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Assessment of texture and storage conditions of mangoes slices dried by a conductive multi-flash process

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ABSTRACT

Glass transition temperature (T_g) and sorption isotherms can be used to establish state diagrams that help to assess storage conditions to keep the food as an amorphous material in a glassy state. In this study, state diagrams and mechanical properties were assessed to predict the storage conditions of mangoes dried by 1) air-drying; 2) freeze-drying; 3) vacuum-drying and 4) conductive multi-flash drying (KMFD - four cycles of heating/vacuum pulse followed by vacuum-drying). Dried mangoes showed a typical sorption isotherm behavior of hygroscopic materials. In the relative humidity (RH) range investigated (between 11.3% and 90.3%), T_g of processed samples decreased from 44 °C to −68 °C, due to the plasticizing effect of water. Dried mangoes stayed structurally stable at room temperature (25 °C) if storage RH was kept at 25%, in this conditions the moisture content was 0.036 g g $^{-1}$ (d.b.). The puncture tests results confirmed that, at room temperature, samples stored at RH higher than 30% lost their crispness.

1. Introduction

The high consumption of mangoes has been associated with their attractive taste and health benefits. Mangoes have a high content of carotenoids, vitamins, and phenolic compounds. These fruits can be processed into many different products, e.g. juices, purees, jams, canned slices, fruit bars, and dehydrated products. However, only 0.22% of world mangoes production is processed (Yahia, 2011).

Fruit processing allows the development of new products, with increased shelf life. In this context, drying processes can be used to the development of mango snacks, with attractive sensorial properties, added value, and a convenience based on its preservation at ambient temperature. If suitable time-temperature binomial is carefully chosen during drying, the nutritional properties may be preserved. The literature presents different drying processes to produce crisp snacks of fruits and vegetables, with affordable operating costs. Drying processes such as HTST (high-temperature short-time) (Hofsetz et al., 2007), explosion puffing drying (Zou et al., 2013), instant controlled pressure drop (DIC) (Louka and Allaf, 2002), multi-flash drying (MFD) (Laurindo et al., 2011; Zotarelli et al., 2012; Porciuncula et al., 2016; Monteiro et al., 2016; Link et al., 2017, 2018) were reported as suitable to produce high quality dried fruits and vegetables.

Conductive multi-flash drying (KMFD) is a process developed for simultaneous food dehydration and texturization. This process is based on multiple cycles of heating and vacuum pulses. The heating step is carried out at atmospheric pressure by conduction (by contact with a hot surface) until a desired temperature (commonly 60 °C), then a vacuum pulse (a sudden pressure reduction) is applied causing water flash and cooling down the food. Thus, atmospheric pressure is reestablished and further heating-vacuum pulse cycles are applied to reach the ideal moisture content and/or the desired textural characteristics of the dehydrated product (Zotarelli et al., 2012; Porciuncula et al., 2016; Link et al., 2018).

The relative humidity (RH) and temperature of the storage atmosphere play an important role in the physical-chemical stability of dehydrated fruits. Changes in the moisture content of dried mangoes are related to the modification of thermal and physical-chemical properties, such as volume, pigments oxidation and glass transition temperature (*Tg*) (Vásquez et al., 2013). The water adsorbed acts as a plasticizer, increasing the mobility of the polymer chains that change the physical state of the food matrix. These changes can modify the sorption capacity and produce changes in the visual and thermophysical properties of the dried food (Vásquez et al., 2013).

To predict the stability of a dehydrated food and to assess the moisture content changes during storage, moisture sorption isotherms must be determined (Bazardeh and Esmaiili, 2014). For a specific food, the glass transition temperature (*Tg*) is mainly a function of its moisture content. As a dehydrated food undergoes a glass transition when its

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moisture increases, changes in its texture from a brittle-and-glassy state to a rubbery state, with increased viscous component (Roos, 1995). The relationship between water activity and glass transition temperature is important to understand the stability of a food structure. The use of a state diagram based on both, the Gordon-Taylor and GAB (Guggenheim, Anderson, De Boer) sorption models has been reported as a useful tool for assessing the structural stability of dehydrated fruits (Vásquez et al., 2013; Bazardeh and Esmaiili, 2014).

One of the food quality parameters mostly influenced by the moisture sorption and by the T_g is the texture, particularly for crispy-and-dried products. Moisture sorption during storage may result in loss of crispness, due to the plasticizing effect of water. Moisture increases the material viscous component that induces a transition from a glassy to a rubbery material. If the food crispness is an important quality parameter, water gain must be avoided during storage. The aim of this study was to determine the adequate storage conditions of dried-and-crisp mangoes produced by different drying methods (conductive multi-flash drying (KMFD), air-drying, vacuum-drying and freeze-drying). State diagrams using sorption isotherm and the variation of a_w with T_g are used for this purpose.

2. Materials and methods

2.1. Samples preparation

Mangoes (*Mangífera indica* L., Tommy Atkins variety) were purchased in a local market (Florianopolis, Brazil - 27°35′48″ S, 48°32′57″ W). Fruit samples were selected from their visual appearance and state of ripeness, evaluated from their soluble solids content (using a digital refractometer, AR200, Reichert, USA) and resistance to penetration (using a penetrometer, FT 327, Ø = 8 mm, Effegi, Italy). Selected mangoes (soluble solid content of 13.9 ± 0.7 °Brix and penetration resistance of 4.9 ± 1.9 N) were washed, peeled and sliced in the direction parallel to their fibers to a thickness of 5 mm.

2.2. Drying experiments

After slicing, mangoes were submitted to different drying processes: air-drying (AD), freeze-drying (FD), vacuum drying (VD) and conductive multi-flash drying (KMFD). Fig. 1 shows the schematic of the experimental procedure performed in this study.

Air drying was performed in a convection oven (TE 394/2, TECNAL, Piracicaba, Brazil) at 60 °C. During the drying process, the relative humidity was 23.1 ± 0.8%, measured with a hygrometer (ThermoHygrometer, TESTO610, Germany), while the air velocity was approximately 0.9 m s^{-1}, measured with a portable anemometer (Anemometer TESTO 425, Germany).

Freeze-drying was performed using a lab-scale freeze dryer (Liotop, Model - L101, São Carlos-SP, Brazil) that operates at a pressure of 20 ± 5 Pa. Before freeze-drying, samples were frozen at −60 ± 1 °C.

Vacuum drying was performed in a vacuum oven (440-DE, Ethik Technology, São Paulo, Brazil) at 60 °C and 3.5 kPa.

Conductive multi-flash drying (KMFD) was performed, as described by Link et al. (2017). Mango slices were distributed, in a vacuum drying oven (440-DE, Ethik Technology, São Paulo, Brazil), on plates heated by electrical resistances (90 °C), controlled with a PID (proportional–integral–derivative) system. The temperature of the mango slices was monitored with T-type thermocouples (TF-TX-A-TF-R30AWG, Iope, São Paulo, Brazil) inserted into the center of five samples at different locations in the chamber, and connected to an acquisition data system (34970A, Agilent Technologies, USA). The pressure of the chamber was monitored with a digital manometer (IT-MN-DG, Velki, Itu, Brazil) during the whole drying process. Mango slices were heated at atmospheric pressure up to 60 °C before applying a vacuum pulse. For that, the pressure of the vacuum chamber was sudden reduced to 3.5 kPa, and maintained at this level for 5 min, before restoring the atmospheric pressure to start a new heating-vacuum pulse cycle. Four heating-vacuum pulse cycles were applied, and the drying process was completed by regular vacuum drying, for 105 min at 3.5 kPa.

Moisture content and water activity were determined during drying from samples removed from the dryers at different times, and at the end of the drying process. Moisture content was determined by the gravimetric method, using a vacuum oven at 70 °C (AOAC, 2005), while water activity (a_w) was determined with a hygrometer (Aqualab Model Series 3, Decagon Devices Inc., Pullman, USA).

2.3. Analytical determinations

2.3.1. Moisture sorption isotherms

Moisture sorption isotherms were determined by the static gravimetric method (Greenspan, 1977). Mango samples, dehydrated by the different drying methods (AD, FD, VD, and KMFD), were freeze-dried for 24 h (to remove the residual moisture), weighed in plastic capsules (approximately 0.6 g) and placed in air-tight containers and equilibrated to the atmospheres created with nine saturated salt solutions at 25 °C (RH of 11.3%; 22.5%; 32.7%; 43.8%; 52.9%; 64.3%; 75.3%; 84.3% and 90.3%).

Capsules containing the samples were weighed in an analytical balance (Shimadzu, Model - AY220, Philippines) at regular time intervals until equilibrium (approximately 10 weeks). After equilibration, the samples moistures were determined in a vacuum oven (TE-395, TECNAL, Piracicaba, Brazil) at 70 °C (AOAC, 2005).

The GAB (Guggenheim-Anderson-de Boer) model (Equation (1)) was fitted to the experimental sorption isotherm data of dehydrated mango samples.

$$X_{eq} = \frac{(C-1)Ka_wX_m}{1+(C-1)Ka_w} + \frac{Ka_wX_m}{1-Ka_w} \tag{1}$$

in which X_{eq} is the equilibrium moisture content (dry basis, d.b.), X_m is the moisture (d.b.) adsorbed at the monolayer, C is the Guggenheim constant (which can be related to the total heat of sorption in the first layer), and K it is a constant related to the multilayers sorption heat.

The parameters of the GAB equation were estimated using non-linear regression, using the least squares method with MATLAB (R2010a). The goodness of fit of the models was assessed by the adjusted coefficient of determination (R^2_{adj}) and the root mean square error (RMSE).

2.3.2. Glass transition temperature

After reaching the equilibrium at different relative humidities at 25 °C, mango samples were submitted to differential scanning calorimetric analysis, to determine the glass transition temperatures. For that, mango samples equilibrated at different relative humidities were placed in sealed aluminum capsules (volume of 40 μL) and subjected to differential scanning calorimetric analysis (DSC) (Perkin Elmer, model DSC Jade, Waltham, USA). The equipment calibration was carried out with indium (T_{fusion} = 156.6 °C) and zinc (T_{fusion} = 419.5 °C) using a constant flow rate of nitrogen (25 mL min^{-1}).

In DSC analyses, samples were cooled to −70 °C and then heated up to 120 °C at a constant heating rate (10 °C.min^{-1}). The analyses were performed in duplicate and the data were analyzed using the Pyris software (Perkin Elmer, Waltham, USA). The plasticizing effect of water on the glass transition temperature was described using the Gordon-Taylor model (Gordon and Taylor, 1952), Equation (2).

$$T_g = \frac{w_sT_{gs} + kw_wT_{gw}}{w_s + kw_w} \tag{2}$$

in which T_g, T_{gs}, T_{gw} are the glass transition temperatures of the mixture, solid and water (°C), respectively; w_w and w_s are the mass fractions of solids and water in the mixture (wb); and k is the constant of the Gordon-Taylor model. The water glass transition temperature, T_{gw}, was