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Thermophysical properties of yacon (*Smallanthus sonchifolius*): experimental determination and effect of moisture content

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ABSTRACT. The knowledge about thermophysical properties of foods is especially important in thermal processing, influencing the design, optimization and cost reduction of the process, as well as the quality and safety of the final product. This article deals with the determination of some thermophysical properties of yacon, namely, specific mass, specific heat, thermal conductivity and thermal diffusivity during the osmo-convective drying. Yacon is a root with approximately 90% w.b. of moisture content, whose high concentration of fructooligosacharydes and antioxidants has gained attention in the food research field. Yacon slices were osmotically dehydrated for 2 hours in a sucralose solution and then dried in a convective tray dryer for 2 hours, varying the osmotic solution's temperature and stirring rate and temperature of the drying air. All thermophysical properties were determined during the drying process at 30-minute intervals. The thermophysical properties were determined not only experimentally but also calculated by models available in literature based on the product's centesimal composition. A satisfactory agreement between experimental and predicted results was obtained. Further, empirical models obtained by nonlinear regression were successfully fitted to the experimental data, as a function of moisture content, within a 94% - 3% w.b. range.

Keywords: thermophysical properties, yacon, osmotic dehydration, convective drying, heat and mass transfer.

Propriedades termofísicas do yacon (*Smallanthus sonchifolius*): determinação experimental e efeito do conteúdo de umidade

RESUMO. O conhecimento das propriedades termofísicas de alimentos é de extrema importância no processamento térmico, influenciando o *design*, a otimização e a redução de custos do processo. Este artigo trata da determinação de algumas propriedades termofísicas do yacon, tais como massa específica, calor específico, condutividade térmica e difusividade térmica, obtidas durante a secagem osmo-convectiva. O yacon é uma raiz com cerca de 90% de umidade b.u., cuja alta concentração de frutooligossacarídeos e antioxidantes tem despertado crescente atenção no campo da pesquisa de alimentos. Fatias de yacon foram desidratadas osmoticamente por 2h em uma solução de sucralose e então secas em um secador de bandejas por mais 2h, variando-se a temperatura e a taxa de agitação da solução e a temperatura de secagem. Todas as propriedades foram determinadas a cada 30 min. de processo. Além de determinadas experimentalmente, as propriedades termofísicas também foram calculadas por um modelo disponível na literatura, baseado na composição centesimal do produto, e uma concordância satisfatória entre dados experimentais e preditos foi obtida. Em seguida, um modelo empírico obtido por regressão não-linear foi ajustado com sucesso aos dados experimentais em função do conteúdo de umidade, em uma faixa de 94% a 3% b.u.

Palavras-chave: propriedades termofísicas, yacon, desidratação osmótica, secagem convectiva, transferência de calor e massa.

Introduction

Despite the extensive data of food thermophysical properties available in literature (RAO et al., 2005; SAHIN; SUMNU, 2006), no studies applied to yacon are extant. Yacon (*Smallanthus sonchifolius*) is a tuber grown in several regions of the world, with about 90% of moisture content, whose high prebiotic potential has attracted increasing interest in the field of food research.

The root's high concentration of natural phenolic antioxidants and fructooligosacharydes (GRAEFE et al., 2004; OJANSIVU et al., 2011) improves the digestive system's bifidogenic activity, reduces the glycemic and triglyceride blood levels (VALENTOVÁ; ULRICHOVÁ, 2003; CAMPOS et al., 2012), provides protection from colon carcinogenesis (MOURA et al., 2012) and beneficial effects on obesity and insulin resistance (GENTA et al., 2009). Since yacon has an extremely short shelf life, several drying processes have been successfully investigated to solve this problem (BERNARDI et al., 2009; SCHER et al., 2009; REIS et al., 2012). Consequently, the determination of its thermophysical properties is of fundamental importance to design and optimize thermal processes involving yacon.

There are direct and indirect methods for determining thermophysical properties of foods. In the first case, experiments provide direct results or rates that are transformed into the desired properties through mathematical equations. Specific mass, for instance, is usually determined by a pycnometer (QUIRION et al., 2012) or by the liquid displacement method (HASSAN; RAMASWAMY, 2011). The most common technique to determine thermal conductivity is the linear probe developed by Sweat (1974), based on heat conduction in transient state. The properties specific heat, enthalpy and heat capacity are commonly assessed by Differential Scanning Calorimeter (DSC). Although thermal properties are easily measured over a wide range of temperatures using DSC, it is an expensive method (RAO et al., 2005). Thermophysical properties of foods may also be obtained by indirect methods, based on the numerical solution of the transient heat transfer problem, followed by an optimization procedure to obtain the parameters considered therein. However, the above methodology is complex due to the great amount of information required (MARIANI et al., 2008). Empirical correlations between the product's chemical composition and its thermophysical properties, given as a function of temperature or moisture content, are available to estimate such properties (RAO et al., 2005). Although these relationships do not consider the influence of the interaction between the pure components on the food product's thermophysical properties, there are several studies using this methodology (VAN DER SMAN, 2008; DIMA et al., 2012; PERUSSELLO et al., 2012, 2013).

In the current analysis, certain thermophysical properties of yacon, namely, thermal conductivity, specific mass, specific heat and thermal diffusivity, were determined experimentally during an osmo-convective drying process. Empirical models, obtained by nonlinear regression, were fitted to the experimental results. All the mentioned thermophysical properties were also determined during the convective drying by equations based on the yacon's centesimal composition data, providing a comparison between the results obtained by different methodologies. The thermophysical properties were evaluated over a temperature range between 20 and 80°C and a moisture content range between 94 and 3% wet basis.

Material and methods

Materials

Yacon roots (*Smallanthus sonchifolius*), sourced from a local market in Curitiba, Paraná State, Brazil, and kept under refrigeration up to 7 days, were peeled and cut into radial slices of 2 mm thick. Sucralose (brand Linea Ltd.), a sugar cane derivate with caloric rates close to zero, was used as the osmotic agent.

Centesimal Composition Determination

The centesimal composition of yacon *in natura* was analyzed according to standard techniques (IAL, 2005). The analysis of moisture content followed the gravimetric method and the protein analysis was carried out by the Kjeldahl digestion method. The evaluation of fats followed the continuum extraction in Soxhlet type equipment and the ash analysis or fixed mineral residue was conducted by the mass loss through the incineration of the sample in a mufla stove at 550°C. Total carbohydrates were calculated by difference. All analyzes were conducted in triplicate.

Osmotic Pre-treatment and Convective Drying

Yacon slices were treated in a sucralose solution 20% (w w^{-1}) concentration with yacon and solution mass at the ratio 1:5. Temperature was set at 30 and 50°C and stirring rate was set at 0 and 4 cm s^{-1}, according to the 2^3 full factorial design shown in Table 1.

Table 1. Experimental design sketch.

Variable	Variable code	Level -1	Level +1
Solution temperature (°C)	*x1*	30	50
Solution stirring rate (cm s^{-1})	*x2*	0	4
Drying temperature (°C)	*x3*	60	80

The 2-hours osmotic pre-treatment was carried out in a thermostatic bath (Quimis, model Dubnoff Q-226M2) with temperature and stirring control. The osmotic treatment was not conducted to reduce the product's moisture content, but to maintain and, in some conditions, to improve certain quality attributes, such as color, texture and structural integrity of the yacon slices during the convective drying.

After the osmotic pre-treatment, the slices were dried for 2 hours in a forced convection tray dryer (Fabbe, model 170) at 60 and 80°C. The temperature profile during both operations was obtained using T-type thermocouples connected to a data acquisition system (Field Logger, brand Novus). The sensors were placed at the center of the slices.

During convective drying, the yacon's thermophysical properties, namely, specific mass, specific heat, thermal conductivity and thermal diffusivity, were determined at every 30 minutes of process by direct methods, as described in the next section. The slices' moisture content was determined in the beginning of the process by the gravimetric method (IAL, 2005) and calculated along drying based on mass variation measurements. Since the food's composition varied continuously during drying due to the water loss, the variation of mass fraction of each yacon's pure component could also be calculated throughout the experiment.

Physical Analyses

Specific mass was obtained by the liquid displacement method (SAHIN; SUMNU, 2006), used by several authors (CANSEE et al., 2008; KARIMI et al., 2009; HASSAN; RAMASWAMY, 2011), providing fast and satisfactory results. A sample of yacon with known mass was placed in a 250 mL beaker containing 150 mL of distilled water. Specific mass was then determined by dividing the sample mass by the volume of liquid displaced, according to Figure 1.

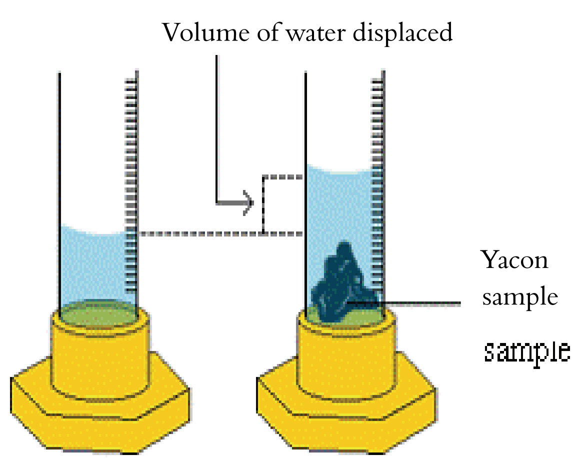

Figure 1. Determination of specific mass by the liquid displacement method.

Specific heat and thermal conductivity were determined by a thermal properties analyzer (Decagon KD2 Pro) respectively with sensors SH-1 and TR-1 (Figure 2). Sensor SH-1 determines the volumetric specific heat within a range of 0.5 to 4 mJ $m^{-3}\cdot K$ with a ± 10% accuracy, while sensor TR-1 measures a range of 0.10 to 4 W $m^{-1}\cdot K$ with a ± 10% accuracy between 0.2 and 0.4 W $m^{-1}\cdot K$ and ± 0.03 W $m^{-1}\cdot K$ from 0.1 to 0.2 W $m^{-1}\cdot K$. The KD2 Pro is a portable device that employs the transient line heat source method, developed by Sweat (1974), to measure thermal conductivity, resistivity, diffusivity and specific heat in a fast and accurate way. In this method, a known heat flow is generated from the product's center to its periphery, resulting in the establishment of a continuous current. After a brief interval, the relationship between temperature – in a point close to the probe – and time becomes linear in a mono-log scale. Thermal conductivity may be obtained by solving the Fourier equation using the above results (PERUSSELLO et al., 2010). Although the line heat source probe is recommended for a wide range of food products because of its simplicity, fastness, convenience and low cost (SWEAT, 1974), it is not adequate for non viscous fluids due to the rising of natural convection during the experiment (Tansakul; Chaisawang, 2006).

Thermal conductivity was thus provided directly by the properties analyzer, in W $m^{-1}\cdot K$, while specific heat was obtained by multiplying the volumetric specific heat given by the device, in mJ $m^{-3}\cdot K$, by the yacon's specific mass, in kg m^{-3}.

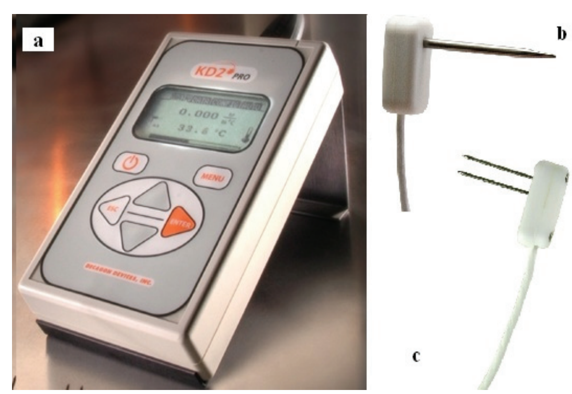

Figure 2. Device used to determine specific heat and thermal conductivity: (a) Thermal properties analyzer KD2-Pro; (b) sensor TR-1; (c) sensor SH-1.

Thermal diffusivity was calculated by (Equation 1):

$$\alpha = \frac{k}{\rho Cp} \quad (1)$$

where:

ρ is the specific mass [kg m^{-3}];
Cp is the specific heat [J $kg^{-1}\cdot K$];
k is the thermal conductivity [W $m^{-1}\cdot K$].

Empirical Correlations

The thermophysical properties of yacon in different moisture contents were evaluated by a nonlinear regression procedure which related the rates of the experimental properties with moisture content by the minimization of the least square function. Additionally, another approach was also used to calculate the specific mass, specific heat and thermal conductivity of yacon from its centesimal composition. The thermal properties were obtained from Equations (2) to (5) (SINGH; HELDMAN, 1993) using the properties of each yacon's pure component (water, carbohydrates, fats, proteins and ashes) given in Table 2.

Table 2. Thermophysical properties of pure components of food products (SINGH; HELDMAN, 1993).

Component	Proteins	Fats	Minerals	Carbohydrates	Water
Specific mass (kg m^{-3})	1380	930	2165	1550	1000
Specific heat (J kg^{-1}·K)	1900	1900	1100	1500	4108
Thermal conductivity (W m^{-1}·K)	0.20	0.18	0.26	0.25	0.56

The comparison between experimental results and data obtained by the two models (developed in the current work and given by the equations below) may indicate whether it is necessary to use the entire product's chemical composition or only its moisture content in order to obtain the thermophysical properties of yacon.

$$\rho = \frac{1}{\sum \frac{x_j}{\rho_j}} \quad (2)$$

$$Cp = \sum \left(x_j \times Cp_j \right) \quad (3)$$

$$k = \frac{1}{2}\left[\sum x_{vj} \times k_j + \frac{1}{\sum \left(\frac{x_{vj}}{k_j} \right)} \right] \quad (4)$$

$$x_{vj} = \frac{\frac{x_j}{\rho_j}}{\sum \frac{x_j}{\rho_j}} \quad (5)$$

where:

x_j is the mass fraction of each pure component of a food and x_{vj} is the volumetric fraction.

Results and discussion

Centesimal Composition

The centesimal composition analysis revealed that yacon is basically composed of water and carbohydrates, as Table 3 shows. The results are similar to those reported by Hermann and Freire (1998) for the chemical composition of 10 types of yacon grown in Peru, Equador, Bolívia and Argentina. According to these authors, the moisture content (w.b.) varies from 86.4 to 90.2%; total carbohydrates, from 8.9 to 12.7%; proteins, from 0.3 to 0.5%; fats, from 0.1 to 0.5%. The above data indicate that yacon roots used in the current work contains a slightly higher moisture content and lower carbohydrate content, which may be attributed to differences related to the type of cultivar, climate, soil, growing conditions and post-harvest time and temperature.

Table 3. Centesimal composition of yacon *in natura*.

Component	Content (%)
Moisture (w.b.)	93.61 ± 0.06
Moisture (d.b.)	14.64 ± 0.15
Proteins	0.53 ± 0.06
Fats	0.39 ± 0.03
Minerals	0.31 ± 0.05
Total carbohydrates	5.09 ± 0.03

Osmo-convective Drying

The moisture profile of yacon during the osmotic treatment in different conditions is presented in Figure 3a. The moisture content of the yacon slices varied slightly, from 90.64 to 88.35% w.b. As mentioned previously, the osmotic pre-treatment has been commonly used in several researches to enhance some quality attributes, such as flavor, color, texture and stability of nutrients during storage (EL-AOUAR; MURR, 2003) but not to provide significant water loss.

Although processes using 50ºC provided a higher weight loss (Figure 3b), especially when stirring was employed, the yacon slices became dark and with fissures. In their turn, the slices treated at 30ºC maintained their structural integrity and presented a color similar to the fresh yacon. Processes conducted at 50ºC provided a higher weight loss (from 28.72 ± 1.01 g of fresh yacon to 15.66 ± 3.38 g) when compared to those at 30°C (from 28.72 ± 1.01 g of fresh yacon to 28.73 ± 1.63 g). The positive effect of temperature on weight loss may be attributed to the heat action on the cellular tissue softening, leading to an increase in permeability (OZDEMIR et al., 2008; ISPIR; TOGRUL, 2009). In addition, higher temperatures decreased the solution's viscosity and led to higher water diffusion rates (SINGH et al., 2007). The stirring rate also influenced the results of weight loss, since it increased the transfer rate of solids and water from yacon to the osmotic solution. The above phenomenon may be ascribed to the transfer velocity of a component in a medium, which is the result of the contribution of diffusive (due to the concentrations' gradient) and convective motions (due to the fluid's global movement).

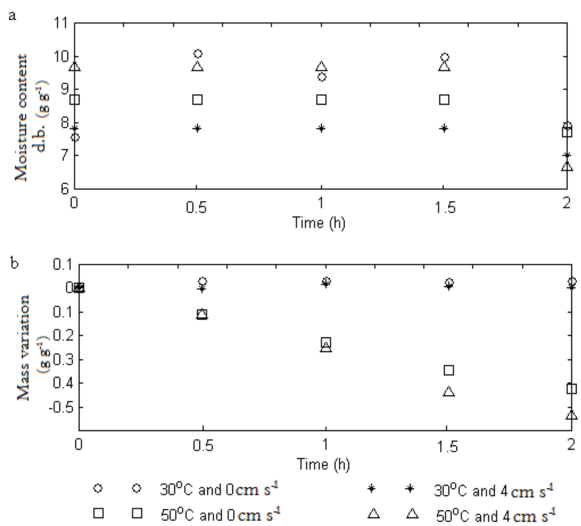

Figure 3. (a) Moisture content and (b) Mass variation of yacon during osmotic treatment.

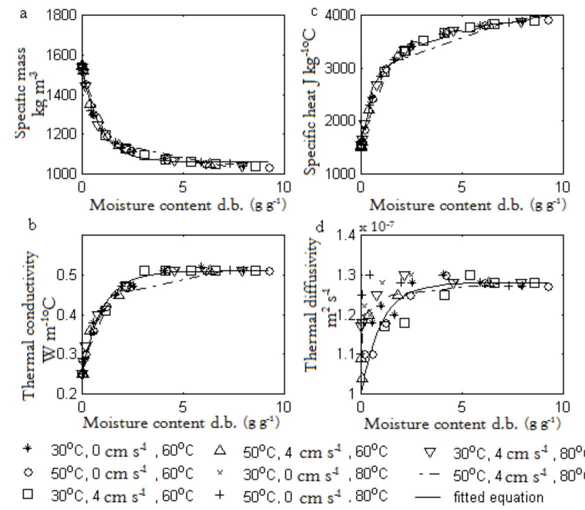

Figure 4. Yacon (a) specific mass, (b) specific heat, (c) thermal conductivity and (d) thermal diffusivity versus moisture contents during convective drying.

Figure 4 presents the thermophysical properties' variation during convective drying, obtained experimentally, which is dependent on the product's moisture content. Since water's thermophysical properties are very different from those of the other components – proteins, carbohydrates, fats and minerals – its influence on thermophysical properties of foods is significant. Specific heat, thermal conductivity and thermal capacity increase with the rise of moisture content. Thermal conductivity is more dependent on moisture content than on temperature, which is usual in food featuring high moisture content (SHMALKO et al., 1996). These figures also demonstrate that the thermophysical properties' rates are the same for a given moisture content whatever the process conditions are. These results confirm the high influence of the product's moisture content on these properties. Specific mass varied from 1037 to 1644 kg m^{-3} and decreased according to the product's water fraction, since the other food components – except fats – have a much higher specific mass compared to water. As water is removed from yacon, specific heat (1304 to 3919 J $kg^{-1o}C$), thermal conductivity (0.21 to 0.52 W $m^{-1o}C$) and thermal diffusivity (9.69e-8 to 1.30e-7 $m^2\ s^{-1}$) also decrease. This figure further shows the good agreement between measured and predicted properties' rates. Table 4 shows the fitted mathematical models used in Figure 4, obtained by a common procedure of nonlinear regression, which describe the measured thermophysical properties of yacon as a function of its moisture content. The determination coefficient confirms the good fitting between predicted and experimental rates. The form of the empirical models in Table 4 (exponential or logarithmic) was chosen according to the best data fitting.

Table 4. Fitted equations to calculate yacon's thermophysical properties as a function of moisture content during convective drying and its determination coefficient.

Property	Equation	R^2
Specific mass (kg m^{-3})	$\rho(X)$ = 1525.18-466.07×(1-exp(-X/0.9325))	0.9896
Specific heat (J $kg^{-1o}C$)	$Cp(X)$ = 433ln(X)+ 2959	0.9660
Thermal conductivity (W $m^{-1o}C$)	$k(X)$ = 0.25+0.2594×(1-exp(-X/1.0034))	0.9883
Thermal diffusivity ($m^2\ s^{-1}$)	$\alpha(X)$ = -1e-7+2.8e-8×(1-exp(-X))	0.9023

Figure 5 shows the comparison between experimental results and predicted rates obtained from Equations 2 to 5 (SINGH; HELDMAN, 1993), based on the centesimal composition of yacon. Results confirm that the equations available in literature may be used to predict specific mass, specific heat and thermal conductivity in a satisfactory manner.

With regard to thermal diffusivity prediction, a not so good agreement exists between predicted and experimental rates when compared to the other thermophysical properties (Figure 5d). The above may be associated to the fact that thermal diffusivity rates were evaluated indirectly by Equation 1 and thus rounding errors may have occurred. It is also worthwhile to mention that thermal diffusivity rates are numbers of much smaller magnitude when compared to those of the other thermophysical properties. Consequently, any error propagation would affect them much more.

In the current analysis, two methodologies for predicting the thermophysical properties of yacon during the osmo-convective drying were evaluated. One of them fitted the experimental results to empirical models obtained by nonlinear regression as a function of moisture content.

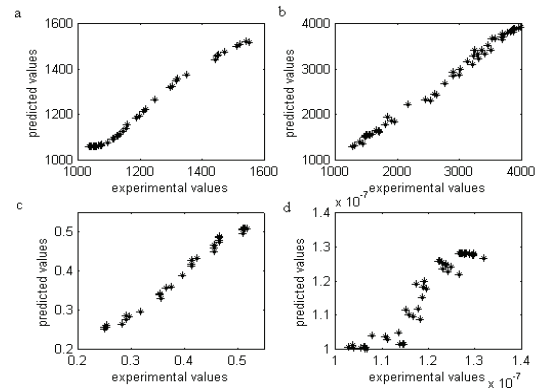

Figure 5. Experimental versus predicted rates for yacon (a) specific mass, (b) specific heat, (c) thermal conductivity, and (d) thermal diffusivity during convective drying.

The other one was based on the calculation of the properties from yacon's centesimal composition, using equations available in literature. Both methodologies provided good and similar results. This similarity confirmed the great influence of moisture content on the thermophysical properties of yacon, since the first approach only considered the moisture content, while the second one comprised the whole centesimal composition, with similar results. It is also worthwhile to point out that the empirical models presented in Table 4 may be used for yacon roots from different growing regions, since the composition differences between the yacon used in current research and other products reported in the literature are very small, as discussed previously.

Conclusion

A decrease in the moisture content of yacon during the osmo-convective drying led to a reduction in thermal conductivity, specific heat and thermal diffusivity and to an increase in specific mass. The comparison between experimental results and the rates predicted by correlations based on the chemical composition was satisfactory. The experimental data were also successfully adjusted to nonlinear empirical models which provided rates of yacon's thermophysical properties as a function of its moisture content only. Forasmuch as the results given by the two models were very similar, the thermophysical properties of yacon may be estimated by the moisture content-based models.

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