Research Article

Evaluation of water sorption isotherm, glass transistion temperature, vitamin C and color stability of mango peel powder during storage

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Received: 30 November 2020 / Accepted: 19 January 2021 / Published online: 25 January 2021

Abstract
The purpose of this work was to study the physical and chemical stability of the mango peel powder produced by hot-air drying. Sorption isotherms at 25 °C and glass transition temperatures (T_g) of the samples in equilibrium at different a_w were determined. The degradation of vitamin C and color parameter b* was evaluated along storage under controlled conditions (relative humidity = 60%, temperature = 10, 25 and 35 °C) during 180 days. GAB model well-described water adsorption of the product, showing a monolayer moisture content (X_m) of 0.1260 g water/g dry solids and a critical a_w of 0.56. The Gordon-Taylor model predicted the plasticizing effect of water on glass transition temperature, since T_g of the powders kept at different relative humidity conditions decreased as water activity increased. No visual signs of agglomeration and darkening were observed for samples stored at $a_w \leq 0.529$. The powders are a source of calcium and rich in potassium, copper, magnesium and manganese. The concentration of inorganic contaminants and pesticide residues were below the maximum allowed limits. The degradation of vitamin C and color parameter b* followed the first and zero-order kinetic models, respectively. The study indicated good stability for the powders along the storage at 10 and 25 °C, which can be incorporated into different food products, showing high retention of vitamin C, phenolic compounds, antioxidant activity and maintenance of color characteristics.

Keywords Hot-air drying · Contaminants · Nutrients · Kinetics · By-products

1 Introduction

The fruit processing industry produces a large amount of organic waste along its productive chain (up to 50% w/w), which results in significant expenses and causes a great environmental impact. There are significant post-harvest losses of agricultural products in the several stages of the production chain, from production in the field to the time of consumption. These wastes often have their limited use as organic fertilizers, such as animal feed or disposal in the environment. Although this residual biomass is biodegradable, it takes time for it to be mineralized, requiring significant investments in effluent treatment to control pollution. In addition to the environmental concern, the inadequate discarding of these co-products provides a major waste of potentially valuable raw material in the food industry [1].

Current studies have indicated that these by-products are rich in nutrients and antioxidant compounds with beneficial health properties, mainly polyphenols, present in higher amounts in the peels when compared to fruit pulp. The use of these by-products has received more attention in recent years, due to their high economic and nutritional potential. Researches have been encouraged to minimize the waste and to obtain higher value-added products, creating new market niches [1, 2].

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Mango is a widely consumed tropical fruit in fresh or processed form throughout the world and Brazil is one of the largest producers. Mango peel is the main by-product obtained during the processing of mango products, containing high levels of fibers, vitamins, minerals, carotenoids and polyphenols. Mangiferin (2-C-β-D-glucopyranosyl-1,3,6,7-tetrahydroxyxanone), the major phenolic compound, has several pharmacological actions, including antioxidant, analgesic, antidiabetic, antiinflammatory, antitumor, immunomodulatory and anti-HIV effects [2].

Since the fruit by-products are very perishable, it is important to ensure their stability for subsequent incorporation into novel foods. Drying is an interesting option to the stabilization of these co-products, since powder products are easier to store, handling and shipping for marketing in more distant places. Furthermore, they have low water activity, which hinders or avoids microbial growth and the physicochemical reactions responsible for their deterioration [3]. Therefore, the processing of mango peel into flours represents an excellent alternative to add value to these fruit by-products, answering the new food trends, besides reducing postharvest losses and increasing the sustainability of the food chain.

The sorption isotherms and the glass transition temperature are important tools to evaluate food stability and to understand the role of water in food [4]. The sorption isotherm, which correlates moisture content and water activity in equilibrium, at a given temperature, is useful to provide information about the interaction of water and solid porous structure. The glass transition temperature (T_g) is defined as the temperature at which an amorphous system changes from the glassy to the rubbery state. This property has a strong effect on the stability of food since below this temperature water is immobilized, avoiding the occurrence of degradation reactions. However, the product becomes more susceptible to the chemical, microbiological and physical changes, such as stickiness, collapse and crystallization, as the temperature increases above Tg, causing loss of quality along the storage [3–5].

Several factors affect a food's shelf life, such as temperature, relative humidity and the presence of light. Kinetics modeling of the quality deterioration during storage describes the reaction rate as a function of storage time and can predict changes in the food product along storage. The stability studies are essential to investigate the degradation mechanisms of quality parameters and to obtain the kinetic parameters for the shelf-life estimation [6]. The stability of dried products has been reported in the literature for different products and drying processes: drum drying [7], refractance-window® drying [3] and freeze-drying [8]. However, the behavior of mango peel powder obtained by hot-air drying at the controlled storage has not been reported yet. Some studies available in the international literature with drying of mango peels evaluated the chemical composition, antioxidant compounds and functional properties of mango peel flours [9, 10], the suitability of dried mango peel for the recovery of functional co-products, such as pectin and dietary fibers [11] or as a natural flavoring agent [12]. In this context, the aim of this work was to study the physical and chemical stability of the mango peel powder produced with hot-air drying. The sorption isotherms and the influence of different relative humidities on glass transition temperature of the product were evaluated to determine the storage critical conditions. The effect of different temperatures (10, 25 and 35 °C) on the degradation kinetics of quality parameters (vitamin C and color) along storage for 6 months was also analyzed.

2 Material and methods

2.1 Material

Mangoes (Palmer variety) from a São Francisco Valley's producer (Brazil), harvested in January/February 2018, were obtained directly from De Marchi Ltda., Campinas, Brazil. Approximately 20 kg of raw material were purchased and transported to the laboratory by car. Mangoes were selected based on their soluble solids content (between 14 and 18 °Brix).

2.2 Drying of mango peels

Fruits were sanitized in a solution containing sodium hypochlorite for 10 min (concentration of 100 ppm). The manual peeling was done with sharp stainless steel knives. Before drying, peels were cut into small pieces (10 mm thickness), using a cutter (model P.A., Urschel, Valparaíso, USA). Drying experiments were performed in a tray dryer with air circulation and velocity of 1.5 m/s (model K13964, Proctor & Schwartz, Lexington, USA) at 65 °C for 5 h. Around 15 kg of raw material (30–35 fruits) were used, resulting in about 2.5 kg of mango peels. After drying, samples were milled to a fine powder using a grinder mill (Treu, 74064G, São Paulo, Brazil) and mesh sieves (1.25 µm).

The powders were packed in low-density polyethylene (LDPE) packaging (0.15 mm thick) and they were wrapped in polyester/aluminum/low-density polyethylene (PET/Al/LDPE) bags, with 70 µm nominal thickness. A vacuum sealer (MULTIVAC, P300 MCB01 218,021, São Paulo, Brazil) was used for sealing the outer bags. For the stability study, the packages were stored in climatic chambers (LS370, Logen Scientific, São Paulo, Brazil) at 10, 25 and 35 °C, at 60% relative humidity (RH), while for the evaluation of

sorption isotherms and glass transition temperature, the packages containing the samples were stored at 25 °C until the analyses were performed.

2.3 Sorption isotherms

Saturated solutions of different salts were prepared [LiCl, CH_3COOK, $MgCl_2$, K_2CO_3, $Mg(NO_3)_2$, KI, NaCl, KCl] to provide relative humidity values between 11 and 84% [13]. About 1 g of the mango peel powder was weighed, in triplicate, in aluminum vials, and equilibrated with the salt solutions. The containers were stored at room temperature (25 ± 1 °C). Samples were weighed periodically (each 3 days) until a constant value (mass variation lower than 0.0001 g) was reached, when the equilibrium was assumed, which occurred around 5 weeks. These criteria to determine the equilibrium was based on some previous works [7, 14]. During this period, samples were visually observed concerning color, the occurrence of caking (agglomeration) and microbial growth. The vials containing the samples stored at different water activities were photographed together and the comparisons between the samples were made through these photos.

The mathematical model of GAB (Guggenheim, Anderson, & de Boer) (Eq. 1) was adjusted to the experimental data using Statistica® 8.0 software (StatSoft Inc., Tulsa, USA) by non-linear regression. GAB is one of the most popular mathematical models that describe the sorption behavior of water in food, due to its strong theoretical basis. This model represents adequately the experimental data for water activity ranges from 0.05 to 0.90 [15, 16].

$$MC_{eq} = \frac{X_m.\mathrm{C.K}.a_w}{\left(1-\mathrm{K}.a_w\right).\left(1-\mathrm{K}.a_w+\mathrm{C.K}.a_w\right)} \quad (1)$$

where: MC_{eq} = equilibrium moisture content (g water/g dry solids); X_m = monolayer moisture content (g water/g dry solids); C, K = constants.

The criteria to choose the best fit were: higher coefficients of determinations (R^2) and lower mean relative percentage deviation (P) (Eq. 2).

$$P = \frac{100}{N} x \sum_{i=1}^{N} \frac{|V_E - V_P|}{V_E} \quad (2)$$

where P = mean relative percentage deviation; V_E = experimental values; V_P = predicted values; N = number of experimental observations.

2.4 Glass transition temperature (T_g)

Samples in equilibrium at the different relative humidities were analyzed regarding the glass transition temperature using differential scanning calorimeter (TA Instruments, TA-DSC250, New Castle, USA), with cooling controlled by a Refrigerated Cooling Accessory, operating with nitrogen gas at 150 ml/min [5]. Equipment calibration was performed with Indium (Tmelting = 156.6 °C) and verification with azobenzol (Tmelting = 68.0 °C). About 7 mg of each sample were placed in aluminum capsules (20 µL) and hermetically sealed for the analysis. The samples were placed in the equipment and cooled to − 70 °C, kept at this temperature for 10 min and then heated to 90 °C, at a constant heating rate of 5 °C/min. All measurements were done in duplicate and the data were analyzed using the software Universal Analysis 2.6 (TA Instruments, New Castle, USA).

The plasticizing effect of water on the glass transition temperature of a product is pointed out by the Gordon-Taylor model [17], which describes the variation of T_g with a_w and the *water fraction* (w_w).

$$T_g = \frac{w_s \times T_{gs} + k_{GT} \times w_w \times T_{gw}}{w_s + k_{GT} \times w_w} \quad (3)$$

where w_s = solids fraction (g solids/g total); w_w = water fraction (g water/g total); Tg_s = glass transition temperature of solids (K); Tg_w = glass transition temperature of water (K); k_{GT} = constant.

The model parameters (k_{GT} and Tg_s) were estimated using the Solver tool of the Microsoft Excel software (Microsoft, Redmond, USA), considering Tg_w = -135 °C.

2.5 Stability under controlled storage

The concentration of minerals, inorganic contaminants and pesticide residues were determined at the beginning of storage, while the moisture content, water activity, antioxidant activity and total phenolic compounds were also analyzed at the end of storage. All samples were also periodically evaluated for vitamin C and color parameters throughout the study (approximately every 20 days during 180 days).

The variations of the properties were analyzed using kinetic models of zero and first-order [7] by regression analysis with Microsoft Excel software (Microsoft, Redmond, USA). The order of the reaction was determined based on the best fit to the model, that is, higher R^2. The reaction rates (k) were obtained and the following kinetic parameters were calculated:

$$Q_{10} = \frac{k_T}{k_{T-10}} \quad (4)$$

$$t_{\frac{1}{2}\mathrm{life}_0} = \frac{C_0}{-2k} \quad (5)$$

$$t_{\frac{1}{2}life_1} = \frac{0.693}{-k} \quad (6)$$

where k_T = the reaction rate constant at temperature T (days^{-1}); $k_{T\text{-}10}$ = reaction rate constant at a temperature 10 °C lower (days^{-1}); C_0 = initial concentration of the component at zero time; $t_{1/2life0}$ = half-life time for zero-order model (days); $t_{1/2life1}$ = half-life time for first-order model (days); Q_{10} = temperature coefficient.

2.6 Analytical methods

2.6.1 Moisture content

The moisture content was determined in a vacuum oven at 70 °C for 24 h [18].

2.6.2 Water activity

Water activity was evaluated using a digital hygrometer (Aqualab 3 TE, Decagon Devices Inc, Pullman, USA) at 25ºC.

2.6.3 Pesticide residues

The mini-luke extraction method was used for the multi-residue analysis of 822 pesticides in mango peel powder according to Regulation (EC) No 396/2005 of the European Parliament and of the Council of 23 February 2005 on maximum residue levels of pesticides in or on food and feed of plant and animal origin. The obtained extract was analyzed by GC–MS/MS and LC–MS/MS.

2.6.4 Concentration of minerals and inorganic contaminants

The method was adapted from A.O.A.C. [19]. The samples were digested using a closed microwave system (Start E, Milestone, Sorisole, Italy) and the minerals and inorganic contaminants were determined by inductively coupled plasma optical emission spectrometry (ICP OES) (Agilent Technologies, model 5100 VDV ICP OES, Tokyo, Japan).

2.6.5 Total phenolic compounds

The total phenolic compounds of the mango powders were determined using *Folin Ciocalteau´s* spectrophotometry method [20]. Absorbance readings were performed at 750 nm in the spectrophotometer (Agilent Technologies, Cary 60 MY13110012, Richardson, USA).

2.6.6 Antioxidant activity

The evaluation of the antioxidant activity by DPPH method (2,2-diphenyl-1-picrylhydrazyl) was done according to Brand-Williams et al. [21] ABTS method is based on the capture of the 2,2′-azinobis (3-ethylbenzothiazoline-6-sulfonic acid) radical (ABTS•+), following the method proposed by Rufino et al. [22]. Absorbance readings were done at 515 and 734 nm, respectively, using a spectrophotometer (Agilent Technologies, Cary 60 MY13110012, Richardson, USA).

2.6.7 Vitamin C

The vitamin C content of the mango powders was evaluated using Tillmans´ titration method [18] based on the reduction of the 6-dichlorophenolindophenol-sodium indicator (DCPIP) by ascorbic acid.

2.6.8 Color parameters

Color parameters of mango powders were measured using a colorimeter (model CR400, Konica Minolta, Osaka, Japan), with a CIELab scale (L*, a* and b*), D65 as an illuminant and a 10° observer angle as a reference system. The color measurements were expressed in terms of lightness L* (L* = 0 for black and L* = 100 for white) and the chromaticity parameters a* (green [–] to red [+]) and b* (blue [–] to yellow [+]).

3 Results and discussion

3.1 Sorption isotherms

The sorption isotherm of the product is shown in Fig. 1a. The parameters ($R^2 = 0.99$, P = 4.86%) indicate an excellent fit of the GAB model to the experimental data. The sorption isotherms of mango peel powder show a continuous increase in water absorption as water activity increased, following a type III sigmoidal curve, typical of sugar-rich products, showing higher water adsorption capacities at a_w above 0.5, according to Brunauer et al. [23]. This behavior is due to the prevailing effect of solute–solvent interactions related to sugar dissolution observed for higher water activity values [24]. Moreover, according to the constants ($0 < K \leq 1$ and $0 \leq C \leq 2$), the adjusted GAB model can also be classified as type III [25]. Similar sorption curves were also observed for other products with high sugar content

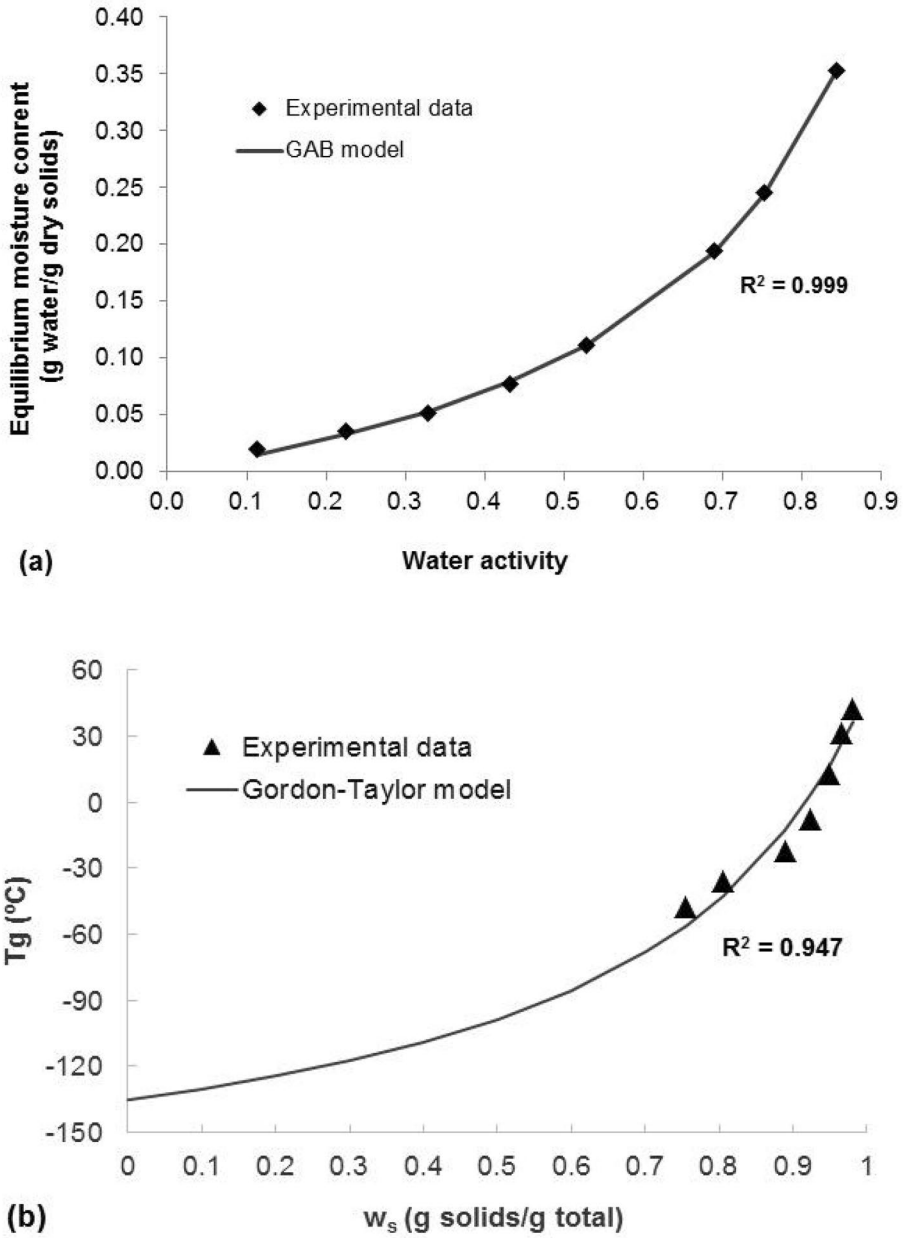

Fig. 1 **a** Sorption isotherm of mango peel powder obtained by hot-air drying at 25 °C (experimental data and GAB model). $X_m = 0.1260$ g water/g dry solids; C = 1.078; K = 0.869). **b** Effect of solids fraction (w_s) on glass transition temperature (T_g) of mango peel powder obtained by hot-air drying (experimental points and curve according to Gordon-Taylor model, whose parameters are: $Tg_s = 50.18$ °C; $k_{GT} = 4.14$)

such as osmo-dehydrated apple and pear [26], spray-dried orange juice powder [15] and freeze-dried permission slices [27].

The monolayer moisture content (X_m) of mango peel powder was 0.1260 g water/g dry solids. It corresponds to the amount of water strongly bound to the solid food matrix and is described as the safest water content for maintaining food stability over a long period of storage. Besides, it is considered a critical value, since the rate of some degradation reactions increases above X_m. Similar values were observed in other products, such as freeze-dried mango ($X_m = 0.109$ g water/g dry solids) [28] and freeze-dried persimmon slices ($X_m = 0.138$ g water/g dry solids) [27]. However, Islam et al. [15] reported lower X_m values for spray-dried orange juice powder (0.034–0.040 g water/g dry solids), while Caparino et al. [5] found monolayer moisture values of 0.078 g water/g dry solids for mango powder produced by refractance-window® drying. According to the authors, the variations in monolayer water content of sugar-rich materials could be attributed to the different drying processes applied and the sugar composition of these fruits.

Figure 2 shows the physical changes that occurred in the mango peel powders at equilibrium (after 5 weeks) and stored under different relative humidities at 25 ± 1 °C. According to the photos, agglomeration and darkening

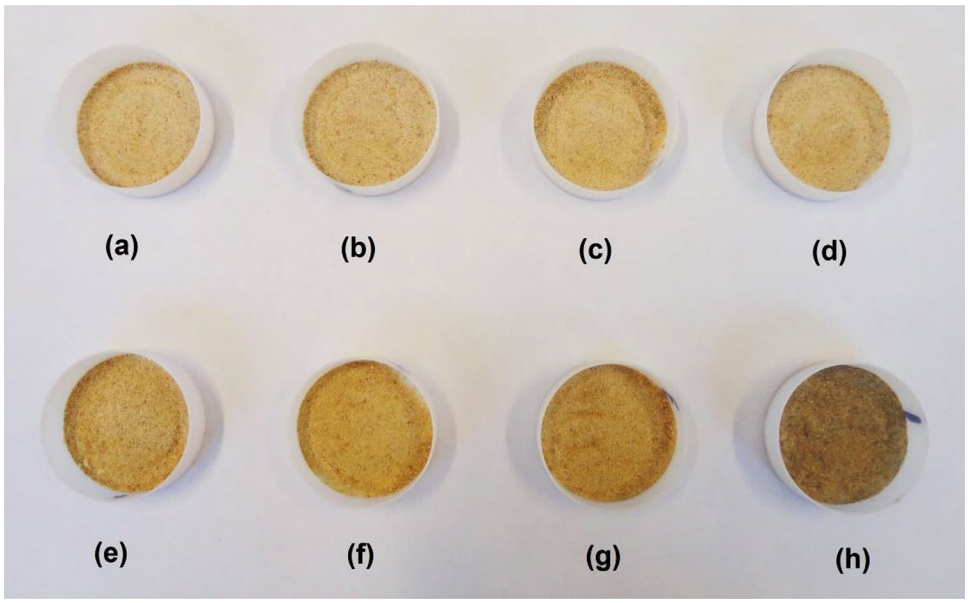

Fig. 2 Mango peel powder obtained by hot-air drying at equilibrium (after 5 weeks) and stored under different conditions of water activity at 25 °C. **a** $a_w = 0.122$, **b** $a_w = 0.226$, **c** $a_w = 0.328$, **d** $a_w = 0.432$, **e** $a_w = 0.529$, **f** $a_w = 0.689$, **g** $a_w = 0.753$ and **h** $a_w = 0.843$

were verified in some conditions. The product stored up to $a_w = 0.529$ remained dry and free-flowing with intense color (Fig. 2a, b, c, d, e). The most relevant changes were verified from $a_w = 0.689$, when the product showed the first signs of caking. As water activity increased, the powders gradually became darker and more agglomerated. Microbial growth was also observed in the highest water activity ($a_w = 0.843$). These visual observations indicate that the critical moisture level for the mango peel powder corresponds approximately to the obtained monolayer moisture content (X_m), that is, a_w corresponding to X_m (0.1260 g water/g dry solids) in sorption isotherm (Fig. 1a) is around 0.56. Therefore, the storage of the powders in environments with relative humidity above 56% contributed to the increase of darkening and agglomeration, reducing their stability (Figs. 2f, g, h).

3.2 Glass transition temperature (T_g)

The experimental glass transition temperature (T_g) of mango peel powder decreased as water activity increased (Table 1), showing the plasticizing effect of water, which is in agreement with the results stated for spray-dried acai powder [4], spray-dried orange juice powder [15], osmo-dehydrated apple and pear [26] and freeze-dried persimmon [27]. T_g values obtained for mango peel powder were lower in comparison to some works available in the literature. Islam et al. [15] reported T_g values ranging from 61 to −2 °C when a_w varied from 0.11 to 0.75 for spray-dried orange juice powder with 50% (w/w) maltodextrin. Tonon et al. [4] found T_g values in the range of 73.95 to -56.62 °C with a_w varying between 0.112 to 0.843 in açai powder produced by spray-drying using 6% cassava starch (w/w). As seen in Table 1, the lowest T_g values found in the current study (42.40 °C for $a_w = 0.112$ and −47.60 °C for $a_w = 0.753$) can be related to the non-use of carrier agents in the conventional hot-air drying process. Another possible reason is the concentration of reducing sugars in mango peel (around 15 g/100 g dry basis, corresponding to 35% of the total sugar content), since these compounds have low molecular weight, decreasing T_g of the product.

The experimental T_g data of mango peel powder were adjusted using the Gordon-Taylor model and Fig. 1b shows the effect of solids content on T_g values. High R^2 (0.947) and the low relative mean deviation P (2.72%) indicated a good fit of the model to the experimental results. K_{GT} (4.14) obtained in the current work is lower than the value reported for freeze-dried mango (4.48) [28] and freeze-dried persimmon (4.63) [27]. This parameter is related to the degree of curvature of the variation of T_g concerning the water content (in a binary water and solids system) and is associated with the interaction forces between the components. Lower K_{GT} values imply a low interaction of powders' solids with water molecules [29].

According to Fig. 1b, the glass transition temperature increases with the solids fraction of the product, reaching the limit of 50.18 °C for the pure solid (Tg_s). The obtained value is lower than the Tg_s values pointed out for freeze-dried blueberry bagasse (74.6 °C) [29] and spray-dried orange powder (71.9 °C) [15]. Truong et al. [30] stated that stickiness in dehydrated powder products begins at temperatures about 10–23 °C higher than the glass transition temperature (T_g), a condition named "sticky point temperature". In this context, the caking of mango peel powder with $a_w = 0.432$ and $T_g = -8$ °C (Table 1), would start at a temperature between 2 and 15 °C. As previously

Table 1 Glass transition temperature (T_g) of mango peel powder obtained by hot-air drying as a function of water activity (a_w) and physicochemical properties of mango peel powder obtained by hot-air drying at different storage periods and temperatures (T)

Analysis		Storage period			
		Zero time	After 180 days		
			T = 10 °C	T = 25 °C	T = 35 °C
Moisture content (%)		4.26 ± 0.09a	4.18 ± 0.13a	4.21 ± 0.06a	4.10 ± 0.05a
Water activity		0.358 ± 0.002a	0.432 ± 0.002b	0.421 ± 0.001b	0.428 ± 0.003b
Total phenolic compounds (mg GAE/100 g d.b.)		2678.91 ± 15.97a	2718.15 ± 41.01a	2531.60 ± 8.01b	2544.18 ± 57.55b
Antioxidant activity (μmol TE/g d.b.)	DPPH	304.74 ± 6.70a	293.31 ± 12.02a	283.02 ± 12.25b	286.48 ± 3.49b
	ABTS	334.47 ± 10.42a	270.58 ± 17.67b	267.60 ± 15.74b	285.44 ± 10.44b
Glass transition temperature T_g (°C)	a_w	Zero time			
	0.112	42.40 ± 1.90			
	0.226	31.37 ± 2.36			
	0.328	12.45 ± 0.97			
	0.432	−8.03 ± 0.88			
	0.529	−21.94 ± 2.59			
	0.689	−36.17 ± 2.43			
	0.753	−47.60 ± 2.97			
	0.843	n.p			

Different letters in the same line indicate significant difference ($P \leq 0.05$) according to Tukey's test

n.p. = not performed in this condition due to the microbial growth

reported in sorption isotherm analysis, the powders showed free-flowing characteristics at 25 °C in this condition ($a_w = 0.432$). The sample stored at $a_w = 0.529$ presented the same behavior. In this case, according to Truong et al. [30], the sticky point temperature would start at a temperature between −11 to 2 °C. The first visible signs of agglomeration and the increase in stickiness occurred in samples stored at $a_w = 0.689$ (Fig. 2f), showing the high stability of mango peel powder along storage at different relative humidities, despite the low T_g values for samples stored at $a_w > 0.432$ (Table 1), as previously discussed.

3.3 Concentration of minerals, inorganic contaminants and pesticide residues

Table 2 shows the results of minerals, inorganic contaminants and pesticide residues for the mango peel powder. The predominant minerals were potassium, calcium and magnesium. Chiocchetti et al. [31], evaluating the mineral composition of some by-products of the industrial processing of fruits, also observed higher calcium content (~ 203 mg/100 g d.b.) and potassium (~ 743 mg/100 g d.b.) for the mango peels.

The Technical Regulation "Supplementary Nutritional Information" (RDC Resolution No. 54, November 12th, 2012) from ANVISA (National Health Surveillance Agency) considers products containing 15% of the recommended daily intake (RDI) of minerals and vitamins as a source of these compounds. On the other hand, to be considered rich in a certain mineral or vitamin, the food must contain at least 30% of their RDI. Therefore, according to RDC Resolution No. 269, September 22nd, 2005 from ANVISA regarding the recommended daily intake of protein, vitamins and minerals, the mango peel powder obtained in the current work can be considered as a source of calcium and rich in potassium, copper, magnesium and manganese (taking into account a daily intake of 100 g of mango peel powder). As seen in Table 2, a portion of 100 g of the product provides more than 100% of the recommended daily intake for copper and manganese, while contributes with 38 and 43% of the RDI for potassium and magnesium, respectively.

Concerning the inorganic contaminants, no traces of cadmium was identified in the sample. The nickel content is below the threshold allowed by WHO/SDE/WSH/05.08/55 (2005), which establishes a tolerable daily intake (TDI) of 22 μg/kg body weight. For aluminum, the Codex Alimentarius Commission (CF/13 INF/1 document from April 2019) presents a PTWI (Provisional Tolerable Weekly Intake) value of 2 mg/kg body weight. This means that an adult weighing 70 kg and consuming 100 g of mango peel per week containing 3.29 mg/kg of Al would reach only 1.6% of PTWI. For lead, the Codex Alimentarius Commission establishes a maximum tolerance of 0.10 mg/kg for fruits. Therefore, the lead content observed in the sample (0.06 mg/kg) is not a risk for consumers' health.

The pesticide residues found on the mango peel powder were cyfluthrin, difenoconazole, azoxystrobin

Table 2 Concentration of minerals, inorganic contaminants and pesticide residues of mango peel powder obtained by hot air drying (n = 3) at the beginning of stability study

Element	Concentration (mg/kg d.b.)	% of the recommended daily intake (RDI)*
Minerals		
Calcium	1919.27 ± 8.19	19.19
Copper	9.10 ± 0.03	101.11
Iron	9.05 ± 0.21	6.46
Potassium	13,524.57 ± 230.81	38.53
Magnesium	1133.06 ± 15.53	43.58
Manganese	28.08 ± 0.47	122.09
Sodium	20.24 ± 0.68	0.08
Phosporus	445.40 ± 3.92	6.36
Zinc	3.14 ± 0.10	4.49
Inorganic contaminants		
Aluminum	3.29 ± 0.03	–
Cadmium	Nd	
Nickel	0.42 ± 0.07	
Lead	0.06 ± 0.01	
Pesticides residues		
Cyfluthrin	0.048	–
Difenoconazole	0.106	
Azoxystrobin	0.138	
Carbendazim	0.013	

Nd, not detected: < 0.03 mg/kg; d.b., dry basis

*Considering a portion of 100 g of mango peel powder

and carbendazim. According to Resolution RE No. 165 (August 29th, 2003), Resolution RE No. 635 (February 27th, 2009) and Resolution RE No. 1.404 (May 24th, 2019) from ANVISA, the acceptable daily intake (ADI) for difenoconazole is 0.6 mg/kg body weight, while the ADI for cyfluthrin, azoxystrobin and carbendazim is 0.02 mg/kg body weight. Thus, the concentrations of pesticides observed in the samples (Table 2) are below the ADI recommended, meaning that mango peel powder is safe for the consumers. Furthermore, more rigid agricultural practices must be adopted regarding the use of pesticides to decrease or avoid the contamination of the peels.

3.4 Changes in some physicochemical properties at different storage conditions

According to Table 1, no significant differences ($p > 0.05$) were observed between the moisture content of the powders at the beginning and the end of storage. Regarding the water activity, a statistically significant increase at $p \leq 0.05$ was verified after 180 days of storage in all samples. However, the final a_w at the different temperatures were below the critical a_w ($a_w = 0.56$), as previously reported.

The content of total phenolic compounds remained practically constant over time, despite the statistical differences at $p \leq 0.05$ observed in the samples stored at 25 and 35 °C after 180 days. Similar behavior was also verified for the antioxidant activity of the powders (DPPH method), as seen in Table 1. On the other hand, the antioxidant activity determined by the ABTS method at time zero was higher (approximately 335 µmol TE/g d.b.), showing a significant reduction at the final time for all the samples. Sogi et al. [32], working with hot-air drying of mango pulp at 60 °C, also reported higher antioxidant activity values for the ABTS method (90 µmol TE/g d.b.), in comparison to DPPH method (75 µmol TE/g d.b.).

3.5 Stability of vitamin C

The degradation kinetics of vitamin C of mango peel powder followed the first-order model over the storage, with R^2 varying from 0.81 to 0.95. The initial vitamin C content was around 370 mg/100 g d.b. Figure 3a shows the loss of vitamin C along storage at different temperatures, while Table 3 presents the kinetic parameters. Gamboa-Santos et al. [33] also obtained first-order kinetic models for vitamin C degradation in dried strawberries. The degradation of vitamin C in food is susceptible to environmental

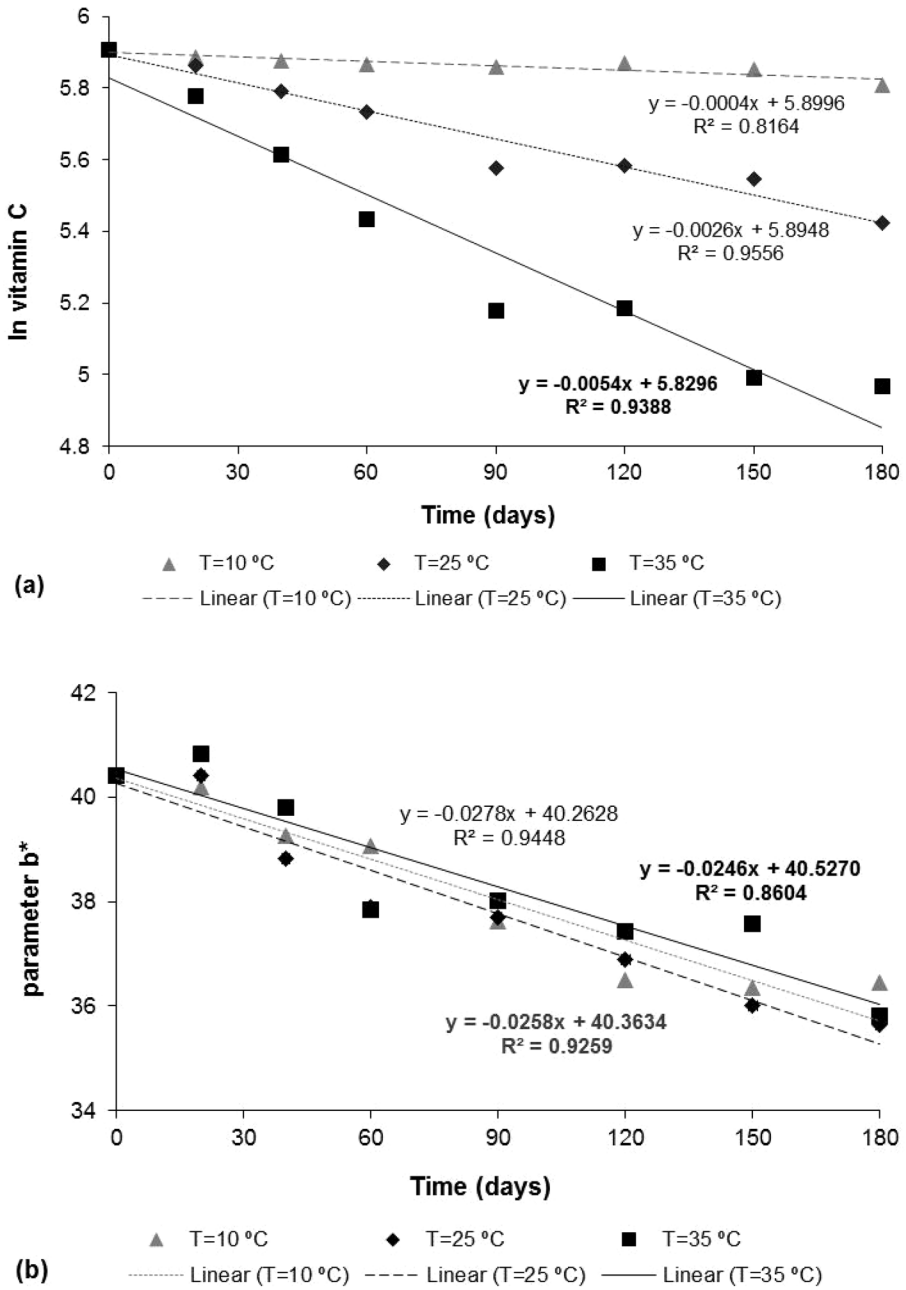

Fig. 3 Degradation kinetics of **a** vitamin C and **b** color (parameter b*) of mango peel powder obtained by hot-air drying along the storage at 10, 25 and 35 °C

Table 3 Kinetic parameters of vitamin C and color degradation of mango peel powder obtained by hot-air drying under different temperatures (T)

T (°C)	Analysis	Reaction Order	k (days^{-1})	Linear Coefficient	R^2	Q_{10}	$t_{1/2}$ (days)
10	Vitamin C	1	−0.0004	5.8996	0.8164	–	1682.30
25			−0.0026	5.8948	0.9556	2.07	264.43
35			−0.0054	5.8296	0.9388		127.58
10	Color parameter b*	0	−0.0258	40.3634	0.9259	–	783.52
25			−0.0278	40.2628	0.9448	0.89	727.16
35			−0.0246	40.5270	0.8604		821.74

conditions, such as temperature and water activity. The reaction mechanism of its decomposition occurs through different pathways, giving origin to many breakdown products.

The reaction rate (*k*) increased with temperature ranging from 0.0004 to 0.0054 $days^{-1}$. These values are lower than those reported by Yamato et al. [7] in the drum drying of mango pulp (0.0206 and 0.0253 $days^{-1}$ at 25 and 35 °C, respectively). Furthermore, the authors reported half-life times ($t_{½}$) of approximately 30 days, while $t_{½}$ values in the current work were 1682, 264 and 127 days at 10, 25 and 35 °C (Table 3), demonstrating higher stability of vitamin C in mango peel powder. The half-life time for the powder stored at 10 °C was approximately 13 times higher concerning the sample stored at 35 °C. The Q_{10} (temperature coefficient) obtained was 2.07, meaning that the temperature had a strong effect on the degradation rate of vitamin C. Germer et al. [34], studying the vitamin C degradation of dried papaya, found Q_{10} values between 3.08 and 3.90, while the half- half-life times ($t_{½}$) were around 60 and 18 days for the samples stored at 25 and 35 °C during 100 days, respectively.

3.6 Stability of color parameters (L*, a*, b*)

The color parameters of the raw material (mango peels) were: $L^* = 36.35 \pm 7.94$, $a^* = 14.96 \pm 9.31$ and $b^* = 16.75 \pm 9.17$. The high values of the standard deviation may be due to the great variation in the color of the peels. After the drying process, the values obtained for L*, a* and b* were 67.36 ± 1.34, 0.75 ± 0.15 and 40.42 ± 1.08, respectively. The lightness L* of the dried samples were higher in comparison to the raw material, meaning that drying resulted in lighter powders. This behavior may be attributed to the reflection of the light by the irregular particles of the powder, making the color closer to white [35]**.** The chromaticity parameter a* was almost 0, while the parameter b*, responsible for the yellow color of the mango, increased after the drying, indicating the concentration of the pigments.

The lightness (L*) of mango peel powder was kept practically constant along storage (between 64 and 67), while parameter a* values were very close to 0 throughout the stability study. As the coefficients of determinations (R^2) were lower than 0.5, it was not possible to adjust these color parameters to kinetic models.

The reduction of color parameter b*, responsible for the yellow color of mango, after 180 days of storage was less than 10% for all the samples (Fig. 3b). The experimental data were fitted to a zero-order kinetic model, with R^2 ranging from 0.86 to 0.94. Zero-order kinetic models have also been used to describe the color changes in dehydrated sweet corn [36].

The kinetic parameters of color degradation of mango peel powder under different temperatures are presented in Table 3. The reaction rate (*k*) values were very similar (between 0.0246 and 0.0278 $days^{-1}$), regardless of the storage temperature. Moreover, the Q_{10} (temperature coefficient) was close to 1, indicating no significant influence of temperature on this parameter and, consequently, high retention of color along storage. Likewise, the half-life times ($t_{½}$) of the powders showed a small variation (approximately 15%), ranging from 727 to 821 days.

Evaluating the color stability of dried papaya obtained by osmotic dehydration and conventional air drying, Germer et al. [34] reported parameter b* degradation rates of 0.113 $days^{-1}$ (25 °C) and 0.260 $days^{-1}$ (35 °C), besides shorter $t_{1/2}$ values (207 days at 25 °C and 92 days at 35 °C) and higher Q_{10} (2.30).

4 Conclusions

GAB model showed a good fit to the experimental data of water adsorption of the mango peel powder obtained by hot-air drying. The glass transition temperature of the samples stored at different relative humidity conditions decreased as water activity increased, confirming the plasticizing effect of water on this property. The product stored up to $a_w = 0.529$ remained dry with free-flowing characteristics and intense yellow color, while the first visual signs of caking occurred in samples stored at $a_w = 0.689$. The mango peel powder can be considered as a source of calcium and rich in potassium, copper, magnesium and manganese. The concentration of inorganic contaminants and pesticide residues were below the limits established by the regulation. The degradation of vitamin C and color parameter b* of mango peel powder followed a first and zero-order kinetic models, respectively.

In general, mango peel powder obtained by hot-air drying showed good storage stability and can be used in the formulations of different foods. The incorporation of the by-products from industrial processing of mango, a natural ingredient with a high content of antioxidant compounds, in the development of new food products allows a greater innovation in the supply of healthy foods.

Authors' contribution Cristhiane Caroline Ferrari, Ph.D.: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Resources, Validation, Visualization, Writing—original draft, Writing—review and editing. Marcelo Antonio Morgano, Ph.D.: Formal analysis, Methodology, Validation, Writing—review and editing. Silvia Pimentel Marconi Germer, Ph.D.: Conceptualization, Funding acquisition, Investigation, Project administration, Supervision, Writing—original draft, Writing—review and editing.

Funding The authors are grateful for FAPESP (Process number 2015/12303–3) and CAPES—PROAP (Process number 1792/2016) for their financial support.

Compliance with ethical standards

Conflicts of interest The authors have no conflict of interest to declare.

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