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A convective multi-flash drying process for producing dehydrated crispy fruits

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ABSTRACT

The aim of this work was to evaluate the application of a convective multi-flash drying process (CMFD) to producing dehydrated and crisp fruits. To accomplish this process, samples of banana (*Musa sapientum* L.) or mango (*Mangifera indica* L.) were heated to 60 °C by hot air, and a vacuum pulse was applied, which resulted in dehydration by a combination of convective drying and flash evaporation. Banana processed by CMFD had a moisture content of 0.293 g/g (dry basis) and $a_w = 0.272$ after 3 h of processing. Mango had a moisture content of 0.09 g/g and $a_w = 0.359$ after 4 h of processing. Puncture tests on fruits dehydrated by CMFD and on commercial freeze-dried fruits showed strain–force curves with many peaks (jagged curves). For CMFD much smaller global shrinkage was observed. These results indicate that the CMFD process can be applied for producing crispy fruits and is an alternative to the freeze-drying process.

1. Introduction

Bananas and mangoes are climacteric fruits of significant economic importance in many tropical countries. Both fruits are sources of carbohydrates, fiber and polyphenols with antioxidant capacity, such as flavonoids, anthocyanins and tannins (Pérez et al., 2011). The development of new technologies for fruit preservation and processing is necessary to reduce losses, to obtain better products and to add value.

The dehydration of foods is one of the oldest techniques of preservation. The reduction of moisture content and water activity to safe levels inhibits microbial growth and enzymatic activity, increasing shelf life (Van Arsdel, 1963; Fellows, 2000; Ratti, 2001; Aguilera et al., 2003; Cano-Chauca et al., 2004). Historically, solar drying and drying with hot air (convective drying) have been the most common food drying techniques. Solar drying is cheap and traditional, but its application depends on weather conditions and requires large processing areas. Moreover, it is necessary to protect the fruits from insects and small animals and from contact with airborne dirt. In convective drying, it is possible to control these adverse factors and increase the average drying rate. However, the texture properties of dried fruits can be severely damaged because of strong shrinking of the solid matrix and thermal degradation. The shrinkage affects the texture and rehydration capacity of the dehydrated product. Shrinkage also increases product thermal conductivity, which leads to a higher product heating rate and can damage the nutritional and sensory properties of the final product (Fellows, 2000; Louka et al., 2004; Lewicki, 2006).

Freeze-drying has been considered the best dehydration process for thermo-labile products because it reduces nutritional and sensorial degradation. As water is removed from a pre-frozen product, a porous structure is formed, which results in a dehydrated product that has better properties when rehydrated (Mujumdar, 2007). However, freeze-drying is a time-consuming and relatively costly process, which limits its use to products with high added value (Louka and Allaf, 2002).

Literature has reported many works on the influence of the dehydration procedure on the structural properties of fruits, vegetables and other agricultural products (Karathanos et al., 1996; Krokida et al., 1998; Krokida and Maroulis, 1997; Oikonomopoulou et al., 2011). Krokida et al. (1998) reported the effect of freeze-drying conditions on the structural properties of apple, banana, carrot and potato. When the process was performed at temperatures above the glass transition temperature of the concentrated amorphous solution (assumed as −45 °C), they reported that the overall sizes and bulk densities of freeze-dried materials decreased. Karathanos et al. (1996) reported results on the porosities of potato, apples, carrots and cabbage dehydrated by freeze-drying and by air drying. They observed that freeze drying resulted in much higher bulk porosity when compared to air drying. Moreover, the pore sizes of air dried materials were much smaller than the pore sizes of freeze dried samples, due to the collapse of the products

Abbreviations: CMFD, convective multi-flash drying; *DIC*, (Détente Instantanée Controlée in French) or controlled sudden decompression; *P*, pressure (Pa); c_p, specific heat of the product during the vacuum pulse application (kJ kg^{-1} °C^{-1}); m_p, mass of the product before the application of the vacuum pulse (kg); m_w, water mass (kg); Δm_w, water evaporated (kg) from the product during a vacuum pulse; x_w, mass fraction of water; *T*, temperature (°C); ΔT, difference between the sample temperature before and after the vacuum pulse (°C); $\Delta \hat{H}_v$, enthalpy of vaporization of water at 1500 Pa (kJ kg^{-1}); *t*, time (s); *X*, moisture content (g/g) – (dry basis).

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structures during air drying. The explosion puffing process is based on the compression–decompression of a chamber and self-evaporation of product moisture, and the first records related to the process are the patent documents U.S. 2,091,372 and U.S. 2,278,469 from the 1930s and 1940s (Moore, 1937; Musher, 1942). The process was developed in order to dehydrate fruits and vegetables at large scale, with operating costs comparable to convective drying (Mujumdar, 2007). The explosion puffing process is performed by submitting the partially dehydrated product to a high pressure (600–800 kPa) and high temperature and then performing a sudden decompression to atmospheric pressure.

A texturizing process called DIC (Détente Instantanée Contrôlée, in French) is a process that uses a controlled, sudden decompression of a vessel with pre-heated fruits and is based on the self-vaporization of food moisture (Louka and Allaf, 2002, 2004; Louka et al., 2004). The products are heated with steam at about 500 kPa and submitted to a controlled, sudden decompression to create texture during water evaporation. This process was successful applied to potatoes, carrots, onions, broccoli and tomatoes (Louka and Allaf, 2002, 2004; Louka et al., 2004).

Before applying DIC or explosion puffing processes, product pre-dehydration is essential to avoid product damage during the sudden decompression. Because these processes have sizeable temperature differences before and after system decompression, a large amount of steam is generated, which can cause disintegration of the product (Thakur and Thakur, 2000; Louka and Allaf, 2002; Iguedjtal et al., 2008).

Other technologies for obtaining dry and crisp products have been reported by literature. Argyropoulos et al. (2011) investigated the use of hot-air combined with microwave-vacuum and freeze-drying methods for mushrooms. They reported that combined drying with hot air and microwave-vacuum resulted in a dried product of superior quality when compared to the slices dried completely by conventional hot air, exhibiting higher porosity, greater rehydration ratio and softer texture. In a dry state, mushrooms with a puffy structure and crispy texture were created by the combined drying method.

Chips of fruits have also been produced by frying. However, these products generally contain high oil content, which is not desirable, because oil oxidation leads to short shelf lives, and they are not considered healthy foods (Prachayawarakorn et al., 2008). Other alternative for obtaining crispy fruits is the combination of a pre-dehydration at 70 °C with a step at high temperatures and short time, as reported by Hofsetz and Lopes (2005). They produced crispy banana using hot air at 140 °C for 12 min or 150 °C for 15 min in the HTST stage. However, this procedure can causes undesirable changes on the fruits color, as reported by Prachayawarakorn et al. (2008).

The convective multi-flash drying process (CMFD) is also a dehydration process. It was initially developed for dehydrating fruits and vegetables while also performing product texturization. The process is based on the application of successive cycles of heating and vacuum pulses. The product is heated at atmospheric pressure using hot air that causes partial dehydration of the product. When the product reaches the desired temperature, a sudden pressure reduction (vacuum pulse) is applied, which leads to water evaporation (flash drying) and product cooling, as reported in a patent solicitation (Laurindo et al., 2011). Additional heating-vacuum pulse cycles can be applied to achieve the desired characteristics of the dehydrated product. The CMFD process does not use pressures higher than atmospheric pressure. Because it is possible to apply many cycles, the heating temperature can be compatible with the food's sensitivity to heat treatment.

The objective of this study was to investigate the use of the CMFD process for dehydrating mango and banana. We also compare dehydration times, physical structures and an instrumental texture property of the dehydrated fruits with fruits prepared by convective drying, vacuum drying and freeze-drying.

2. Materials and methods

2.1. Sample preparation

Banana (*Musa sapientum* L., Prata var.) and mango fruits (*Mangifera indica* L., Tommy Atkins var.) were purchased in a local market (Florianópolis, SC, Brazil). The fruits were selected based on their appearance and state of ripeness, which was evaluated using the soluble solids content (using a digital handheld refractometer, AR200 Reichert, USA) and from the resistance to penetration (using a penetrometer, Effegi Mod FT 327, Ø = 8 mm, Italy). The soluble solids were 23.1 ± 1.4 Brix and 12.7 ± 0.9 Brix for bananas and mangoes, respectively. The selected fruits were washed and peeled manually before use. Banana samples were sliced to a 5 mm thickness, and peeled mango samples were sliced in a direction parallel to their fibers to a thickness of 7 mm.

2.2. Experimental setup and dehydration procedure

Fig. 1 shows a sketch of the experimental device used to perform the dehydration of fruits by the CMFD process. The experi-

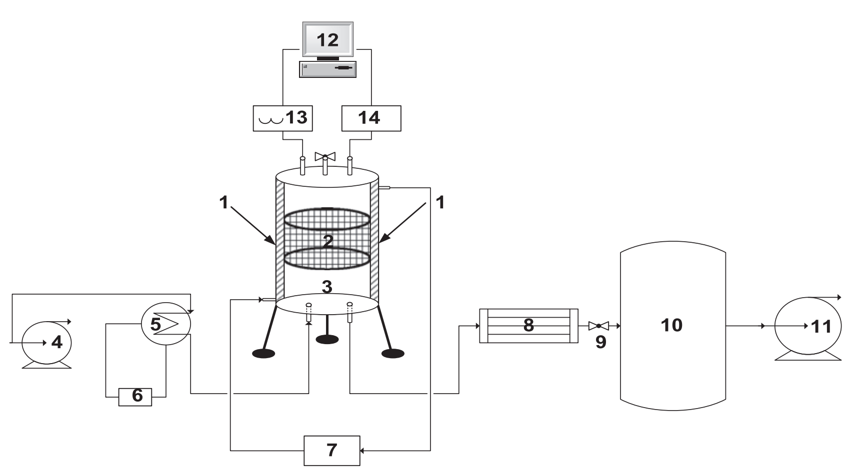

Fig. 1. Experimental device used to apply the convective multi-flash drying process – CMFD. 1-Container jacket; 2-grid; 3-jacketed container; 4-air compressor; 5-serpentine tube; 6-thermostatic bath; 7-thermostatic bath; 8-condenser; 9-globe valve; 10-vacuum chamber; 11-vacuum pump; 12-computer with a data acquisition system; 13-temperature sensors; 14-pressure sensor.

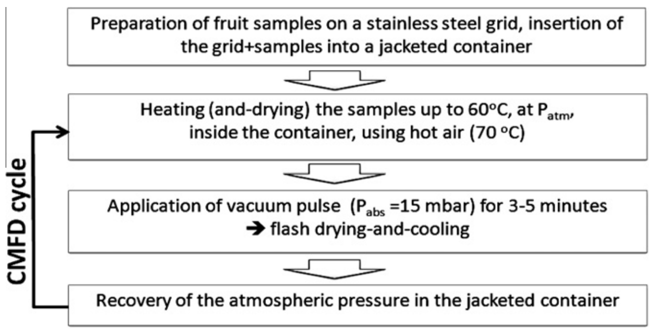

Fig. 2. Schematic diagram of the CMFD process.

mental apparatus consists of a jacketed container (3) with an internal volume of 0.035 m^3, which is connected to a 1 m^3 tank (10) that is kept under vacuum (P = 1.5 kPa) by a vacuum pump (11) with a pumping capacity of 350 m^3/h (LC305-DVP Vacuum Technology, Italy). A globe valve was installed between the jacketed container (10) and the vacuum tank (3) to allow the application of vacuum pulses to the jacketed container (3). A condenser device (vapor trapping, 8) was used to improve the vacuum system efficiency. The pressure in the jacketed container was monitored with a digital vacuum gauge (14) (Multi-Range Vacuum Gauge PIZA 111 – ILMVAC, Germany). The container (3) was heated both by hot water (98 °C) circulating in its jacket (1) and by hot air injected at its base (70 °C). The heating air was supplied by a medical oil-free compressor (MSV 6/30 – SCHULZ, Brazil) (4) and was heated to 70 °C in a serpentine tube immersed in boiling water (5). Time–temperature variations of the samples during the process were monitored using T-type thermocouples (Iope, model A-TX-TF-TF-R30AWG, Brazil), which were inserted in three samples and connected to a data acquisition system (34970A, Agilent Technologies, USA).

A sketch of the CMFD process is presented in Fig. 2. Sample fruits (banana or mango), prepared as described before, were placed in a stainless steel grid (2) and inserted into the jacketed container (3) during the dehydration process. The fruit samples were heated to approximately 60 °C, and the pressure in the jacketed container (3) was reduced to the vacuum chamber pressure (1.5 kPa) by opening the globe valve. The vacuum pulse duration was 5 min. After this period, atmospheric pressure was restored in the container (3), and additional heating-vacuum pulse cycles were applied. A schematic representation of the temperature and pressure profiles during the CMFD process is presented in Fig. 3. For both fruits, 12 heating-vacuum pulse cycles were applied. Mango fruit samples were heated by both mechanisms, conduction (hot water circulating in the container jacket, which heats the grid supporting the fruit samples) and convection (circulations of hot air inside the container). Radiation heat transfer from the container wall was also present, but it represented less than 5% of the total heat transfer to the fruits, as discussed in Section 2.3. Banana samples were heated in the first two cycles of drying only by conduction (and radiation), but convection was also used from the third cycle onward. These heating strategy choices were based on technical reasons and the different characteristics (composition and texture) of the fruits; i.e., banana is a starchy fruit with approximately 75% moisture (3 kg of water/kg dry solid), whereas mango is a fibrous fruit with approximately 86% moisture (6 kg of water/kg dry solid). This decision was supported by exploratory experiments (not shown), but the main reason is related to the different times necessary to heat the fruits in the beginning of the CMFD process. As mango is less hygroscopic and with higher initial moisture content, it needs longer heating periods, because hot air energy causes water evaporation.

After each drying cycle, the moisture contents of fruit samples were determined by the gravimetric method (AOAC, 2000). The water activities in the samples were determined with a hygrometer (Aqualab Model Series 3, Decagon Devices Inc., Pullman, USA). These analyses were performed in triplicate.

2.3. Estimation of water evaporation during a vacuum pulse

It was hypothesized that water evaporation during a vacuum pulse occurs mainly due to sample cooling, which supplies the enthalpy necessary for water vaporization (adiabatic process). Thus, the amount of water evaporated from the product during a vacuum pulse can be estimated with Eq. (1).

$$\Delta m_w = \frac{c_p \cdot m_p \cdot \Delta T}{\Delta \hat{H}_v} \quad (1)$$

where Δm_w is the water loss (kg), c_p (kJ kg^{-1} °C^{-1}) is the average specific heat of the product during the vacuum pulse application (c_p depends on the sample moisture content), m_p is the mass of the product before the application of the vacuum pulse (kg), ΔT is the difference between the sample temperature before and after the vacuum pulse (°C) and $\Delta \hat{H}_v$ (kJ kg^{-1}) is the enthalpy of vaporization of water at 1500 Pa. During the 5 min of vacuum application, conduction heat transfer from the supporting grid and radiation heat transfer from the container walls can increase the evaporation, but they were not considered in the calculations. Considering that the stainless steel emissivity is 0.17 (Incropera and DeWitt, 2003) and that the convective heat transfer coefficient between the hot air and the fruits can range from 20 to 40 W m^{-2} K^{-1}, it is possible to verify using the Stefan–Boltzmann law that the contribution of radiation heat transfer to product heating is always less than 5%.

The specific heat of the fruit was estimated at each vacuum pulse using the empirical correlation of Siebel shown in Eq. (2) (Mc Donald and Sun, 2001).

$$c_p = 3.349x_w + 0.8374 \quad (2)$$

where c_p is the sample specific heat (kJ/kg K) and x_w is the mass fraction of water.

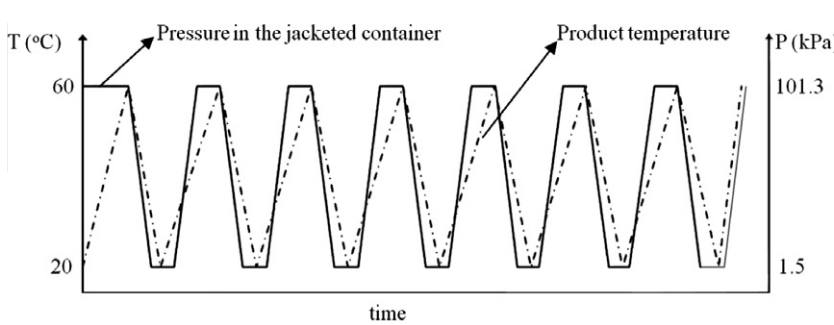

Fig. 3. Schematic temperature and pressure profiles during the cycles of a CMFD process.

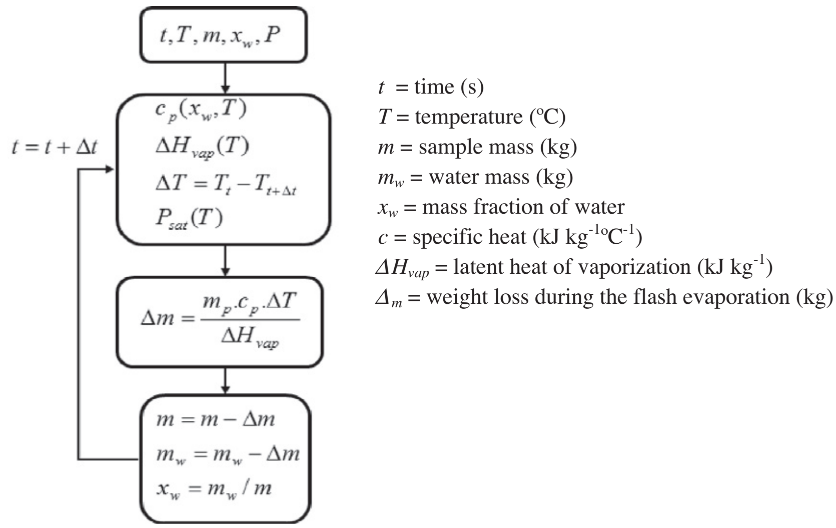

Fig. 4. Algorithm used to calculate the temporal evolution of water loss due to the application of vacuum pulses during the CMFD process.

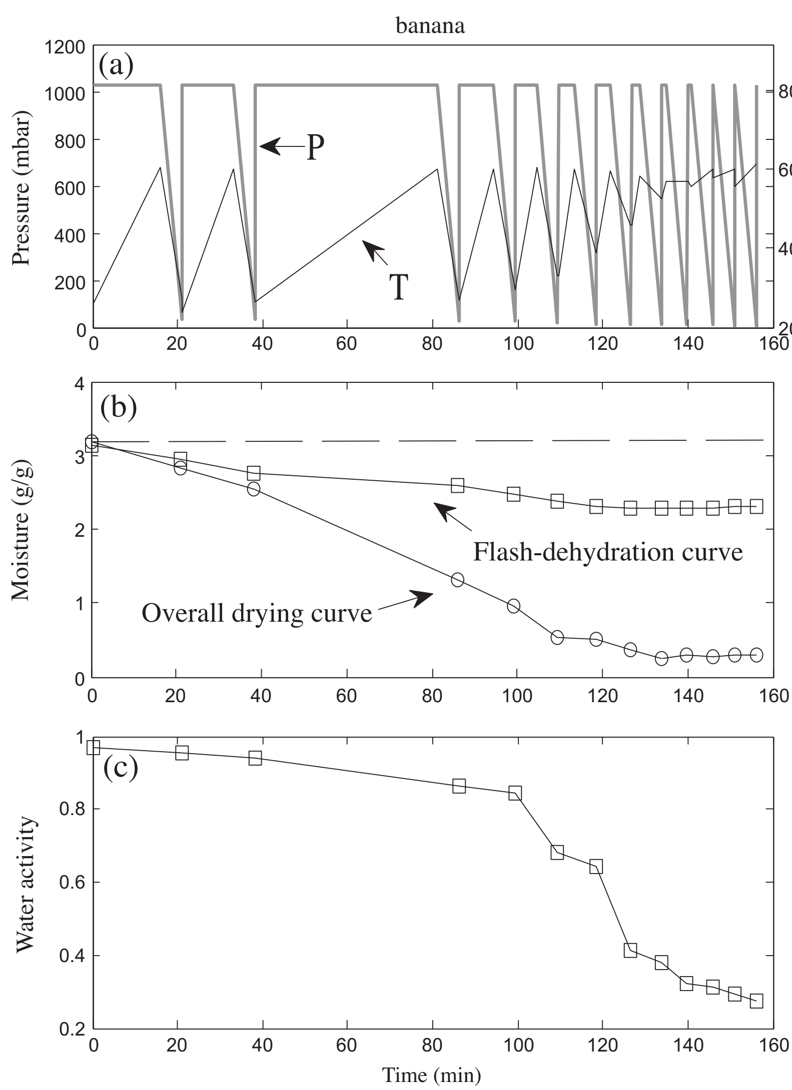

Fig. 5. (a) Temporal evolution of pressure in the jacketed container (—) and fruit temperature (——) during the CMFD process applied to banana samples. (b) Evolution of experimental moisture content of banana during the CMFD process and the estimated contribution of flash evaporation to the drying process. (c) Evolution of water activity in banana samples during processing.

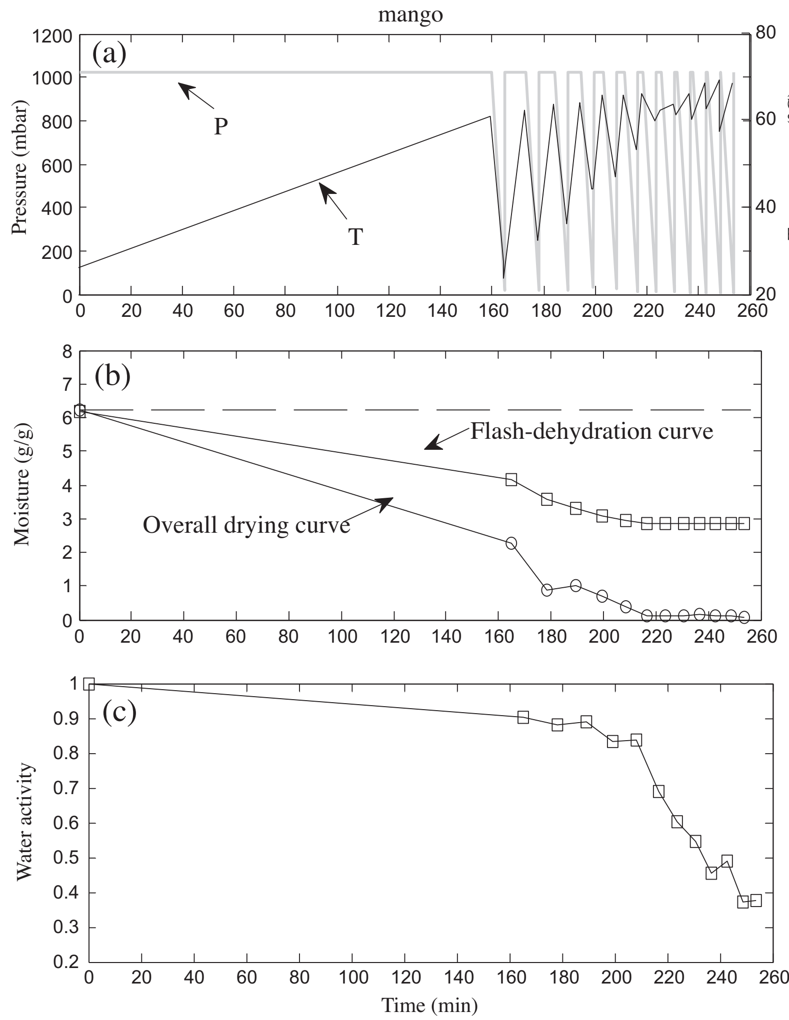

Fig. 6. (a) Temporal evolution of pressure in the jacketed container (—) and fruit temperature (——) during the CMFD process applied to mango samples; (b) Evolution of experimental moisture content of mango during the CMFD process and the estimated contribution of flash evaporation to the drying process; (c) Evolution of water activity in mango samples during processing.

In Fig. 4, the algorithm used to calculate the temporal evolution of water loss due to flash evaporation (vacuum pulses) is presented. The simulation was performed using the initial sample weight, the initial sample moisture and the pressure variation for each vacuum pulse. These calculations allowed estimation of the relative importance of vacuum pulses on the drying process, which has contributions from both convective-conductive drying during the sample heating and flash-drying during the vacuum pulse application.

2.4. Convective drying (oven drying) and vacuum drying

Banana and mango samples were dried in a convective oven (TE 394/2, TECNAL, Brazil) at 60 °C, relative humidity of 12% and air velocity of 1 m/s. Air relative humidity (ThermoHygrometer, TESTO 610, Germany) and air velocity (Anemometer TESTO 425, Germany) were monitored during the drying process. The fruits moistures were determined throughout the drying process by weighing the samples every 15 min during the first 2 h, every 30 min the next 10 h, and every 60 min the rest of the experiment, until they reached constant weight. Samples of banana and mango were also dried in a vacuum oven (TE-395, TECNAL, Brazil) at 60 °C. The moisture evolution was determined throughout the drying period by breaking the vacuum and weighing the samples every 30 min until they reached constant weight.

2.5. Freeze-dried samples

Freeze-dried fruits (banana and mango) were purchased from a local retail store (Florianópolis, SC, Brazil).

2.6. Characterization of dehydrated fruits

2.6.1. Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) was used to analyze the internal structure of fruits dried by CMFD, vacuum drying and convective drying as well as commercial samples of freeze-dried fruits. To prepare the samples for SEM analysis, the dehydrated fruits were freeze-dried (Liotop L101, Liobras, Brazil) to remove the residual moisture. Images of the samples were obtained using a JEOL JSM 6390LV-Japan scanning electron microscope. The samples were coated with a fine gold layer, using a LEICA device (EM SCD500), before obtaining the micrographs. All samples were examined using an accelerating voltage of 10 kV.

2.6.2. Texture analyses

Puncture tests of dehydrated fruits were carried out using a 2 mm-diameter cylindrical probe and a texturometer (Stable Micro Systems TA-XT2i, UK). For samples of dried banana, a strain of 50% of its original thickness was used, while for samples of dried mango, a strain of 70% of their original thickness was applied.

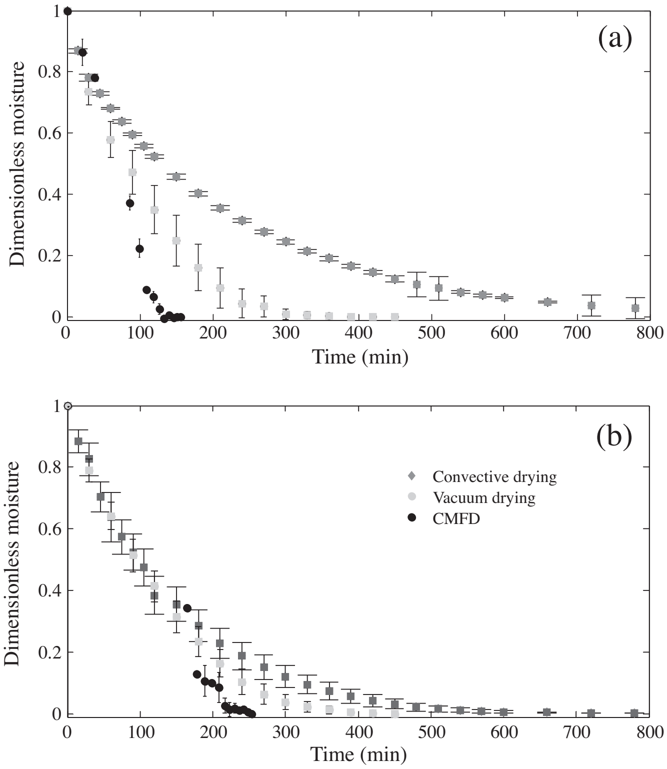

Fig. 7. Drying curves for (a) banana and (b) mango by convective drying, vacuum drying and CMFD processes. In all cases, a temperature of 60 °C was used. Fruit moistures are dimensionless for ease of comparison.

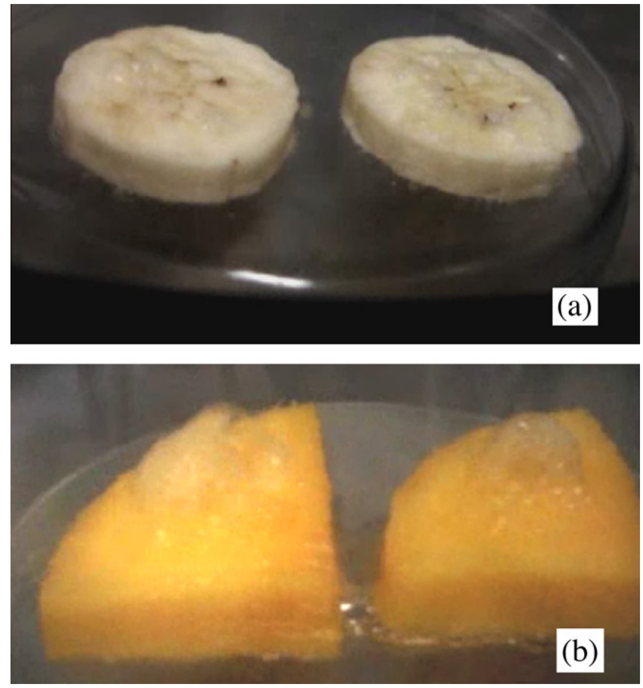

Fig. 8. Pictures of (a) banana and (b) mango fruits during vacuum pulse application. Observe that during flash evaporation, part of the internal moisture is pulled to the fruit surface, which improves convective drying during the heating step by hot air.

Force–strain curves for banana and mango dried by CMFD were compared with force–strain curves for oven-dried and freeze-dried samples.

2.6.3. Shrinkage determination

Five samples of each fruit were submitted to hot air drying, vacuum drying and CMFD, and their final thicknesses were measured with a caliper (Mytutoyo, Brazil). Samples shrinkage was estimated from the reduction of their main dimensions after the dehydration process.

3. Results and discussion

3.1. Temperature and pressure during the CMFD process

Chamber pressure variations and temperature profiles during the CMFD process for samples of banana and mango are given in Figs. 5 and 6, respectively. The heating rate of mango samples was lower than that observed for banana samples because of the importance of convective drying observed for mango samples (the water evaporation prevented a fast temperature rise). The heating of the bananas was only by conduction and radiation during the first two drying cycles, leading to a lower evaporation rate in those cycles. Temperature drops of about 33 °C were observed during the first vacuum pulse for both banana and mango samples. This is because both fruits were heated to approximately 60 °C and had large amounts of free water (the initial moisture contents of banana and mango samples were approximately 76% and 85%, respectively). It is important to observe that approximately 63% of the amount of water present in the mango samples had been evaporated before the application of the first vacuum pulse. Considering the entire process, convective drying (helped by conduction and radiation) was responsible for approximately 80% of water evaporation.

For banana samples, heat transfer during the first two drying cycles was only via conduction and radiation because there was no air flow through the container. In this way, the samples were heated quickly because of the lower water evaporation during this step. After the second drying cycle, the samples were heated by conduction, radiation and convection, resulting in higher moisture loss between the second and third vacuum pulses, as shown in Fig. 5. The high drying rate at this stage happened because the samples had high content of heated, free water. For mango samples, approximately 63% of the water present in the samples was evaporated by the hot air injected into the container before application of the first vacuum pulse. Convective drying was responsible for approximately 80% of total drying of mango samples.

For the same pressure drop applied at each vacuum pulse, Figs. 5a and 6a showed that the sample temperature drop decreased with each successive pulse, which reduced the relative importance of flash evaporation on the dehydration process. This effect could be estimated using the simulated dehydration curve and considering only the flash evaporation at each vacuum pulse calculated from only the experimental temperature drops. One could attribute this behavior to the reduction in free water in the samples and to the reduction of heat capacity because the specific heats are strongly dependent on the moisture content (Eq. (2)). However, the CMFD process was designed to produce texture during dehydration, which justifies the application of vacuum pulses until the product reached the desired moisture and texture. After twelve cycles of CMFD (approximately 135 min of processing), banana samples reached a moisture content of 0.29 ± 0.01 g/g (d.b.). Samples of mango reached 0.08 ± 0.01 g/g (d.b.) after twelve cycles over approximately 210 min of processing. In both cases, very crispy dehydrated fruits were obtained.

At the end of the process, the water activities in the dehydrated fruits were 0.276 ± 0.015 and 0.374 ± 0.05 for banana and mango, respectively. Intermediate-moisture foods have a water activity

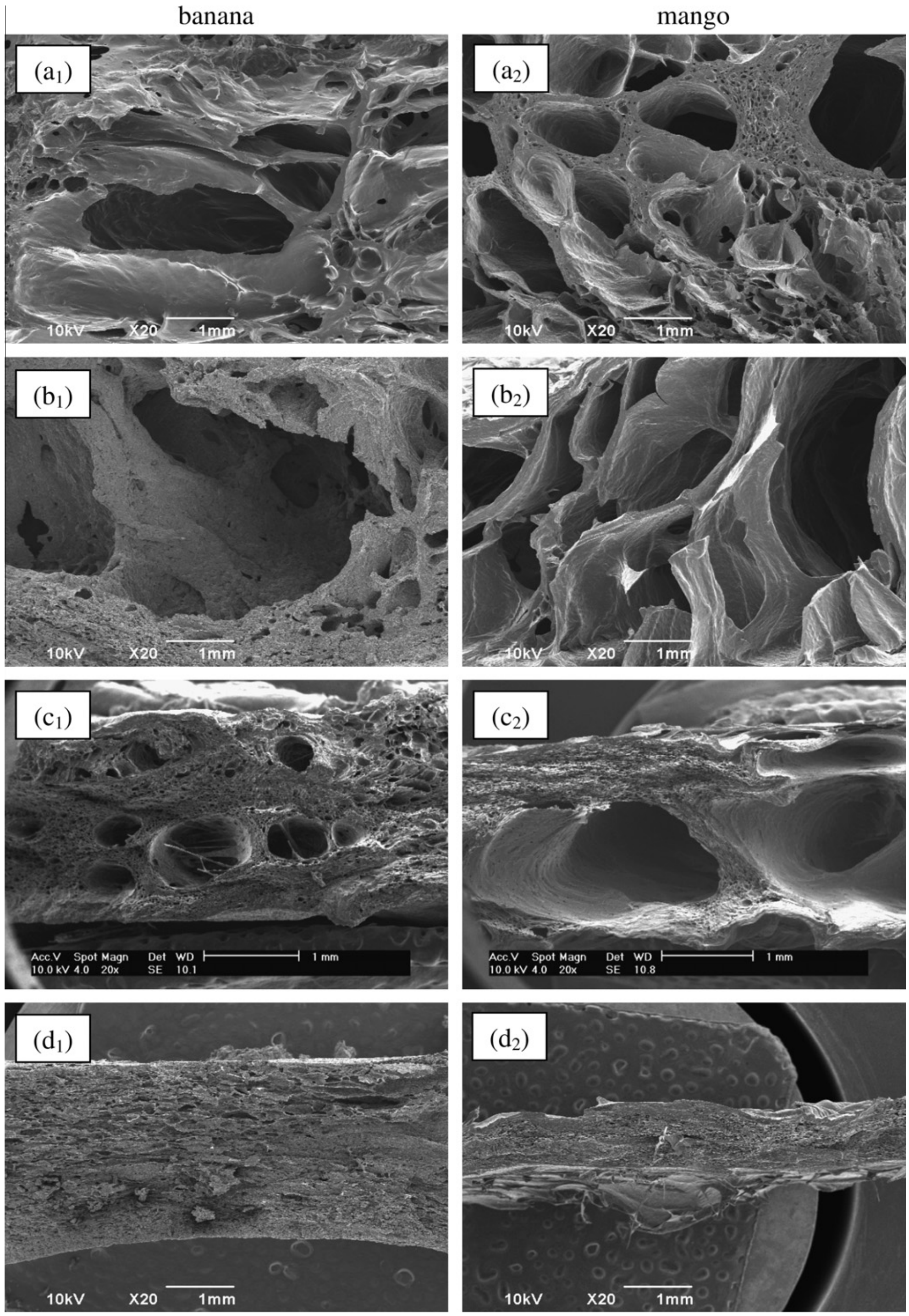

Fig. 9. SEM micrographs: (a_1) freeze-dried banana (magnification of 20×); (a_2) freeze-dried mango (20×); (b_1) banana dehydrated by CMFD (20×); (b_2) mango dehydrated by CMFD (20×); (c_1) banana dehydrated by vacuum drying (20×); (c_2) mango dehydrated by vacuum drying (20×); (d_1) banana dehydrated by convective drying (20×); (d_2) mango dehydrated by convective drying.

between 0.65 and 0.85–0.90 (Chirife and Buera, 1994; Fellows, 2000); thus, one can conclude that the twelve cycles of CMFD led to very low water-activity foods. Figs. 5c and 6c show that, by the 3rd pulse, both fruits had obtained water activity values corresponding to intermediate-moisture foods.

3.2. Comparison of drying curves from different processes

Drying curves for banana and mango dried with different processes are presented in Fig. 7. To allow for comparison of the curves, convective drying and vacuum drying were performed at 60 °C because that was the maximum temperature of the CMFD process. The characteristic drying time observed for the CMFD process, for both fruits, is about half the time required by the vacuum drying process and much shorter than the drying time observed for drying by hot air. CMFD is a very efficient dehydration technique for two main reasons: (i) during flash evaporation, part of the internal moisture is pulled to the fruit surface, which improves the efficiency of the convective drying step (see Fig. 8), and (ii) after flash evaporation (which is also a vacuum cooling process), the fruit temperature drops to 15–20 °C (a pressure of approximately 1.5 kPa), which creates a large temperature difference between hot air (70 °C) and cooled fruit and leads to improved heat transfer to the product. These effects are not present in vacuum drying, which is a constant-temperature process, or in convective drying, which is a process in which the product temperature increases during the drying process, reducing the heat transfer efficiency. Because of these differences, the CMFD process produced much higher drying rates.

3.3. Scanning electron microscopy of dehydrated fruits

Fig. 9 presents micrographs of fractured sections of dehydrated fruits. The micrographs of bananas are presented on the left, and the micrographs of mangoes are the shown on the right. These fruits have been dehydrated by: (a_1 and a_2) freeze-drying, (b_1 and b_2) CMFD process, (c_1 and c_2) vacuum drying and (d_1 and d_2) hot air. Despite the differences between the dehydration mechanisms of CMFD and freeze-drying, the structures of the final products are similar with respect to the presence of many pores, although the pores in the products obtained by CMFD are larger and heterogeneous. Louka and Allaf (2002) reported that potatoes submitted to the DIC process showed a non-homogeneous porous structure. In the freeze-drying process, the quick-freezing step protects the food structure and shape and results in minimal volume reduction (Ratti, 2001). Freeze-drying tends to preserve the product structure, whereas the CMFD process tends to expand it. Despite a global shrinking of approximately 15% (estimated from all sample dimensions), the thicknesses of banana and mango dehydrated by the CMFD process increased approximately 5% and 7%, respectively. The micrographs of vacuum-dried and air-dried samples (Fig. 9c_1, d_1 c_2, and d_2) showed that the air drying and vacuum drying caused collapse of the fruit structure, with a global shrinking of approximately 40–45% (thicknesses reductions of approximately 17% for banana and 23% for mango), despite the presence of pores that are larger than those in air-dried samples (Fig. 9d_1 and d_2). The reduction in the sample volumes is a result of large gradients in moisture within the product that induced microstructural stresses, collapsing most of the capillaries and causing irreversible structures changes (Mujumdar, 2007; Panyawong and Devahastin, 2007).

3.4. Mechanical tests

Texture is important to the acceptability of foodstuffs, and it is important to develop instrumental methods capable of quickly quantifying texture properties that can be correlated with product sensory properties (Peleg, 2006). Results of mechanical puncture tests performed with samples of banana and mango dehydrated by CMFD, lyophilized and dried by air at 60 °C are presented in

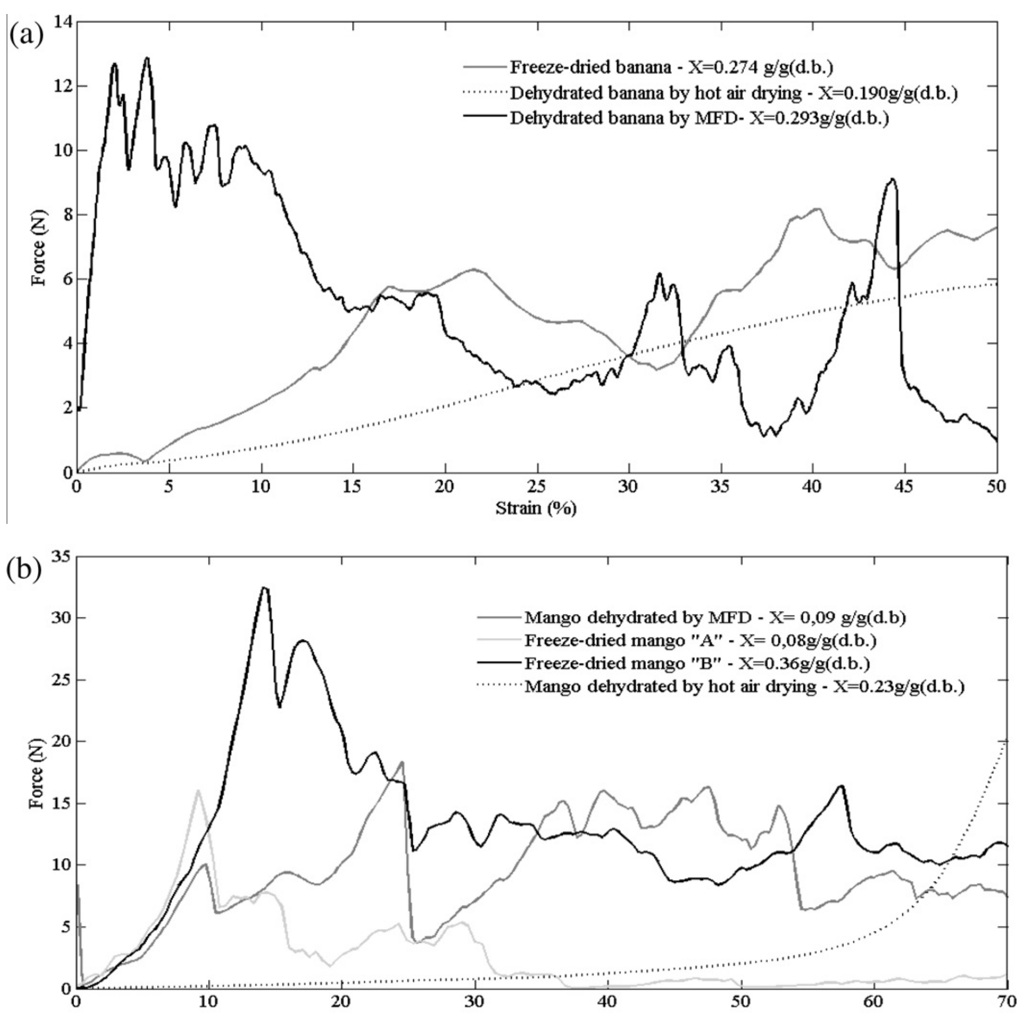

Fig. 10. Strain–force curves of fruits dehydrated by CMFD, freeze-drying and hot air drying (temperature 60 °C, relative humidity 12% and velocity of air 1 m/s): (a) banana, (b) mango.

Fig. 10a and b. In both figures, the force–strain curves of samples of banana and mango dried by CMFD and samples of commercial freeze-dried fruits showed similar patterns, i.e., irregular curves. These results are characteristic of crunchy foods and are associated with their brittle structure (Dijksterhuis et al., 2007; Laurindo and Peleg, 2007, 2008). The similar pattern of puncture test results found for freeze-dried fruits and fruits dehydrated with the CMFD are consistent with the microstructures of dehydrated products, as showed in the SEM micrographs.

In spite of their moisture contents being similar to the freeze-dried commercial samples (brand B), samples of mango dehydrated by convective drying had a force–deformation curve without peaks, which is a result of the collapse of its structure (shrinkage) during drying (Dijksterhuis et al., 2007).

4. Conclusions

The multi-flash drying technology allowed the production of dehydrated fruits with moisture content, water activity and mechanical properties similar to those observed for commercial freeze-dried fruits. Bananas and mangoes processed by CMFD are at least as crispy as the freeze-dried fruits. Additionally, product color is preserved due to the use of moderate temperatures. It is notable that the CMFD process is a very efficient dehydration technique that can be completed in shorter times (3–4 h) and probably at lower costs than freeze-drying. CMFD is a very efficient dehydration technique for two main reasons: (i) during flash evaporation, part of the internal moisture is pulled to the fruit surface, which improves convective drying during the heating step and (ii) after flash evaporation, the fruit temperature drops to 15–20 °C, which leads to a large temperature difference between the hot air and cooled fruit and to improved heat transfer to the product. Moreover, the equipment and process are simpler, use low pressures and temperatures, have smaller capital costs and require less energy than freeze-drying.

Acknowledgment

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