, the reduction was from 90.1 to about 82.5%. The difference in drying rate was caused by differences in the initial moisture contents, as well as structural differences (Bimbenet *et al.* 1985). The result indicated that if a similar moisture content of strawberries and apples is needed to form restructured frozen bars, less drying time is needed for strawberries than apples.

The decreased moisture content of the slices through IR partial dehydration resulted in increased soluble solids and decreased water activities as expected (Fig. 3b). The soluble solids (data not shown) and water activity changed almost linearly with the moisture content (Fig. 4). It is important to notice that at the same moisture content strawberry samples showed higher water activities, but lower soluble solids than apples, most likely due to the lower sugar and higher acid contents in the strawberries.

It was also observed that the total phenolic and vitamin C content (on a dry basis [d.b.]) decreased with increased drying time (Fig. 5a,b). Rapid loss of nutrients occurred in the early drying stages. For example, the total phenolic content of strawberries decreased from 27.9 to 18.4 (mg/g d.b.) after 2.5-min drying, which indicated significant loss of total phenolics caused by drying. These results are consistent with the reported results (Rao *et al.* 1981; Dewanto *et al.* 2002; Böhm *et al.* 2006). However, the losses of total phenolic and vitamin C in apple were less than the losses of total phenolic and vitamin C in strawberries. The difference may be due to the higher initial concentrations of these nutrients in strawberries.

Even though the partial dehydration caused significant nutrient losses, the total phenolic and vitamin C contents were increased in the final partially dehydrated frozen products due to concentrating effects, as shown in Table 1. For partially dehydrated strawberries, the concentrations of total phenolic and vitamin C increased by 115.2 and 157.9%, respectively, when dried from 92.7 to 70.8% moisture. For the partially dehydrated apples, the concentrations of total phenolic and vitamin C also increased by 54.6 and 16.0%, respectively, when they were dried from 90.1 to 75.3% moisture. These results indicated that more nutrients can be obtained from a given amount of partially dehydrated frozen bars than from fresh products.

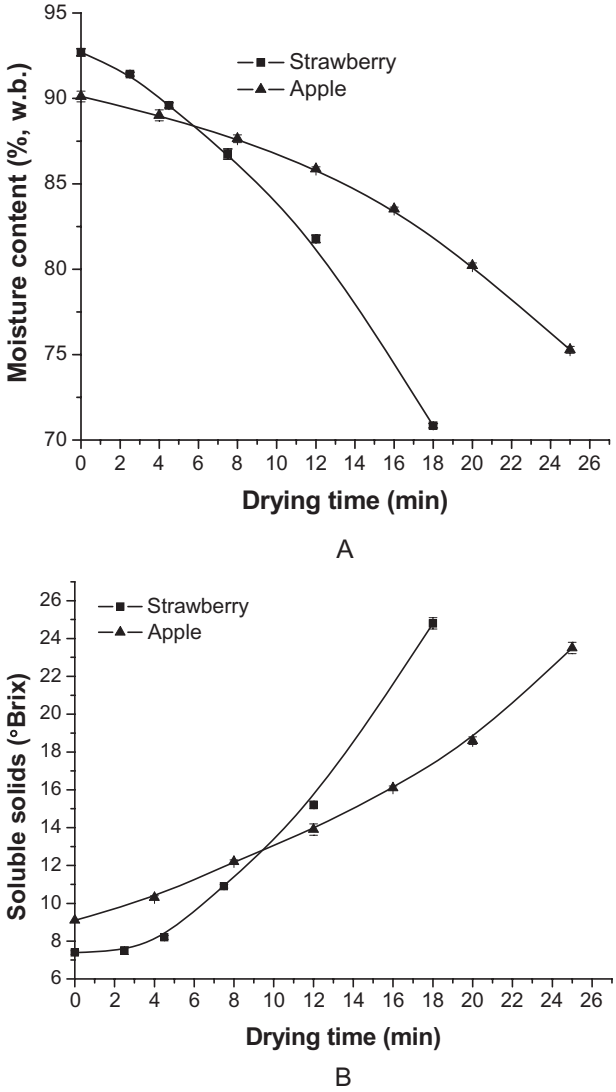

FIG. 3. MOISTURE CONTENT (A) AND SOLUBLE SOLIDS (B) OF PARTIALLY DEHYDRATED STRAWBERRY AND APPLE SLICES AT DIFFERENT IR DRYING TIMES
IR, infrared; w.b., wet basis.

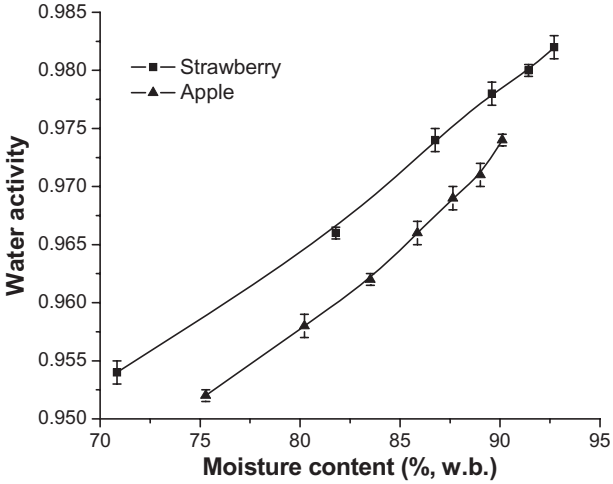

FIG. 4. RELATIONSHIP BETWEEN WATER ACTIVITY AND MOISTURE CONTENT OF PARTIALLY DEHYDRATED STRAWBERRY AND APPLE SLICES
w.b., wet basis.

After dipping the apple slices, soluble solid content was reduced from 10.9 to 9.1°Brix, which indicated a loss of solids and water absorption. The dipping increased the vitamin C content to 20.2 mg/100 g (w.b.) from 5.9 mg/100 g (w.b.) of fresh sliced apples. This was due to the absorption of vitamin C from the dipping solution.

The appearance of the frozen restructured fruit bars is shown in Fig. 6a,b. In general, both apple and strawberry bars became darker with a decrease in moisture content. This could be due to the water loss and/or concentration of solids. The moisture content also showed significant effect on the color of frozen bars ($P < 0.05$). As the moisture content decreased, L and b values of frozen apple bar increased while the values of frozen bar slightly decreased (Fig. 7a). Fresh apple contains yellow and green pigments (phenolic and chlorophyll) in its flesh. During dehydration, these natural color pigments were concentrated, resulting in an increase of b value (more yellow) and a decrease of a value (greener). In addition, the heat from IR radiation might also contribute to the color development (increased b value), which needs to be further studied. Figure 7b showed that when moisture was removed, all the Hunter color parameters of strawberry bar increased in the beginning and slightly decreased in the later stages of drying. Strawberry has red pigment (anthocyanin) in its flesh. The quick

TABLE 1. TOTAL PHENOLIC AND VITAMIN C CONTENTS OF FROZEN BARS WITH DIFFERENT MOISTURE CONTENTS (PER 100 G)

	Moisture content (g)	Total phenolic (mg)	Vitamin C (mg)
Apple	89.0 ± 0.3 (Fresh)	152.7 ± 1.9	5.9 ± 1.3
	90.1 ± 0.3 (Dipped)	168.2 ± 2.1	20.2 ± 3.6
	89.0 ± 0.3	154.1 ± 3.2	19.1 ± 1.6
	87.6 ± 0.2	164.9 ± 4.9	18.3 ± 1.6
	85.9 ± 0.1	176.6 ± 8.1	17.5 ± 1.7
	83.5 ± 0.1	196.3 ± 15.0	18.8 ± 1.8
	80.2 ± 0.2	224.9 ± 4.6	20.4 ± 1.7
	75.3 ± 0.2	260.1 ± 14.1	23.2 ± 1.5
Strawberry	92.7 ± 0.2 (Fresh)	203.8 ± 3.5	52.1 ± 1.3
	91.4 ± 0.1	158.1 ± 1.7	53.6 ± 1.9
	89.6 ± 0.2	182.6 ± 8.7	60.6 ± 1.3
	86.8 ± 0.3	209.4 ± 3.4	72.7 ± 1.9
	81.8 ± 0.2	279.1 ± 6.1	90.2 ± 0.9
	70.8 ± 0.1	438.6 ± 10.4	134.4 ± 4.3

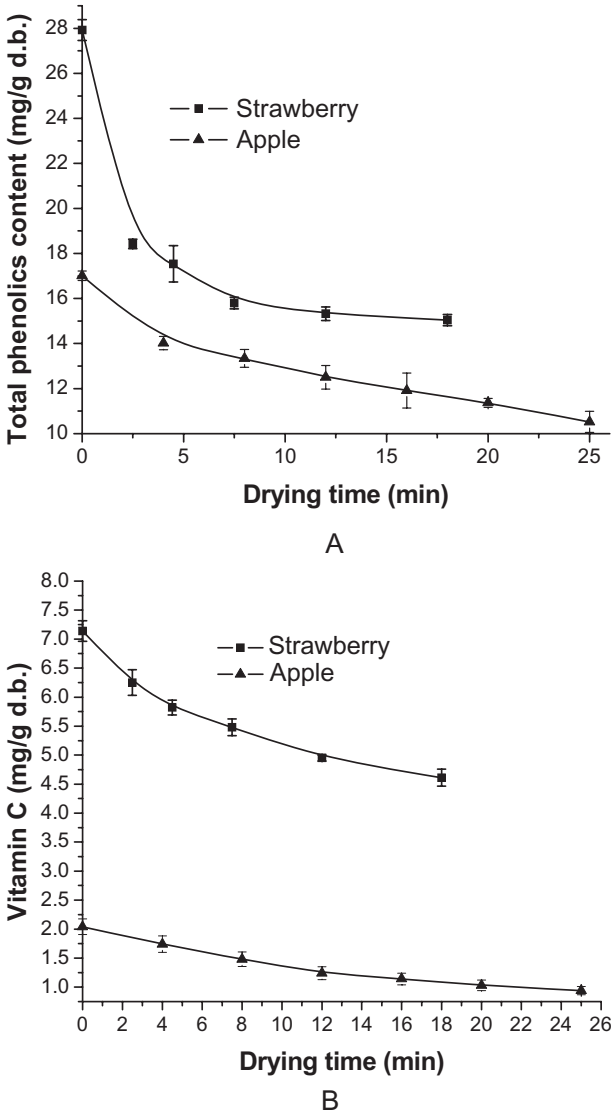

FIG. 5. EFFECT OF IR DRYING TIME ON TOTAL PHENOLIC CONTENT (A) AND VITAMIN C (B) OF PARTIALLY DEHYDRATED STRAWBERRY AND APPLE SLICES
d.b., dry basis; IR, infrared.

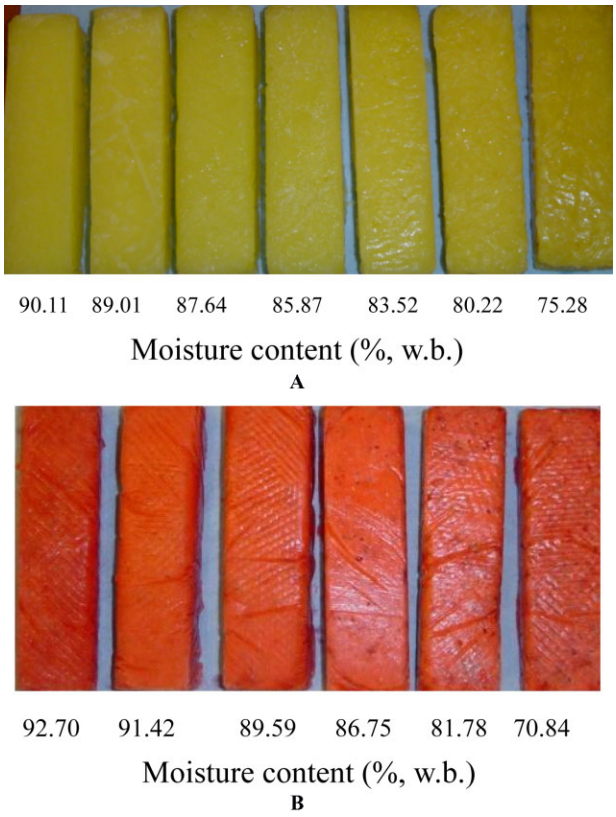

FIG. 6. APPEARANCE OF FROZEN APPLE (A) AND STRAWBERRY (B) BARS
w.b., wet basis.

dehydration in the early drying state resulted in the concentration of red pigments and the increase of *b* value (more yellow) and *a* value (more red). In the later drying state, the red pigment might be degraded as anthocyanin is sensitive to heat, so that *a* and *b* values slightly decreased.

The hardness of restructured frozen fruit bars decreased with the decrease in moisture content (Fig. 8a). This was because less free water was available to form ice crystals during freezing after the partial dehydration. It has been observed that the frozen apple bars generally had lower hardness values than the frozen strawberry bars at the same moisture content, due to the difference in soluble solids. The high soluble solids in apple bars corresponded to high sugar content (low water activity) acting as cryoprotectant. When the hardness results are plotted against the water activities, it was found that the similar hardness was obtained at the same water activity regardless of the fruit variety (Fig. 8b). Therefore, it is important to control the water activity to achieve desirable hardness.

An informal sensory evaluation of the frozen bars was also conducted in the Food Processing Laboratory in the Department of Biological and Agricultural Engineering, University of California, Davis. Based on the color and hardness of the frozen bars, all bars with water activity below 0.97 were judged acceptable. The recommended water activities of the frozen bars are 0.96–0.97, which correspond to the moisture contents from 81.4 to 88.2% (w.b.) for apple bars and from 76.0 to 83.7% (w.b.) for strawberry bars.

If a restructured frozen whole apple bar is made by reducing water activity to 0.96 (moisture content of 83.5%), 28.5 and 218.4%, more total phenolic and vitamin C will be available, respectively, compared with the same amount of fresh apples. Similarly, if a restructured frozen whole strawberry bar is made by reducing water activity to 0.97 (mois-

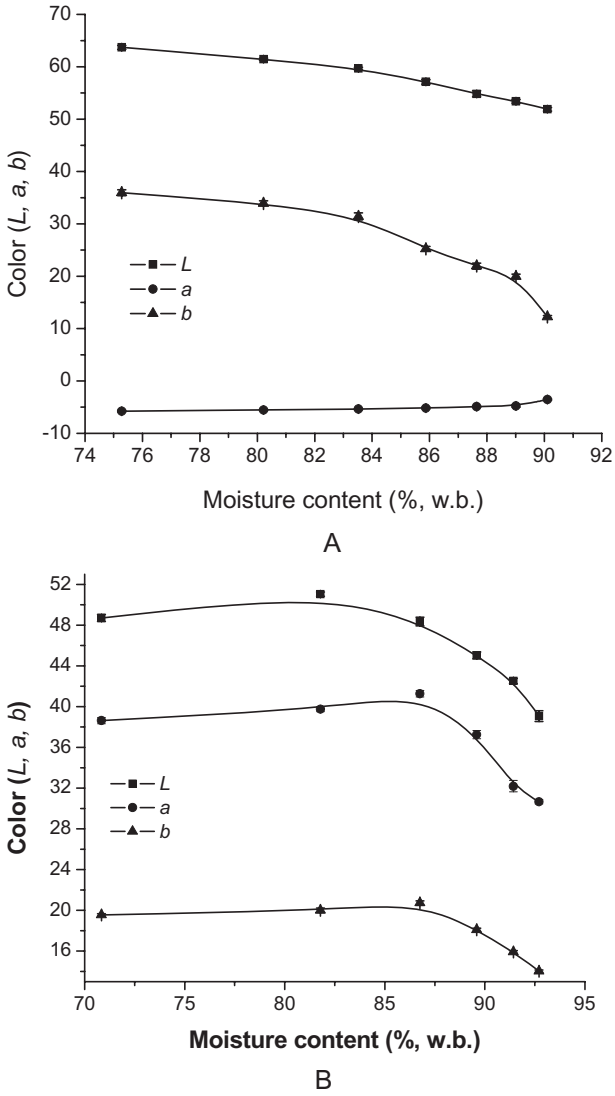

FIG. 7. *L*, *A* AND *B* VALUES OF FROZEN APPLE (A) AND STRAWBERRY (B) BARS
w.b., wet basis.

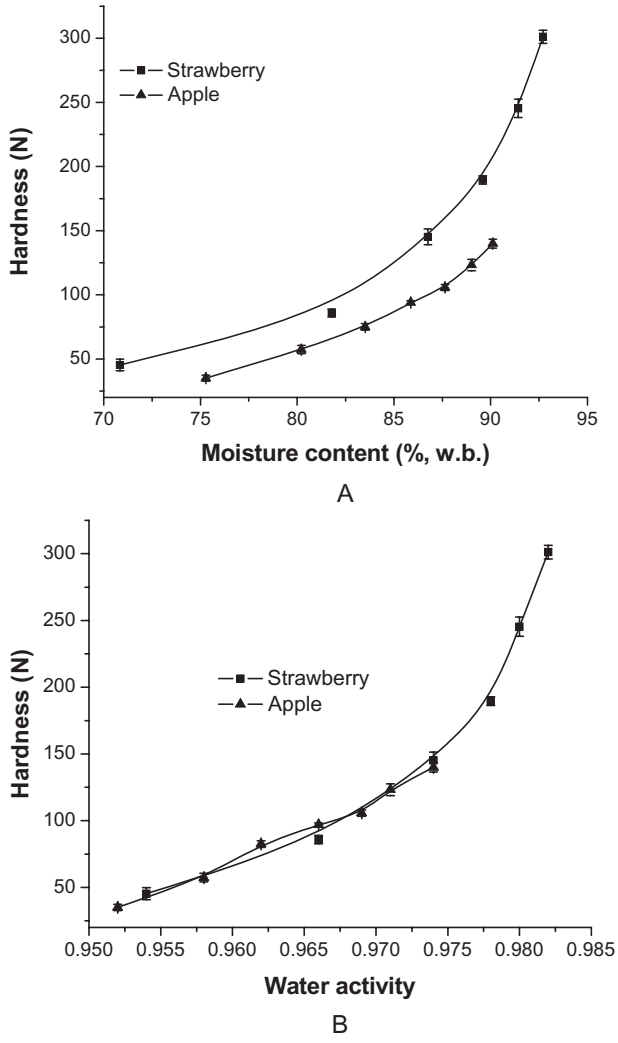

FIG. 8. HARDNESS OF FROZEN STRAWBERRY AND APPLE BARS WITH DIFFERENT MOISTURE CONTENTS (A) AND WATER ACTIVITIES (B)
w.b., wet basis.

ture content of 81. 8%), 37.0 and 73.3%, more total phenolic and vitamin C will be available, respectively, compared with the same amount of fresh strawberry. Based on this research, a 100-g frozen fruit bar can provide the full recommended daily allowance of vitamin C (based on a 2,000 calorie diet; for adults and children 4 or more years of age, USDA) (Anon 2011b). As the dietary fiber and minerals in the dehydrated fruits may not change, dehydration will increase the concentrations of the nutrients. Assuming that 100-g fresh apple contains 1.27-g total dietary fiber (Anon 2011c), a 100-g frozen bar with 83.5% moisture content will have 1.90-g dietary fiber, which provides 7.6% of the daily recommended dietary fiber. Similarly, if assuming that 100-g fresh strawberry contains 1.97-g total dietary fiber (Anon 2011d), a 100-g frozen bar with 81.8% moisture content can provide 19.7% of recommended daily dietary fiber.

CONCLUSIONS

This research has demonstrated that high-quality restructured frozen fruit bars can be made from apples and strawberries by partial dehydration using IR heating followed by restructuring and freezing. Strawberry slices showed a higher drying rate than apple slices due to the differences in their structure and initial moisture content. The partial dehydration caused a certain degree of degradation in total phenolic and vitamin C. However, because of the loss of water in the partially dehydrated apples and strawberries, the concentrations of nutrients in the finished frozen bar were increased. This indicates that higher amount of nutrients can be obtained by consuming frozen bars than by consuming the same amount of fresh fruits. This new form of fruit and vegetable products can promote the consumption of fruits and vegetables, resulting in improved human health.

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