Development of dehydrated products from peach palm–tucupi blends with edible film characteristics using refractive window

Rebeca Desireé Sousa da Costa¹ · Antonio Manoel da Cruz Rodrigues¹ ·
João Borges Laurindo² · Luiza Helena Meller da Silva¹

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Abstract This study aimed to obtain a dehydrated product with film characteristics with superior functional and technological quality, prepared from different varieties of peach palm (*Bactris gasipaes*) using the refractance window drying (RW) process. The experiments were carried out at 70 °C and drying was fully performed at an increasing rate. The physicochemical characteristics and mechanical, technological, and morphological properties were determined and the moisture and water activity curves of the different peach palm varieties were assessed. The dehydrated product by refractance window have good visual appearance and bright yellowish color due to the carotenoid content found in the samples used as raw material. All dehydrated products had non-homogenous microstructure, however, the products had low tensile strength, percent elongation, hygroscopicity, and water absorption and solubility, desired properties to obtain a food product. The presence of components such as proteins, lipids, and fibers had important effects on the mechanical properties of the products because the mechanical resistance of the biopolymers is influenced by the cohesion of the constituents of the polymer matrix. The production of a dehydrated product with film characteristics through the RW technique presented some advantages over conventional casting drying as such as short drying

times, lower costs and without addition of plasticizers or non-food grade components. In general, the products dehydrated by RW are promising and can be consumed immediately after production as snacks or in the substitution of other ingredients, such as algae in sushi.

Keywords Refractance window · Film · *Bactris gasipaes* · Tucupi · Technological properties

Introduction

Edible films are defined as a thin layer, consisting of natural polymers, used to partially or completely replace synthetic polymers. Films have achieved considerable importance due to their use as food coatings or as a barrier between food and the surrounding environment, avoiding losses of moisture and aromas, as well as due to their environmental benefits (Bakshi et al. 2010). In addition, they can be used as a film-forming medication when high antimicrobial activity against pathogens microorganisms or infections is required (Bakshi et al. 2010).

Polysaccharides (starch, pectin, cellulose, alginate, and carrageenan), proteins (gelatin, casein, wheat gluten, and zein) and lipids (stearic acid, waxes, and fatty acid esters), or the combination of these compounds, are the main materials used for the preparation of edible films (Bakshi et al. 2011). Starch is the most widely used polysaccharide in the manufacture of edible films because of its low cost, relatively easy handling, fully biodegradability, and availability in large quantities from various plant sources such as cereals, roots and, tubers (Kaur et al. 2013; Pelissari et al. 2013; Andrade et al. 2016; Dehghani et al. 2018).

Film information is limited in films for packaging or food coatings. Whereas several studies have determined the

✉ Luiza Helena Meller da Silva
lheller@ufpa.br

¹ Graduate Program in Food Science and Technology,
Laboratory of Physical Measurements, Federal University of
Pará, Rua Augusto Corrêa, Guamá, Belém, Pará 66075-900,
Brazil

² Department of Chemical Engineering and Food Engineering,
Technology Center, Federal University of Santa Catarina,
Florianópolis, SC 88040-901, Brazil

effects of film formulations on the properties of the resulting materials, few have focused on obtaining a product that could be consumed immediately (Bakshi et al. 2011; Kaur et al. 2013; Dehghani et al. 2018).

Biodegradable and edible films are generally prepared via the classical casting technique, where a polymeric solution or suspension is poured on a plate surface such as a Petri plate. This technique does not allow for the preparation of large dimension films and requires long drying times in ovens with air circulating at 40–60 °C (Moraes et al. 2015). The technique of drying by RW allows for the spreading a film-forming suspension on large supports and on continuous carrying belts and allows for the control of the film thickness (suspension thickness) (Moraes et al. 2015). The drying by RW which involves applying a thin layer of the product onto a transparent sheet of thermally stable, heat- and deformation-resistant plastic (Zotarelli et al. 2015). Under the plastic sheet, hot water circulates to transport thermal energy through conduction and convection into the product (Nindo and Tang 2007). The technique of drying by RW to obtain dehydrated products with characteristics similar to the films shows the ability to produce biodegradable films since products resulting from drying can be consumed and do not generate waste.

Refractance window is used to concentrate and dry solutions and pastes that allow obtaining films and flakes at relatively moderate (40–60 °C) or high (70–90 °C) processing temperatures over short drying times at reasonable cost (Nindo et al. 2003), besides good sensory properties and low nutritional losses (Abonyi et al. 2002; Nindo and Tang 2007). For the same drying capacity, an RW device requires 50–70% less capital and 50% less energy than the lyophilization process (Nindo and Tang 2007).

The North region of Brazil features at least three landraces of peach palm (*Bactris gasipaes*) with different fruit sizes, colors, and flavors and nutritional constituents (Clement et al. 2004; Yuyama 2011). The main classification criterion to differentiate the landraces, i.e., microcarpa, mesocarpa, and macrocarpa, is pulp thickness. The microcarpa landrace has small fruits with a relatively large pit compared to the pulp, which is usually fibrous and oily. The fruits of mesocarpa and macrocarpa landraces are progressively larger with more pulp, which contains more starch and less lipids (Mora-urpí et al. 1997). Peach palm fruits are a source of food because of their high nutritional value and high fiber, fat, carotenoid, essential amino acid contents (Clement et al. 2004; Rojas-Gardanzo et al. 2011) and gelatinization temperature similar to that of traditional sources of starch, such as cassava starch and corn (Melo Neto et al. 2017). According to Valencia et al. (2015) and Melo Neto et al. (2017), the amylose content in peach palm starch indicates that this could be used as a raw material for

films and coatings in food products due to their capacity to form films.

Another widely consumed delicacy in the state of Pará is tucupi, a partially fermented liquid condiment obtained from cassava (*Manihot esculenta* Crantz) roots. After being washed, peeled, ground, and pressed, cassava releases a liquid, known as cassava wastewater or *manipueira*, that is stored for 3 days at room temperature (Chisté and Cohen 2011). Over this period, the starch precipitates and is then removed. After the fermentation step, the cassava wastewater is cooked to obtain tucupi. These products easily spoil, which hinders the commercialization *in natura* of the entire production during the harvest season, therefore industrialization represents an important alternative for the remaining volumes (Mora-Urpí et al. 1997; Carvalho et al. 2010).

Thus, given the limited information on films without the addition of reagents and plasticizers, and the importance of peach palm and tucupi in the Brazilian Amazon, this research aimed to study and analyze the RW drying process of three peach palm varieties to create technological alternatives that add value to these products by developing an dehydrated product with film characteristics with superior functional and technological quality.

Materials and methods

Material

The peach palm fruits used in the study were collected from several street markets in the Belém metropolitan area. The fruits were identified according to Mora-Urpí et al. (1997) as microcarpa, mesocarpa, or macrocarpa. Tucupi was purchased from the family agriculture established in the municipality of Acará (Pará, Brazil) (01°57'39" S and 48°11'48" W).

To prepare the blends, the microcarpa, mesocarpa, and macrocarpa peach palm fruits were peeled, cut, added with tucupi, and ground in a bench food processor. In order to ensure the composition of the peach palm/tucupi blends remained constant, the value of 12.5°Brix (AOAC no. 932.12). Figure 1 shows the procedure employed in all drying processes.

Refractance window drying

The device used for the RW drying experiments was built at the Laboratory of Physical Measurements (UFPA) using the principles of commercial equipment, with the difference of working in a batch-feeding regime (Zotarelli et al. 2015).

Fig. 1 Flow chart for obtaining edible films for different peach palm landraces (microcarpa, mesocarpa and macrocarpa, respectively) and tucupi

The experiments using different peach palm and tucupi blends were performed with heating water at 70 ± 1 °C and 0.5 mm spreading thickness. The dehydrated product obtained in the drying process were stored in polyethylene bags and vacuum sealed. These bags remained sealed until the analyses.

The moisture content was determined by following the sample weight at pre-established time intervals (Zotarelli et al. 2015). Each peach palm and tucupi blend was spread onto the Mylar film and, every 5 min., samples were taken from the initial, central, and final portion of the spread. In each sample extraction, approximately 4 g of the blend were taken with the use of a spatula, weighed on an analytical balance (Gehaka, BG 4000), transferred to a crucible, dried in an air-circulation oven at 105 °C (Ethik Technology, 400-2ND 200 °C), and weighed again to determine moisture (AOAC 1997) at each time interval. Water activity was determined in a Decagon AquaLab Series 3TE thermohygrometer with sensitivity of 0.0001.

Methods

Composition: raw materials, blends and dehydrated products

The methods recommended by the AOAC (1997) were adopted to determine the contents of moisture (no. 925.10),

ash (no. 923.03), lipids (no. 926.06), and total proteins (no. 920.87) (with a conversion factor of nitrogen into protein of 6.25). Carbohydrates and caloric value were determined according to Brasil (2003).

Colour parameter

The color parameter was analyzed in a Minolta CR310 colorimeter using the CIELAB system. The values obtained in the colorimeter, i.e., L^* (luminosity), coordinate a^* (red–green component), coordinate b^* (yellow–blue component), C^* (chroma) h° (hue angle), and ΔE (difference in coloration), were assessed according to Eq. (1):

$$\Delta E = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (1)$$

where L_i^* , a_i^* , and b_i^* are the color parameters of the product and L_0^* , a_0^* , and b_0^* are the color parameters of the control sample (peach palm and tucupi blends).

Total carotenoids: raw materials, blends and dehydrated products

Total carotenoids were determined according to the method described by Godoy and Rodriguez-Amaya (1994). 10 g of the sample were weighed (Shimadzu, AY220) and 20 mL

cold acetone were added. The material was vacuum filtered in a Büchner funnel with filter paper containing Celite and the sample was rinsed with acetone until the extract was colorless. The extract obtained was transferred to a 500 mL separatory funnel containing 50 mL of petroleum ether. The acetone was removed through slow addition of water to prevent emulsion formation. The bottom phase was discarded and the procedure was repeated four times to fully remove the acetone. The top extract was transferred to a 250 mL Erlenmeyer flask containing anhydrous sodium sulfate, transferred again to a 250 mL volumetric flask, and the volume was completed with petroleum ether. Reading was performed in a spectrophotometer between 20 and 500 nm using petroleum ether as blank. Carotenoid content was determined by Eq. (2).

$$CT(\mu\text{g/g}) = \frac{A \times V_{(\text{mL})} \times 10^4}{E_{1\text{ cm}}^{1\%} \times m_{(\text{g})}} \quad (2)$$

where V is the volume of the volumetric flask used in the dilution, in mL, A is the absorbance at the highest peak detected, $E_{1\text{ cm}}^{1\%}$ is the extinction coefficient of β -carotene (2592), and m is the sample mass, in g.

Technological and mechanical properties of the dehydrated products

To determine the water absorption index (WAI) in the dry product, 2.5 g of the sample were weighed in a previously tared centrifuge tube (with cap) and 30 mL of water at 25 °C were added. Next, the tubes were agitated for 30 min in a vortex mixer (Cole Parmer, 04726-01) and centrifuged (Thermo Fisher, Multifuge X1R) at 1046 g for 10 min. After centrifugation, a 10 mL aliquot of the supernatant was collected and transferred to a tared porcelain crucible, which was then placed in an oven at 105 °C (Ethik Technology, 400-2ND 200 °C) for 8 h. The tube with the remaining gel was weighed and the WAI was calculated (Anderson et al. 1969) according to Eq. (3):

$$WAI = \frac{CRW \times 100}{SW - ERW} \quad (3)$$

where CRW is the centrifugation residue weight (g), SW is the sample weight (dry basis), and ERW is the evaporation residue weight (g).

The water solubility index (WSI) was determined following the methodology proposed by Anderson et al. (1969), in which the WSI was calculated from the ratio between the ERW and the SW, according to Eq. (4):

$$WSI = \frac{ERW}{SW} \quad (4)$$

Hygroscopicity of the dry product was determined according to the methodology proposed by Cai and Corke

(2000) with some modifications. About 1 g of each sample was placed into an airtight container with a saturated NaCl solution (75.29% relative humidity) at 25 °C and, after a week, the samples were weighed and hygroscopicity was expressed as g of absorbed moisture per 100 g of the sample ($\text{g } 100 \text{ g}^{-1}$).

The mean thickness (mm) required to calculate the cross-sectional area was determined using five measurements taken along the film with a digital micrometer (3103-25, Insize) with ± 0.002 mm precision. The mechanical properties were analyzed according to the methodology proposed by Costa et al. (2015). Tensile strength and percent elongation at break of the films were determined using a texture analyzer (QTS-25, Brookfield) and the software Texture Pro following the standard ASTM D-882 (1980) method. The film samples were cut into pieces 100 mm long and 25 mm wide. The initial distance between the grips and the test speed were set to 50 mm and 2 mm/s, respectively.

Scanning electron microscopy of the dehydrated products

Scanning electron microscopy (SEM) was carried out in a ZEISS (DSM 940 A, Oberkochen, Germany) scanning electron microscope at 80 mA and 5 kV. The samples were fixated to aluminum cylinders with double-sided tape and coated with a gold layer (Bal-Tec SCD 050).

Statistical analysis

The software Statistica 7.0® (Statsoft Inc., 2006, Tulsa, OK, USA) was used for the statistical analyses of the results. All values are expressed as mean $\pm$ standard deviation ($n = 3$) and the results obtained were submitted to analysis of variance (ANOVA) using Tukey's test at 95% significance ($p < 0.05$).

Results and discussion

Composition total carotenoids and color parameters

The composition and color parameters of the samples, before and after the RW drying process are presented in Table 1. RW drying process reduced by approximately 89% the water present in the blends ($11 \text{ g H}_2\text{O} \cdot 100 \text{ g}^{-1}$ dry matter) of different peach palm varieties and tucupi. Higher moisture values ($17 \text{ g H}_2\text{O} \cdot 100 \text{ g}^{-1}$ dry matter) were observed by Caparino et al. (2012), when compared to the present study, for mango powders obtained by the refractance window drying process at $95 \pm 2^\circ \text{C}$ and for other types of dryers (freeze-drying, spray-dryer and drum dryer). However, Topuz et al. (2009) found lower moisture

Table 1 Parameters and properties of peach palm, tucupi, and their blends and edible films

Properties	<i>In natura</i>				Blends		
	Microcarpa	Mesocarpa	Macrocarpa	Tucupi	Microcarpa	Mesocarpa	Macrocarpa
Component (g 100 g ⁻¹ dry base)							
Moisture	50.76 ± 0.23 ^c	52.76 ± 0.14 ^b	50.69 ± 0.14 ^c	96.13 ± 0.01 ^a	75.48 ± 0.33 ^c	79.37 ± 0.12 ^a	78.38 ± 0.17 ^b
Lipids	11.18 ± 0.21 ^a	9.14 ± 0.21 ^b	4.54 ± 0.20 ^c	0.21 ± 0.04 ^d	10.16 ± 0.21 ^a	5.71 ± 0.22 ^b	4.60 ± 0.47 ^c
Proteins	2.83 ± 0.03 ^a	2.54 ± 0.10 ^b	1.91 ± 0.07 ^c	0.31 ± 0.04 ^d	2.57 ± 0.01 ^b	2.87 ± 0.02 ^a	1.98 ± 0.10 ^c
Ash	2.58 ± 0.12 ^{ab}	2.44 ± 0.30 ^b	2.79 ± 0.02 ^a	0.72 ± 0.08 ^d	2.42 ± 0.47 ^a	2.06 ± 0.15 ^b	2.71 ± 0.10 ^a
Carbohydrates	33.96 ± 0.68 ^b	31.57 ± 0.48 ^c	39.52 ± 0.31 ^a	2.62 ± 0.05 ^d	9.37 ± 1.05 ^c	9.99 ± 0.81 ^b	12.33 ± 0.57 ^a
Carotenoids (× 10 ⁻³)	5.70 ± 0.04 ^c	9.56 ± 0.09 ^a	7.98 ± 0.08 ^b	2.30 ± 0.04 ^d	5.43 ± 0.11 ^c	8.45 ± 0.02 ^a	7.47 ± 0.04 ^b
Energy value (kcal)	242.52 ± 1.57 ^a	224.89 ± 2.44 ^b	208.77 ± 2.75 ^b	13.65 ± 0.49 ^c	138.62 ± 0.82 ^a	113.48 ± 1.26 ^b	90.30 ± 1.30 ^b
Color parameters							
<i>L</i> *	72.93 ± 0.55 ^c	82.97 ± 0.79 ^b	88.76 ± 0.55 ^a	30.62 ± 0.70 ^d	80.06 ± 0.05 ^a	60.70 ± 0.53 ^c	79.22 ± 0.11 ^b
<i>a</i> *	+13.58 ± 0.05 ^a	- 4.07 ± 0.22 ^b	- 5.35 ± 0.10 ^c	- 5.19 ± 0.26 ^c	- 4.15 ± 0.05 ^b	+ 14.77 ± 0.02 ^a	- 12.21 ± 0.15 ^c
<i>b</i> *	+ 66.74 ± 0.40 ^a	+ 34.89 ± 0.59 ^b	+ 20.33 ± 0.86 ^c	+ 9.03 ± 0.38 ^d	+ 32.81 ± 0.06 ^b	+ 44.94 ± 0.07 ^c	+ 43.89 ± 0.34 ^a
<i>C</i>	10.57 ± 0.06 ^a	4.70 ± 0.10 ^b	2.43 ± 0.12 ^c	10.42 ± 0.45 ^a	35.98 ± 0.05 ^b	28.12 ± 0.11 ^c	45.56 ± 0.35 ^a
<i>H</i> ^o	78.50 ± 0.11 ^d	96.65 ± 0.45 ^c	104.67 ± 0.79 ^b	119.90 ± 0.35 ^a	105.55 ± 0.12 ^b	98.48 ± 0.12 ^c	114.23 ± 0.06 ^a
ΔE	-	-	-	-	-	-	-
Mechanical and technological properties							
HG (g H ₂ O absorbed/100 g dry matter)	-	-	-	-	-	-	-
WAI (g H ₂ O/g dry matter)	-	-	-	-	-	-	-
WSI (%)	-	-	-	-	-	-	-
Thickness (mm)	-	-	-	-	-	-	-
Tensile strength (10 ⁻² MPa)	-	-	-	-	-	-	-
Elongation at break (%)	-	-	-	-	-	-	-
Properties	Films				Mesocarpa		
					Microcarpa	Macrocarpa	
Component (g 100 g ⁻¹ dry base)							
Moisture					7.84 ± 0.12 ^b	8.44 ± 0.26 ^b	6.44 ± 0.26 ^c
Lipids					10.23 ± 0.41 ^b	8.39 ± 0.29 ^c	4.50 ± 0.33 ^d
Proteins					2.23 ± 0.04 ^a	2.11 ± 0.07 ^b	1.96 ± 0.21 ^b
Ash					1.79 ± 0.20 ^a	1.76 ± 0.11 ^a	1.73 ± 0.10 ^a
Carbohydrates					77.91 ± 0.51 ^a	78.80 ± 0.64 ^a	85.33 ± 0.33 ^a
Carotenoids (× 10 ⁻³)					5.00 ± 0.16 ^c	7.70 ± 0.03 ^a	6.51 ± 0.04 ^b
Energy value (kcal)					417.13 ± 1.85 ^a	410.66 ± 0.62 ^b	406.91 ± 1.95 ^c

Table 1 continued

Properties	Films		
	Microcarpa	Mesocarpa	Macrocarpa
Color parameters			
L^*	69.26 ± 0.26 ^a	56.33 ± 0.58 ^b	51.73 ± 0.27 ^c
a^*	− 10.43 ± 0.02 ^b	+ 3.20 ± 0.06 ^a	− 19.87 ± 0.04 ^c
b^*	+ 36.84 ± 0.37 ^b	+ 18.69 ± 0.03 ^c	+ 43.76 ± 0.21 ^a
C	36.87 ± 0.36 ^b	18.96 ± 0.04 ^c	48.06 ± 0.18 ^a
H°	92.17 ± 0.11 ^b	80.28 ± 0.17 ^c	135.26 ± 1.48 ^a
ΔE	11.30 ± 0.68 ^c	21.15 ± 0.49 ^a	15.38 ± 0.06 ^b
Mechanical and technological properties			
HG (g H ₂ O absorbed/100 g dry matter)	7.32 ± 0.41 ^b	8.73 ± 0.15 ^a	8.94 ± 0.57 ^a
WAI (g H ₂ O/g dry matter)	5.01 ± 0.02 ^b	5.28 ± 0.01 ^a	5.20 ± 0.02 ^a
WSI (%)	3.15 ± 0.65 ^b	7.54 ± 0.02 ^a	7.28 ± 0.54 ^a
Thickness (mm)	0.21 ± 0.05 ^a	0.20 ± 0.03 ^a	0.21 ± 0.04 ^a
Tensile strength (10 ^{−2} MPa)	8.19 ± 0.03 ^a	7.86 ± 0.03 ^a	6.32 ± 0.04 ^a
Elongation at break (%)	7.04 ± 2.00 ^a	4.76 ± 1.97 ^a	6.60 ± 0.94 ^a

Mean values (mean ± standard deviation), n = 3

HG hygroscopicity, WAI water absorption index, WSI water solubility index

Different letters in the same column indicate significant difference ($p < 0.05$)

values ($4.76 \text{ g H}_2\text{O} \cdot 100 \text{ g}^{-1}$ dry matter) when studying the RW drying of paprika (*Capsicum annuum* L.).

The RW drying process reduced 7.9, 8.9 and 11.5% of total carotenoids of micro, meso and macrocarpa dehydrated products when compared to their blends. Behavior that can also be observed by Abonyi et al. (2002) the β -carotene content in carrots, after drying by refractance window, was reduced by only 9.9% when compared with the values of β -carotene for in natura carrots. Within a drying process, the cumulative time–temperature effect determines the total loss of carotene. According to Rodriguez-Amaya (2001), carotenoids are relatively stable to heat processing, but high temperatures may cause changes in their chemical structures.

The dehydrated product had lower luminosity (Table 1) compared to the standard sample (blends) likely due to the temperature and extended exposure times during the drying process. However, for the microcarpa dehydrated product the dimming reaction was smaller, providing a better color to the films. Studies on color parameters are extremely important, since the first contact of the consumer with a product is through visual presentation, where color and appearance stand out (Ferreira et al. 2000).

Since yellow colour was the dominant color in peach palm pulp, parameter b^* on the Hunter scale was appropriate to distinguish changes in color caused by the drying process. However, according to Abonyi et al. (2002) the degradation of carotenes during drying will inevitably alter the color perception of dry products. Values of b^* were mostly caused by the presence of carotenoids with yellow hue since these were the main pigments found in peach palm (Roja-Gardanzo et al. 2011).

The values of a^* were negative and far from zero for all dehydrated products, indicating the presence of characteristic red tones. According to Pelissari et al. (2013), the yellowish color of flour-based films may be related to the presence of proteins in the polymer matrix. According to Caparino et al. (2012) the high values of b^* found for the samples of dried mangoes by refractance window can be indicative of retention of β -carotene. Wagner and Warthesen (1995) also reported that the yellow and red color of the carrot slices may be attributed to the presence of carotenoids. The values obtained show the drying process caused no significant changes in the product characteristics, showing variations in ΔE similar to those reported by some authors, such as Nindo et al. (2003) and Ocoró-Zamora and Ayala-Aponte (2013), when studying RW drying of asparagus paste and papaya, respectively.

Technological and mechanical properties

The experimental data of the mechanical and technological properties of the product are described in Table 1. The

peach palm samples used showed potential for the formation of edible films by RW. The resulting films have homogeneous thickness, with no significant difference among them, i.e., the values reached in the study are the result of strict control of the blends applied onto the Mylar film. The type of formulation did not affect this characteristic of the films since the percentage of solids was kept constant in the different formulations, leading to the addition of the same amount of solids to the RW dryer.

The films have good visual appearance with bright yellowish coloration, which, according to Andrade et al. (2016), was likely due to the content of carotenoids found in peach palm, used as raw material (Table 1).

Dehydrated products hygroscopicity (HG) (Table 1) ranged from 7.32 to $8.94 \text{ g H}_2\text{O absorbed} \cdot 100 \text{ g}^{-1}$ dry matter. The hygroscopicity value of the dehydrated product prepared with microcarpa peach palm was significantly lower (Tukey's test, $p < 0.05$) than the others. According to Tontul et al. (2018), hygroscopicity may be related to the porosity of the product or to the vitreous state of the sugars present. Therefore, the low values of HG may be associated to the porosity of the macrocarpa film, a behavior that be observed through scanning electron micrographs, where the films presented a more open structure and nonhomogeneous surface (Fig. 2).

The hygroscopicity values were lower than those obtained by Caparino et al. (2012) when studying the effect of different drying methods on the physical and microstructural properties of mango (Philippine 'Carabao' var.) when stored at 75% relative humidity. The hygroscopicity of a food was linked to its physical, chemical, and microbiological stability and, therefore, it was important to know the hygroscopic behavior of such products.

The water solubility of the microcarpa dehydrated products was relatively low in comparison with the other films (Table 1). This specific structure was associated with the composition of peach palm and with the film formation technique employed in this study. According to Pelissari et al. (2013), these results were consequence of the high level of cohesion within the matrix, which results in a compact structure.

The mesocarpa and macrocarpa dehydrated products had low WAI (water absorption index) values, which suggests that water binds poorly with the film. Another component that may have influenced the low WAI values was the lipid content as absorption reflects the water absorption and retention capacity and depends on the exposure of hydrophilic and/or hydrophobic groups of the molecules of a specific sample (Debeaufort et al. 2000; Yang and Paulson 2000; Andrade et al. 2016).

Several authors have compared the solubility of starch-based films from other botanical sources and observed this property is associated with the type of raw material used to

Fig. 2 Scanning electron micrographs of different peach palm films: **a** microcarpa **b** mesocarpa and **c** macrocarpa at $\times 2.00$ k and $\times 5.00$ k magnification, respectively

form the polymer matrix, the type of interactions that occur in the matrix, the use of plasticizers, and the processing conditions, among other factors. The desired solubility value of a film will depend on its application or intended use. Thus, the peach palm films may act as protection of foods with high water activity or may prevent exudation of fresh or frozen products (Pelissari et al. 2013).

No significant difference was found regarding the tensile strength or percent elongation at break of the dehydrated products, which can be justified by the high starch content (approximately $35\text{--}54\text{ g starch}\cdot 100\text{ g}^{-1}$ peach palm) found

in peach palm and the low moisture of the films (Table 1), since moisture plays an important plasticizer role by reducing the mechanical strength and increasing the flexibility of biopolymer films (Delville et al. 2002; Godbillot et al. 2006).

Microcarpa, mesocarpa, and macrocarpa dehydrated products had lower values of tensile strength than those found by Pelissari et al. (2013) for films made with banana flour, indicating that the peach palm films are more flexible. These results confirm that the protein and lipid contents (Table 1) in the peach palm films may contribute to

Fig. 3 Moisture and water activity curves during the refractance window drying process of different blends of peach palm varieties and tucupi at 70 °C. (Circle) microcarpa, (square) mesocarpa, and (diamond), macrocarpa

the plasticizer effect and that protein does not contribute to the formation of a stronger mesh in this case.

Morphological properties

SEM images are presented in Fig. 2 and the morphology of the external surfaces of the dehydrated products was assessed. The microstructure of all dehydrated products was non-homogenous, i.e., a less smooth surface with imperfections. According to Pelissari et al. (2013), the unevenness of peach palm dehydrated products may be related to the presence of more than one macromolecule in the polymer matrix (starch, proteins, lipids, and fibers), as well as the interaction among those components, such as protein–starch, starch–cellulose (fibers), and the more stable complexes such as amylose–lipids. Although the protein and lipid contents are lower than 5% (Table 1), they play an important role in the final structure of films. Some particles of different shapes and sizes can also be observed, such as non-gellified or partially gellified starch granules. An analysis of the SEM images shows the internal structure of these starch granules change. However, even after drying at 70 °C, some starch granules can still be observed, which suggests they are resistant to the temperature applied.

Moisture and water activity curves

The initial moisture contents of the blends were 2.49, 2.56, and 3.27 g water·g⁻¹ dry solid for the microcarpa, mesocarpa, and macrocarpa peach palm varieties, respectively (Fig. 3). This moisture content quickly decreased. The mesocarpa and microcarpa samples reached 0.04 and

0.07 g water·g⁻¹ dry solid, whereas the macrocarpa blend reached 0.12 g water·g⁻¹ dry solids, respectively, within 1800s. The moisture content of the different samples was constant during drying. This behavior can be explained by the high initial moisture value of the blends (79%, wet basis) and their small thicknesses (0.5 mm). According to Zotarelli et al. (2015), water vapor pressure on the sample surface is close to the saturation pressure during the drying process and the internal resistance to mass transfer is insignificant (due to the small thickness). If the external conditions do not impact the drying rate (convection drying is insignificant), it can be stated that the RW drying process occurs through classical evaporation and is controlled by heat transfer from the circulating water. Similar results were observed during RW drying of mango (Ochoa-Martínez et al. 2012).

The mean initial water activity was 0.92 and, by the end of the RW drying process, the value was approximately 0.25. It can be seen that the different peach palm varieties did not significantly impact the water activity values. These results indicate restriction to the growth of pathogenic microorganisms such as fungi, yeasts, and bacteria, which is characteristic of highly shelf-stable foods (Labuza and Ball, 2000).

Conclusion

The results found in the present study indicate that the drying process by the RW is a viable alternative for the production of dehydrated products from peach palm and tucupi with superior technological qualities. These products present a good source of carbohydrates, carotenoids retention, in addition to similar characteristics to those films obtained from traditional drying methods. The process of drying by RW did not require the addition of components with plasticizing properties; instead, the components of the raw materials themselves were valued. Like this, the main advantage of the RW process is that the resulting products from drying can be consumed immediately and therefore do not generate waste to the environment. According to the properties found and depending on the characteristics of each variety of peach palm, the product can be applied for the purpose of component separator, as in pizzas, in which the mass has low humidity and the cover has high humidity; replace the algae in sushi; like snacks; to protect food with high water activity; or to prevent the exudation of fresh or frozen products. Therefore, RW allows obtaining films and flakes at relatively low processing temperatures, with reasonable costs.

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