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DATA ACQUISITION FOR MODELING CONVECTIVE DRYING OF YACÓN (*Smallanthus sonchifolius*) SLICES

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KEYWORDS

kinetics, thermophysical properties, shrinkage, fructo-oligosaccharides

ABSTRACT

Poor in simple sugars and rich in fructo-oligosaccharides, *yacón* roots are considered as functional foods. However, their short shelf life demands a treatment prior to storage. This work aims to describe the convective drying of *yacón* slices and their properties, for posterior use in a numerical model to describe the process. Weight, diameter and height data were acquired for *yacón* slices dried in a specific convective dryer. Images obtained while drying show that samples underwent some browning, despite the blanching process prior to drying. Samples underwent some deformation and presented structural irregularities, apparently in random positions. Thermal properties obtained for the samples were similar to those of the literature, but soluble solids content was inferior. The absence of a constant rate period on the drying rate curve suggests that capillary diffusion and similar mechanisms control the drying rate along drying process.

INTRODUCTION

Yacón (*Smallanthus sonchifolius*) is a tuberous crop originary from the Andean region. Its mildly sweet roots are normally eaten raw. Due to a carbohydrate profile rich in fructo-oligosaccharides (FOS) and inulin, and low on simple sugars, the *yacón* is currently considered beneficial for diets of low sugar intake (Santana; Cardoso, 2008).

Inulin and FOS are reserve polysaccharides found in plants, considered by some authors as dietary fiber (Englyst, 1989; Espinal-Ruiz et al., 2014; Franck; Alexiou, 2009.). Their β (2-1) bonds are not digested in the human gastrointestinal tract, so these compounds reach the colon practically intact and are fermented by anaerobic bacteria. Even though they do not provide energy directly, they are broken down in molecules that may be digested or act indirectly as metabolic regulators (Mussatto; Mancilha, 2007). There is evidence that inulin and FOS act as prebiotics, promoting growth of *Bifidobacterium* and *Lactobacillus* populations (Watzl; Gurrbach; Roller, 2005). Increasing these populations hinders the growth of

pathogenic bacteria populations, leading to a healthier microbiota (Roberfroid; Gibson, 1995).

Fresh *yacón* roots have a high water content, above 850 g/kg (Hermann; Freire; Pazos, 1998), and high water activity. At room temperature, the shelf life of a *yacón* root is only about a week. The availability of water makes *yacón* roots vulnerable to spoilage by micro-organisms and enzymatic degradation of FOS (Roberfroid; Gibson, 2010; Reis et al., 2012). Refrigeration is a way to extend shelf life up to three months (Seminario; Valderrama; Manrique, 2003; Santana; Cardoso, 2008). Drying *yacón* roots is a way to reduce water activity and increase their shelf life, without major technologic inconvenient.

Aside from microbial degradation, *yacón* roots darken rapidly after cut. The presence of polyphenoloxidase (PPO) and oxygen causes hydroxylation of monophenols in *yacón* roots, forming quinones, that polymerize and become dark pigments (Lachman; Fernández; Orsák, 2003; Rodrigues; Asquieri; Orsi, 2014). This coloration may be a reason for rejection by final consumers, and is preventable by either chemical or vapor blanching, to inactivate the PPO. However, inulin and FOS are vulnerable to drying and pretreatments. Scher, Rios and Noreña (2009) dried *yacón* roots after vapor blanching, and observed a lower amount of inulin than in samples dried without pretreatment.

So far, we have not found in the literature any simulation of convective drying of *yacón* that considers shrinkage and real operational conditions of drying. Bernstein and Noreña (2014) have measured shrinkage of cubic *yacón* slices, and Scher et al. (2009) measured the effect on FOS and inulin content; neither of the authors proceeded to a modelling or simulation step. Curcio et al. (2016) developed a conjugated model to describe drying of vegetables, but did not include heat irradiation in their model. Perrussello et al. (2014) have simulated the osmo-convective drying of *yacón* slices in COMSOL (Comsol Inc.), without mentioning shrinkage, and considering only one slice per simulation.

The present work comprises (i) collection of data, namely characterization of *yacón* roots during drying process, (ii) identification of structural changes, and (iii) measurement of drying kinetics. Data collected will be used as the basis to implement a physics based model describing drying of *yacón* slices that could be used for process optimization. A model is under development by our partners (Plana-Fattori et al., 2020) to study convective drying of cylindrical slices of food products that undergo large deformation.

DRYING EQUIPMENT AND IMAGE ACQUISITION

Drying experiments were performed in a LM-ES20 dryer (Labmaq, Brazil). It consists of a metallic chamber containing four removable perforated trays. Each tray is coupled with a scale that measures mass in real time. The chamber is equipped with a forced air circulation system, able to control air speed, temperature and relative humidity (RH). These data, along with mass changes, are registered by interface in real time. The control system for air conditions is represented in Figure 1.

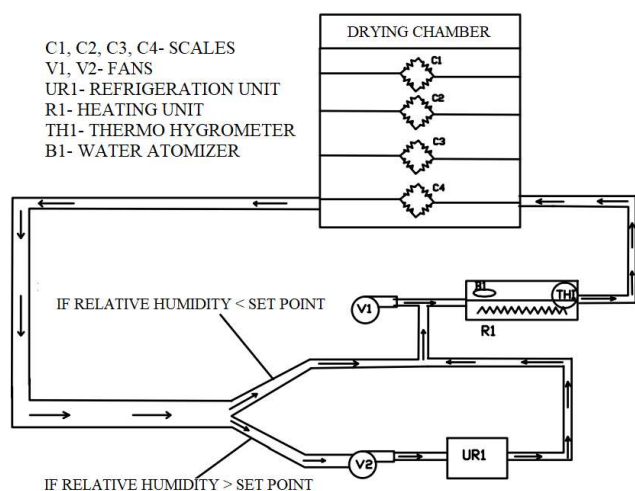


Figure 1: Schematic representation of the dryer control system. Source: Labmaq do Brasil (Adapted)

The dryer has a transparent quartz window with a diameter of approximately 10 cm, located above the center of the upper tray. This window allows visualization of the material being dried, and is equipped with a calibrated stereomicroscope (Leica S6D, Germany). A digital camera (Leica MC170HD, Germany) captures images from the stereomicroscope, and sends them to an image acquisition software (LAS 6, Leica Microsystems Applications, Switzerland) for processing and measuring.

SELECTION OF OPERATIONAL CONDITIONS AND DRYING EXPERIMENTS

Sample size and blanching

Samples were cut as cylinders of the same size. A diameter of 4 cm, approximately the root diameter in the majority of cases, was chosen in order to minimize waste. Sample height was established as 7 mm, a minimum observed in pre-tests to obtain chips that don't stick to the tray and tear up when removed.

Fresh *yacón* roots (cv. Blanco) were obtained from a producer from Piedade, Brazil. An aqueous solution of citric acid (Tate & Lyle, Brazil) 2 g/kg was chosen for samples blanching, based on preliminary tests with solutions of (2, 6 and 10) g/kg, as suggested by Reis et al. (2012).

Yacón slices were cut and immediately immersed in the solution, at ambient temperature, for 3 min.

Drying: pre-tests and experiments

Prior to drying, 3 *yacón* slices were collected for initial moisture content determination (see next section). For drying tests, 42 *yacón* slices were disposed on one of the metallic trays and submitted to the drying for at least 330 min.

A total of 12 preliminary essays were performed, three for each of the conditions of the drying air: a) 50 °C and 20 % of RH; b) 50 °C and 30 % of RH ; c) 60 °C and 20 % of RH ; d) 60 °C and 30 % of RH . The condition that presented the lowest deviation between the three runs was chosen to be presented in this work.

While drying, images were captured each 30 min using the stereomicroscope described previously. Sample height was measured for three samples previously marked, using a micrometer (Mitutoyo 103-137, Brazil), in separate experiments. Each half hour, the chamber door was open, the three samples were removed, measured, and returned.

PROPERTY MEASUREMENTS

Soluble solids

A digital refractometer (ATR-BR, Schmidt-Haensch, Germany) was used to measure soluble solids content (° Brix). Four fresh *yacón* roots were selected randomly, and transversally cut in four pieces of 3 cm height approximately. On each piece, a puree was produced *in loco* using a spatula, and placed on the refractometer, and the soluble solids content was measured.

Moisture content

Moisture content of samples was determined after drying at 70 °C in a vacuum oven, according to the method proposed by Zenebon; Pascuet; Tiglea (2008), based on AOAC standard method 926.12/1996.

Real and apparent volume

For volume determination, 15 *yacón* slices were prepared according to the procedure for drying, cut in four parts, and left in the dryer, at 50 °C and 20 % of RH. Each hour, two portions of approximately 2 g of *yacón* were removed from the tray, weighed, and tested first for real volume, then apparent volume.

Real volume tests were performed in a gas pycnometer (AccupycII, Micromeritics, USA), using helium, a 10 cm³ test chamber, and 5 repetitions.

Apparent volume was measured using toluene, and metallic pycnometers of approximately 25 cm³, according to the volume displacement method described by Rahman (2009).

After real and apparent volume determination, moisture content of samples was determined (see previous section).

Vapor sorption isotherms

Before use, *yacón* samples were cut into slices, with diameter of 4 cm and height of 3 mm, and dried at 60 °C for one hour in a forced circulation oven (N480, Nova Ética, Brazil). A vapor sorption analyzer (VSA 1055, Decagon Devices, USA) was used to obtain vapor sorption isotherms at 60 °C, from a_w

= 0.9 to $a_w = 0.1$, then back to $a_w = 0.9$, using static (DVS) and dynamic (DDI) methods. After each isotherm was completed, the initial dry mass was determined, to calculate initial moisture content (see Moisture Content section).

Thermal properties

Yacón samples were cut and blanched as described for drying tests, except for the height, of 3 mm in this case. 60 slices were put on a perforated metallic rack and dried in a forced circulation oven (N480, Nova Ética, Brazil). Drying temperatures were 50 °C and 60 °C and each test was performed in triplicate.

At 2 h, 4 h and 5 h, samples were removed from the oven, in sufficient quantity to form a 3 cm stack. The sample stack was perforated by a SH-1 double needle probe from the KD2-PRO thermal properties analyzer (Decagon Devices, USA). The head of the sensor, along with samples, was wrapped in PVC film, put in a PVC zip bag, and immersed in a water bath (RE620S, Lauda, Germany) at the same temperature as the drying air (50 °C or 60 °C).

To aid with immersion, glass pieces of approximately 8 cm³ each were added to the plastic bag until it submerged. After temperature stabilization, measurements for thermal properties were performed at least four times. The measurements comprised: thermal conductivity k (W/m K); volumetric specific heat $c_{p,v}$ (mJ/m³ K) and temperature T (°C). After thermal properties measurement, moisture content of each stack of samples was determined in a vacuum oven at 70 °C and P < 100 mm Hg (see Moisture Content section).

RESULTS

Soluble solids

Soluble solid contents for the four roots tested, according to test positions, are shown in Table 1.

Table 1. Soluble solids content in fresh *Yacón* roots*

Position	Soluble solids content (°Brix)			
	Root 1	Root 2	Root 3	Root 4
h = 0 cm	8.33 ^a	7.79 ^b	7.98 ^b	9.03 ^a
h = 3 cm	10.67 ^a	8.00 ^b	7.66 ^b	9.17 ^a
h = 6 cm	10.13 ^a	8.14 ^b	8.46 ^b	9.80 ^a
h = 9 cm	9.20 ^a	8.63 ^b	7.84 ^b	8.81 ^a

*Means of columns with the same letter are not significantly different at a significance level $p < 0,05$.

Soluble solids content can vary not only between different roots, but also between different positions of the same root.

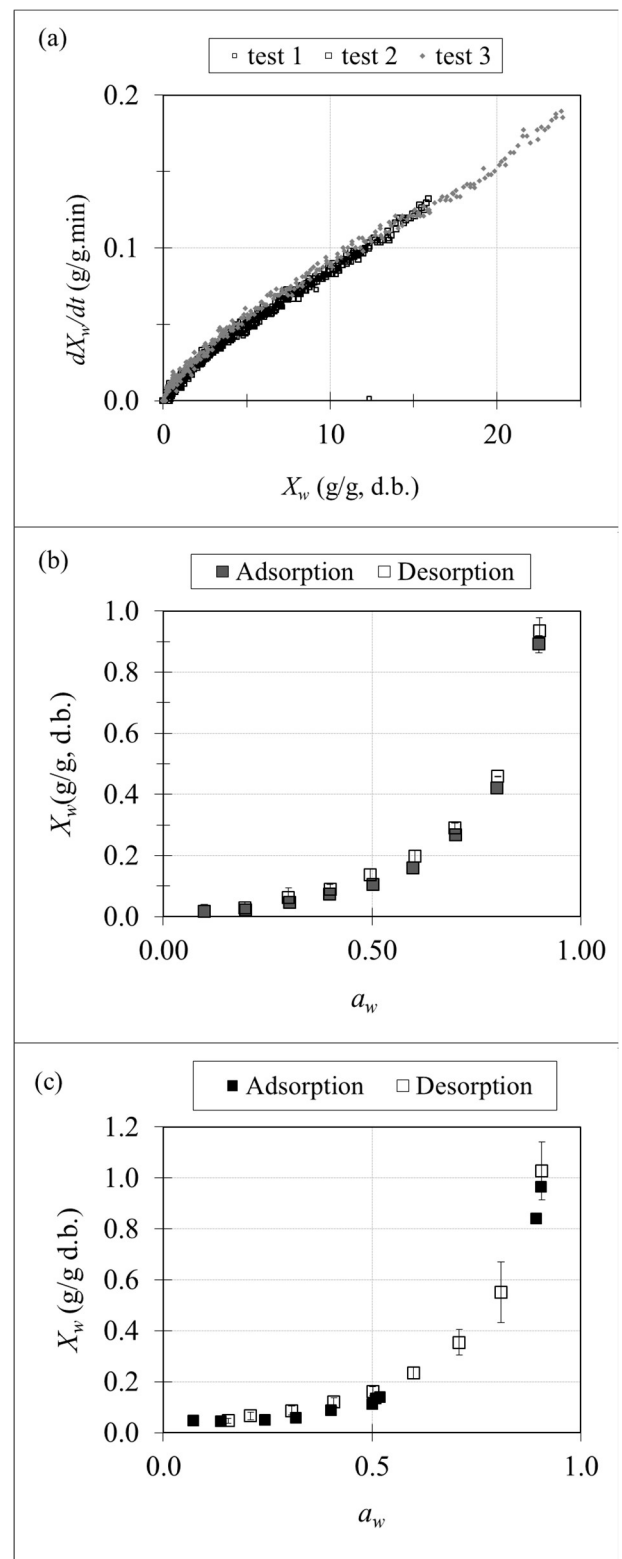


Figure 2. Drying rate curve (a), and vapor sorption isotherms for *Yacón* slices, obtained at 60 °C with (b) static method and (c) dynamic method

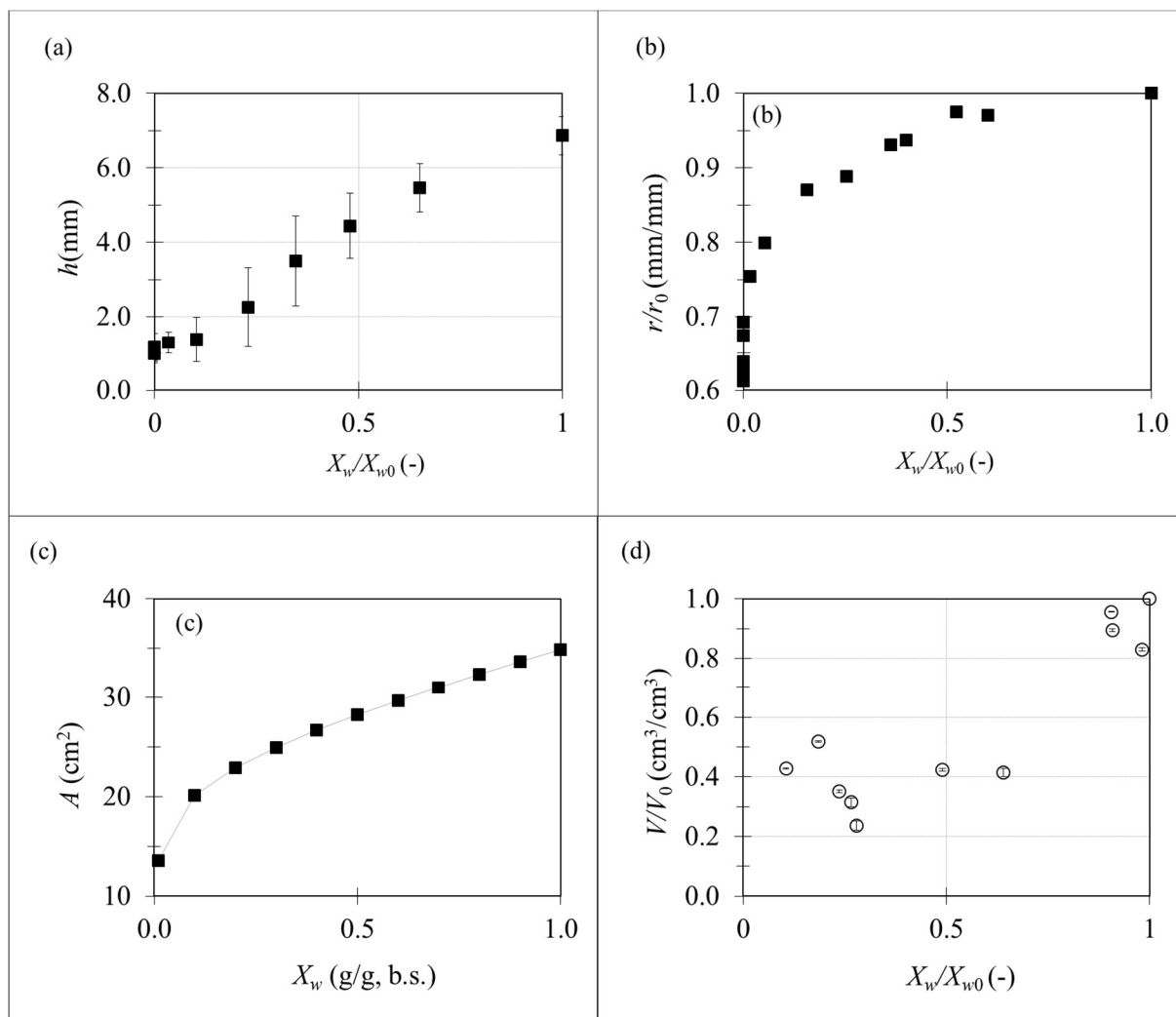


Figure 3. Normalized height (a), normalized radius (b), area (c), and normalized real volume (d) during drying process.

Note that in the literature (Graefe et al., 2004; Perussello et al., 2014; Scher et al., 2009) soluble solids content for *yacón* is reported to be higher (9.3 ° Brix to 17.6 ° Brix) than those obtained in this work. This variation could be due to difference in cultivars, season of harvest and crops conditions. Sugar content may influence in the sorption isotherm behavior, lowering the water vapor partial pressure in the mixture (Lewicki, 2009). However, in Figure 2 (b) and (c), it is noticeable that the variation in sugar content did not hinder isotherm reproducibility.

Choice of drying conditions

The drying condition that presented the lowest deviation between runs was 60 °C, with RH = 20 %. It is the most drastic condition tested, and the fastest to stabilize, due to the control system sprays water in the drying air with less frequency to maintain the desired RH.

Due to the presence of condensed water on the quartz window in the first half hour of tests, it is not possible to capture

images through it until condensation clears out. Hence, sample diameter is assumed to be 4 cm at this time interval.

Drying rate and sample dimensions

Figure 2 (a) shows the drying rate curve for *yacón* slices dried at 60 °C and RH = 20%. The drying rate curve does not exhibit a constant rate period, suggesting that drying rate is mostly controlled by vapor diffusion from inside the solid matrix. The vapor sorption isotherm, shown in Figure 2 (b), was also obtained at 60 °C, in static conditions. It is classified as Type III, common for foods containing soluble components, such as sugars (Rao, Rizvi, and Datta, 2005).

A vapor sorption isotherm obtained in dynamic conditions (Figure 2c) presented a similar behavior that obtained in static conditions, except the adsorption between $a_w = 0,4$ and $a_w = 0,8$. A sharp increase in water content can be observed when samples suffer deliquescence (Schmidt and Lee, 2012); possibly, the dynamic test that did not allow the sample to reach equilibrium caused the apparent absence of a section.

In Figure 3, dimensions of the slices along drying are shown. Note that samples undergo a more significant shrinkage in height (Figure 3a) than in radius (Figure 3b). Sample height has stabilized around a fifth of the original size, while sample radius decreased only up to sixty percent of the original size. These are interesting results if the desired final product is a *yacón* chip, because it will be thin, but relatively large in diameter. Sample area (Figure 3b) was calculated based on sample height and diameter, and exhibits a behavior similar to the radius curve: a faster decrease under $X_w = 0,1$.

Water removal is known to collapse the structure of vegetables (Castro, Mayorga, and Moreno, 2018). Further microcharacterization tests may be able to identify if this phenomenon was more intense at this moment.

Measured real volume (Figure 3d) may appear scattered because the samples tested were not the same, due to the destructive nature of the apparent volume test. Anyway, as expected, sample volume decreases with the removal of water. Apparent and real density exhibit a decreasing tendency with the increase of moisture content (Figure 4). Calculated apparent density appears lower in some points, probably due to a failure in air bubble removal during measurement. *Yacón* samples remained round throughout drying, and underwent a slight change in color (Figure 6 a to l).

Browning was not completely prevented by blanching, and is more visible in thin radial stripes, typical to the *yacón* root structure.

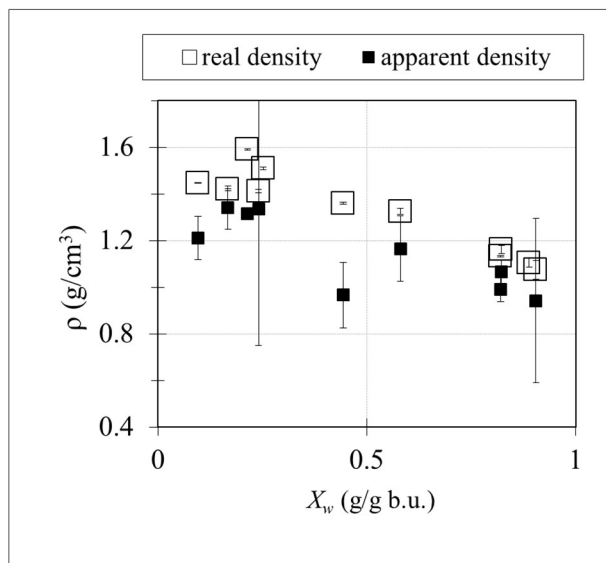


Figure 4. Real and apparent density at various moisture contents.

An ampliation shows that, before drying, *yacón* roots present a regular, smooth structure (Figure 6 m) that becomes more irregular with moisture loss (Figure 6 n).

Some regions on sample surface appear lighter. Further tests may indicate if those light colored areas are sugars that migrated from inside the structure, or only a dried, hardened portion of the surface. In any case, a hardened surface can make moisture loss slower and uneven (Ratti, 1994).

Figure 6 (o) shows a dent-shaped structural irregularity, commonly observed in the final hour of drying. These irregularities appeared in radial stripes from the sample center, in apparently random positions. This phenomenon has influenced randomly the height measurements, given that it was not possible to predict where an irregularity would appear.

Another difficulty in height measurements was the final shape of dried *yacón* slices. Sample borders dried faster than the center, tending to cause deformations. Frequently, the border was raised from the tray while the center remained in contact with it, creating a bowl-like structure (Figure 5). This effect is not perceptible in images taken from above the sample (Figure 6). This is why the change on optical focus height on the stereomicroscope is not suitable to measure sample height.

Thermal properties

Thermal conductivity and volumetric specific heat for *yacón* roots at different moisture contents are shown in Figure 7. These properties are known to be influenced by sample composition, structure, and process conditions. In this case, these properties were more dependent on moisture content than temperature. At high moisture contents, above $X_w = 0,8$, thermal conductivity and specific heat are similar to those of water. As water is removed, thermal conductivity decreases up to 0.2, similar to that of fiber and soluble carbohydrates (Carson, 2006; Rahman, 2009).



Figure 5. Final shape of dried *yacón* slices

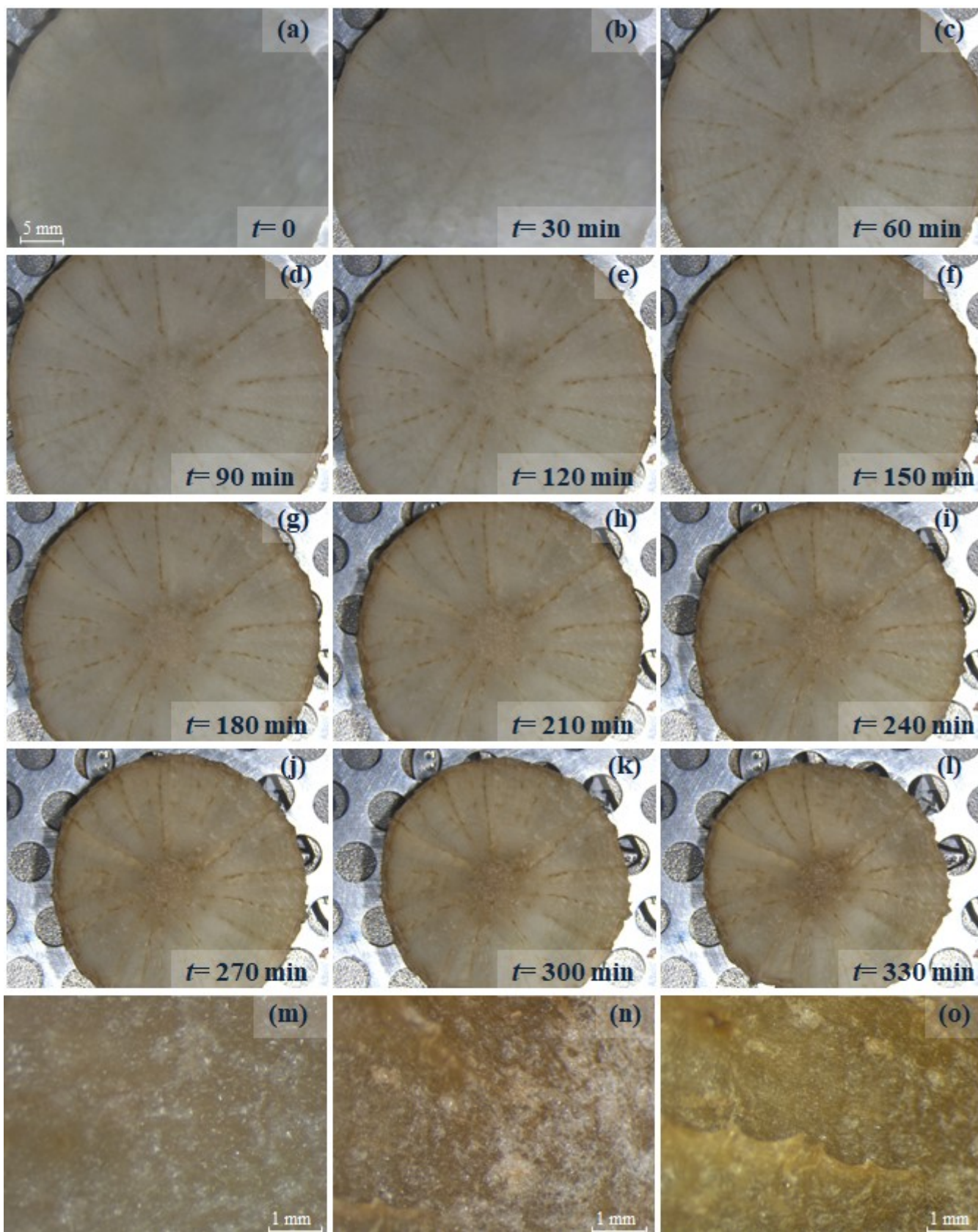


Figure 6. Photos of a single yacón slice during drying process, up to 330 min. (a) to (l): whole slices; (m) to (o): 40 x ampliation, after (m) 0 minutes; (n) 300 minutes and (o) 330 minutes, emphasizing a structural irregularity

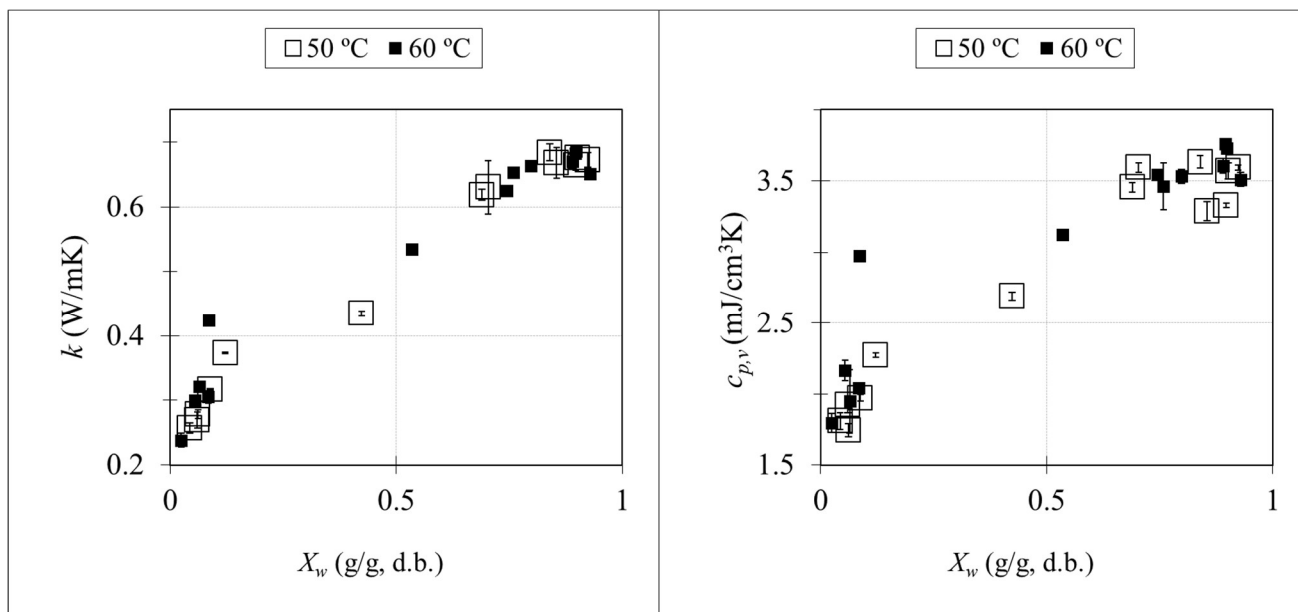


Figure 7. Thermal properties of *yacón*, for 50 and 60 °C.

CONCLUSIONS AND WORK UNDERWAY

It was possible to obtain kinetic parameters and thermophysical properties for *yacón* slices throughout drying process, in a selected condition. Samples were visually accompanied during the drying process, allowing to conclude that blanching was not completed. Weight was also measured in real time. The absence of a constant drying rate period suggests that, throughout all drying process, the limiting factor for moisture loss is migration from the interior of the sample. Sample shape presented some irregularities, specially at the end of the drying process. These irregularities will need to be taken into consideration when modelling. Data for water sorption was also obtained, and can be useful in the future for an assessment of dried sample stability.

For a better understanding of the phenomena occurring during the drying, more data will be collected. Convective heat conduction will be estimated using metal pieces with the same geometry of a *yacón* slice, and its temperature will be monitored using a thermocouple.

We plan on studying the influence of two different temperatures (50 °C and 60 °C) and relative humidities of the drying air (20 % and 30 %) on the final soluble fiber content, for some insight on the nutritional quality of the final product. With these results, the immediate next steps are microcharacterization of *yacón* roots and use of collected data in a mathematical model. There are sufficient data to assume varying thermophysical and geometric properties, and feed real parameters to a simulation. We intend to include the effect of heat irradiation from oven walls, convection from air and conduction inside the sample and from the tray. The available knowledge about the convective drying of *yacón* will be improved by the physics-based modeling; relevant phenomena will be assessed at time and space scales beyond experimental capabilities.

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BIOGRAPHIES

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ARTEMIO PLANA-FATTORI was born in Brazil; he studied Atmospheric Sciences in the Univ. de Sao Paulo and later in the Univ. Lille 1 (Ph.D. in 1994). After 20 years teaching and conducting research in Brazil, he joined AgroParisTech in 2010, where he has been working with numerical modeling applied to food engineering.

CARMEN CECILIA TADINI conducts research on food science and engineering, with applications in pasteurization, bakery, drying and biodegradable films by extrusion. She is Full Professor at Univ. of São Paulo and author of one of the few textbooks about Food Engineering in Portuguese.