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ORIGINAL ARTICLE

Thermodynamic and kinetics study of phenolics degradation and color of yacon (*Smallanthus sonchifolius*) microparticles under accelerated storage conditions

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Abstract This study aimed to investigate the kinetics and thermodynamic of the phenolics degradation and the kinetics of degradation of the total color difference of yacon juice microcapsules produced by spray drying using Gum Arabic and polydextrose as wall materials. The degradation of the microcapsule was evaluated by accelerated tests under controlled conditions at 35 and 45 °C, and relative humidity of 75 and 90%, for 35 days. Degradation of phenolics followed the first order model and the degradation constant was in the range of 0.0124–0.0209 days^{-1}. The microparticles with gum Arabic were more stable than those with polydextrose for all conditions studied, with longer half-lives. Both wall materials showed similar thermodynamic characteristics, indicating similar mechanism of degradation of phenolics. With respect to the color parameters, the first order model adjusted to data of the total color difference, and no significant differences were observed for the conditions studied.

Keywords Yacon · Accelerated test · Phenolics · Kinetic · Thermodynamic

Introduction

When the immune system is suppressed due to excessive production of oxidizing agents, called of free radicals, in the human body, it happens damages in cell membranes, tissue, nucleic acids, cellular proteins and lipids (Andrade et al. 2014). An overloading of these radicals and oxidative stress trigger a number of human diseases, such as cancer, atherosclerosis, inflammatory tissue injury and neurological disorder (Lobo et al. 2010). A strategy to combat free radicals is intake of antioxidants that scavenge free radicals from the cells, and this way to prevent chronic diseases (Li et al. 2014).

Yacon is a tuberous root native to the Andean region, considered a functional food due to the presence of fructooligosaccharides that have prebiotic activity, and phenolic compounds (Ojansivu et al. 2011). Moreover, yacon contains flavonoids, phenolic compounds and tryptophan, with antioxidant activity, anti-inflammatory and anticancer properties (Delgado et al. 2013).

Nowadays, the ingestion of foods containing natural bioactive compounds, particularly polyphenols, is of great interest. Thus, the susceptibility of these compounds to adverse effects of processing and storage conditions and their chemical instability has encouraged studies on microencapsulation techniques aimed to improve their bioavailability (Belščak-Cvitanović et al. 2011).

Environmental factors such as temperature and humidity can promote undesirable chemical reactions and reduce the health benefits of foods during storage due to the low stability of the bioactive compounds. Thus, the changes during both processing and shelf life should be investigated. Studies on the shelf life of the products can be very time consuming and costly, and therefore, accelerated tests are often used (Corrigan et al. 2012). During these tests, the product is subjected to adverse storage conditions and one or more accelerating factors (such as temperature, relative humidity and water activity) higher than normal, so that the degradation is faster, resulting in a shorter shelf life. Thus, knowledge of thermodynamic and kinetic parameters will

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allow understanding the changes occurring during storage (Kechinski et al. 2010). Thus, the aim of this study was to evaluate the effect of temperature, relative humidity, and type of wall material on the stability of phenolic compounds and total color difference of yacon juice microparticles through accelerated tests.

Materials and methods

Material

Yacon roots were harvested in the State of São Paulo, Brazil and transported by a climate controlled truck. They were cleaned and selected considering the absence of visual damage and infections, and stored under refrigeration (8 ± 1 °C) until use.

Encapsulation process

Yacon roots were peeled and sliced with a mean diameter of 0.5 ± 0.1 mm, and then subjected to steam blanching at 100 °C for 4 min, and cooled in ice bath for 3 min (Lago and Noreña 2014), and then blended in a fruit processor. The juice was separated from the bagasse by filtration on Whatman filter paper No. 1 with the aid of vacuum. To the juice was added the encapsulating agent at a concentration of 10% (w/v), and the mixture was homogenized in Ultra Turrax for 4 min at 6000 rpm until complete dissolution.

The gum Arabic (Instantgum BA, Nexira Brasil Comercial Ltda., São Paulo, Brasil) and polydextrose (MasterSense Ing. Alim. Ltda. São Paulo, Brasil) were used as encapsulating agents.

Encapsulation by spray-drying was performed using a dual fluid atomizer, pneumatic type (LM MSDI 1.0, LABMAQ), with a flow rate of 0.60 L/h, drying air temperature 140 °C, air pressure 3.5 kgf/cm^2, and air flow rate 40.5 L/h.

Accelerated stability tests

The samples were stored at high temperatures to accelerate the reactions of interest so that changes could be measured in a short period of time (Ruiz et al. 2012).

For that, 0.5 g sample of the spray dried yacon was placed in eppendorf tubes of 1.5 mL. The study was conducted under two accelerated conditions: relative humidity of 75 and 90% at 35 and 45 °C, values that are within of the range recommended by accelerated shelf life testing (Labuza and Schmidl 1985; Labuza 1980). The relative humidity was controlled in mini desiccators containing saturated solutions of sodium chloride (Aw = 0.75) and barium chloride (Aw = 0.90). The temperature was kept constant by placing the desiccators in an incubator at 35 and 45 °C. The samples were stored for 35 days, and removed every seven days for analyses of total phenolics and color.

Total phenolics

The total phenolics were determined using the Folin–Ciocalteu reagent (Singleton and Rossi 1965). The powder was diluted in distilled water (1:40). To 1 mL of this solution was added 10 mL distilled water and 500 µL Folin-Ciocalteu reagent. After reaction, 1.5 mL sodium carbonate (20%, w/v) was added. The readings were made in a spectrophotometer at 765 nm, and the results were expressed as mg gallic acid equivalent (GAE) per g sample on a dry basis.

Color measurements

The color of the powders was measured using a colorimeter (CR400/410, Minolta), according to the CIELAB (L^*, a^*, b^*) system. The instrument was standardized with a white ceramic plate ($L^* = 97.47$; $a^* = 0.08$; $b^* = 1.76$).

The parameters L^*, a^* and b^* were used to calculate total color difference according to the following equation:

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

where L_o*, a_o* and b_o* are the initial values for powders.

Determination of the kinetic parameters

The experimental data of the phenolics levels and total color differences were adjusted by the first-order inactivation kinetics (Stamp and Labuza 1983), according to Eq. (2):

$$C = C_0 \exp(-kt) \quad (2)$$

where t is time (day), C is either the initial phenolics level or total color difference, C_0 is either the initial phenolics level or total color difference at time zero, respectively, and k is the rate constant (day^{-1}).

The decimal reduction time (D) and the half life ($t_{1/2}$) were calculated according to Eqs. (3) and (4):

$$D = \frac{\ln(10)}{k} \quad (3)$$

$$t_{1/2} = \frac{\ln(2)}{k} \quad (4)$$

The temperature acceleration factor (Q_{10}) was determined from the degradation constants at a given temperature (T) and 10 °C above ($T + 10$ °C) Eq. (5):

$$Q_{10} = \left(\frac{k_{T+10}}{k_T}\right) \quad (5)$$

The activation energy (E_a) was estimated from the Q_{10} value as shown in Eq. (6) (Labuza and Schmidl 1985):

$$E_a = \frac{2.303 \log_{10}(Q_{10}) RT(T+10)}{10} \quad (6)$$

where R is the universal gas constant and T is temperature in Kelvin.

Thermodynamic parameters

The activation energy and the rate constant were used to determine the following thermodynamic parameters: Gibbs free energy change (ΔG), the enthalpy change (ΔH) and entropy change (ΔS), according to the Eqs. (7), (8), and (9) (Labuza 1980):

$$\Delta G = -R \cdot T \cdot \ln\left(\frac{k.h_p}{K_B \cdot T}\right) \quad (7)$$

$$\Delta H = E_a - R \cdot T \quad (8)$$

$$\Delta S = \left(\frac{\Delta H - \Delta G}{T}\right) \quad (9)$$

where K_B is the Boltzmann constant (1.3806×10^{-23} J/K) and h_p is the Planck constant (6.6262×10^{-34} J s).

Statistical analysis

The results were analyzed by ANOVA and Tukey's multiple test for comparison between treatments, using the software SAS 9.3 (SAS Institute Inc.). The estimation of kinetic parameters of the models was performed by non-linear regression analysis using the software Sigma Plot 8.0.

Results and discussion

Degradation of phenolics of yacon microparticles subjected to the accelerated tests

The initial phenolics levels of the spray dried yacon microparticles were 22.4 and 21.3 mg GAE/g dry basis with gum Arabic and polydextrose as wall materials, respectively.

Figures 1a, b show phenolics content during storage of the microparticles containing gum Arabic and polydextrose, respectively, where can be observed that the total phenolics decreased during storage time for all treatments.

After 35 days of storage, the degradation of phenolics in the microparticles with gum Arabic was 46.3 and 47.0% at 35 °C and 75 and 90% RH, respectively. At 45 °C, the degradation was 47.7 and 49.5% at 75 and 90% RH, respectively.

The degradation of phenolics with polydextrose was 46.5% in an environment with 75% RH, and 48.4% at 90% RH and 35 °C after 35 days of storage. At 45 °C, the degradation was 52.9 and 54.1% at 75 and 90% RH, respectively.

For both encapsulating, the phenolic degradations were significantly lower at 35 °C and 75% RH ($p < 0.05$), meanwhile the highest significant degradation happened with polydextrose at 45 °C and 90% RH ($p < 0.05$).

The retention of phenolics depends on both their chemical structure (which affects the susceptibility to oxidation) and the physicochemical properties of the powder such as surface area (which directly affects the interactions via chemical bonding or physical effects such as heat, moisture, and oxygen) (Sun-Waterhouse and Waterhouse 2015). The decrease in total phenolics during storage of the microparticles is probably due to the degradation by oxidation processes, polymerization of phenolic compounds with other components (Cao et al. 2012), or degradation by temperature, since these are highly thermosensitive compounds. The possible degradation pathways of these phenolic compounds may be due to oxidation, hydrolysis, or isomerization (Chang et al. 2006).

Several earlier studies have demonstrated the protective effect of the wall material in the encapsulation of polyphenols, indicating higher stability of the microparticles when compared to the powder without the encapsulating agent (Çam et al. 2014). Those authors suggested that the phenolics on the surface of particles without wall material were more susceptible to oxidation than the microparticles, since the encapsulating agent serves as a protective barrier. The main objective of the encapsulation process is to build a barrier between the encapsulated component and the environment, composed of branched chains, forming a network (Fuchs et al. 2006). In addition, gum Arabic has good physical properties to be used in different application in food industry, such as an emulsifier, a stabilizer and a thickener (Montenegro et al. 2012).

Another factor responsible for the degradation of phenolics is the relative humidity of the environment. Both for the microparticles with gum Arabic as polydextrose in environments with higher humidity caused further degradation of phenolics, because the molecular mobility within the food is greater with increasing the amount of water, which facilitates degradation reactions (Tonon et al. 2010). The moisture content also affects both the pore network inside the wall material and the oxygen diffusion and retention of the encapsulated compound inside the particles (Drush et al. 2007). Thus, the degradation of phenolics can be a result of hydrolytic reactions, due to the increased

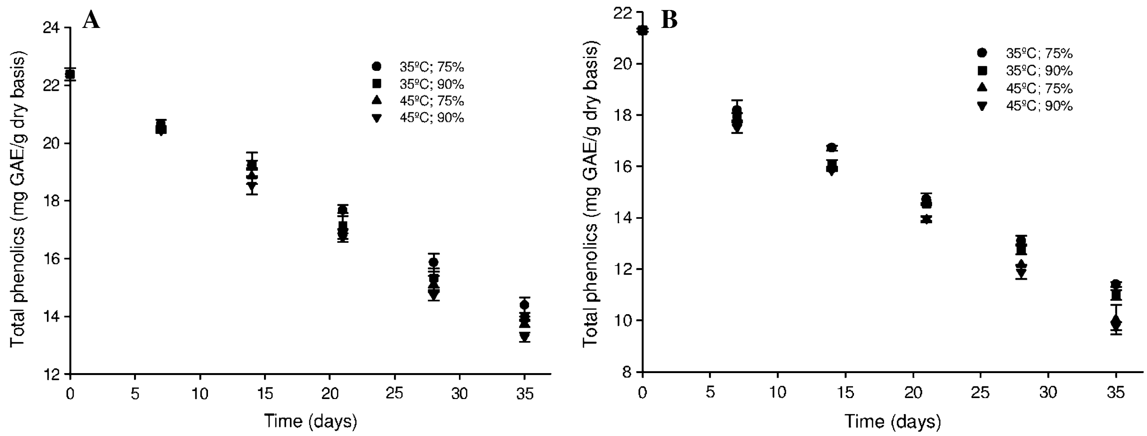

Fig. 1 Effect of storage temperature (35 and 45 °C) and relative humidity (75 and 90%) on the stability of phenolic compounds of yacon microparticles using gum Arabic (**a**) and polydextrose (**b**) as wall materials

moisture within the microparticles, which can facilitate the oxygen diffusion, leading to oxidation reactions (Cai and Corke 2000).

The balance between water vapor pressure of food and the environment that surrounds the system is a dynamic system rather than a static system (Esse and Saari 2004). Hence, when a food product is exposed to an environment above or below its balance point, the protective packaging and its barrier level (in our study the wall material) will determine the impact on food (Esse and Saari 2004).

Kinetics of phenolics degradation of yacon microparticles subjected to the accelerated tests

For a proper comparison between the two types of wall materials and the different storage conditions, the results were adjusted to a first order kinetics equation. The coefficients of determination (R^2) and the degradation constants (k) of each wall material for each condition are shown in Table 1.

The results of regression analysis showed that data were well adjusted to the first order model, with a coefficient of determination higher than 0.99 for all storage conditions and wall materials. Several studies have shown that food degradation reactions follow the first-order model as degradation of anthocyanins, phenolic compounds, and antioxidant activity (Kechinski et al. 2010; Tonon et al. 2010; Mercali et al. 2015; Wang and Xu 2007).

The degradation rate constant increased with the increase in temperature, and this increase was statistically significant ($p < 0.05$). This remarkable increase in degradation constant caused by temperature increase is consistent with the fundamentals of chemical kinetics, resulting mainly from the increased number of collisions caused by temperature (Al-Zubaidy and Khalil 2007).

The microparticles with gum Arabic were more stable, and the degradation reaction occurred more slowly at 35 °C/75% RH ($k = 0.0124$ days^{-1}), with no significant differences between the storage conditions at 35 °C/90% RH ($k = 0.0134$ days^{-1}) and 45 °C/75% RH ($k = 0.0139$ days^{-1}). On the other hand, the degradation in the microparticles with polydextrose was faster at 45 °C/90% RH ($k = 0.0209$ days^{-1}), with no significant differences for the microparticles stored at 75% RH at the same temperature. In addition, the increase in humidity caused no significant increase ($p > 0.05$) in the degradation constant.

The kinetic parameters of phenolic degradation in yacon microparticles were obtained from the rate constant after adjustment to the first order model, as shown in Table 1. It is observed that the highest D values, i.e. the time required for 90% degradation was 186 days of storage at 35 °C and 75% RH, and 172 days at 90% RH for the microparticles with gum Arabic, with no significant difference between both storage conditions. Consequently, these microparticles had the longest half-life, with 56 and 52 days, respectively. Table 1 also shows that decimal reduction time and half life values decreased significantly with increase in temperature ($p < 0.05$).

During the anthocyanin degradation in acai juice microparticles with gum Arabic was reported $t_{1/2}$ values of 239 and 169 days at 25 and 35 °C respectively, stored in an environment with low water activity (0.328), which may explain the higher $t_{1/2}$ values when compared to the present study (Tonon et al. 2010).

When comparing both wall materials, it was found that the microparticles with gum Arabic were more stable than those with polydextrose for all storage conditions, with higher half-lives and lower rate constant values. It is well recognized that the higher the temperature, the higher the

Table 1 Kinetic parameters of the degradation of phenolic compounds in the yacon microparticles stored under different conditions

	k (days^{-1})	$t_{1/2}$ (days)	D (days)	Q_{10}	E_a (J mol^{-1})
75% 35 °C GA	0.0124 ± 0.0005^{a}	55.9 ± 2.3^{a}	185.7 ± 7.5^{a}		
75% 45 °C GA	0.0139 ± 0.0004^{b}	49.9 ± 1.4^{bc}	165.7 ± 4.8^{b}	1.12 ± 0.01^{bc}	9322.1 ± 642.7^{bc}
90% 35 °C GA	0.0134 ± 0.0006^{b}	51.7 ± 2.3^{ab}	171.8 ± 7.7^{ab}		
90% 45 °C GA	0.0149 ± 0.0004^{c}	46.5 ± 1.2^{c}	154.5 ± 4.2^{c}	1.11 ± 0.02^{c}	8676.8 ± 997.0^{c}
75% 35 °C PD	0.0173 ± 0.0007^{d}	40.1 ± 1.6^{d}	133.1 ± 5.4^{d}		
75% 45 °C PD	0.0204 ± 0.0009^{e}	34.0 ± 1.5^{e}	112.9 ± 5.0^{e}	1.18 ± 0.00^{a}	13,416.1 ± 298.3^{a}
90% 35 °C PD	0.0182 ± 0.0008^{d}	38.1 ± 1.7^{d}	126.5 ± 5.6^{d}		
90% 45 °C PD	0.0209 ± 0.0011^{e}	33.2 ± 1.8^{e}	110.2 ± 5.8^{e}	1.15 ± 0.01^{ab}	11,243.3 ± 708.5^{ab}

Values expressed as mean ± standard deviation

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

GA gum Arabic, *PD* polydextrose)

k value and the lower the $t_{1/2}$ values (Lago and Noreña 2014).

According to Ruiz et al. (2012) by accelerated shelf life testing, the study the effect of the temperature might be realized using at least two temperature, a reference temperature and more another a temperature either higher or lower by 10 °C. Several studies on accelerated tests were performed at two temperatures, such as in guavira powder (Breda et al. 2012); in blackberry microparticles with maltodextrin and gum Arabic (Ferrari et al. 2013); in açaí microparticles with maltodextrin, gum Arabic and cassava starch (Tonon et al. 2010).

The activation energy indicates the sensitivity of the reaction to temperature, and higher values indicate a strong dependence on temperature, and the reaction occurs slowly at low temperatures, but relatively rapid at elevated temperatures (Mercali et al. 2015). Higher activation energy values were obtained for the microparticles with polydextrose, with 13,416 and 11,243 J mol^{-1} at 75 and 90% RH, respectively, when compared with the microparticles with gum Arabic, which presented values of 9322 and 8677 J mol^{-1} at 75 and 90% RH, respectively. This indicates that the phenolic compounds in microparticles with polydextrose were more susceptible to degradation with increasing temperature when compared with the microparticles with gum Arabic (Wang and Xu 2007). The Q_{10} values obtained for the microparticles with gum Arabic were smaller than those observed for the micropaticules with polydextrose, confirming that the latter was more sensitive to temperature variations (Labuza 1980). This parameter is a way to characterize the effect of temperature on the reaction constant, and represents the degradation rate as the temperature is increased by 10 °C (Kechinski et al. 2010). Q_{10} value shows the importance of the number of collisions and molecular associations, being that collisions supply an excess of energy that might deliver the molecules to the activation state and, as a consequence to increase the rate of degradation (Al-Zubaidy and Khalil 2007). The results showed that the increase in RH did not affect significantly Q_{10} and E_a values ($p > 0.05$).

With regard to the various encapsulating agents, the particles produced with gum Arabic showed lower Q_{10} values and the largest half-lives in all conditions studied, indicating greater stability of the wall material against humidity and temperature variations. Gum Arabic is a heterogeneous material having both hydrophobic and hydrophilic affinities, and its physicochemical responses depend on the balance of hydrophilic and hydrophobic interactions (Montenegro et al. 2012). According to these authors, the functional properties of the wall material are closely related to its structure, which determines the solubility, viscosity, the degree of interaction with a water and oil emulsion, and excellent ability to microencapsulation. Gum Arabic has a highly branched structure of a polymer of sugar with a little amount of protein covalently linked to the chain (Montenegro et al. 2012). Polydextrose is a glucose polymer and it has also a highly branched and complex structure (Röytiö and Ouwehand 2014). Those branched structures confer to both polymers good properties as encapsulating.

Thermodynamic analysis of the degradation of phenolic compounds of yacon microparticles under accelerated tests

The thermodynamic parameters are shown in Table 2, which can provide important information about the degradation phenomenon (Al-Zubaidy and Khalil 2007).

The ΔG values refer to the equilibrium and spontaneity criteria, and represent the difference between the active and the reactant state, and the positive sign means that phenolic degradation is a non-spontaneous reaction (Al-Zubaidy and Khalil 2007; Kouadio et al. 2013). All values were similar for both wall materials in the range of 86.56–89.36 and

Table 2 Thermodynamic parameters of the degradation of phenolic compounds of yacon microparticles stored under different conditions

	ΔG (kJ mol^{-1})	ΔH (kJ mol^{-1})	ΔS (J mol^{-1}K^{-1})
75% 35 °C GA	86.75	6.74	− 259.79
75% 45 °C GA	89.35	6.65	− 260.06
90% 35 °C GA	86.55	6.08	− 261.29
90% 45 °C GA	89.17	5.99	− 261.55
75% 35 °C PD	85.90	10.86	− 243.63
75% 45 °C PD	88.34	10.78	− 243.90
90% 35 °C PD	85.77	8.71	− 250.22
90% 45 °C PD	88.27	8.62	− 250.49

GA gum Arabic, *PD* polydextrose)

85.77–88.34 kJ mol^{-1} for gum Arabic and polydextrose, respectively, indicating that similar factors can affect the degradation of phenolics (Labuza 1980; Al-Zubaidy and Khalil 2007).

Lower ΔH values were observed for the treatments using gum Arabic, indicating that the energy barrier that must be exceeded to achieve the transition state was greater for the microparticles with polydextrose, and the positive sign means that phenolic degradation is an endothermic reaction, which leads to an increase in degradation with increasing temperature (Al-Zubaidy and Khalil 2007).

ΔS values measure the level of disorder of the molecules in the system. These values were similar for both encapsulating agents for all conditions, in the range of -243.64 to -261.56 J mol^{-1} K^{-1}. Negative ΔS values also were observed for degradation of anthocyanins, suggesting that the transition state is structurally more organized than the reactants and, for this reason, the formation of the activated complex is associated with a decrease in entropy (Mercali et al. 2015). The low activation entropy means that the state of the material approaches its thermodynamic equilibrium and consequently, has low reactivity, increasing the time required to form the activated complex (Georgieva et al. 2012). On the other contrary, the high activation entropy values, as observed in the present study, indicate that the material is far from its thermodynamic equilibrium, and the system can react more rapidly to produce the activated complex due to the higher reactivity.

Degradation of the total color difference of the yacon microparticles under accelerated tests

The total color difference was determined considering the values of the beginning of storage as reference (day 0). Figure 2 shows the total color difference of the microparticules as a function of time for both wall materials, indicating the increase of this parameter during storage and showing that it was largely affected by relative humidity and temperature conditions.

The initial values of the color coordinates were: $L^* = 91.85 \pm 0.35$; $a^* = -1.82 \pm 0.03$ and $b^* = 12.13 \pm 0.67$ for the microparticles with gum Arabic and $L^* = 90.49 \pm 0.07$; $a^* = -2.15 \pm 0.06$ and $b^* = 15.33 \pm 0.60$ for microparticles with polydextrose. Usually, color in food is associated with presence of phenolic compounds, and color change might be due to several chemical changes, such as of oxidation, reactions with free radicals, enzymatic browning, reactions of non-enzymatic browning, and degradation of these compounds (Tonon et al. 2010; Sun-Waterhouse and Waterhouse 2015, Kechinski et al. 2010; Andrade et al. 2014).

The microparticles became gradually darker over time, and the L^* values decreased for both wall materials and storage conditions, and were more pronounced during the first seven days of the experiment, whereas little variation was observed for the color parameters a^* and b^*.

After 35 days of storage, the total color difference values for the spray dried particles with gum Arabic were 61.14 and 66.83 at 35 °C and 75 and 90% RH, and 64.95 and 69.90 at 45 °C and 75 and 90% RH, respectively. The ΔE values of the microparticles with polydextrose were very close to the gum Arabic, being 69.19; 68.68; 69.96; and 69.71 at 35 °C/75% RH; 35 °C/90% RH; 45 °C/75% RH; and 45 °C/90% RH, respectively. The water sorption kinetics is governed by several factors such as the amount of water absorbed by the dry material, environmental conditions (especially temperature and relative humidity) and product microstructure (Borges and Cal-Vidal 1994). The structural changes caused by the collapse (due to moisture adsorption) of the powder affect some of the physical properties, such as color or mechanical behavior (Moraga et al. 2012).

In this study, the temperatures of storage may have contributed to the formation of Maillard reaction products, as evidenced by an increase in the color intensity of the microparticles. Browning may have also occurred due to thermal degradation of phenolic compounds, especially in the presence of oxygen and enzymes such as peroxidase and polyphenol oxidase that may have residual activity

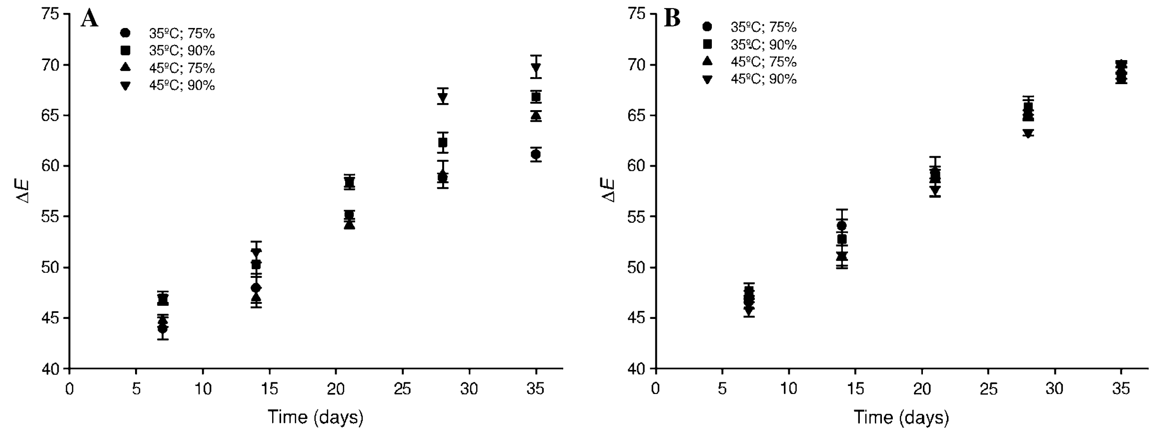

Fig. 2 Effect of storage temperature and relative humidity on total color difference of yacon microparticles with gum Arabic (**a**) and polydextrose (**b**)

even after blanching. In the oxidation reactions that participate the peroxidase as catalysator, either peroxide or oxygen might be used as the hydrogen acceptor, while the phenolic compounds may act as the hydrogen donor (Soysal and Söylemez 2005). The polyphenol oxidase is a copper containing enzyme that catalyzes the oxidation of phenolic substrates into quinones in the presence of oxygen, which in turn are polymerized in brown, red or black pigments (Mc Evily and Iyengar 1992).

Degradation kinetics of total color difference of yacon microparticles under accelerated tests

The first order model properly adjusted the data of the total color difference as a function of the storage time of yacon juice microparticles, with determination coefficients (R^2) above 0.95. The degradation kinetic parameters (k), half-life ($t_{1/2}$), and temperature coefficients (Q_{10}) are shown in Table 3.

The constant degradation of the total color difference was not significantly different for all conditions studied ($p > 0.05$). This indicates that all samples showed very similar degradation rate independent of temperature, humidity, and type of wall material. The half-life values were 56–46 days, with no statistical difference between them ($p > 0.05$), as well as the temperature acceleration factor, which indicates that all microparticles suffered similar effect with the temperature variation.

Table 3 kinetics parameters of the total color difference as a function of the storage time of yacon juice microparticles stored under different conditions

	k (days^{-1})	$t_{1/2}$ (days)	Q_{10}
75% 35 °C GA	0.0123 ± 0.0015^a	56.3 ± 7.0^a	
75% 45 °C GA	0.0139 ± 0.0010^a	49.9 ± 3.6^a	1.13 ± 0.06^a
90% 35 °C GA	0.0131 ± 0.0012^a	52.9 ± 4.9^a	
90% 45 °C GA	0.0151 ± 0.0012^a	45.9 ± 3.7^a	1.15 ± 0.01^a
75% 35 °C PD	0.0139 ± 0.0013^a	49.9 ± 4.7^a	
75% 45 °C PD	0.0148 ± 0.0010^a	46.8 ± 3.2^a	1.06 ± 0.03^a
90% 35 °C PD	0.0136 ± 0.0010^a	51.0 ± 3.8^a	
90% 45 °C PD	0.0150 ± 0.0004^a	46.2 ± 4.1^a	1.10 ± 0.05^a

Values expressed as mean ± standard deviation

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

GA gum Arabic, *PD* polydextrose

Conclusion

The phenol degradation and total color difference of yacon juice spray dried microparticles with gum Arabic and polydextrose exhibited first order kinetics. The increase in storage temperature had a negative impact on the phenolic degradation in the microparticles with polydextrose. However, the increase in relative humidity had no significant effect on the stability of the phenolic compounds of microparticles for polydextrose. Gum Arabic was the wall material that best protected the bioactive compound, with higher half-life for all conditions. Similar thermodynamic parameters were observed for all storage conditions, indicating that similar factors have affected the degradation of phenolic compounds in both wall materials. Kinetic analysis of total color difference as a function of storage time showed that the increase in temperature and humidity caused no significant effect on the degradation rate constant and the half-life of the spray dried microparticles with gum Arabic and polydextrose.

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