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Bianca Cristine Marques, Artemio Plana-Fattori, Denis Flick, Carmen Cecilia Tadini. Convective drying of yacón (*Smallanthus sonchifolius*) slices: A simple physical model including shrinkage. *LWT - Food Science and Technology*, 2022, 159, pp.113151. 10.1016/j.lwt.2022.113151 . hal-03579343v1

HAL Id: hal-03579343

<https://hal.science/hal-03579343v1>

Submitted on 7 Aug 2023 (v1), last revised 21 Aug 2023 (v2)

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LWT

CONVECTIVE DRYING OF YACÓN (SMALLANTHUS SONCHIFOLIUS) SLICES: A SIMPLE PHYSICAL MODEL INCLUDING SHRINKAGE

--Manuscript Draft--

Manuscript Number:	LWT-D-21-04829R3
Article Type:	Research paper
Keywords:	Yacón; Convective drying; Drying kinetics; shrinkage behavior
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Abstract:	<p>Yacón is a tuberous root from the Andean region, and a potential functional food because of the presence of fructo-oligosaccharides (FOS). Due to its high moisture in natura, the product is prone to microbial degradation. The evolution of yacón cylindrical slices under convective drying is here studied from experimental work and theoretical considerations about bulk properties. The operation of a pilot-scale convective dryer allowed monitoring the moisture and dimensions of yacón slices. Evolution of moisture under temperature, and relative humidity, controlled conditions is described through a two-parameter drying kinetic model. A novel approach for estimating shrinkage effects is proposed, comparing measured dimensions with predictions based upon hypothetical shrinkage behaviors. The drying kinetics and the shrinkage approach are finally combined with the global energy balance for a single slice, in order to describe the evolution of surface temperature and other yacón slice properties along the drying period.</p>



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Prof. Rakesh. K. SINGH

Editor-in-Chief

LWT - Food Science and Technology

São Paulo, January 10th 2022

Dear Prof. SINGH,

We are sending you a revised version of the manuscript that we have submitted in July 2021, co-authored by Artemio Plana-Fattori, Denis Flick, Carmen C. Tadini and myself. This version contains improvements, marked **in red**, motivated by the constructive criticism demonstrated by the Reviewers.

We thank you for considering our paper for publication.

Looking forward to hearing from you.

Yours sincerely,

Bianca Cristine Marques

On behalf of all authors

Responses to reviewer's remarks

We would like to thank the Editors and Reviewers for their suggestions, that were carefully reviewed. A new section in the manuscript (3.5) is marked in red. We kindly invite you to verify this new version, hoping that it is now appropriate for publishing at LWT. Thank you again for helping us improve our work.

HIGHLIGHTS

The evolution of yacón slices under convective drying was studied at pilot scale. 81

Experimental data were collected under controlled air temperature and humidity. 79

Moisture loss observations were approximated through a novel two-parameter model. 81

Shrinkage of yacón slices was described by a combination of hypothetical models. 80

The global energy balance allowed to predict surface water activity and temperature. 84

1

1 **CONVECTIVE DRYING OF YACÓN (*SMALLANTHUS SONCHIFOLIUS*) SLICES:**

2 **A SIMPLE PHYSICAL MODEL INCLUDING SHRINKAGE**

3
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13 **ABSTRACT**

14 Yacón is a tuberous root from the Andean region, and a potential functional food because of the
15 presence of fructo-oligosaccharides (FOS). Due to its high moisture *in natura*, the product is prone
16 to microbial degradation. The evolution of yacón cylindrical slices under convective drying is here
17 studied from experimental work and theoretical considerations about bulk properties. The operation
18 of a pilot-scale convective dryer allowed monitoring the moisture and dimensions of yacón slices.
19 Evolution of moisture under temperature, and relative humidity, controlled conditions is described
20 through a two-parameter drying kinetic model. A novel approach for estimating shrinkage effects
21 is proposed, comparing measured dimensions with predictions based upon hypothetical shrinkage
22 behaviors. The drying kinetics and the shrinkage approach are finally combined with the global
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24 yacón slice properties along the drying period.

25

26

27 **KEYWORDS**

28 Yacón, convective drying, drying kinetics, shrinkage behavior

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33 Experimental data were collected under controlled air temperature and humidity. 79

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35 Shrinkage of yacón slices was described by a combination of hypothetical models. 80

36 The global energy balance allowed to predict surface water activity and temperature. 84

37

38 1. Introduction

39 The mechanisms underlying the processing of food raw materials must be understood in order to:
40 a) manufacture, in a reproducible manner, products for consumption, b) assess the influence of
41 raw material variability, and c) provide insight into process optimization. Consumers are
42 increasingly interested in the ingredients and processes associated with their food. “Clean labels”
43 with recognizable ingredients, and as few preservatives as possible, are a trend in the food market
44 (Asioli et al., 2017).

45 Here we focus on yacón (*Smallanthus sonchifolius*), a tuberous crop from the Asteraceae family,
46 originally from the Andean region and nowadays cultivated worldwide. Its roots, described as
47 succulent and mildly sweet, with a thin peel, can be eaten raw. While in the majority of storage
48 roots the energy is stored as starch, in yacón it is stored as inulin and fructo-oligo-saccharides
49 (FOS) instead. These compounds naturally exist in plants, but in concentrations usually lower
50 than those in yacón roots. The human gastrointestinal tract does not have enzymes to digest these
51 compounds, so they reach the gut microbiota practically intact (Grau and Rea, 1997; Hermann et
52 al., 1999; Seminario et al., 2003; Lebeda et al., 2012). In other words, albeit sweet, they have a
53 low caloric value for humans, making them an interesting option for diabetics. In addition, inulin
54 and FOS are appreciated as effective and safe prebiotics (Fernandez et al., 2013) with claims of
55 immunomodulatory effects (Watzl et al., 2005). Root flesh colors vary from white to yellow,
56 orange, and purple, depending on the genotype (Hermann et al., 1999). Chemical characteristics,
57 such as phenolic compounds and saccharides, may vary significantly between cultivars (Graefe et
58 al., 2004; Khajehei et al., 2018b).

59 As a source of inulin and fructose, tuberous roots of yacón can be employed in the production of
60 cold drinks and alcohol, dry crisps, jams and stewed fruits, sweeteners and some dairy products
61 like yoghurt (Lebeda et al., 2012). A major portion of tuberous root biomass of yacón is
62 composed of water (> 70% of fresh weight) (Lachman et al., 2003). Water activity is also high,
63 leading to a short shelf life; partial hydrolysis of oligo-fructans can start within only a few days
64 after harvest (Graefe et al., 2004). Drying is a convenient way to prepare yacón for storage, and
65 the influence of drying conditions on the chemical composition of yacón samples has been
66 investigated (Scher et al., 2009; Campos et al., 2016; Khajehei et al., 2018a; Salinas et al., 2018).

67 Several techniques have been applied to dehydrate yacón samples, including hot air convection
68 drying (Scher et al., 2009), vacuum drying (Reis et al., 2012), freeze drying (Khajehei et al.,
69 2018a), as well as hybrid techniques combining forced convection with osmotic dehydration
70 (Perussello et al., 2013, 2014) or microwave heating (Shi et al., 2015). However, in drying yacón
71 samples, none of these studies have controlled the air relative humidity. In other words, caution
72 should be exercised in discussing these results: without control of relative humidity, ambient
73 conditions may vary due to drying of the product. Such a control has been implemented in the
74 drying of many foods, including apples (Assis et al., 2019; Sjöholm & Gekas, 1995) and potatoes
75 (Hassini et al., 2007; Sandoval-Torres et al., 2017; Chua et al., 2000).

76 One of the most important physical changes undergone by food during drying is the reduction of
77 its volume. Loss of water and heating cause stresses in the cellular structure of the food matrix,
78 leading to changes in shape and decrease in dimension (Mayor and Sereno, 2004). The volume

79 reduction and shape modification of yacón samples under convective drying has been scarcely
80 investigated (Bernstein and Noreña, 2014).

81 Different modeling approaches have been used for studying the evolution of fruits and other
82 high-moisture-content food materials under convective drying (Castro et al., 2018). A complete
83 thermo-hygro-mechanical model requires, in addition to thermal conductivity and water
84 diffusivity, the knowledge of rheological parameters (Young's modulus, Poisson's coefficient,
85 contraction coefficient due to water loss...). Especially under large deformation, the food material
86 cannot be considered as purely elastic. Thermo-physical and mechanical parameters depend on
87 temperature and moisture, and they are difficult to measure or estimate (Curcio and Aversa,
88 2014). In the case of yacón, these parameters were assessed under selected conditions (Blahovec
89 et al., 2013; Perussello et al., 2013). The coupling of large deformation with heat and mass
90 transfer phenomena in a single physical model constitutes a formidable challenge for yacón
91 samples, because of the high water content in the fresh product and the significant volume
92 reduction along the drying period. Determining the best approach for modelling requires, as a
93 previous step, to choose the purpose and application of the model itself; simple models can fit the
94 results properly, allowing the implementation of engineering aims (Castro et al., 2018).

95

96 This study concerns the convective drying of sets of cylindrical slices of yacón, after experiments
97 carried out in a pilot-scale convective dryer; the operating conditions of air flow, temperature and
98 relative humidity (RH) were controlled, which allowed stable ambient conditions. In accordance
99 with literature (Bernstein and Noreña, 2014), our preliminary tests have shown that the shrinkage

100 of yacón is by no means negligible. This result motivated us to design the set of experiments so
101 we could measure the dimensions of selected samples throughout the drying period. Our first
102 objective is thus to investigate the existence of relations between the ambient conditions and the
103 modifications undergone by yacón cylinders during the drying period. The second objective is to
104 study selected parameters associated with the convective drying of yacón samples, while
105 considering a generalization of the shrinkage behavior identified from measurements.

106

107 **2. Material and Methods**

108 Tuberos roots of yacón used in this work were cultivated in Piedade, Sao Paulo, Brazil, and later
109 purchased from a local market in two batches of 17 kg: one in July 2020, and the other in
110 September 2020. The selected roots were free of injuries, and had a diameter higher than 40 mm.
111 These roots had a tan surface and light-yellow flesh (Figs. 1a and 1b).

112

113 *2.1. Vapor sorption isotherms*

114 A VSA1055 vapor sorption analyzer (Decagon Devices, USA) was used to obtain vapor sorption
115 isotherms. Yacón roots were cut into slices with 40 mm diameter and 3 mm thickness, and pre-
116 dried in a forced circulation oven (model N480; Nova Ética, Brazil) for one hour. Isotherms were
117 run using static (DVS) and dynamic (DDI) methods, from $a_w = 0.9$ to $a_w = 0.1$, then returning to
118 $a_w = 0.9$. Experimental data were adjusted assuming the Guggenheim, Anderson and De Boer
119 (GAB) model (van der Berg, 1984):

$$\frac{X_w}{X_{w,\text{mono}}} = \frac{CKa_w}{(1-Ka_w)(1+(C-1)Ka_w)} \quad , \quad (1)$$

121 wherein X_w is the water content (kg/kg db); $X_{w,\text{mono}}$ is the monolayer water content (kg/kg db); C
122 is the Guggenheim constant, K is the GAB correction factor, and a_w is the water activity in the
123 food matrix.

124

125 2.2. Pretreatment

126 One setback in drying yacón is a browning effect caused by polyphenol oxidase (PPO), right after
127 cutting the roots and exposing the enzyme to oxygen (Lachman et al., 2003; Yan et al., 1999); a
128 blanching pretreatment is necessary in order to minimize this effect. Following Reis et al. (2012),
129 a citric acid pretreatment was used: firstly, using molds, approximately 500 g of yacón roots were
130 cut into cylindrical slices (40 mm diameter and 7 mm height) (Fig. 1b); secondly, the slices were
131 submerged in 500 mL of a 2 g/L aqueous citric acid (purity 95 g/100g; Tate & Lyle, Brazil)
132 solution for 3 min; finally, the slices were placed on absorbent paper before use.

133 Before each experiment, three slices were randomly picked to have their moisture determined.

134 The dry-matter mass was determined according to AOAC method 926.12 (1996); results ranged
135 from 9 to 11% of fresh weight.

136

137 2.3. Drying experiments at pilot-scale

138 Drying experiments were performed in a LM-ES20 drying oven (Labmaq, Brazil). This oven has
139 a chamber with four removable trays, each placed upon a scale, which allows real-time recording
140 of weight. It is also possible to control the temperature and relative humidity at the air-drying
141 inlet. On the roof of the oven, there is a 10 cm quartz window, equipped with a S6D stereo-
142 microscope (Leica, Germany); images of a single sample can be acquired during the whole
143 drying period.

144 For each drying experiment, 42 yacón slices (360 g total) were placed on the top tray, and dried
145 until no variation in weight was recorded for fifteen minutes. The following ambient conditions
146 were studied: [$T_{air} = 50\text{ °C}$, $RH = 20\%$]; [60 °C , 20%]; [50 °C , 30%] and [60 °C , 30%], all at an
147 airspeed of 4 m/s. Three full drying experiments were conducted under each of these four
148 ambient conditions.

149

150 *2.4. Dimensions*

151 To determine the slice diameter over time, images acquired along with the drying experiments
152 with the stereo-microscope setup were analyzed through an image processing software (version
153 LAS6; Leica Microsystems Applications, Switzerland). In the case of the sample height, in a
154 separate experiment, three yacón slices were dried in the same pilot unit. The height was
155 measured using a micrometer (model 103-137; Mitutoyo, Brazil), in a point near the border and
156 also at the center. The whole procedure was repeated many times along the drying period, for
157 each of the four controlled ambient conditions. This method assumes that the cylindrical format
158 was maintained during the drying process. Although irregularities appeared on the samples and

159 the shape became somewhat disturbed, the circular shape was roughly retained. It is possible to
 160 consistently identify a diameter and a height along the drying period.

161

162 **3. Macroscopic modeling**

163 In this work, the average properties are estimated from measurements collected over ensembles
 164 of many cylindrical slices of yacón slices (Fig.1b).

165

166 *3.1. Shrinkage*

167 Shrinkage during drying takes place simultaneously with moisture diffusion, and thus may affect
 168 the moisture removal rate; volume changes and deformation depend on several factors including
 169 sample geometry, dehydration method and drying conditions (Moreira et al., 2000). Experimental
 170 work has demonstrated that shrinkage behavior encountered during drying of real food products
 171 is neither ideally three-dimensional, nor unidimensional (Sjoholm and Gekas, 1995).

172 In the scope of this study, the sample volume was calculated by adding the volumes of the dry
 173 matter and the water:

$$174 \quad V = m_{dm} \left(\frac{1}{\rho_{dm}} + \frac{X_w}{\rho_w} \right) \quad (2)$$

$$175 \quad V_0 = m_{dm} \left(\frac{1}{\rho_{dm}} + \frac{X_{w0}}{\rho_w} \right), \quad (3)$$

176 wherein V is the volume (m^3); V_0 is the initial volume before drying (m^3); m_{dm} is the mass of the
 177 dry-matter mass (kg); ρ_{dm} is the density of the dry-matter mass (kg m^{-3}); ρ_w is the water density
 178 (kg m^{-3}); and X_{w0} is the initial water content of the product (kg water/kg dry matter), on dry basis,
 179 before drying.

180 The water content was expressed in its normalized form (X_w^*):

$$181 \quad X_w^* = \frac{X_w}{X_{w0}} . \quad (4)$$

182 Dimensionless volume (V^*) and surface (S^*) of the sample can be computed from measured
 183 dimensions and water content, as:

$$184 \quad V^* = \frac{1 + \left(\frac{\rho_{dm}}{\rho_w}\right) X_{w0} X_w^*}{1 + \left(\frac{\rho_{dm}}{\rho_w}\right) X_{w0}} \quad (5)$$

185 or, alternatively:

$$186 \quad V^* = \frac{(\pi D^2 H/4)}{(\pi D_0^2 H_0/4)} = H^* (D^*)^2 \quad (6)$$

$$187 \quad S^* = \frac{(2 \pi D^2/4) + \pi D H}{(2 \pi D_0^2/4) + \pi D_0 H_0} = D^* \left(\frac{D^* + 2 H^* H_0/D_0}{1 + 2 H_0/D_0} \right) . \quad (7)$$

188 Simplified models, based on different assumptions, may describe the shrinkage behavior of the
 189 slices. For all the approaches, the slice surface area can be expressed in the form of Eq. 7.

190 A first approach, named as “vertical model”, based on measurements performed at the beginning
 191 of drying, assumes that the shrinkage in the radial direction is negligible compared to the vertical
 192 one:

$$193 \quad H_{\text{vert}}^* = \frac{V}{V_0}; D_{\text{vert}}^* = 1 \quad . \quad (8)$$

194 A second approach assumes isotropic shrinkage. This approach resembles the linear, uniform
 195 model described by Mayor and Sereno (2004) for a cube, but to predict height and diameter
 196 directly, instead of the area:

$$197 \quad H_{\text{iso}}^* = D_{\text{iso}}^* = \left(\frac{V}{V_0}\right)^{\frac{1}{3}} \quad . \quad (9)$$

198 Finally, after seeing that the measurements did not match any of these approaches, we looked for
 199 intermediate behaviors allowing a satisfying match with the experimental results. Hereafter, Eq. 8
 200 and 9 are combined. The dimensionless height assuming combined shrinkage is expressed as:

$$201 \quad H_{\text{comb}}^* = (H_{\text{iso}}^*)^b (H_{\text{vert}}^*)^{(1-b)}; \quad D_{\text{comb}}^* = (D_{\text{iso}}^*)^b \quad , \quad (10)$$

202 wherein b is the moisture-dependent weighting parameter.

203 The first approach ($D^* = 1$) fits the measurements at the beginning of drying (Fig. 4). Yet
 204 progressively (as X_w^* decreases) the diameter of the slices also decreases. This is why we propose
 205 increasing the relative importance of the isotropic approach along with the drying process. An
 206 approach using a similar principle was proposed by Suzuki et al. (1976); it was described by
 207 Mayor and Sereno (2004) as a “semi-core drying model”. Our approach, however, involves a

208 different geometry and does not require as many parameters. At the end ($X_w^* \approx 0$), equal
 209 importance is given to the purely-vertical and isotropic approaches, resulting in:

$$210 \quad b = \frac{1}{2}(1 - X_w^*) \quad . \quad (11)$$

211 Assuming such a combined shrinkage behavior, the dimensionless total surface (S_{comb}^*) is
 212 calculated through Eq. 7, using the dimensionless height and diameter from Eq. 10.

213

214 *3.2. Drying kinetics*

215 Semi-theoretical models have been derived by simplifying general series solutions of Fick's
 216 second law; they are thus valid within the air temperature, relative humidity, flow velocity and
 217 moisture content range for which they were developed; further, these models require less
 218 time compared to theoretical thin-layer models and do not need assumptions of geometry of a
 219 typical food, its mass diffusivity or conductivity. Many of these semi-theoretical drying models
 220 have been compared in the literature (e.g., Panchariya et al., 2002); some of them are shown in
 221 Table 2.

222 The evolution of the overall moisture in the product under drying can be described through the
 223 moisture ratio:

$$224 \quad MR = \frac{X_w - X_{we}}{X_{w0} - X_{we}} \quad , \quad (12)$$

225 where X_{we} is the water content in equilibrium, estimated from vapor sorption isotherms. In the
 226 scope of this study, the following two-parameter model was adjusted to the drying kinetics data:

$$227 \quad MR = \exp(-k_1 t - (k_2 t)^2) ; \quad (13)$$

228 the inverse value of parameter k_1 can be called characteristic drying time. Equation 13 can be
 229 seen as an extension of the Lewis (1921) drying model, which considers the first term in the
 230 exponential only.

231 The time derivative of Eq. 13 can be expressed as:

$$232 \quad \frac{dMR}{dt} = (-k_1 - 2 t k_2^2) \exp(-t k_1 - t^2 k_2^2) . \quad (14)$$

233 When drying starts ($t = 0$), it follows $dMR/dt = -k_1$. By defining the dimensionless time t^*
 234 $= t k_1$ (at any time), the evaporative water loss per dimensionless area can be expressed as:

$$235 \quad \frac{dMR}{dt^* S^*} = -MR \left(1 + \frac{2 t k_2^2}{k_1} \right) \frac{1}{S_{comb}^*} . \quad (15)$$

236

237 *3.3 Heat transfer coefficient between yacón samples and surrounding air*

238 *3.3.1. Experimental method*

239 The heat transfer coefficient is a key parameter for assessing the importance of exchanges
 240 between the product under consideration and its surroundings. Looking for its experimental
 241 determination, a well-known material of regular geometry was heated in the same conditions as

242 the yacón slices were dried. Two aluminum cylinders, each containing a hole (1 mm radius, 10
243 mm height), were used in this experiment. Their properties are summarized in Table 1.

244 For each experiment, two calibrated thermocouples were used: one inserted in the aluminum
245 cylinder, filled with thermal paste (MasterGel Maker, Cooler Master, Taiwan) and the other
246 exposed to the air, as shown in Fig. 1d. The measurements (carried out at $T_{air} = 60 \text{ }^\circ\text{C}$, $RH =$
247 20% and speed of 4 m/s) were carried out until the recorded temperatures became constant, or
248 almost. Data acquisition was performed using Labview software (National Instruments, USA).

249 The heat transfer coefficient was determined using a two-step approach, based on the lumped
250 capacitance method (Incropera et al., 2007, pp.256-263). The energy balance takes the form:

$$251 \quad -\square A_S (T - T_{air}) = m C_P \frac{dT}{dt} , \quad (16)$$

252 wherein h is the heat transfer coefficient ($\text{Wm}^{-2} \text{K}^{-1}$), A_S is the surface area exposed to airflow
253 (m^2), T is the product temperature at any time ($^\circ\text{C}$), T_{air} is the air temperature ($^\circ\text{C}$), m is the mass
254 (kg) and C_P the specific heat ($\text{J kg}^{-1} \text{K}^{-1}$) of the product, and t is the time (s).

255 Observations revealed that the air temperature did not reach perfect steady state evolution. Hence,
256 in the first step, Eq. 16 was integrated numerically using an in-house source code written in
257 Python 3.7 language. The second step involved the minimization of the sum squared differences
258 of residuals between measured and predicted temperatures, these latter obtained after assuming
259 selected h values. Such minimization has considered the Nelder-Mead method.

260

261 3.3.2. Global energy balance method

262 Assuming that all the incoming heat is translated into evaporation at the surface temperature, it

263 follows (McCabe et al., 2014, p.807):

$$264 \quad -\frac{dm_w}{dt S} = -\frac{d(m_{dm} X_w)}{dt S} = \frac{\square}{L_v} (T_{air} - T_{surf}) \rightarrow -\frac{dX_w}{dt} = \frac{\square S (T_{air} - T_{surf})}{m_{dm} L_v}, \quad (17)$$

265 wherein m_w is the mass of water in the sample (kg).

266 The time derivative of Eq. 12 is:

$$267 \quad \frac{dMR}{dt} = \frac{1}{X_{w0} - X_{we}} \frac{dX_w}{dt} \rightarrow -\frac{dX_w}{dt} = -(X_{w0} - X_{we}) \frac{dMR}{dt}. \quad (18)$$

268 Combining Eqs. 17 and 18, the time derivative of Eq. 12 can be expressed in terms of

269 temperature values in ambient air and at the product surface:

$$270 \quad -(X_{w0} - X_{we}) \frac{dMR}{dt} = \frac{\square S (T_{air} - T_{surf})}{m_{dm} L_v} \rightarrow \frac{dMR}{dt} = -\frac{\square S (T_{air} - T_{surf})}{m_{dm} L_v (X_{w0} - X_{we})}. \quad (19)$$

271 When drying starts, $dMR/dt = -k_1$; hence, at this moment:

$$272 \quad \square = k_1 \frac{m_{dm} L_v (X_{w0} - X_{we})}{S_0 (T_{air} - T_{wb})}, \quad (20)$$

273 assuming that $T_{surf} = T_{wb}$ at $t = 0$.

274 Application of Eq. 20 requires the mass of dry-matter in the sample. The mass density of dry-

275 matter in our samples was estimated to be about 1590 kg/m^3 . Firstly, data provided by Hermann

276 et al. (1999) about nine accessions of fresh yacón allowed us to assess the averaged weight
 277 fraction of selected pure components: 0.374 % for proteins, 0.0235 % for fat, 10.8 % for
 278 carbohydrates, 0.361 % for fibers, and 0.505 % for ash. These values were considered in applying
 279 the Choi and Oikos (1986)'s approach for estimating the mass density of dry-matter of yacón
 280 samples at the temperature 40 °C. This temperature value is between the temperature prevailing
 281 in the product when drying starts (about 20 °C) and the ambient surrounding temperature (60 °C
 282 during the drying period).

283

284 3.4. Global energy balances

285 The evaporative water loss can be expressed by a global energy balance assuming that all the heat
 286 entering the sample causes water evaporation. Equation 17 can be applied if the variation of
 287 sensible heat can be neglected. This is approximately the case except at the beginning of drying,
 288 when the sample temperature increases toward the wet-bulb one if free water is available on the
 289 surface.

290 The initial water content is very high ($X_{w0} \approx 11$ kg/kg d.b.); therefore, it can be assumed that the
 291 water activity is close to 1 and that the product surface temperature is close to the wet-bulb one
 292 ($T_{surf} = T_{wb}$). Thus, combining Eqs. 19 and 20, we obtain:

$$293 \frac{T_{air} - T_{surf}}{T_{air} - T_{wb}} = \frac{(dMR/dt)/S}{(dMR/dt)|_{t=0}/S_0} = \frac{1}{1 - X_{we}/X_{w0}} \frac{S}{S_0} \frac{dX_w^*}{k_1 dt} = \frac{1}{(1 - X_{we}/X_{w0}) S^*} \frac{dX_w^*}{dt^*}, \quad (21)$$

294 where:

$$295 \quad \frac{dMR}{dt} = \frac{1}{1-X_{we}/X_{w0}} \frac{dX_w^*}{dt} . \quad (22)$$

296 The water mass balance can also express the evaporative water loss:

$$297 \quad \frac{-dm_w}{dt S} = k(c_{w,surf} - c_{w,air}) , \quad (23)$$

298 wherein k is the mass transfer coefficient (m s^{-1}), $c_{w,surf}$ is the concentration of water vapor in the
 299 air on the surface of the product (kg m^{-3}), and $c_{w,air}$ is the water vapor concentration in the
 300 surrounding air (kg m^{-3}).

301 Eq. 23 can be written in terms of dimensionless water content evolution:

$$302 \quad \frac{dX_w}{dt} = \frac{k S (c_{w,surf} - c_{w,air})}{m_{dm}} . \quad (24)$$

303 Comparing Eqs. 17 and 24, and rearranging water vapor concentration values in the place of
 304 temperatures, we can estimate the water activity at the slice surface as:

$$305 \quad \frac{c_{w,air} - a_w c_{w,sat}(T_{surf})}{c_{w,air} - c_{w,sat}(T_{wb})} = \frac{T_{air} - T_{surf}}{T_{air} - T_{wb}} . \quad (25)$$

306 The saturated water vapor concentration is obtained from the ideal gas law and Clausius-
 307 Clapeyron relation (Çengel et al., 2015):

$$308 \quad c_{w,sat}(T_{surf}) = \frac{P_{sat}^{T_{surf}} M_w}{R T_{surf}} , \quad (26)$$

309 wherein $P_{\text{sat}}^{T_{\text{surf}}}$ is the saturated vapor pressure at a temperature T and R is the gas constant (8.314
310 J K⁻¹ mol⁻¹). The water concentration at the surface was estimated through a GAB model for
311 parameters $X_{w,\text{mono}}$, C and K resulting from desorption measurements.

312 In summary:

313 a) pilot-scale drying experiments allowed the monitoring of water content X_w and slice
314 dimensions D and H under controlled ambient conditions;

315 b) for each of these ambient conditions, desorption models enabled us to estimate the equilibrium
316 moisture X_{we} value;

317 c) with the latter, the evolution of the moisture ratio MR was represented through the two-
318 parameter drying kinetics, providing the initial drying rate;

319 d) monitoring the slice dimensions allowed us to identify a mean shrinkage behavior, and hence
320 to predict the slice surface evolution;

321 e) finally, the availability of water content and surface evolutions allowed us to estimate the
322 surface temperature and the surface water activity (Eq. 25).

323

324 **4. Results**

325 *4.1. Vapor sorption isotherms*

326 Vapor sorption isotherms for yacón (Fig. 2) can be characterized as being type III, which are
327 common for products with a high quantity of soluble sugars (Rizvi, 2005; Al-Muhtaseb et al.,

328 2002). It can be observed that there was little difference between static and dynamic methods,
329 and between tested temperatures, and no visible hysteresis.

330 GAB model parameters, adjusted to the isotherms, are shown in Table 3. $X_{w,mono}$ is an estimation
331 of the monolayer water content; under this value, food materials tend to be very stable (Roos,
332 2008). However, packaging conditions are important to delay the re-absorption of water.

333

334 4.2. Drying kinetics

335 Figure 3 shows the evolution of the moisture ratio of ensembles of yacón slices, under the
336 ambient conditions here considered. Table 4 summarizes the results obtained after applying
337 Eq.13, and other models available in the literature, to the data obtained from each of the three
338 tests carried out under each of the four controlled conditions; averaged values were compared
339 using ANOVA and a post-hoc Tukey test ($p < 0.05$), carried out using Statgraphics software
340 (version 19 Centurion; Statgraphics Technologies, USA). A number of findings emerge from
341 these results.

342 a) Under the ambient conditions considered, the application of Eq. 13 allows a smaller root-
343 mean-square-error (RMSE) than other two-parameters models available in the literature.

344 We argue that the Eq. 13 constitutes a good candidate for engineering aims.

345 b) The influence of ambient conditions on the values estimated for model parameters is here
346 preliminary assessed, because only three runs were conducted under each ambient
347 condition. Excepting the Page model, the influence of both air temperature and relative

348 humidity on parameter k_1 seems significant. This finding is consistent with the physical
349 meaning of this parameter; it is directly related to the initial drying rate, and its value
350 increases with the driving force ($T_{air} - T_{wb}$). The influence of air temperature on the
351 second parameter of Eq. 13, of Modified Page, and of Henderson-Pabis models seems
352 significant.

353 c) It is quite hard to compare model parameters estimated from our experimental data with
354 those provided by other authors. Air flow and temperature conditions were different, and
355 there was no control of air relative humidity, allowing ambient conditions which were
356 perhaps unsteady. An additional difficulty comes from the diversity of yacón; Hermann et
357 al. (1999) studied nine different cultivars of yacón, and they differed in appearance and
358 composition: the dry matter content alone could range from 98 to 136 g/kg, suggesting
359 that the drying kinetics can vary from a cultivar to another. Reis et al. (2012) reported the
360 time of purchase, but not the location; Shi et al (2013) purchased their roots in China; and
361 Lisboa et al. (2018) reported a purchase in Brazil, but not the season. None of these
362 studies reported the variety used, nor any descriptors, there thus being a possibility that
363 those authors studied different varieties of yacón.

364

365 4.3. Shrinkage

366 Left-hand side of Fig. 4 summarizes all the available experimental data, in terms of
367 dimensionless values for the slice height (Fig. 4a) and diameter (4c) as function of the
368 dimensionless water content. Triplicates were conducted. Right-hand side of Fig. 4 compares

369 measurements with similar predicted by hypothetical shrinkage behaviors; in the case of slice
370 height, triangles indicate averaged values; in the case of slice diameter, measurements do not
371 correspond to same water content and then averaging was not possible.

372 Figures 4b and 4d compare measurements and hypothetical shrinkage behaviors: purely-vertical,
373 isotropic and combined models for both diameter and height (Eqs. 8, 9, and 10, respectively). Up
374 to $X_w^* = 0.2$, the slice diameter remained at more than 90 % of the initial value; the proposed
375 vertical model is thus a more realistic approach than the isotropic one. Afterward, there was a
376 drastic reduction in diameter. Figures 4b and 4d suggest that the combined behavior, which mixes
377 the vertical and the isotropic approaches, describes the slice shrinkage better than the others.
378 Looking for a consistent approach for predicting the shrinkage of yacón slices under convective
379 drying, the combined approach was considered.

380

381 *4.4. Heat transfer coefficient between yacón samples and surrounding air*

382 A first estimation of the heat transfer coefficient relevant to our problem comes from
383 experimental work with aluminum slices (sub-section 3.3.1). The results obtained were $h = 41 \text{ W}$
384 $\text{m}^{-2} \text{K}^{-1}$ for the 35 mm cylinder and $53 \text{ W m}^{-2} \text{K}^{-1}$ for the 20 mm one.

385 The consistency of these findings can be discussed using the correlation method. Taking in
386 account uniform heat flux conditions over a flat plate under laminar flow, it can be shown that the
387 averaged Nusselt, Reynolds and Prandtl numbers are related through the correlation

388 $\text{Nu} = \alpha \text{Re}^\beta \text{Pr}^\gamma$ (Incropera et al., 2007, p.410). In our case, this expression can be

389 rewritten in order to indicate the heat transfer coefficient as a function of the cylinder diameter:
390 $h = \delta D^{\beta-1}$ wherein $\beta - 1 < 0$. According to this rationale, the heat transfer coefficient should
391 increase during drying while the yacón dimension reduces. Hence, it is consistent to reach $h = 41$
392 $\text{W m}^{-2} \text{K}^{-1}$ for experimental data collected with a 35 mm aluminum cylinder and $53 \text{ W m}^{-2} \text{K}^{-1}$
393 with a 20 mm one.

394 A second estimation of the heat transfer coefficient between yacón samples and surrounding air
395 can be obtained by applying the expression $h = \delta D^{\beta-1}$ to our experimental conditions. Given
396 the airflow and temperature conditions above the surface of the cylinders, we can estimate the
397 Reynolds number to be about 10000 for a 40 mm cylinder (yacón sample, before any drying),
398 hence lower than the critical value for the laminar-turbulent transition for external flow
399 (Incropera et al., 2007, p.361). For these conditions, that correlation yields a heat transfer
400 convective coefficient $39 \text{ Wm}^{-2}\text{K}^{-1}$ for a 40 mm cylinder. Note that the aforementioned
401 correlation and the experimental values correspond to a physical problem bounded by an
402 adiabatic surface below the cylinder.

403 Finally, the heat transfer coefficient between yacón samples and surrounding air was estimated
404 by applying Eq. 20, i.e. by considering the initial evaporative rate results. The value obtained
405 ($32 \text{ W m}^{-2} \text{K}^{-1}$) implicitly takes into account the global influence of a number of factors affecting
406 the heat and mass transfer relevant to the problem, including: a) the fact that not one but an
407 ensemble of 42 yacón slices were simultaneously processed in the convective dryer pilot unit; b)
408 the role played by the heterogeneous exposure of slices to air flow, c) the influence of thermal

409 radiation interaction of slices with the metallic walls of the dryer, and d) the fact that there was a
410 metallic holed surface below the yacón samples, allowing a complex situation of heat and mass
411 transfer.

412

413 *4.5. Predictions of temperature and water activity on the surface*

414 Experimental results displayed in Fig. 3 suggest that the most reproducible condition was $T_{air} =$
415 $60\text{ }^{\circ}\text{C}$, $RH = 20\%$. We hypothesize that better reproducibility is due to the humidity stabilization
416 system of the convective dryer pilot unit. On the one hand, when the thermo-hygrometer detects a
417 value of RH below the set point, the control system of the drying oven sprays water into the
418 airflow and as it is not preheated, it could destabilize the temperature in the oven. On the other
419 hand, when humidity is above the set point, the air passes through a refrigerating system, where
420 water condensates and is removed, and the air must be heated again before re-entering the oven.
421 At the highest temperature ($60\text{ }^{\circ}\text{C}$), the air has a higher ability to hold water from the samples
422 without going over the set point; and, in the lowest RH , there is no need to add moisture to the
423 air at the end of the drying process, to keep a high RH , leading to less destabilization. In the
424 forthcoming last steps of this study, we restrict our attention to measurements and predictions
425 corresponding to the ambient condition $T_{air} = 60\text{ }^{\circ}\text{C}$, $RH = 20\%$.

426 The identification of a suitable shrinkage behavior allows to predict the slice surface, which is
427 exposed to surrounding air along the drying period (S^*). Representing the drying kinetics
428 through the two-parameter model allows to predict, also along the whole period, the drying rate

429 $\frac{dX_w^*}{dt^*}$. Figure 5a shows the predictions for the slice surface (Eq. 7) and for the drying rate (Eqs. 14
430 and 22) as a function of the dimensionless water content. The influence of the total surface
431 decrease on the drying rate $\frac{dX_w^*}{dt^*S^*}$ is noticeable, but only partially explains the drop in this drying
432 rate. Figure 5b exhibits the same variables as function of time, which can be compared with the
433 classical drying curves (Mujumdar, 2006). Note that $\frac{dX_w^*}{dt^*S^*}$ does not present a constant rate
434 period, indicating that some drying limitation due to the resistance of water migration from the
435 center to the surface of the product may exist.

436
437 The availability of key quantities S^* and $\frac{dX_w^*}{dt^*}$ enables to estimate surface-averaged values for the
438 temperature T , the water activity a_w and the water content X_w at the slice surface along the
439 drying period. Figure 5c shows that, as expected, the predicted water content at the surface
440 decreases more rapidly than the volume-averaged value for the sample. Note that GAB models do
441 not accurately represent the sorption phenomena at very high ($a_w > 0.93$) water activities (Basu et
442 al., 2006); hence, the predicted water content at the surface tends to be underestimated at the
443 beginning of drying.

444 Finally, Fig. 5d displays the water activity and temperature at the product surface. In the case of
445 the water activity, the departure from pre-drying conditions is immediate, contrarily to
446 experimental results (see for instance Figure 1 of Bernstein and Norena, 2014). In the case of
447 temperature, firstly the surface-averaged temperature increases almost instantaneously from the

448 initial product temperature (20 °C) up to the wet bulb temperature (about 35 °C); later on, this
449 temperature increases from the wet-bulb temperature up to the air temperature along the
450 remaining drying period. It would be interesting to assess the reliability of these predictions, for
451 instance using a non-invasive technique, such as an infrared thermometer.

452

453 *4.6. A remark about moisture diffusivity*

454 Shi et al. (2013) and Lisboa et al. (2018) used the Crank (1975) solutions to the Fick's laws in
455 order to estimate the effective moisture diffusion coefficient for yacón samples. These solutions,
456 however, assume that the shrinkage is negligible. Results in Section 4.3 demonstrate that this is
457 not the case for yacón samples as tested here. The infinite slab and the finite cylinder models,
458 common in the literature, revealed to be unreliable fits for the experimental drying data displayed
459 in Fig. 3. In the case of the infinite slab model, estimated moisture diffusivity was $4.0 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$
460 at 50 °C, and $7.4 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$ at 60 °C, and a root mean square error of 0.033 and 0.060 in *MR*
461 units, respectively. However, the fitted curve tended to underestimate the moisture ratio in the
462 beginning of the drying period, and to overestimate it after two hours of drying. Anyway, given
463 the drastic differences in sample's water content, dimensions and temperature between the
464 beginning and the end of the drying process, it is likely incorrect to attribute a single, constant
465 moisture diffusivity value over the whole drying process.

466

467 **5. Conclusions and Recommendations**

468 The study focused on the evolution of yacón samples having a particular shape and being
469 exposed to convective drying under controlled ambient conditions (mean air velocity of 4 m/s, air
470 temperature of 50 and 60 °C, air relative humidity of 20 and 30 %). The slice dimensions were
471 measured along the drying period, as an original contribution to the classical monitoring of
472 moisture loss. A dataset including triplicates of samples' water content, diameter and height
473 allowed us to study the evolution of yacón slices while including the influence of shrinkage.
474 Surface-averaged temperature and water activity tendencies were estimated from standard
475 assumptions about heat and mass transfer phenomena, providing a useful insight about the drying
476 evolution of a complex food product. The following conclusions were reached.

477

478 i) The diameter of yacón slices decreased to about 60-70 % of initial value after 6 hours of
479 drying without a clear dependence on the ambient condition under consideration, i.e. following
480 nearly the same decreasing tendency. The height of yacón slices was more difficult to determine,
481 because irregularities which progressively appeared on upper and lower surfaces along the drying
482 period. Available results indicated a reduction to 5-30 % of initial value after 6 hours of drying,
483 with the decreasing tendency being a little different under relative humidity of 20 and 30 %.

484

485 ii) In the case of yacón slices as tested here, a combined shrinkage behavior was identified: it
486 mixes purely-vertical (no diameter modification) with isotropic shrinkage (that progressively
487 operates inside the product matrix). Such a novel approach was later applied in predicting firstly

488 the slice total surface as a function of the water content inside it, and secondly the evolution of
489 selected properties at the yacón slice surface along the drying period.

490

491 iii) The application of two-parameter model for representing the drying kinetics (Eq. 13) allowed
492 us to estimate the heat transfer coefficient between yacón samples and surrounding ambient
493 conditions. The value obtained ($32 \text{ W m}^{-2} \text{ K}^{-1}$) implicitly includes the global influence of a
494 number of factors affecting the heat and mass transfer relevant to the problem. Two other
495 approaches (experimental work with aluminum cylinders, and correlation involving
496 dimensionless numbers) provided independent estimates of this transfer coefficient, and the
497 whole set of results seems consistent.

498

499 iv) Evolutions of moisture ratio from measurements were poorly represented by the semi-
500 theoretical model proposed by Lewis (1921), towards the ending of the drying period (Fig. 3).
501 That classical model was proposed under a number of assumptions including negligible
502 shrinkage, which constitutes a hypothesis unacceptable for yacón samples. The inclusion of a
503 quadratic term in Eq. 13 apparently mitigates this problem (Fig. 3). We argue that the Eq. 13
504 constitutes a good candidate for engineering aims, in which the whole drying period must be
505 represented as properly as possible.

506 The crucial issue of this study was to follow the dimensions of the sample throughout the drying
507 period. Our pioneering strategy could be improved, for example by measuring the height of the
508 sample using an optical detection method.

509 The suitability of our approach to the design and optimization of the process as well as of the
510 final product could be explored. As a preliminary step, testing this approach should consider
511 wider ranges of ambient conditions (airflow, temperature and relative humidity) and including
512 different varieties of yacón and other raw food products. Much work remains to be done in order
513 to clarify the relationship between shrinkage and moisture loss.

514

515 **ACKNOWLEDGMENTS**

516 The authors have received grants from the São Paulo Research Foundation (FAPESP), grants
517 2018/21327-1 and 2019/21832-0; from the Coordination for the Improvement of Higher
518 Education Personnel - Brazil (CAPES) - Finance Code 001; and from the National Council for
519 Scientific and Technological Development (CNPq), grant 306414/2017-1. We would like to
520 thank AgroParistech and UMR Sayfood for receiving the first author for a one-year research
521 internship abroad; and Emmanuel Bernuau, for his valuable help to calculate the heat transfer
522 coefficient.

523 Declarations of interest: none.

524 **REFERENCES**

525 Al-Muhtaseb, A. H., McMinn, W. A. M., & Magee, T. R. A. (2002). Moisture sorption isotherm
526 characteristics of food products: A review. *Food Bioprocess Process*, *80*, 118–128.
527 <https://doi.org/10.1205/09603080252938753>.

- 528 AOAC. (1996). Moisture and volatile matter in oils and fats (926.12-1926). In *Official Methods*
529 *of Analysis, 15th ed.*, Association of Official Analytical Chemists, Washington, USA.
- 530 Asioli, D., Aschemann-Witzel, J., Caputo, V., Vecchio, R., Annunziata, A., Næs, T., & Varela, P.
531 (2017). Making sense of the “clean label” trends: A review of consumer food choice behavior
532 and discussion of industry implications. *Food Research International*, 99, 58–71.
533 <https://doi.org/10.1016/j.foodres.2017.07.022>.
- 534 Assis, F. R., Rodrigues, L. G. G., Tribuzi, G., de Souza, P. G., Carciofi, B. A. M., & Laurindo, J.
535 B. (2019). Fortified apple (*Malus* spp., var. Fuji) snacks by vacuum impregnation of calcium
536 lactate and convective drying. *LWT – Food Science and Technology*, 113, 108298.
537 <https://doi.org/10.1016/j.lwt.2019.108298>.
- 538 Basu, S., Shivhare, U. S., & Mujumdar, A. S. (2006). Models for sorption isotherms for foods: A
539 review. *Drying Technology*, 24, 917–930. <https://doi.org/10.1080/07373930600775979>.
- 540 * Bernstein, A., & Noreña, C. P. Z. (2014). Study of thermodynamic, structural, and quality
541 properties of yacón (*Smallanthus sonchifolius*) during drying. *Food and Bioprocess Technology*,
542 7, 148-160. <https://link.springer.com/article/10.1007/s11947-012-1027-y>.
- 543 Blahovec, J., Lahodova, M., Kindl, M., & Fernandez, E. C. (2013). DMA thermal analysis of
544 yacón tuberous roots. *International Agrophysics*, 27, 479-483. [https://doi.org/10.2478/intag-](https://doi.org/10.2478/intag-2013-0018)
545 2013-0018.

- 546 Campos, D., Aguilar-Galvez, A., & Pedreschi, R. (2016). Stability of fructooligosaccharides,
547 sugars and colour of yacón (*Smallanthus sonchifolius*) roots during blanching and drying.
548 *International Journal of Food Science and Technology*, *51*, 1177-1185.
549 <https://doi.org/10.1111/ijfs.13074>.
- 550 Çengel, Y., Boles, M., & Kanoğlu, M. (2015). Thermodynamic property relations. In:
551 *Thermodynamics an engineering approach*. Mc McGraw-Hill.
- 552 Castro, A. M., Mayorga, E. Y., & Moreno, F. L. (2018). Mathematical modelling of convective
553 drying of fruits: A review. *Journal of Food Engineering*, *223*, 152-167. [https://doi.org/](https://doi.org/10.1016/j.jfoodeng.2017.12.012)
554 [10.1016/j.jfoodeng.2017.12.012](https://doi.org/10.1016/j.jfoodeng.2017.12.012).
- 555 Choi, Y., & Okos, M. R. (1986). Effects of temperature and composition on the thermal
556 properties of foods. In M. Le Mageur, & P. Jelen (Eds.), *Food Engineering and Process*
557 *Applications* (pp. 93-101). Elsevier Applied Science.
- 558 Chua, K. J., Mujumdar, A. S., Chou, S. K., Hawlader, M. N. A., & Ho, J. C. (2000). Convective
559 drying of banana, guava and potato pieces : Effect of cyclical variations of air temperature on
560 drying kinetics and color change. *Drying Technology*, *18*, 907–936.
561 <https://doi.org/10.1080/07373930008917744>.
- 562 Crank, J. (1975). *The Mathematics of Diffusion* (2nd ed.). Oxford University Press.

- 563 Curcio, S., & Aversa, M. (2014). Influence of shrinkage on convective drying of fresh
564 vegetables: A theoretical model. *Journal of Food Engineering*, *123*, 36-49.
565 <http://dx.doi.org/10.1016/j.jfoodeng.2013.09.014>.
- 566 Fernández, E. C., Rajchl, A., Lachman, J., Čížková, H., Kvasnička, F., Kotíková, Z., & Voldřich,
567 M. (2013). Impact of yacón landraces cultivated in the Czech Republic and their ploidy on the
568 short- and long-chain fructo-oligosaccharides content in tuberous roots. *LWT - Food Science and*
569 *Technology*, *54*, 80–86. <https://doi.org/10.1016/j.lwt.2013.05.013>.
- 570 Graefe, S., Hermann, M., Manrique, I., Golombek, S., & Buerkert, A. (2004). Effects of post-
571 harvest treatments on the carbohydrate composition of yacon roots in the Peruvian Andes. *Field*
572 *Crops Research*, *86*, 157–165. <https://doi.org/10.1016/j.fcr.2003.08.003>.
- 573 Grau, A., & Rea, J. (1997). Yacón, *Smallanthus sonchifolius* (Poepp. et Endl.) H. Robinson. In:
574 M. Hermann & J. Heller (Eds.), *Promoting the conservation and use of underutilized and*
575 *neglected crops, #21, Andean roots and tubers: Ahipha, arracacha, maca and yacón* (pp. 199-
576 242). International Plant Genetic Resources Institute.
- 577 Hassini, L., Azzouz, S., Peczalski, R., & Belghith, A. (2007). Estimation of potato moisture
578 diffusivity from convective drying kinetics with correction for shrinkage. *Journal of food*
579 *engineering*. *79*, 47–56. <https://doi.org/10.1016/j.jfoodeng.2006.01.025>.
- 580 * Hermann, M., Freire, I., & Pazos, C. (1999). Compositional diversity of the yacón storage root.
581 In *Andean Roots and Tuber Crops* (pp. 425-432). International Potato Center Program Report
582 1997-1998.

- 583 Incropera, F. P., Witt, D. P., Bergman, T. L., Lavine, A. S. (2007). *Fundamentals of heat and*
584 *mass transfer* (6th ed.). Wiley.
- 585 Khajehei, F., Hartung, J., & Graeff-Hönninger, S. (2018a). Total phenolic content and antioxidant
586 activity of yacón (*Smallanthus sonchifolius* Poepp. and Endl.) chips: Effect of cultivar, pre-
587 treatment, and drying. *Agriculture*, 8, 183. <https://doi.org/10.3390/agriculture8120183>.
- 588 Khajehei, F., Merkt, N., Claupein, W., & Graeff-Hönninger, S. (2018b). Yacón (*Smallanthus*
589 *sonchifolius* Poepp. & Endl.) as a novel source of health promoting compounds: Antioxidant
590 activity, phytochemicals and sugar content in flesh, peel, and whole tubers of seven cultivars.
591 *Molecules*, 23, 278. <http://dx.doi.org/10.3390/molecules23020278>.
- 592 Lachman, J., Fernández, E. C., & Orsák, M. (2003). Yacón [*Smallanthus sonchifolia* (Poepp. et
593 *Endl.*) *H. Robinson*] chemical composition and use: A review. *Plant, Soil and Environment*, 49,
594 283–290. <https://doi.org/10.17221/4126-PSE>.
- 595 Lebeda, A., Doležalová, I., Fernández, E., & Viehmannová, I. (2012). Yacón (*Asteraceae*;
596 *Smallanthus sonchifolius*). In R. J. Singh (Ed.), *Genetic Resources, Chromosome Engineering,*
597 *and Crop Improvement. Volume 6: Medicinal Plants* (pp. 641-702). CRC Press.
- 598 * Lewis, W. K. (1921). The rate of drying of solid materials. *Industrial & Engineering Chemistry*
599 *Research*, 13, 427–432. <https://doi.org/10.1021/ie50137a021>.

600 Lisboa, C., Gomes, J., Figueirêdo, R., Queiroz, A., Diógenes, A., & de Melo, J. (2018). Effective
601 diffusivity in yacón potato cylinders during drying. *Revista Brasileira de Engenharia Agrícola e*
602 *Ambiental*, 22, 564–569. <https://doi.org/10.1590/1807-1929/agriambi.v22n8p564-569>.

603 * Mayor, L., & Sereno, A. M. (2004). Modelling shrinkage during convective drying of food
604 materials: A review. *Journal of Food Engineering*, 61, 373-386. [http://dx.doi.org/10.1016/S0260-](http://dx.doi.org/10.1016/S0260-8774(03)00144-4)
605 8774(03)00144-4.

606 McCabe, W., Smith, J., & Harriott, P. (2014). Drying of solids. In: *Unit operations of chemical*
607 *engineering* (7th ed.). Mc Graw Hill.

608 Moreira, R., Figueiredo, A., & Sereno, A. (2000). Shrinkage of apple disks during drying by
609 warm air convection and freeze drying. *Drying Technology*, 18, 279-294.
610 <https://doi.org/10.1080/07373930008917704>.

611 Mujumdar, A. S. (2006). Principles, Classification, and Selection of Dryers. In *Handbook of*
612 *Industrial Drying*. Taylor and Francis.

613 Panchariya, P. C., Popovic, D., & Sharma, A. L. (2002). Thin-layer modelling of black tea drying
614 process. *Journal of Food Engineering*, 52, 349-357. [https://doi.org/10.1016/S0260-](https://doi.org/10.1016/S0260-8774(01)00126-1)
615 8774(01)00126-1.

616 Perussello, C. A., Mariani, V. C., Masson, M. L., & Castilhos, F. (2013). Determination of
617 thermophysical properties of yacón (*Smallanthus sonchifolius*) to be used in a finite element

- 618 simulation. *International Journal of Heat and Mass Transfer*, 67, 1163-1169.
619 <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.004>.
- 620 Perussello, C. A., Kumar, C., De Castilhos, F., & Karim, M. A. (2014). Heat and mass transfer
621 modeling of the osmo-convective drying of yacón roots (*Smallanthus sonchifolius*). *Applied*
622 *Thermal Engineering*, 63, 23–32. <https://doi.org/10.1016/j.applthermaleng.2013.10.020>.
- 623 Perry, R. H., & Green, D. W. (1997). Section 2: Physical and chemical data. In *Perry's*
624 *Engineers' Handbook* (7th ed.). Mc Graw-Hill.
- 625 Rizvi, S. H. (2005). Thermodynamic Properties of Foods in Dehydration. In *Engineering*
626 *Properties of Foods* (3rd ed.). Boca Raton: CRC Press.
- 627 Reis, F. R., Lenzi, M. K., de Muñoz, G. I. B., Nisgoski, S., & Masson, M. L. (2012). Vacuum
628 drying kinetics of yacón (*Smallanthus sonchifolius*) and the effect of process conditions on fractal
629 dimension and rehydration capacity. *Drying Technology*, 30, 13–19.
630 <https://doi.org/10.1080/07373937.2011.611307>.
- 631 Roos, Y.H. (2008). Water Activity and Glass Transition. In *Water Activity in Foods:*
632 *Fundamentals and Applications*, (1st ed.). Blackwell Publishing Professional.
- 633 * Scher, C. F., Rios, A., & Noreña, C. (2009). Hot air drying of yacón (*Smallanthus sonchifolius*)
634 and its effect on sugar concentrations. *International Journal of Food Science and Technology*, 44,
635 2169–2175. <https://doi.org/10.1111/j.1365-2621.2009.02056.x>.

- 636 Salinas, J. G., Alvarado, J. A., Bergenståhl, B., & Tornberg, E. (2018). The influence of
637 convection drying on the physicochemical properties of yacón (*Smallanthus sonchifolius*). *Heat*
638 *and Mass Transfer*, *54*, 2951-2961. <https://doi.org/10.1007/s00231-018-2334-2>.
- 639 Sandoval-Torres, S., Tovilla-Morales, A. S., & Hernández-Bautista, E. (2017). Dimensionless
640 modeling for convective drying of tuberous crop (*Solanum tuberosum*) by considering shrinkage.
641 *Journal of Food Engineering*, *214*, 147–157. <https://doi.org/10.1016/j.jfoodeng.2017.06.014>.
- 642 Seminario, J., Valderrama, M., & Manrique, I. (2003). *El Yacón : Fundamentos para el*
643 *Aprovechamiento de un Recurso Promisorio*. Lima (Peru): Centro Internacional de la Papa (CIP),
644 Universidad Nacional de Cajamarca, Agencia Suiza para el Desarrollo y la Cooperacion
645 (COSUDE).
- 646 Shi, Q., Zheng, Y., & Zhao, Y. (2013). Mathematical modeling on thin-layer heat pump drying of
647 yacón (*Smallanthus sonchifolius*) slices. *Energy Conversion and Management*, *71*, 208–216.
648 <https://doi.org/10.1016/j.enconman.2013.03.032>.
- 649 Shi, Q., Zheng, Y., & Zhao, Y. (2015). Thermal transition and state diagram of yacón dried by
650 combined heat pump and microwave method. *Journal of Thermal Analysis and Calorimetry*, *119*,
651 727–735. <https://doi.org/10.1007/s10973-014-4198-0>.
- 652 Sjöholm, I., & Gekas, V. (1995). Apple shrinkage upon drying. *Journal of Food Engineering*, *25*,
653 123-130. [https://doi.org/10.1016/0260-8774\(94\)00001-P](https://doi.org/10.1016/0260-8774(94)00001-P).

- 654 Suzuki, K., Kubota, K., Hasegawa, T., & Hosaka, H. (1976). Shrinkage in dehydration of root
655 vegetables. *Journal of Food Science*, *41*, 1189–1193. <https://doi.org/10.1111/j.1365->
656 [2621.1976.tb14414.x](https://doi.org/10.1111/j.1365-2621.1976.tb14414.x).
- 657 van den Berg, C. (1984). Description of water activity of foods for engineering purposes by
658 means of the G.A.B. model of sorption. In B. M. McKenna (Ed.), *Engineering and Food*
659 *(Proceedings of the Third International Congress on Engineering and Food held between 26 and*
660 *28 September 1983 at Trinity College, Dublin, Ireland)* (vol. 1, pp. 311-321). London (UK):
661 Elsevier Applied Science Publishers.
- 662 Watzl, B., Girrbach, S., & Roller, M. (2005). Inulin, oligofructose and immunomodulation.
663 *British Journal of Nutrition*, *93*, S49. <https://doi.org/10.1079/BJN20041357>.
- 664 Yan, X., Suzuki, M., Ohnishi-Kameyama, M., Sada, Y., Nakanishi, T., & Nagata, T. (1999).
665 Extraction and identification of antioxidants in the roots of yacón (*Smallanthus sonchifolius*).
666 *Journal of Agricultural and Food Chemistry*, *47*, 4711–4713. <https://doi.org/10.1021/jf981305o>.

667

668 **Figure captions**

669 **Fig. 1.** Yacón roots: (a) in *natura*, still with their tan-colored peel; (b) being cut for the drying
670 experiments, with their light-yellow flesh visible; (c) dried, with the perforated tray on the
671 background; and (d) experimental arrangement to estimate the heat transfer coefficient.

672 **Fig. 2.** Sorption isotherms (desorption and adsorption) for yacón obtained at two temperatures
673 through the methods DDI and DVS, in comparison with the adjusted GAB model for DVS test at
674 60 °C.

675 **Fig. 3.** Moisture ratio of yacón slices, expressed in function of time (a) at $T_{air} = 50$ °C and $RH =$
676 30 %; (b) at 60 °C and 30 %; (c) at 50 °C and 20 %; (d) at 60 °C and 20 %, compared to the
677 drying kinetics model proposed in this work, and to the Lewis (1921) model.

678 **Fig. 4.** Dimensionless height and diameter of yacón slices as a function of dimensionless water
679 content along with the drying: (a) all height measurements performed under four ambient
680 conditions; (b) height measurement averages, compared to predictions reached after assuming
681 different hypothetical behaviors for slice shrinkage; (c) as in (a) but for the diameter; (d) as in (b)
682 but for the diameter. In the case of the vertical shrinkage assumption, the dimensionless diameter
683 equals unity (Eq.8).

684 **Fig. 5.** Predictions about the drying behavior of yacón slices. In display (a), the dimensionless
685 surface S^* comes from Eq.7, the drying rate dX_w^*/dt^* comes from Eq.22 with dMR/dt from
686 Eq.14. In display (b), same as (a) but as a function of time. In display (c), slice-averaged and
687 surface moisture as a function of time. In display (d), surface temperature from Eq.21 and water
688 activity from Eq.25 as a function of time.

689

690

691 **Justifying key references**

692 Please see below our remarks regarding our five key references, sorted by year of publication. They
693 are indicated by a star in the reference section of our manuscript.

694

695 1) Lewis, W. K. - 1921 - The rate of drying the solid materials. The Journal of Industrial and
696 Engineering Chemistry, 13: 427-432. <https://doi.org/10.1021/ie50137a021>.

697 > This founding article allowed us to understand the basic rationale of semi-theoretical drying
698 kinetics models. The Lewis' model can be presented as

$$699 \quad dMR / dt = -k t,$$

700 where symbols are explained in our Nomenclature. In the present study we propose an extension
701 of the Lewis' model:

$$702 \quad dMR / dt = -k_1 t - k_2 t^2.$$

703 The second-order term might incorporate, implicitly, the bulk influence of complex phenomena in
704 drying the solid matrix (including shrinkage, which was neglected by Lewis). Results suggest that
705 this extended model fits better our experimental data than the Lewis' one.

706

707 2) Hermann, M., Freire, I., Pazos, C. - 1999 - Compositional diversity of the yacón storage root. In
708 « Andean Roots and Tuber Crops », International Potato Center Program Report 1997-1998, Lima
709 (Peru), pp.425-432.

710 > Very few articles compare the physico-chemical composition (fibers, proteins, carbohydrates,
711 etc) of different yacón varieties. This article allowed us to estimate the dry-matter mass density
712 associated with an averaged composition over nine yacón cultivars.

713

714 3) Mayor, L., Sereno, A. M. - 2004 - Modelling shrinkage during convective drying of food
715 materials: A review. Journal of Food Engineering, 61: 373-386. [https://doi.org/10.1016/S0260-](https://doi.org/10.1016/S0260-8774(03)00144-4)
716 [8774\(03\)00144-4](https://doi.org/10.1016/S0260-8774(03)00144-4).

717 > This classical reference inspired us in our analysis of experimental data, more precisely in
718 comparing measurements of dimensions of yacón slices along the drying period with predictions
719 from hypothetical shrinkage behaviors.

720

721

722 4) Scher, C. F., Rios, A. O., Norena, C. P. Z. - 2009 - Hot air drying of yacón (*Smallanthus*
723 *sonchifolius*) and its effect on sugar concentrations. *International Journal of Food Science and*
724 *Technology*, 44 : 2169-2175. <https://doi.org/10.1111/j.1365-2621.2009.02056>.

725 > This dense article discusses the influence of drying conditions on yacón sugar contents and water
726 activity, among other relevant characteristics. The design of our own experimental work was, in
727 some extent, inspired by this article.

728
729 5) Bernstein, A., Norena, C. P. Z. - 2014 – Study of thermodynamic, structural, and quality
730 properties of yacón (*Smallanthus sonchifolius*) during drying. *Food and Bioprocess Technology*,
731 7: 148-160. <https://link.springer.com/article/10.1007/s11947-012-1027-y>.

732 > This very interesting article provided us insight about yacón samples: their volume reduction
733 along some hours of drying, their micro-structure after different treatments, and water activity at
734 selected temperatures.

735

1 **CONVECTIVE DRYING OF YACÓN (*SMALLANTHUS SONCHIFOLIUS*) SLICES:**
2 **A SIMPLE PHYSICAL MODEL INCLUDING SHRINKAGE**

3
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12 **ABSTRACT**

13 Yacón is a tuberous root from the Andean region, and a potential functional food because of
14 the presence of fructo-oligosaccharides (FOS). Due to its high moisture *in natura*, the product
15 is prone to microbial degradation. The evolution of yacón cylindrical slices under convective
16 drying is here studied from experimental work and theoretical considerations about bulk
17 properties. The operation of a pilot-scale convective dryer allowed monitoring the moisture
18 and dimensions of yacón slices. Evolution of moisture under temperature, and relative
19 humidity, controlled conditions is described through a two-parameter drying kinetic model. A
20 novel approach for estimating shrinkage effects is proposed, comparing measured dimensions
21 with predictions based upon hypothetical shrinkage behaviors. The drying kinetics and the
22 shrinkage approach are finally combined with the global energy balance for a single slice, in
23 order to describe the evolution of surface temperature and other yacón slice properties along
24 the drying period.

25

26 **KEYWORDS**

27 Yacón, convective drying, drying kinetics, shrinkage behavior

28

29 **HIGHLIGHTS**

30 The evolution of yacón slices under convective drying was studied at pilot scale. 81

31 Experimental data were collected under controlled air temperature and humidity. 79

32 Moisture loss observations were approximated through a novel two-parameter model. 81

33 Shrinkage of yacón slices was described by a combination of hypothetical models. 80

34 The global energy balance allowed to predict surface water activity and temperature. 84

35 **1. Introduction**

36 The mechanisms underlying the processing of food raw materials must be understood in order
37 to: a) manufacture, in a reproducible manner, products for consumption, b) assess the
38 influence of raw material variability and c) provide insight into process optimization.

39 Consumers are increasingly interested in the ingredients and processes associated with their
40 food. “Clean labels” with recognizable ingredients, and as few preservatives as possible, are a
41 trend in the food market (Asioli et al., 2017).

42 Here we focus on yacón (*Smallanthus sonchifolius*), a tuberous crop from the Asteraceae
43 family, originally from the Andean region and nowadays cultivated worldwide. Its roots,
44 described as succulent and mildly sweet, with a thin peel, can be eaten raw. While in the
45 majority of storage roots the energy is stored as starch, in yacón it is stored as inulin and
46 fructo-oligosaccharides (FOS) instead. These compounds naturally exist in plants, but in
47 concentrations usually lower than those in yacón roots. The human gastrointestinal tract does
48 not have enzymes to digest these compounds, so they reach the gut microbiota practically
49 intact (Grau and Rea, 1997; Hermann et al., 1999; Seminario et al., 2003; Lebeda et al.,
50 2012). In other words, albeit sweet, they have a low caloric value for humans, making them
51 an interesting option for diabetics. In addition, inulin and FOS are appreciated as effective and
52 safe prebiotics (Fernandez et al., 2013) with claims of immunomodulatory effects (Watzl et
53 al., 2005). Root flesh colors vary from white to yellow, orange, and purple, depending on the
54 genotype (Hermann et al., 1999). Chemical characteristics, such as phenolic compounds and
55 saccharides, may vary significantly between cultivars (Graefe et al., 2004; Khajehei et al.,
56 2018b).

57 As a source of inulin and fructose, tuberous roots of yacón can be employed in the production
58 of cold drinks and alcohol, dry crisps, jams and stewed fruits, sweeteners and some dairy
59 products like yogurt (Lebeda et al., 2012). A major portion of the tuberous root biomass of

60 yacón is composed of water (>0.7 g/g w.b.) (Lachman et al., 2003). Water activity is also
61 high, leading to a short shelf-life; partial hydrolysis of oligo-fructans can start within only a
62 few days after harvest (Graefe et al., 2004). Drying is a convenient way to prepare yacón for
63 storage, and the influence of drying conditions on the chemical composition of yacón samples
64 has been investigated (Scher et al., 2009; Campos et al., 2016; Khajehei et al., 2018a; Salinas
65 et al., 2018).

66 Several techniques have been applied to dehydrate yacón samples, including hot air
67 convection drying (Scher et al., 2009), vacuum drying (Reis et al., 2012), freeze-drying
68 (Khajehei et al., 2018a), as well as hybrid techniques combining forced convection with
69 osmotic dehydration (Perussello et al., 2013, 2014) or microwave heating (Shi et al., 2015).

70 However, in drying yacón samples, none of these studies have controlled the air relative
71 humidity. In other words, caution should be exercised in discussing these results: without
72 control of relative humidity, ambient conditions may vary due to the drying of the product.

73 Such control has been implemented in the drying of many foods, including apples (Assis et
74 al., 2019; Sjöholm & Gekas, 1995) and potatoes (Hassini et al., 2007; Sandoval-Torres et al.,
75 2017; Chua et al., 2000).

76 One of the most important physical changes undergone by food during drying is the reduction
77 of its volume. Loss of water and heating cause stresses in the cellular structure of the food
78 matrix, leading to changes in shape and a decrease in dimension (Mayor and Sereno, 2004).
79 The volume reduction and shape modification of yacón samples under convective drying has
80 been scarcely investigated (Bernstein and Noreña, 2014).

81 Different modeling approaches have been used for studying the evolution of fruits and other
82 high-moisture-content food materials under convective drying (Castro et al., 2018). A
83 complete thermo-hygro-mechanical model requires, in addition to thermal conductivity and
84 water diffusivity, the knowledge of rheological parameters (Young's modulus, Poisson's

85 coefficient, contraction coefficient due to water loss...). Especially under large deformation,
86 the food material cannot be considered purely elastic. Thermo-physical and mechanical
87 parameters depend on temperature and moisture, and they are difficult to measure or estimate
88 (Curcio and Aversa, 2014). In the case of yacón, these parameters were assessed under
89 selected conditions (Blahovec et al., 2013; Perussello et al., 2013). The coupling of large
90 deformation with heat and mass transfer phenomena in a single physical model constitutes a
91 formidable challenge for yacón samples, because of the high water content *in natura* and the
92 significant volume reduction along the drying period. Determining the best approach for
93 modeling requires, as a previous step, to choose the purpose and application of the model
94 itself; simple models can fit the results properly, allowing the implementation of engineering
95 aims (Castro et al., 2018).

96 This study concerns the convective drying of sets of cylindrical slices of yacón, after
97 experiments carried out in a pilot-scale convective dryer; the operating conditions of airflow,
98 temperature and relative humidity (RH) were controlled, which allowed stable ambient
99 conditions. In accordance with the literature (Bernstein and Norena, 2014), our preliminary
100 tests have shown that the shrinkage of yacón is by no means negligible. This result motivated
101 us to design the set of experiments so we could measure the dimensions of selected samples
102 throughout the drying period. Our first objective is thus to investigate the existence of
103 relations between the ambient conditions and the modifications undergone by yacón cylinders
104 during the drying period. The second objective is to study selected parameters associated with
105 the convective drying of yacón samples while considering a generalization of the shrinkage
106 behavior identified from measurements.

107 **2. Material and Methods**

108 Tuberos roots of yacón used in this work were cultivated in Piedade, Sao Paulo, Brazil, and
109 later purchased from a local market in two batches of 17 kg: one in July 2020, and the other in

110 September 2020. The selected roots were free of injuries and had a diameter higher than 40
 111 mm. These roots had a tan surface and light-yellow flesh (Figs. 1a and 1b).

112 2.1. Vapor sorption isotherms

113 A VSA1055 vapor sorption analyzer (Decagon Devices, USA) was used to obtain vapor
 114 sorption isotherms. Yacón roots were cut into slices with 40 mm diameter and 3 mm
 115 thickness, and pre-dried in a forced circulation oven (model N480; Nova Ética, Brazil) for one
 116 hour. Isotherms were run using static (DVS) and dynamic (DDI) methods, from $a_w = 0.9$ to
 117 $a_w = 0.1$, then returning to $a_w = 0.9$. Experimental data were adjusted assuming the
 118 Guggenheim, Anderson and De Boer (GAB) model (van der Berg, 1984):

$$119 \frac{X_w}{X_{w,mono}} = \frac{CKa_w}{(1-Ka_w)(1+(C-1)Ka_w)} \quad (1)$$

120 Wherein X_w is the water content (kg/kg db); $X_{w,mono}$ is the monolayer water content (kg/kg
 121 db); C is the Guggenheim constant, K is the GAB correction factor, and a_w is the water
 122 activity in the food matrix.

123 2.2. Pretreatment

124 One setback in drying yacón is a browning effect caused by polyphenol oxidase (PPO), right
 125 after cutting the roots and exposing the enzyme to oxygen (Lachman et al., 2003; Yan et al.,
 126 1999); a blanching pretreatment is necessary in order to minimize this effect. Following Reis
 127 et al. (2012), a citric acid pretreatment was used: firstly, approximately 500 g of yacón roots
 128 were cut into cylindrical slices (40 mm diameter and 7 mm height) (Fig. 1b), using circular
 129 cutters; secondly, the slices were submerged in 500 mL of a 2 g/L aqueous citric acid (purity
 130 95 g/100g; Tate & Lyle, Brazil) solution for 3 min; finally, the slices were placed on
 131 absorbent paper before use.

132 Before each experiment, three slices were randomly picked to have their moisture determined.
133 The dry-matter mass was determined according to AOAC method 926.12 (1996); results
134 ranged from 0.09 to 0.11 g/g w.b.

135 *2.3. Drying experiments at pilot-scale*

136 Drying experiments were performed in a LM-ES20 drying oven (Labmaq, Brazil). This oven
137 has a chamber with four removable trays, each placed upon a scale, which allows real-time
138 recording of weight. It is also possible to control the temperature and relative humidity at the
139 air-drying inlet. On the roof of the oven, there is a 10 cm quartz window, equipped with a
140 S6D stereo-microscope (Leica, Germany); images of a single sample can be acquired during
141 the whole drying period.

142 For each drying experiment, 42 yacón slices (360 g total) were placed on the top tray and
143 dried until no variation in weight was recorded for fifteen minutes. The following drying air
144 conditions were studied: [$T_{air} = 50\text{ °C}$, $RH = 20\%$]; [60 °C , 20%]; [50 °C , 30%] and [60 °C , 30%],
145 all at an airspeed of 4 m/s. Three full drying experiments were conducted under each of
146 these four conditions.

147 *2.4. Dimensions*

148 To determine the slice diameter over time, images acquired along with the drying experiments
149 with the stereo-microscope setup were analyzed through an image processing software
150 (version LAS6; Leica Microsystems Applications, Switzerland). In the case of the sample
151 height, in a separate experiment, three yacón slices were dried in the same pilot unit. The
152 height was measured using a micrometer (model 103-137; Mitutoyo, Brazil), at a point near
153 the border and also at the center. The whole procedure was repeated many times along the
154 drying period, for each of the four controlled ambient conditions. This method assumes that
155 the cylindrical format was maintained during the drying process. Although irregularities
156 appeared on the samples and the shape became somewhat disturbed, the circular shape was

157 roughly retained. It is possible to consistently identify a diameter and a height along the
 158 drying period.

159 **3. Macroscopic modeling**

160 In this work, the average properties are estimated from measurements collected over
 161 ensembles of many cylindrical slices of yacón slices (Fig.1b).

162 *3.1. Shrinkage*

163 Shrinkage during drying takes place simultaneously with moisture diffusion, and thus may
 164 affect the moisture removal rate; volume changes and deformation depend on several factors
 165 including sample geometry, dehydration method and drying conditions (Moreira et al., 2000).
 166 Experimental work has demonstrated that shrinkage behavior encountered during drying of
 167 real food products is neither ideally three-dimensional nor unidimensional (Sjoholm and
 168 Gekas, 1995).

169 In the scope of this study, the sample volume was calculated by adding the volumes of the dry
 170 matter and the water:

$$171 \quad V = m_{dm} \left(\frac{1}{\rho_{dm}} + \frac{X_w}{\rho_w} \right) \quad (2)$$

$$172 \quad V_0 = m_{dm} \left(\frac{1}{\rho_{dm}} + \frac{X_{w0}}{\rho_w} \right) \quad (3)$$

173 wherein V is the volume (m^3); V_0 is the initial volume before drying (m^3); m_{dm} is the mass of
 174 the dry-matter mass (kg); ρ_{dm} is the density of the dry-matter mass (kg m^{-3}); ρ_w is the water
 175 density (kg m^{-3}); and X_{w0} is the initial water content of the product (kg water/kg dry matter),
 176 on a dry basis, before drying.

177 The water content was expressed in its normalized form (X_w^*):

$$178 \quad X_w^* = \frac{X_w}{X_{w0}} \quad (4)$$

179 Dimensionless volume (V^*) and surface (S^*) of the sample can be computed from measured
 180 dimensions and water content, as:

$$181 \quad V^* = \frac{1 + \left(\frac{\rho_{dm}}{\rho_w}\right) X_{w0} X_w^*}{1 + \left(\frac{\rho_{dm}}{\rho_w}\right) X_{w0}} \quad (5)$$

182 or, alternatively:

$$183 \quad V^* = \frac{(\pi D^2 H/4)}{(\pi D_0^2 H_0/4)} = H^* (D^*)^2 \quad (6)$$

$$184 \quad S^* = \frac{\left(2\pi \frac{D^2}{4}\right) + \pi D H}{\left(2\pi \frac{D_0^2}{4}\right) + \pi D_0 H_0} = D^* \left(\frac{D^* + 2H^* \frac{H_0}{D_0}}{1 + \frac{2H_0}{D_0}} \right) \quad (7)$$

185 Simplified models, based on different assumptions, may describe the shrinkage behavior of
 186 the slices. For all the approaches, the slice surface area can be expressed in the form of Eq. 7.
 187 A first approach, named as “vertical model”, based on measurements performed at the
 188 beginning of drying, assumes that the shrinkage in the radial direction is negligible compared
 189 to the vertical one:

$$190 \quad H_{vert}^* = \frac{V}{V_0}; D_{vert}^* = 1 \quad (8)$$

191 A second approach assumes isotropic shrinkage. This approach resembles the linear, uniform
 192 model described by Mayor and Sereno (2004) for a cube, but to predict height and diameter
 193 directly, instead of the area:

$$194 \quad H_{iso}^* = D_{iso}^* = \left(\frac{V}{V_0}\right)^{\frac{1}{3}} \quad (9)$$

195 Finally, after seeing that the measurements did not match any of these approaches, we looked
 196 for intermediate behaviors allowing a satisfying match with the experimental results.

197 Hereafter, Eq. 8 and 9 are combined. The dimensionless height assuming combined shrinkage
 198 is expressed as:

$$199 \quad H_{comb}^* = (H_{iso}^*)^b (H_{vert}^*)^{(1-b)}; \quad D_{comb}^* = (D_{iso}^*)^b \quad (10)$$

200 wherein b is the moisture-dependent weighting parameter.

201 The first approach ($D^* = 1$) fits the measurements at the beginning of drying (Fig. 4). Yet
 202 progressively (as X_w^* decreases) the diameter of the slices also decreases. This is why we
 203 propose increasing the relative importance of the isotropic approach along with the drying
 204 process. An approach using a similar principle was proposed by Suzuki et al. (1976); it was
 205 described by Mayor and Sereno (2004) as a “semi-core drying model”. Our approach,
 206 however, involves a different geometry and does not require as many parameters. At the end
 207 ($X_w^* \approx 0$), equal importance is given to the purely-vertical and isotropic approaches, resulting
 208 in:

$$209 \quad b = \frac{1}{2}(1 - X_w^*) \quad (11)$$

210 Assuming such a combined shrinkage behavior, the dimensionless total surface (S_{comb}^*) is
 211 calculated through Eq. 7, using the dimensionless height and diameter from Eq. 10.

212 3.2. Drying kinetics

213 Semi-theoretical models have been derived by simplifying general series solutions of Fick’s
 214 second law; they are thus valid within the air temperature, relative humidity, flow velocity
 215 and moisture content range for which they were developed; further, these models require less
 216 time compared to theoretical thin-layer models and do not need assumptions of the geometry
 217 of typical food, its mass diffusivity or conductivity. Many of these semi-theoretical drying
 218 models have been compared in the literature (e.g., Panchariya et al., 2002); some of them are
 219 shown in Table 2.

220 The evolution of the overall moisture in the product under drying can be described through
 221 the moisture ratio:

$$222 \quad MR = \frac{X_w - X_{we}}{X_{w0} - X_{we}} \quad (12)$$

223 where X_{we} is the water content in equilibrium, estimated from vapor sorption isotherms. In
 224 the scope of this study, the following two-parameter model was adjusted to the drying kinetics
 225 data:

$$226 \quad MR = \exp(-k_1 t - (k_2 t)^2) \quad (13)$$

227 the inverse value of parameter k_1 can be called characteristic drying time. Equation 13 can be
 228 seen as an extension of the Lewis (1921) drying model, which considers the first term in the
 229 exponential only.

230 The time derivative of Eq. 13 can be expressed as:

$$231 \quad \frac{dMR}{dt} = (-k_1 - 2 t k_2^2) \left(\exp(-t k_1 - t^2 k_2^2) \right) \quad (14)$$

232 When drying starts ($t = 0$), it follows $dMR/dt = -k_1$. By defining the dimensionless time $t^* = t k_1$
 233 (at any time), the evaporative water loss per dimensionless area can be expressed as:

$$234 \quad \frac{dMR}{dt^* S^*} = -MR \left(1 + \frac{2 t k_2^2}{k_1} \right) \frac{1}{S_{comb}^*} \quad (15)$$

235 *3.3 Heat transfer coefficient between yacón samples and surrounding air*

236 *3.3.1. Experimental method*

237 The heat transfer coefficient is a key parameter for assessing the importance of exchanges
 238 between the product under consideration and its surroundings. Looking for its experimental
 239 determination, a well-known material of regular geometry was heated in the same conditions
 240 as the yacón slices were dried. Two aluminum cylinders, each containing a hole (1 mm radius,
 241 10 mm height), were used in this experiment. Their properties are summarized in Table 1.

242 For each experiment, two calibrated thermocouples were used: one inserted in the aluminum
 243 cylinder, filled with thermal paste (MasterGel Maker, Cooler Master, Taiwan) and the other
 244 exposed to the air, as shown in Fig. 1d. The measurements (carried out at $T_{air} = 60$ ° C, $RH =$
 245 20% and speed of 4 m/s) were carried out until the recorded temperatures became constant, or
 246 almost. Data acquisition was performed using Labview software (National Instruments,
 247 USA).

248 The heat transfer coefficient was determined using a two-step approach, based on the lumped
 249 capacitance method (Incropera et al., 2007). The energy balance takes the form:

$$250 \quad -h A_S (T - T_{air}) = m C_P \frac{dT}{dt} \quad (16)$$

251 wherein h is the heat transfer coefficient ($W m^{-2} K^{-1}$), A_S is the surface area exposed to airflow
 252 (m^2), T is the product temperature at any time (°C), T_{air} is the air temperature (°C), m is the
 253 mass (kg) and C_P the specific heat ($J kg^{-1} K^{-1}$) of the product, and t is the time (s).

254 Observations revealed that the air temperature did not reach perfect steady-state evolution.

255 Hence, in the first step, Eq. 16 was integrated numerically using an in-house source code

256 written in Python 3.7 language. The second step involved the minimization of the sum

257 squared differences of residuals between measured and predicted temperatures, these latter

258 were obtained after assuming selected h values. Such minimization has been considered the

259 Nelder-Mead method.

260 3.3.2. Global energy balance method

261 Assuming that all the incoming heat is translated into evaporation at the surface temperature,

262 it follows (McCabe et al., 2014, p.807):

$$263 \quad -\frac{dm_w}{dt S} = -\frac{d(m_{dm} X_w)}{dt S} = \frac{h}{L_v} (T_{air} - T_{surf}) \rightarrow -\frac{dX_w}{dt} = \frac{h S (T_{air} - T_{surf})}{m_{dm} L_v} \quad (17)$$

264 wherein m_w is the mass of water in the sample (kg).

265 The time derivative of Eq. 12 is:

$$266 \quad \frac{dMR}{dt} = \frac{1}{X_{w0}-X_{we}} \frac{dX_w}{dt} \rightarrow -\frac{dX_w}{dt} = -(X_{w0}-X_{we}) \frac{dMR}{dt} \quad (18)$$

267 Combining Eqs. 17 and 18, the time derivative of Eq. 12 can be expressed in terms of
268 temperature values in ambient air and at the product surface:

$$269 \quad -(X_{w0}-X_{we}) \frac{dMR}{dt} = \frac{hS (T_{air}-T_{surf})}{m_{dm} L_v} \rightarrow \frac{dMR}{dt} = -\frac{h S (T_{air}-T_{surf})}{m_{dm} L_v (X_{w0}-X_{we})} \quad (19)$$

270 When drying starts, $dMR/dt = -k_1$; hence, at this moment:

$$271 \quad h = k_1 \frac{m_{dm} L_v (X_{w0}-X_{we})}{S_0 (T_{air}-T_{wb})} \quad (20)$$

272 assuming that $T_{surf} = T_{wb}$ at $t = 0$.

273 Application of Eq. 20 requires the mass of dry matter in the sample. The mass density of dry
274 matter in the samples used in this work was estimated to be about 1590 kg/m^3 . Firstly, we
275 used data provided by Hermann et al. (1999) about nine accessions of fresh yacón, including
276 the averaged weight fraction of selected pure components, as an estimation for the
277 composition of the samples used in this work: 0.37 % for proteins, 0.024 % for fat, 11 % for
278 carbohydrates, 0.36 % for fibers, and 0.51 % for ash. These values were considered in
279 applying the Choi and Oikos (1986)'s approach for estimating the mass density of dry-matter
280 of yacón samples at the temperature of $40 \text{ }^\circ\text{C}$. This temperature value is between the
281 temperature prevailing in the product when drying starts (about $20 \text{ }^\circ\text{C}$) and the ambient
282 surrounding temperature ($60 \text{ }^\circ\text{C}$ during the drying period).

283 3.4. Global energy balances

284 The evaporative water loss can be expressed by a global energy balance assuming that all the
285 heat entering the sample causes water evaporation. Equation 17 can be applied if the variation
286 of sensible heat can be neglected. This is approximately the case except at the beginning of

287 drying when the sample temperature increases toward the wet-bulb one if free water is
 288 available on the surface.

289 The initial water content is very high ($X_{w0} \approx 11$ kg/kg d.b.); therefore, it can be assumed that
 290 the water activity is close to 1 and that the product surface temperature is close to the wet-
 291 bulb one ($T_{surf} = T_{wb}$). Thus, combining Eqs. 19 and 20, we obtain:

$$292 \frac{T_{air} - T_{surf}}{T_{air} - T_{wb}} = \frac{(dMR/dt)/S}{(dMR/dt)|_{t=0}/S_0} = \frac{1}{1 - X_{we}/X_{w0}} \frac{S}{S_0} \frac{dX_w^*}{k_1 dt} = \frac{1}{(1 - X_{we}/X_{w0}) S^*} \frac{dX_w^*}{dt^*} \quad (21)$$

293 wherein:

$$294 \frac{dMR}{dt} = \frac{dX_w^*}{dt} \quad (22)$$

295 The water mass balance can also express the evaporative water loss:

$$296 \frac{-dm_w}{dt S} = k(c_{w,surf} - c_{w,air}) \quad (23)$$

297 wherein k is the mass transfer coefficient ($m s^{-1}$), $c_{w,surf}$ is the concentration of water vapor in
 298 the air on the surface of the product ($kg m^{-3}$), and $c_{w,air}$ is the water vapor concentration in the
 299 surrounding air ($kg m^{-3}$).

$$300 \frac{dX_w}{dt} = \frac{k S (c_{w,surf} - c_{w,air})}{m_{dm}} \quad (24)$$

301 Comparing Eqs. 17 and 24, and rearranging water vapor concentration values in the place of
 302 temperatures, we can estimate the water activity at the slice surface as:

$$303 \frac{c_{w,air} - a_w c_{w,sat}(T_{surf})}{c_{w,air} - c_{w,sat}(T_{wb})} = \frac{T_{air} - T_{surf}}{T_{air} - T_{wb}} \quad (25)$$

304 The saturated water vapor concentration is obtained from the ideal gas law and Clausius-
 305 Clapeyron relation (Çengel et al., 2015):

$$306 c_{w,sat}(T_{surf}) = \frac{P_{sat}^{T_{surf}} M_w}{R T_{surf}} \quad (26)$$

307 wherein $P_{\text{sat}}^{T_{\text{surf}}}$ is the saturated vapor pressure at a temperature T and R is the gas constant
308 ($8.314 \text{ J K}^{-1} \text{ mol}^{-1}$). The water concentration at the surface was estimated through a GAB
309 model for parameters $X_{w,\text{mono}}$, C and K resulting from desorption measurements.

310 In summary:

- 311 a) pilot-scale drying experiments allowed the monitoring of water content X_w and slice
312 dimensions D and H under controlled ambient conditions;
- 313 b) for each of these ambient conditions, desorption models enabled us to estimate the
314 equilibrium moisture X_{we} value;
- 315 c) with the latter, the evolution of the moisture ratio MR was represented through the two-
316 parameter drying kinetics, providing the initial drying rate;
- 317 d) monitoring the slice dimensions allowed us to identify a mean shrinkage behavior, and
318 hence to predict the slice surface evolution;
- 319 e) finally, the availability of water content and surface evolutions allowed us to estimate the
320 surface temperature and the surface water activity (Eq. 25).

321 *3.5 Statistical analyses*

322 Vapor sorption isotherm data were fitted using nonlinear regression, through the Statgraphics
323 Centurion XV software (StatPoint, Inc., USA). The agreement between the experimental data
324 and the calculated values was assessed by the coefficient of determination (r^2) and root-mean-
325 square error (RMSE).

326 Drying kinetics data were fitted using nonlinear regression, using the Solver tool from Excel
327 2019 (Microsoft, USA), and the agreement between experimental and model values was
328 evaluated using the root mean square error (RMSE). The model parameters (eq. 13) were
329 analyzed by the ANOVA applying Tukey's test at a 95% confidence level as a posthoc test,
330 using Statgraphics Centurion XV software (StatPoint, Inc., USA).

331 4. Results

332 4.1. Vapor sorption isotherms

333 Vapor sorption isotherms for yacón (Fig. 2) can be characterized as being type III, which are
334 common for products with a high quantity of soluble sugars (Rizvi, 2005; Al-Muhtaseb et al.,
335 2002). It can be observed that there was little difference between static and dynamic methods,
336 and between tested temperatures, and no visible hysteresis.

337 GAB model parameters, adjusted to the isotherms, are shown in Table 3. $X_{w,mono}$ is an
338 estimation of the monolayer water content; under this value, food materials tend to be very
339 stable (Roos, 2008). However, packaging conditions are important to delay the re-absorption
340 of water.

341 4.2. Drying kinetics

342 Figure 3 shows the evolution of the moisture ratio of ensembles of yacón slices, under the
343 ambient conditions here considered. Table 4 summarizes the results obtained after applying
344 Eq.13, and other models available in the literature, to the data obtained from each of the three
345 tests, carried out under each of the four controlled conditions. ANOVA performed along with
346 an analysis of residuals, showed no evidence of heteroscedasticity in any of the tested models
347 (Table 4). Some findings emerge from these results.

- 348 a) Under the ambient conditions considered, the application of Eq. 13 allows a smaller
349 root-mean-square-error (RMSE) than other two-parameters models available in the
350 literature. We argue that Eq. 13 constitutes a good option for engineering aims.
- 351 b) The influence of ambient conditions on the values estimated for model parameters is
352 here preliminarily assessed because only three runs were conducted under each
353 ambient condition. Excepting the Page model, the influence of both air temperature
354 and relative humidity on parameter k_1 seems significant. This finding is consistent

355 with the physical meaning of this parameter; it is directly related to the initial drying
356 rate, and its value increases with the driving force ($T_{air} - T_{wb}$). The influence of air
357 temperature on the second parameter of Eq. 13, of Modified Page, and Henderson-
358 Pabis models seems significant.

359 c) It is quite hard to compare model parameters estimated from our experimental data
360 with those provided by other authors. Airflow and temperature conditions were
361 different, and there was no control of air relative humidity, allowing ambient
362 conditions which be perhaps unsteady. An additional difficulty comes from the
363 diversity of yacón; Hermann et al. (1999) studied nine different cultivars of yacón, and
364 they differed in appearance and composition: the dry matter content alone could range
365 from 98 to 136 g/kg, suggesting that the drying kinetics can vary from a cultivar to
366 another. Reis et al. (2012) reported the time of purchase, but not the location; Shi et al
367 (2013) purchased their roots in China, and Lisboa et al. (2018) reported a purchase in
368 Brazil, but not the season. None of these studies reported the variety used, nor any
369 descriptors, there thus being a possibility that those authors studied different varieties
370 of yacón.

371 4.3. Shrinkage

372 The left-hand side of Fig. 4 summarizes all the available experimental data, in terms of
373 dimensionless values for the slice height (Fig. 4a) and diameter (4c) as a function of the
374 dimensionless water content. Triplicates were conducted. The right-hand side of Fig. 4
375 compares measurements with similar predicted by hypothetical shrinkage behaviors; in the
376 case of slice height, triangles indicate averaged values; in the case of slice diameter,
377 measurements do not correspond to the same water content and then averaging was not
378 possible.

379 Figures 4b and 4d compare measurements and hypothetical shrinkage behaviors: purely-
 380 vertical, isotropic and combined models for both diameter and height (Eqs. 8, 9, and 10,
 381 respectively). Up to $X_w^* = 0.2$, the slice diameter remained at more than 90 % of the initial
 382 value; the proposed vertical model is thus a more realistic approach than the isotropic one.
 383 Afterward, there was a drastic reduction in diameter. Figures 4b and 4d suggest that the
 384 combined behavior, which mixes the vertical and the isotropic approaches, describes the slice
 385 shrinkage better than the others. Looking for a consistent approach for predicting the
 386 shrinkage of yacón slices under convective drying, the combined approach was considered.

387 *4.4. Heat transfer coefficient between yacón samples and surrounding air*

388 A first estimation of the heat transfer coefficient relevant to our problem comes from
 389 experimental work with aluminum slices (sub-section 3.3.1). The results obtained were $h = 41$
 390 $\text{W m}^{-2} \text{K}^{-1}$ for the 35 mm cylinder and $53 \text{ W m}^{-2} \text{K}^{-1}$ for the 20 mm one.

391 The consistency of these findings can be discussed using the correlation method. Taking into
 392 account uniform heat flux conditions over a flat plate under laminar flow, it can be shown that
 393 the averaged Nusselt, Reynolds and Prandtl numbers are related through the correlation
 394 $\text{Nu} = \alpha \text{Re}^\beta \text{Pr}^\gamma$ (Incropera et al., 2007, p.410). In our case, this expression can be rewritten
 395 to indicate the heat transfer coefficient as a function of the cylinder diameter: $h = \delta D^{\beta-1}$
 396 wherein $\beta - 1 < 0$. According to this rationale, the heat transfer coefficient should increase
 397 during drying while the yacón dimension reduces. Hence, it is consistent to reach $h = 41 \text{ W m}^{-2}$
 398 K^{-1} for experimental data collected with a 35 mm aluminum cylinder and $53 \text{ W m}^{-2} \text{K}^{-1}$ with
 399 a 20 mm one.

400 A second estimation of the heat transfer coefficient between yacón samples and surrounding
 401 air can be obtained by applying the expression $h = \delta D^{\beta-1}$ to our experimental conditions.

402 Given the airflow and temperature conditions above the surface of the cylinders, we can

403 estimate the Reynolds number to be about 10000 for a 40 mm cylinder (yacón sample, before
404 any drying), hence lower than the critical value for the laminar-turbulent transition for
405 external flow (Incropera et al., 2007, p.361). For these conditions, that correlation yields a
406 heat transfer convective coefficient $39 \text{ W m}^{-2}\text{K}^{-1}$ for a 40 mm cylinder. Note that the
407 aforementioned correlation and the experimental values correspond to a physical problem
408 bounded by an adiabatic surface below the cylinder.

409 Finally, the heat transfer coefficient between yacón samples and surrounding air was
410 estimated by applying Eq. 20, i.e. by considering the initial evaporative rate results. The value
411 obtained ($32 \text{ W m}^{-2} \text{ K}^{-1}$) implicitly takes into account the global influence of many factors
412 affecting the heat and mass transfer relevant to the problem, including: a) the fact that not one
413 but an ensemble of 42 yacón slices were simultaneously processed in the convective dryer
414 pilot unit; b) the role played by the heterogeneous exposure of slices to airflow, c) the
415 influence of thermal radiation interaction of slices with the metallic walls of the dryer, and d)
416 the fact that there was a metallic holed surface below the yacón samples, allowing a complex
417 situation of heat and mass transfer.

418 *4.5. Predictions of temperature and water activity on the surface*

419 Experimental results displayed in Fig. 3 suggest that the most reproducible condition was T_{air}
420 $= 60 \text{ }^\circ\text{C}$, $RH = 20 \%$. We hypothesize that better reproducibility is due to the humidity
421 stabilization system of the convective dryer pilot unit. On the one hand, when the thermo-
422 hygrometer detects a value of RH below the set point, the control system of the drying oven
423 sprays water into the airflow and as it is not preheated, it could destabilize the temperature in
424 the oven. On the other hand, when humidity is above the set point, the air passes through a
425 refrigerating system, where water condensates and is removed, and the air must be heated
426 again before re-entering the oven. At the highest temperature ($60 \text{ }^\circ\text{C}$), the air has a higher
427 ability to hold water from the samples without going over the set point; and, in the lowest RH ,

428 there is no need to add moisture to the air at the end of the drying process, to keep a high RH ,
 429 leading to less destabilization. In the forthcoming last steps of this study, we restrict our
 430 attention to measurements and predictions corresponding to the ambient condition $T_{air} = 60$
 431 $^{\circ}\text{C}$, $RH = 20\%$.

432 The identification of a suitable shrinkage behavior allows predicting the slice surface, which
 433 is exposed to surrounding air along the drying period (S^*). Representing the drying kinetics
 434 through the two-parameter model allows to predict, also along the whole period, the drying
 435 rate $\frac{dX_w^*}{dt^*}$. Figure 5a shows the predictions for the slice surface (Eq. 7) and the drying rate (Eqs.
 436 14 and 22) as a function of the dimensionless water content. The influence of the total surface
 437 decrease on the drying rate $\frac{dX_w^*}{dt^* S^*}$ is noticeable, but only partially explains the drop in this
 438 drying rate. Figure 5b exhibits the same variables as a function of time, which can be
 439 compared with the classical drying curves (Mujumdar, 2006). Note that $\frac{dX_w^*}{dt^* S^*}$ does not present
 440 a constant rate period, indicating that some drying limitations due to the resistance of water
 441 migration from the center to the surface of the product may exist.

442 The availability of key quantities S^* and $\frac{dX_w^*}{dt^*}$ enables to estimate surface-averaged values for
 443 the temperature T , the water activity a_w and the water content X_w at the slice surface along the
 444 drying period. Figure 5c shows that, as expected, the predicted water content at the surface
 445 decreases more rapidly than the volume-averaged value for the sample. Note that GAB
 446 models do not accurately represent the sorption phenomena at very high ($a_w > 0.93$) water
 447 activities (Basu et al., 2006); hence, the predicted water content at the surface tends to be
 448 underestimated at the beginning of drying.

449 Finally, Fig. 5d displays the water activity and temperature at the product surface. In the case
 450 of the water activity, the departure from pre-drying conditions is immediate, contrarily to

451 experimental results (see for instance Figure 1 of Bernstein and Norena, 2014). In the case of
452 temperature, firstly the surface-averaged temperature increases almost instantaneously from
453 the initial product temperature (20 °C) up to the wet-bulb temperature (about 35 °C); later on,
454 this temperature increases from the wet-bulb temperature up to the air temperature along the
455 remaining drying period. It would be interesting to assess the reliability of these predictions,
456 for instance using a non-invasive technique, such as an infrared thermometer.

457 *4.6. A remark about moisture diffusivity*

458 Shi et al. (2013) and Lisboa et al. (2018) used the Crank (1975) solutions to Fick's laws to
459 estimate the effective moisture diffusion coefficient for yacón samples. These solutions,
460 however, assume that the shrinkage is negligible. Results in Section 4.3 demonstrate that this
461 is not the case for yacón samples as tested here. The infinite slab and the finite cylinder
462 models, common in the literature, revealed to be unreliable fits for the experimental drying
463 data displayed in Fig. 3. In the case of the infinite slab model, estimated moisture diffusivity
464 was $4.0 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$ at 50 °C, and $7.4 \cdot 10^{-10} \text{ m}^2 \text{ s}^{-1}$ at 60 °C, and a root mean square error of
465 0.033 and 0.060 in *MR* units, respectively. However, the fitted curve tended to underestimate
466 the moisture ratio at the beginning of the drying period and to overestimate it after two hours
467 of drying. Anyway, given the drastic differences in the sample's water content, dimensions
468 and temperature between the beginning and the end of the drying process, it is likely incorrect
469 to attribute a single, constant moisture diffusivity value over the whole drying process.

470 **5. Conclusions and Recommendations**

471 The study focused on the evolution of yacón samples having a particular shape and being
472 exposed to convective drying under controlled ambient conditions (mean air velocity of 4 m/s,
473 air temperature of 50 and 60 °C, air relative humidity of 20 and 30 %). The slice dimensions
474 were measured along the drying period, as an original contribution to the classical monitoring
475 of moisture loss. A dataset including triplicates of samples' water content, diameter and

476 height allowed us to study the evolution of yacón slices while including the influence of
477 shrinkage. Surface-averaged temperature and water activity tendencies were estimated from
478 standard assumptions about heat and mass transfer phenomena, providing a useful insight
479 about the drying evolution of a complex food product. The following conclusions were
480 reached.

481 i) The diameter of yacón slices decreased to about 60-70 % of the initial value after 6 hours
482 of drying without a clear dependence on the ambient condition under consideration, i.e.
483 following nearly the same decreasing tendency. The height of yacón slices was more difficult
484 to determine because of irregularities that progressively appeared on upper and lower surfaces
485 along the drying period. Available results indicated a reduction to 5-30 % of the initial value
486 after 6 hours of drying, with the decreasing tendency being faster in the samples dried at 20%
487 than in the samples dried at 30%, which can be explained by the faster dehydration if
488 Equations 10 and 11 are considered.

489 ii) In the case of yacón slices as tested here, a combined shrinkage behavior was identified: it
490 mixes purely-vertical (no diameter modification) with isotropic shrinkage (that progressively
491 operates inside the product matrix). Such a novel approach was later applied in predicting
492 firstly the slice total surface as a function of the water content inside it, and secondly the
493 evolution of selected properties at the yacón slice surface along the drying period.

494 iii) The application of a two-parameter model for representing the drying kinetics (Eq. 13)
495 allowed us to estimate the heat transfer coefficient between yacón samples and surrounding
496 ambient conditions. The value obtained ($32 \text{ W m}^{-2} \text{ K}^{-1}$) implicitly includes the global
497 influence of many factors affecting the heat and mass transfer relevant to the problem. Two
498 other approaches (experimental work with aluminum cylinders, and correlation involving
499 dimensionless numbers) provided independent estimates of this transfer coefficient, and the
500 whole set of results seems consistent.

501 iv) Evolutions of moisture ratio from measurements were poorly represented by the semi-
502 theoretical model proposed by Lewis (1921), towards the ending of the drying period (Fig. 3).
503 That classical model was proposed under some assumptions including negligible shrinkage,
504 which constitutes a hypothesis unacceptable for yacón samples. The inclusion of a quadratic
505 term in Eq. 13 mitigates this problem (Fig. 3). We argue that Eq. 13 constitutes a good option
506 for engineering aims, in which the whole drying period must be represented as properly as
507 possible.

508 v) The results from the energy balance allowed to estimate properties that could not be
509 directly measured, or that would disturb the system. It gave insight on aspects that were not
510 clear from the experimental data, such as the immediate decrease in the water activity and the
511 different evolution of the water content on the sample surface and center.

512 The crucial issue of this study was to follow the dimensions of the sample throughout the
513 drying period. Our pioneering strategy could be improved, for example by measuring the
514 height of the sample using an optical detection method.

515 The suitability of our approach to the design and optimization of the process as well as of the
516 final product could be explored. As a preliminary step, testing this approach should consider
517 wider ranges of ambient conditions (airflow, temperature and relative humidity) and include
518 different varieties of yacón and other raw food products. Much work remains to be done to
519 clarify the relationship between shrinkage and moisture loss.

520 **ACKNOWLEDGMENTS**

521 The authors have received grants from the São Paulo Research Foundation (FAPESP), grants
522 2018/21327-1 and 2019/21832-0; from the Coordination for the Improvement of Higher
523 Education Personnel - Brazil (CAPES) - Finance Code 001; and from the National Council
524 for Scientific and Technological Development (CNPq), grant 306414/2017-1. We would like
525 to thank AgroParistech and UMR Sayfood for receiving the first author for a one-year
526 research internship abroad; and Emmanuel Bernuau, for his valuable help to calculate the heat
527 transfer coefficient.

528 Declarations of interest: none.

529 **REFERENCES**

- 530 Al-Muhtaseb, A. H., McMinn, W. A. M., & Magee, T. R. A. (2002). Moisture sorption
531 isotherm characteristics of food products: A review. *Food Bioprocesses Process*, *80*, 118–128.
532 <https://doi.org/10.1205/09603080252938753>.
- 533 AOAC. (1996). Moisture and volatile matter in oils and fats (926.12-1926). In *Official*
534 *Methods of Analysis, 15th ed.*, Association of Official Analytical Chemists, Washington,
535 USA.
- 536 Asioli, D., Aschemann-Witzel, J., Caputo, V., Vecchio, R., Annunziata, A., Næs, T., &
537 Varela, P. (2017). Making sense of the “clean label” trends: A review of consumer food
538 choice behavior and discussion of industry implications. *Food Research International*, *99*,
539 58–71. <https://doi.org/10.1016/j.foodres.2017.07.022>.
- 540 Assis, F. R., Rodrigues, L. G. G., Tribuzi, G., de Souza, P. G., Carciofi, B. A. M., &
541 Laurindo, J. B. (2019). Fortified apple (*Malus* spp., var. Fuji) snacks by vacuum impregnation
542 of calcium lactate and convective drying. *LWT – Food Science and Technology*, *113*, 108298.
543 <https://doi.org/10.1016/j.lwt.2019.108298>.

- 544 Basu, S., Shivhare, U. S., & Mujumdar, A. S. (2006). Models for sorption isotherms for
545 foods: A review. *Drying Technology*, 24, 917–930.
546 <https://doi.org/10.1080/07373930600775979>.
- 547 * Bernstein, A., & Noreña, C. P. Z. (2014). Study of thermodynamic, structural, and quality
548 properties of yacón (*Smallanthus sonchifolius*) during drying. *Food and Bioprocess
549 Technology*, 7, 148-160. <https://link.springer.com/article/10.1007/s11947-012-1027-y>.
- 550 Blahovec, J., Lahodova, M., Kindl, M., & Fernandez, E. C. (2013). DMA thermal analysis of
551 yacón tuberous roots. *International Agrophysics*, 27, 479-483. [https://doi.org/10.2478/intag-](https://doi.org/10.2478/intag-2013-0018)
552 2013-0018.
- 553 Campos, D., Aguilar-Galvez, A., & Pedreschi, R. (2016). Stability of fructooligosaccharides,
554 sugars and colour of yacón (*Smallanthus sonchifolius*) roots during blanching and drying.
555 *International Journal of Food Science and Technology*, 51, 1177-1185.
556 <https://doi.org/10.1111/ijfs.13074>.
- 557 Çengel, Y., Boles, M., & Kanoglu, M. (2015). Thermodynamic property relations. In:
558 *Thermodynamics an engineering approach*. Mc McGraw-Hill.
- 559 Castro, A. M., Mayorga, E. Y., & Moreno, F. L. (2018). Mathematical modelling of
560 convective drying of fruits: A review. *Journal of Food Engineering*, 223, 152-167.
561 <https://doi.org/10.1016/j.jfoodeng.2017.12.012>.
- 562 Choi, Y., & Okos, M. R. (1986). Effects of temperature and composition on the thermal
563 properties of foods. In M. Le Mageur, & P. Jelen (Eds.), *Food Engineering and Process
564 Applications* (pp. 93-101). Elsevier Applied Science.
- 565 Chua, K. J., Mujumdar, A. S., Chou, S. K., Hawlader, M. N. A., & Ho, J. C. (2000).
566 Convective drying of banana, guava and potato pieces : Effect of cyclical variations of air
567 temperature on drying kinetics and color change. *Drying Technology*, 18, 907–936.
568 <https://doi.org/10.1080/07373930008917744>.

- 569 Crank, J. (1975). *The Mathematics of Diffusion* (2nd ed.). Oxford University Press.
- 570 Curcio, S., & Aversa, M. (2014). Influence of shrinkage on convective drying of fresh
571 vegetables: A theoretical model. *Journal of Food Engineering*, *123*, 36-49.
572 <http://dx.doi.org/10.1016/j.jfoodeng.2013.09.014>.
- 573 Fernández, E. C., Rajchl, A., Lachman, J., Čížková, H., Kvasnička, F., Kotíková, Z., &
574 Voldřich, M. (2013). Impact of yacón landraces cultivated in the Czech Republic and their
575 ploidy on the short- and long-chain fructo-oligosaccharides content in tuberous roots. *LWT -*
576 *Food Science and Technology*, *54*, 80–86. <https://doi.org/10.1016/j.lwt.2013.05.013>.
- 577 Graefe, S., Hermann, M., Manrique, I., Golombek, S., & Buerkert, A. (2004). Effects of post-
578 harvest treatments on the carbohydrate composition of yacón roots in the Peruvian Andes.
579 *Field Crops Research*, *86*, 157–165. <https://doi.org/10.1016/j.fcr.2003.08.003>.
- 580 Grau, A., & Rea, J. (1997). Yacón, *Smallanthus sonchifolius* (Poepp. et Endl.) H. Robinson.
581 In: M. Hermann & J. Heller (Eds.), *Promoting the conservation and use of underutilized and*
582 *neglected crops, #21, Andean roots and tubers: Ahípa, arracacha, maca and yacón* (pp. 199-
583 242). International Plant Genetic Resources Institute.
- 584 Hassini, L., Azzouz, S., Peczalski, R., & Belghith, A. (2007). Estimation of potato moisture
585 diffusivity from convective drying kinetics with correction for shrinkage. *Journal of food*
586 *engineering*. *79*, 47–56. <https://doi.org/10.1016/j.jfoodeng.2006.01.025>.
- 587 * Hermann, M., Freire, I., & Pazos, C. (1999). Compositional diversity of the yacón storage
588 root. In *Andean Roots and Tuber Crops* (pp. 425-432). International Potato Center Program
589 Report 1997-1998.
- 590 Incropera, F. P., Witt, D. P., Bergman, T. L., Lavine, A. S. (2007). *Fundamentals of heat and*
591 *mass transfer* (6th ed.). Wiley, pp.253-263.
- 592 Khajehei, F., Hartung, J., & Graeff-Hönninger, S. (2018a). Total phenolic content and
593 antioxidant activity of yacón (*Smallanthus sonchifolius* Poepp. and Endl.) chips: Effect of

- 594 cultivar, pre-treatment, and drying. *Agriculture*, 8, 183.
595 <https://doi.org/10.3390/agriculture8120183>.
- 596 Khajehei, F., Merkt, N., Claupein, W., & Graeff-Hönninger, S. (2018b). Yacón (*Smallanthus*
597 *sonchifolius* Poepp. & Endl.) as a novel source of health promoting compounds: Antioxidant
598 activity, phytochemicals and sugar content in flesh, peel, and whole tubers of seven cultivars.
599 *Molecules*, 23, 278. <http://dx.doi.org/10.3390/molecules23020278>.
- 600 Lachman, J., Fernández, E. C., & Orsák, M. (2003). Yacón [*Smallanthus sonchifolia* (Poepp.
601 *et Endl.*) *H. Robinson*] chemical composition and use: A review. *Plant, Soil and Environment*,
602 49, 283–290. <https://doi.org/10.17221/4126-PSE>.
- 603 Lebeda, A., Doležalová, I., Fernández, E., & Viehmannová, I. (2012). Yacón (*Asteraceae*;
604 *Smallanthus sonchifolius*). In R. J. Singh (Ed.), *Genetic Resources, Chromosome*
605 *Engineering, and Crop Improvement. Volume 6: Medicinal Plants* (pp. 641-702). CRC Press.
- 606 * Lewis, W. K. (1921). The rate of drying of solid materials. *Industrial & Engineering*
607 *Chemistry Research*, 13, 427–432. <https://doi.org/10.1021/ie50137a021>.
- 608 Lisboa, C., Gomes, J., Figueirêdo, R., Queiroz, A., Diógenes, A., & de Melo, J. (2018).
609 Effective diffusivity in yacón potato cylinders during drying. *Revista Brasileira de*
610 *Engenharia Agrícola e Ambiental*, 22, 564–569. [https://doi.org/10.1590/1807-](https://doi.org/10.1590/1807-1929/agriambi.v22n8p564-569)
611 [1929/agriambi.v22n8p564-569](https://doi.org/10.1590/1807-1929/agriambi.v22n8p564-569).
- 612 * Mayor, L., & Sereno, A. M. (2004). Modelling shrinkage during convective drying of food
613 materials: A review. *Journal of Food Engineering*, 61, 373-386.
614 [http://dx.doi.org/10.1016/S0260-8774\(03\)00144-4](http://dx.doi.org/10.1016/S0260-8774(03)00144-4).
- 615 McCabe, W., Smith, J., & Harriott, P. (2014). Drying of solids. In: *Unit operations of*
616 *chemical engineering* (7th ed.). Mc Graw Hill.

- 617 Moreira, R., Figueiredo, A., & Sereno, A. (2000). Shrinkage of apple disks during drying by
618 warm air convection and freeze drying. *Drying Technology*, 18, 279-294.
619 <https://doi.org/10.1080/07373930008917704>.
- 620 Mujumdar, A. S. (2006). Principles, Classification, and Selection of Dryers. In *Handbook of*
621 *Industrial Drying*. Taylor and Francis.
- 622 Panchariya, P. C., Popovic, D., & Sharma, A. L. (2002). Thin-layer modelling of black tea
623 drying process. *Journal of Food Engineering*, 52, 349-357. <https://doi.org/10.1016/S0260->
624 [8774\(01\)00126-1](https://doi.org/10.1016/S0260-8774(01)00126-1).
- 625 Perussello, C. A., Mariani, V. C., Masson, M. L., & Castilhos, F. (2013). Determination of
626 thermophysical properties of yacón (*Smallanthus sonchifolius*) to be used in a finite element
627 simulation. *International Journal of Heat and Mass Transfer*, 67, 1163-1169.
628 <http://dx.doi.org/10.1016/j.ijheatmasstransfer.2013.09.004>.
- 629 Perussello, C. A., Kumar, C., De Castilhos, F., & Karim, M. A. (2014). Heat and mass
630 transfer modeling of the osmo-convective drying of yacón roots (*Smallanthus sonchifolius*).
631 *Applied Thermal Engineering*, 63, 23–32.
632 <https://doi.org/10.1016/j.applthermaleng.2013.10.020>.
- 633 Perry, R. H., & Green, D. W. (1997). Section 2: Physical and chemical data. In *Perry's*
634 *Engineers' Handbook* (7th ed.). Mc Graw-Hill.
- 635 Rizvi, S. H. (2005). Thermodynamic Properties of Foods in Dehydration. In *Engineering*
636 *Properties of Foods* (3rd ed.). Boca Raton: CRC Press.
- 637 Reis, F. R., Lenzi, M. K., de Muñiz, G. I. B., Nisgoski, S., & Masson, M. L. (2012). Vacuum
638 drying kinetics of yacón (*Smallanthus sonchifolius*) and the effect of process conditions on
639 fractal dimension and rehydration capacity. *Drying Technology*, 30, 13–19.
640 <https://doi.org/10.1080/07373937.2011.611307>.

- 641 Roos, Y.H. (2008). Water Activity and Glass Transition. In *Water Activity in Foods:*
642 *Fundamentals and Applications*, (1st ed.). Blackwell Publishing Professional.
- 643 * Scher, C. F., Rios, A., & Noreña, C. (2009). Hot air drying of yacón (*Smallanthus*
644 *sonchifolius*) and its effect on sugar concentrations. *International Journal of Food Science*
645 *and Technology*, 44, 2169–2175. <https://doi.org/10.1111/j.1365-2621.2009.02056.x>.
- 646 Salinas, J. G., Alvarado, J. A., Bergenståhl, B., & Tornberg, E. (2018). The influence of
647 convection drying on the physicochemical properties of yacón (*Smallanthus sonchifolius*).
648 *Heat and Mass Transfer*, 54, 2951-2961. <https://doi.org/10.1007/s00231-018-2334-2>.
- 649 Sandoval-Torres, S., Tovilla-Morales, A. S., & Hernández-Bautista, E. (2017). Dimensionless
650 modeling for convective drying of tuberous crop (*Solanum tuberosum*) by considering
651 shrinkage. *Journal of Food Engineering*, 214, 147–157.
652 <https://doi.org/10.1016/j.jfoodeng.2017.06.014>.
- 653 Seminario, J., Valderrama, M., & Manrique, I. (2003). *El Yacón : Fundamentos para el*
654 *Aprovechamiento de un Recurso Promisorio*. Lima (Peru): Centro Internacional de la Papa
655 (CIP), Universidad Nacional de Cajamarca, Agencia Suiza para el Desarrollo y la Cooperacion
656 (COSUDE).
- 657 Shi, Q., Zheng, Y., & Zhao, Y. (2013). Mathematical modeling on thin-layer heat pump
658 drying of yacón (*Smallanthus sonchifolius*) slices. *Energy Conversion and Management*, 71,
659 208–216. <https://doi.org/10.1016/j.enconman.2013.03.032>.
- 660 Shi, Q., Zheng, Y., & Zhao, Y. (2015). Thermal transition and state diagram of yacón dried
661 by combined heat pump and microwave method. *Journal of Thermal Analysis and*
662 *Calorimetry*, 119, 727–735. <https://doi.org/10.1007/s10973-014-4198-0>.
- 663 Sjöholm, I., & Gekas, V. (1995). Apple shrinkage upon drying. *Journal of Food Engineering*,
664 25, 123-130. [https://doi.org/10.1016/0260-8774\(94\)00001-P](https://doi.org/10.1016/0260-8774(94)00001-P).

- 665 Suzuki, K., Kubota, K., Hasegawa, T., & Hosaka, H. (1976). Shrinkage in dehydration of root
666 vegetables. *Journal of Food Science*, *41*, 1189–1193. [https://doi.org/10.1111/j.1365-](https://doi.org/10.1111/j.1365-2621.1976.tb14414.x)
667 [2621.1976.tb14414.x](https://doi.org/10.1111/j.1365-2621.1976.tb14414.x).
- 668 van den Berg, C. (1984). Description of water activity of foods for engineering purposes by
669 means of the G.A.B. model of sorption. In B. M. McKenna (Ed.), *Engineering and Food*
670 *(Proceedings of the Third International Congress on Engineering and Food held between 26*
671 *and 28 September 1983 at Trinity College, Dublin, Ireland)* (vol. 1, pp. 311-321). London
672 (UK): Elsevier Applied Science Publishers.
- 673 Watzl, B., Girrbaach, S., & Roller, M. (2005). Inulin, oligofructose and immunomodulation.
674 *British Journal of Nutrition*, *93*, S49. <https://doi.org/10.1079/BJN20041357>.
- 675 Yan, X., Suzuki, M., Ohnishi-Kameyama, M., Sada, Y., Nakanishi, T., & Nagata, T. (1999).
676 Extraction and identification of antioxidants in the roots of yacón (*Smallanthus sonchifolius*).
677 *Journal of Agricultural and Food Chemistry*, *47*, 4711–4713.
678 <https://doi.org/10.1021/jf981305o>.

679 **Figure captions**

680 **Fig. 1.** Yacón roots: (a) *in natura*, still with their tan-colored peel; (b) being cut for the drying
 681 experiments, with their light-yellow flesh visible; (c) dried, with the perforated tray on the
 682 background; and (d) experimental arrangement to estimate the heat transfer coefficient.

683 **Fig. 2.** Sorption isotherms (desorption and adsorption) for yacón obtained at two temperatures
 684 through the methods DDI and DVS, in comparison with the adjusted GAB model for DVS
 685 test at 60 °C.

686 **Fig. 3.** Moisture ratio of yacón slices, expressed in function of time (a) at $T_{air} = 50$ °C and RH
 687 = 30 %; (b) at 60 °C and 30 %; (c) at 50 °C and 20 %; (d) at 60 °C and 20 %, compared to the
 688 drying kinetics model proposed in this work, and to the Lewis (1921) model.

689 **Fig. 4.** Dimensionless height and diameter of yacón slices as a function of dimensionless
 690 water content along with the drying: (a) all height measurements performed under four
 691 ambient conditions; (b) height measurement averages, compared to predictions reached after
 692 assuming different hypothetical behaviors for slice shrinkage; (c) as in (a) but for the
 693 diameter; (d) as in (b) but for the diameter. In the case of the vertical shrinkage assumption,
 694 the dimensionless diameter equals unity (Eq.8).

695 **Fig. 5.** Predictions about the drying behavior of yacón slices. In-display (a), the dimensionless
 696 surface S^* comes from Eq.7, the drying rate dX_w^*/dt^* comes from Eq.22 with dMR/dt
 697 from Eq.14. In-display (b), same as (a) but as a function of time. In-display (c), slice-averaged
 698 and surface moisture as a function of time. In-display (d), surface temperature from Eq.21 and
 699 water activity from Eq.25 as a function of time.

700 **Justifying key references**

701 Please see below our remarks regarding our five key references, sorted by year of publication.

702 They are indicated by a star in the reference section of our manuscript.

703 1) Lewis, W. K. - 1921 - The rate of drying the solid materials. The Journal of Industrial and
704 Engineering Chemistry, 13: 427-432. <https://doi.org/10.1021/ie50137a021>.

705 > This founding article allowed us to understand the basic rationale of semi-theoretical drying
706 kinetics models. The Lewis' model can be presented as

707
$$d MR / dt = -k t,$$

708 where symbols are explained in our Nomenclature. In the present study we propose an extension
709 of the Lewis' model:

710
$$d MR / dt = -k_1 t - k_2 t^2.$$

711 The second-order term might incorporate, implicitly, the bulk influence of complex phenomena
712 in drying the solid matrix (including shrinkage, which was neglected by Lewis). Results suggest
713 that this extended model fits better our experimental data than Lewis' one.

714 2) Hermann, M., Freire, I., Pazos, C. - 1999 - Compositional diversity of the yacón storage root.
715 In « Andean Roots and Tuber Crops », International Potato Center Program Report 1997-1998,
716 Lima (Peru), pp.425-432.

717 > Very few articles compare the physicochemical composition (fibers, proteins, carbohydrates,
718 etc) of different yacón varieties. This article allowed us to estimate the dry-matter mass density
719 associated with an averaged composition over nine yacón cultivars.

720 3) Mayor, L., Sereno, A. M. - 2004 - Modelling shrinkage during convective drying of food
721 materials: A review. Journal of Food Engineering, 61: 373-386. [https://doi.org/10.1016/S0260-](https://doi.org/10.1016/S0260-8774(03)00144-4)
722 [8774\(03\)00144-4](https://doi.org/10.1016/S0260-8774(03)00144-4).

723 > This classical reference inspired us in our analysis of experimental data, more precisely in
724 comparing measurements of dimensions of yacón slices along the drying period with
725 predictions from hypothetical shrinkage behaviors.

726 4) Scher, C. F., Rios, A. O., Norena, C. P. Z. - 2009 - Hot air drying of yacón (*Smallanthus*
727 *sonchifolius*) and its effect on sugar concentrations. *International Journal of Food Science and*
728 *Technology*, 44: 2169-2175. <https://doi.org/10.1111/j.1365-2621.2009.02056>.

729 > This dense article discusses the influence of drying conditions on yacón sugar contents and
730 water activity, among other relevant characteristics. The design of our experimental work was,
731 to some extent, inspired by this article.

732 5) Bernstein, A., Norena, C. P. Z. - 2014 – Study of thermodynamic, structural, and quality
733 properties of yacón (*Smallanthus sonchifolius*) during drying. *Food and Bioprocess*
734 *Technology*, 7: 148-160. <https://link.springer.com/article/10.1007/s11947-012-1027-y>.

735 > This very interesting article provided us insight about yacón samples: their volume reduction
736 along some hours of drying, their micro-structure after different treatments, and water activity
737 at selected temperatures.

NOMENCLATURE

a_w	Water activity [-]
$a_{w,surf}$	Water activity at the slice surfaces [-]
b	Moisture-dependent weighting parameter [-]
C	Guggenheim constant, GAB model [-]
C_P	Specific heat [J kg ⁻¹ K ⁻¹]
$c_{w,air}$	Water vapor concentration in the surrounding air [kg m ⁻³]
$c_{w,sat}(T)$	Concentration of water in saturated air at a temperature T [kg m ⁻³]
$c_{w,surf}$	Concentration of water vapor in the air at the surface of the product [kg m ⁻³]
D	Diameter [m]
D_0	Initial diameter of the food slice before drying [m]
D^*	Dimensionless diameter of the food slice (D/D_0)
D_{comb}^*	D^* assuming combined shrinkage behavior [-]
D_{iso}^*	D^* assuming isotropic shrinkage [-]
D_{vert}^*	D^* assuming vertical shrinkage only [-]
h	Heat transfer coefficient [Wm ⁻² K ⁻¹]
H	Height [m]
H_0	Initial height of the food slice before drying [m]
H^*	Dimensionless height of the food slice (H/H_0)
H_{comb}^*	H^* assuming combined shrinkage behavior [-]
H_{iso}^*	H^* assuming isotropic shrinkage [-]
H_{vert}^*	H^* assuming vertical shrinkage only [-]
k	Convective mass transfer coefficient [m s ⁻¹]

K	GAB correction factor [-]
k_1	Kinetic model parameter [s^{-1}]
k_2	Kinetic model parameter [s^{-1}]
L_v	Latent heat of evaporation of water [$J\ kg^{-1}$]
m	Mass [kg]
m_{dm}	Dry-matter mass [kg]
m_w	Water mass [kg]
MR	Moisture ratio [-]
M_w	Molar mass of water [g/mol]
Nu	Nusselt number [-]
P_{sat}^T	Saturated vapor pressure at a temperature T [Pa]
Pr	Prandtl number [-]
R	Gas constant, $8.314\ [J\ K^{-1}\ mol^{-1}]$
Re	Reynolds number [-]
S	Total surface of the food slice [m^2]
S_0	Initial total surface of the food slice before drying [m^2]
S^*	Dimensionless total surface of the slice
S_{comb}^*	S^* assuming combined shrinkage behavior [-]
t	Time [s]
t^*	Dimensionless time
T	Temperature [$^{\circ}C$]
T_{air}	Air temperature [$^{\circ}C$]
T_{surf}	Temperature at the slice surface [$^{\circ}C$]

T_{wb}	Wet-bulb temperature [°C]
V	Volume
V_0	Initial volume of the food slice before drying [m ³]
V^*	Normalized volume [-]
X_{we}	Estimated water content in the equilibrium, on dry basis [kg/kg]
X_w	Measured water content in the food product, on dry basis [kg/kg]
$X_{w,mono}$	Monolayer water content [kg/kg], dry basis
X_{w0}	Initial water content of the food product before drying [kg/kg], on dry basis
X_w^*	Dimensionless water content in the food product [-]
Greek letters	
α	Constant for Nusselt correlation [-]
β	Constant for Nusselt correlation [-]
γ	Constant for Nusselt correlation [-]
δ	Constant for Nusselt correlation [-]
λ	Thermal conductivity [Wm ⁻¹ K ⁻¹]
ρ	Dry-matter mass density [kg m ⁻³]
ρ_{dm}	Dry-matter mass density [kg m ⁻³]
ρ_w	Water density [kg m ⁻³]

Table 1

Dimensions and thermophysical properties of the aluminum cylinders used to estimate the heat transfer coefficient.

Piece	1	2
D [mm]	35	20
H [mm]	7	3
Hole volume [m ³]	$7.07 \cdot 10^{-8}$	$7.07 \cdot 10^{-8}$
Cylinder volume [m ³]	$6.66 \cdot 10^{-6}$	$0.87 \cdot 10^{-6}$
Mass [g]	17.99	2.35
Surface area (A_S), exposed to airflow [m ²]	$1.7 \cdot 10^{-3}$	$0.5 \cdot 10^{-3}$
Thermophysical properties at 331 K*		
λ (W m ⁻¹ K ⁻¹)	238.0	
C_p (J kg ⁻¹ K ⁻¹)	917.6	
ρ (kg m ⁻³)	2707	

*Source: Perry & Green (1997)

Table 2.

Models used in the literature to describe drying kinetics.

Model	Equation	Reference
Lewis	$MR = \exp(-k_1 t)$	Lewis (1921)
Page	$MR = \exp(-k_1 t^n)$	Panchariya et al. (2002); Shi et al. (2013)
Modified Page	$MR = \exp(-k_1 t)^n$	Panchariya et al. (2002); Shi et al. (2013)
Henderson-Pabis	$MR = a \exp(-k_1 t)$	Panchariya et al. (2002); Shi et al. (2013)

Table 3

GAB model parameters* adjusted to experimental data of yacón, for adsorption and desorption curves, through the dynamic (DDI) and static (DVS) operation modes.

Mode	$X_{w,mono}$ [kg/kg, d.b.]		C [-]		K [-]	
	adsorption	desorption	adsorption	desorption	adsorption	desorption
DDI 50 °C	$1.04 \cdot 10^{-1}$	$1.29 \cdot 10^{-1}$	$1.12 \cdot 10^0$	$1.32 \cdot 10^0$	$1.00 \cdot 10^0$	$9.73 \cdot 10^{-1}$
DDI 60 °C	$1.79 \cdot 10^{-1}$	$1.34 \cdot 10^{-1}$	$7.34 \cdot 10^{-1}$	$2.06 \cdot 10^0$	$9.41 \cdot 10^{-1}$	$9.79 \cdot 10^{-1}$
DVS 50 °C	$1.20 \cdot 10^{-1}$	$1.37 \cdot 10^{-1}$	$1.41 \cdot 10^0$	$1.17 \cdot 10^0$	$9.71 \cdot 10^{-1}$	$9.70 \cdot 10^{-1}$
DVS 60 °C	$1.21 \cdot 10^{-1}$	$1.16 \cdot 10^{-1}$	$9.08 \cdot 10^{-1}$	$1.45 \cdot 10^0$	$9.79 \cdot 10^{-1}$	$9.84 \cdot 10^{-1}$

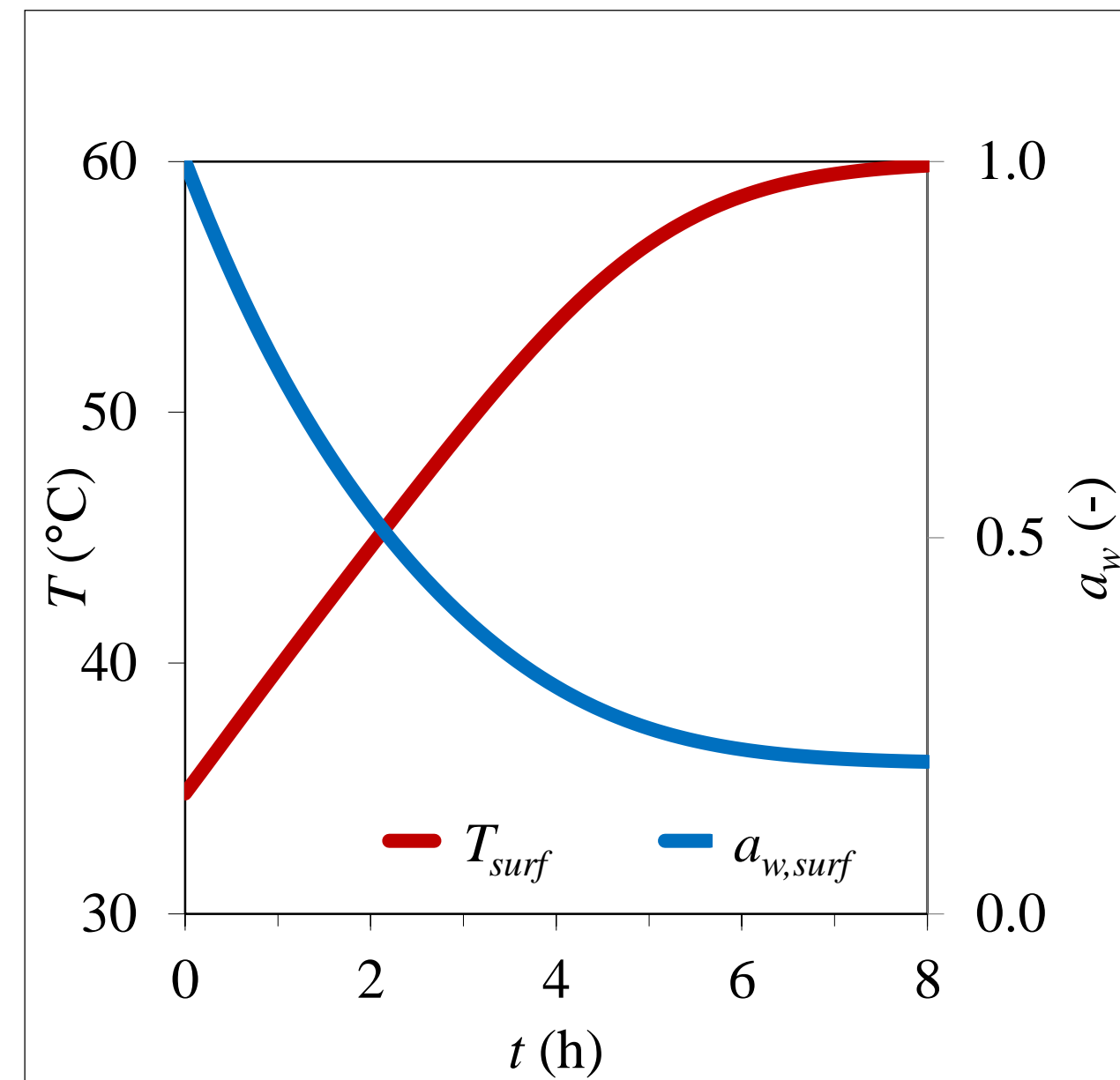
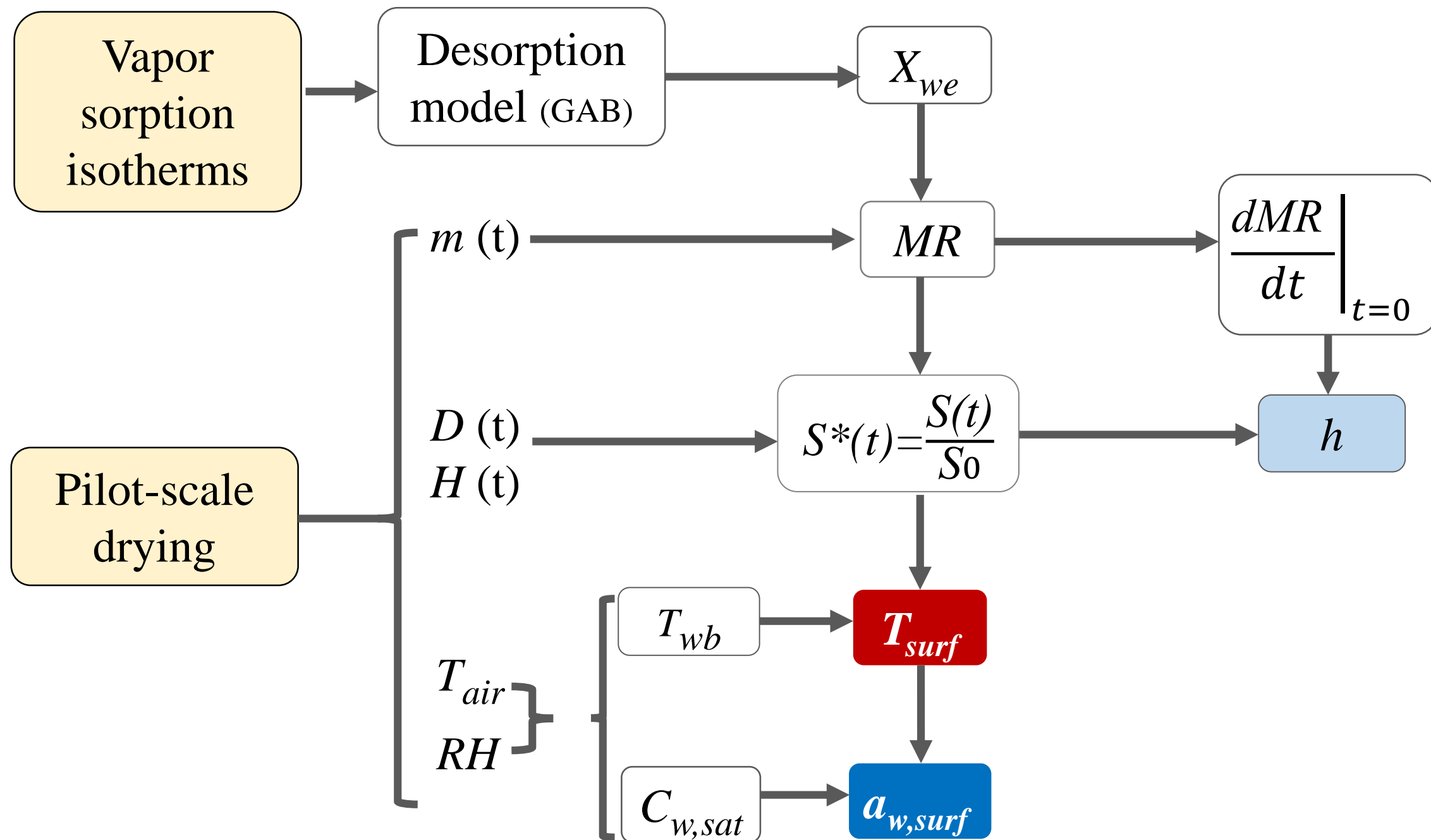
*All adjustments had a Pearson's correlation coefficient higher than 0.997.

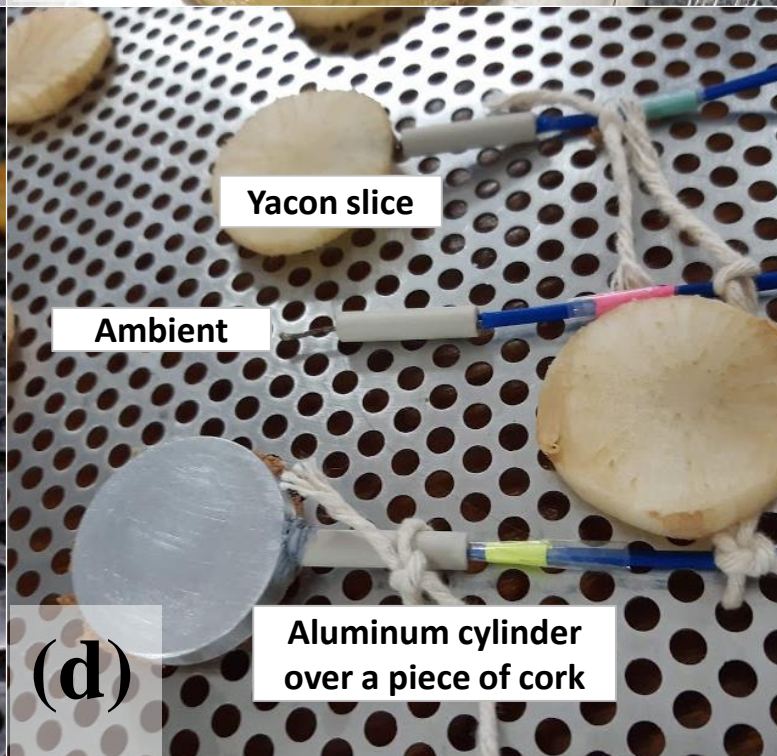
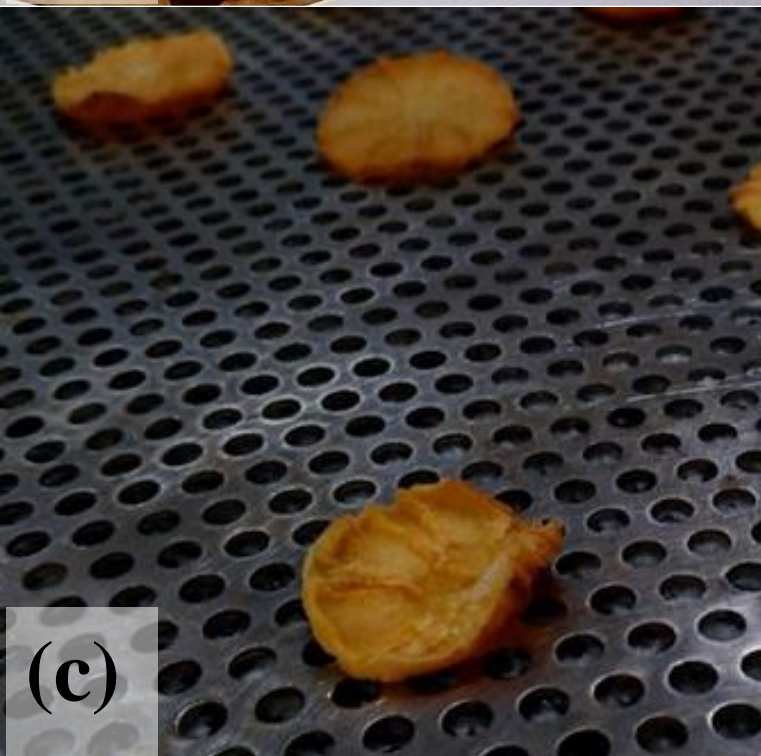
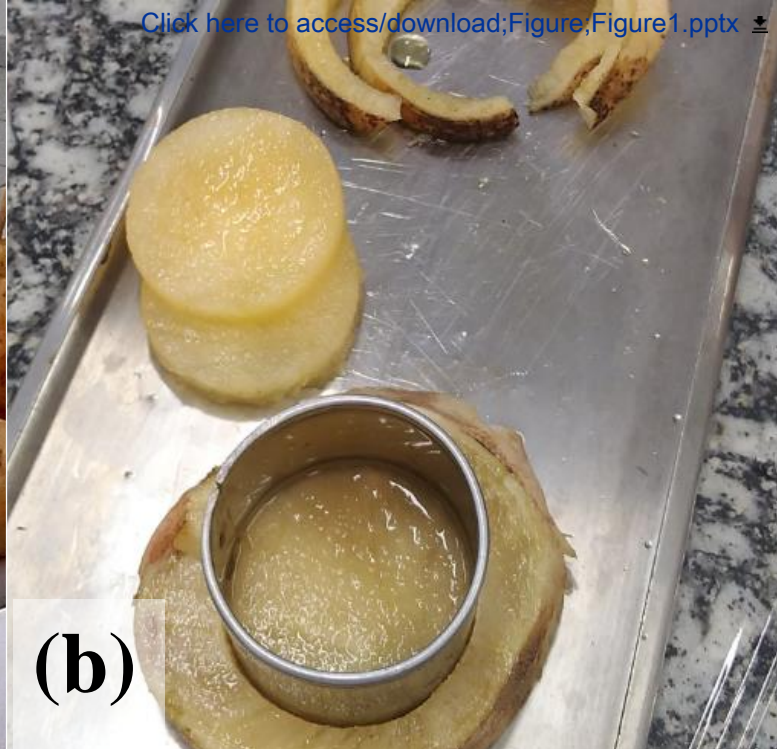
Table 4. Parameters for selected models, estimated from yacón drying kinetics; and comparison between this work and values from the literature. In the case of results from this work, values provided are indicated as arithmetic average \pm standard deviation over triplicates.

Model		This work*				Reis <i>et al.</i> (2012)	Shi <i>et al.</i> (2013)	Lisboa <i>et al.</i> (2018)	
		$T_{air} = 50\text{ }^{\circ}\text{C}$, $RH = 30\%$ ($T_{wb} = 32.6\text{ }^{\circ}\text{C}$), 4 m/s	$T_{air} = 60\text{ }^{\circ}\text{C}$, $RH = 30\%$ ($T_{wb} = 40.0\text{ }^{\circ}\text{C}$), 4 m/s	$T_{air} = 50\text{ }^{\circ}\text{C}$, $RH = 20\%$ ($T_{wb} = 28.7\text{ }^{\circ}\text{C}$), 4 m/s	$T_{air} = 60\text{ }^{\circ}\text{C}$, $RH = 20\%$ ($T_{wb} = 35.4\text{ }^{\circ}\text{C}$), 4 m/s	$T_{air} = 55\text{ }^{\circ}\text{C}$, 11.325 Pa**	$T_{air} = 45\text{ }^{\circ}\text{C}$, 1.5 m/s	$T_{air} = 50\text{ }^{\circ}\text{C}$, 1.5 m/s	$T_{air} = 60\text{ }^{\circ}\text{C}$, 1.5 m/s
Eq.13	$k_1 [\times 10^{-4}\text{ s}^{-1}]$	1.05 ± 0.004^{aA}	1.30 ± 0.09^{bB}	1.15 ± 0.03^{aA}	1.42 ± 0.04^{bB}				
	$k_2 [\times 10^{-5}\text{ s}^{-1}]$	5.94 ± 0.1^{aA}	6.88 ± 0.4^{bA}	5.40 ± 0.9^{aA}	6.08 ± 0.2^{bA}				
	RMSE	1.39×10^{-2}	1.85×10^{-2}	1.16×10^{-2}	8.00×10^{-3}				
Lewis	$k_1 [\times 10^{-4}\text{ s}^{-1}]$	1.37 ± 0.02^{aA}	1.75 ± 0.07^{bA}	1.42 ± 0.05^{aA}	1.72 ± 0.02^{bA}		1.18×10^{-4}		
	RMSE	3.42×10^{-2}	3.46×10^{-2}	2.58×10^{-2}	2.26×10^{-2}		3.38×10^{-2}		
Page	$k_1 [\times 10^{-5}\text{ s}^{-1}]$	2.52 ± 0.7^{aA}	3.03 ± 1^{aA}	3.83 ± 1^{aA}	4.21 ± 0.7^{aA}	3.83×10^{-5}	9.11×10^{-5}	3.03×10^{-5}	4.69×10^{-5}
	$n [-]$	1.19 ± 0.03^{aA}	1.20 ± 0.04^{aA}	1.15 ± 0.04^{aA}	1.20 ± 0.04^{aA}	1.50	1.24	0.95	1.90
	RMSE	1.16×10^{-1}	1.05×10^{-1}	1.09×10^{-1}	9.65×10^{-2}	$R^2 = 0.995$	1.45×10^{-2}	$R^2 = 0.999$	$R^2 = 0.999$
Modified Page	$k_1 [\times 10^{-4}\text{ s}^{-1}]$	1.33 ± 0.02^{aA}	1.60 ± 0.2^{bA}	1.39 ± 0.04^{aA}	1.64 ± 0.07^{bA}	7.42×10^{-5}	1.13×10^{-4}		
	$n [-]$	1.20 ± 0.02^{aA}	1.20 ± 0.04^{aA}	1.16 ± 0.05^{aA}	1.16 ± 0.02^{aA}	1.50	1.24		
	RMSE	1.91×10^{-2}	1.95×10^{-2}	1.56×10^{-2}	1.12×10^{-2}	$R^2 = 0.995$	1.47×10^{-2}		
Henderson- Pabis	$k_1 [\times 10^{-4}\text{ s}^{-1}]$	1.44 ± 0.04^{aA}	1.81 ± 0.2^{bA}	1.49 ± 0.09^{aA}	1.79 ± 0.07^{bA}	8.33×10^{-5}	1.24×10^{-4}	2.31×10^{-6}	2.81×10^{-6}
	$a [-]$	1.06 ± 0.01^{aA}	1.09 ± 0.02^{aA}	1.05 ± 0.03^{aA}	1.06 ± 0.01^{aA}	1.07	1.05	0.98	0.97
	RMSE	2.95×10^{-2}	2.90×10^{-2}	2.31×10^{-2}	1.91×10^{-2}	$R^2 = 0.967$	3.00×10^{-2}	$R^2 = 0.999$	$R^2 = 0.999$

*Same lower-case letters on the same line indicate no significant difference in relation to the temperature, and upper-case letters, in relation to the relative humidity ($p > 0.05$).

**Absolute pressure.



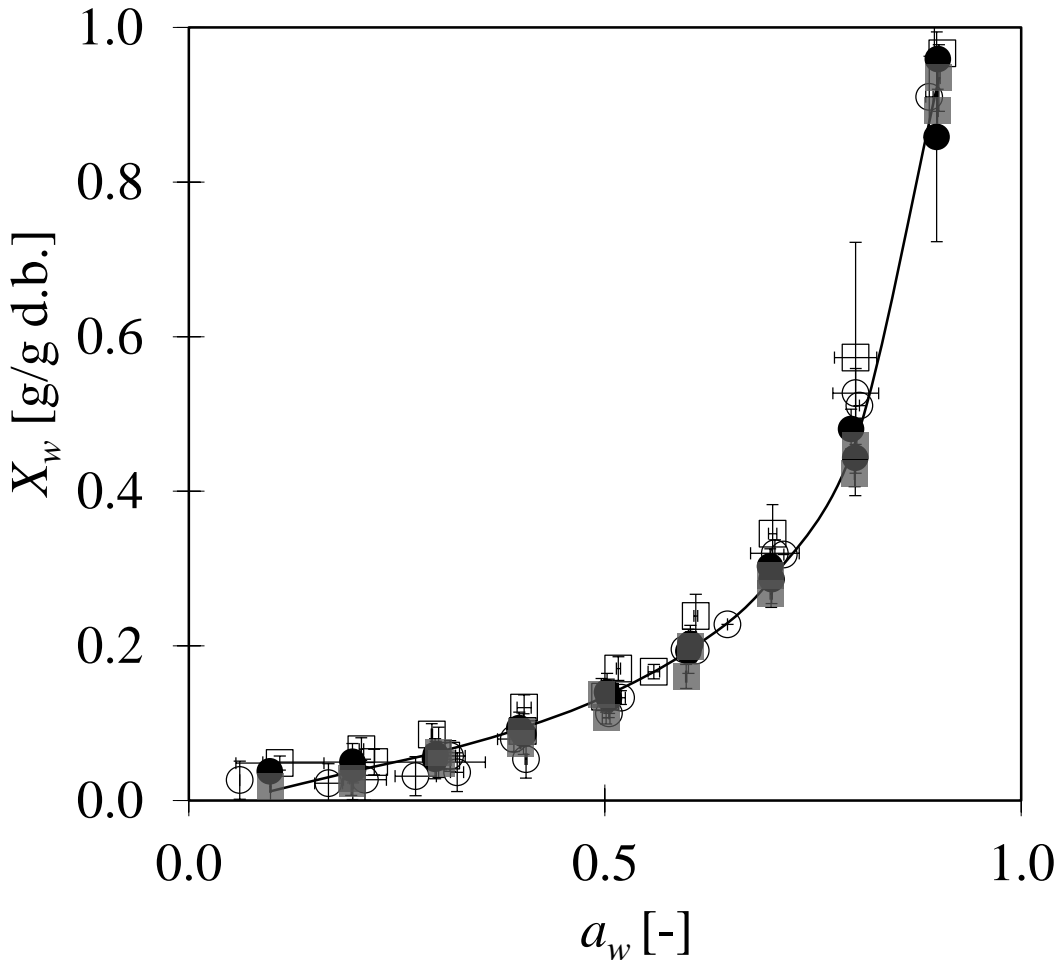


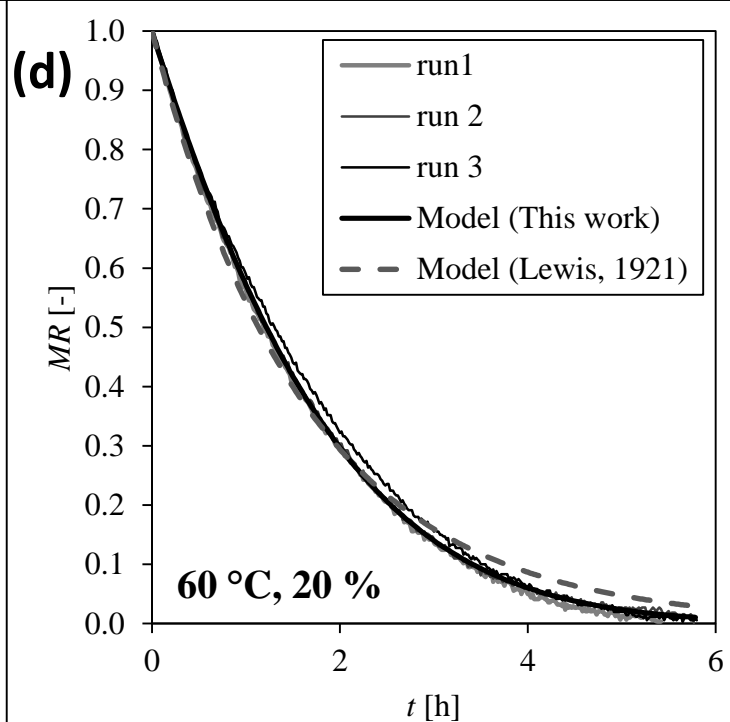
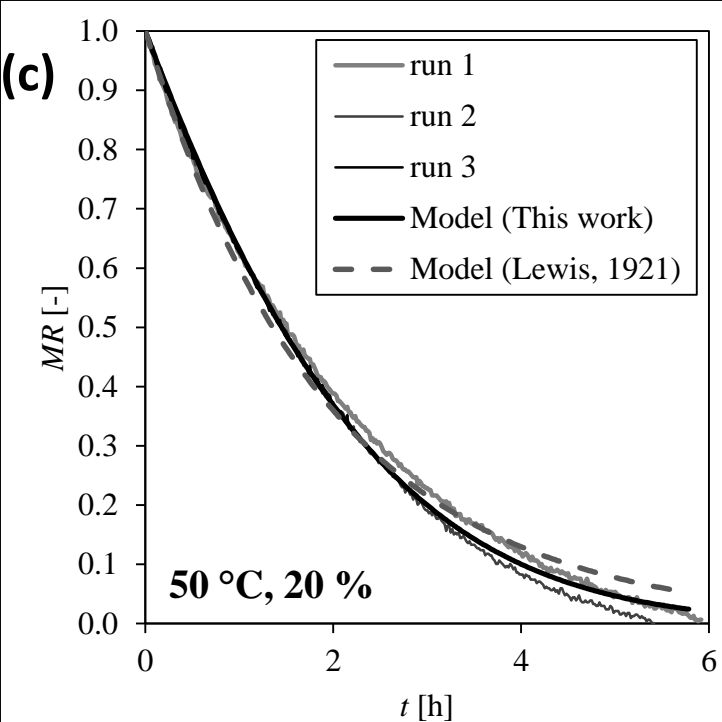
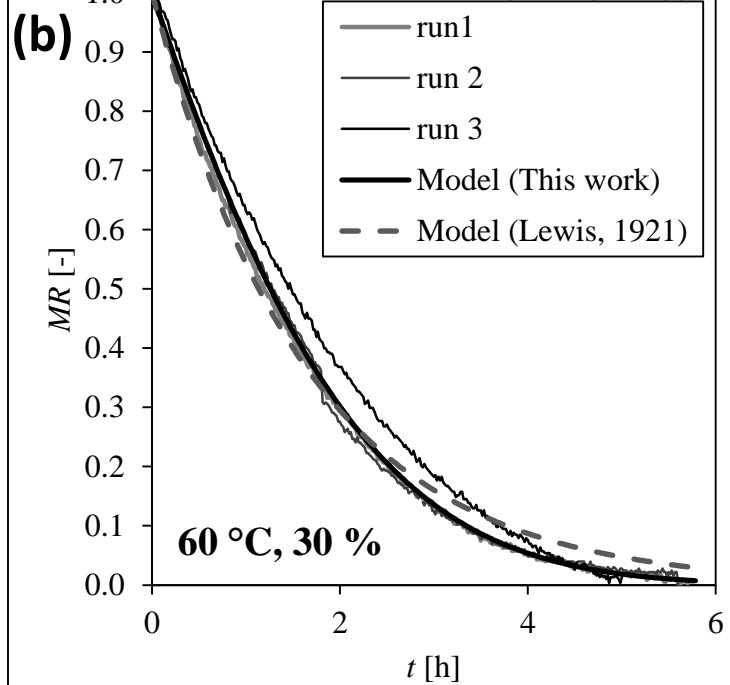
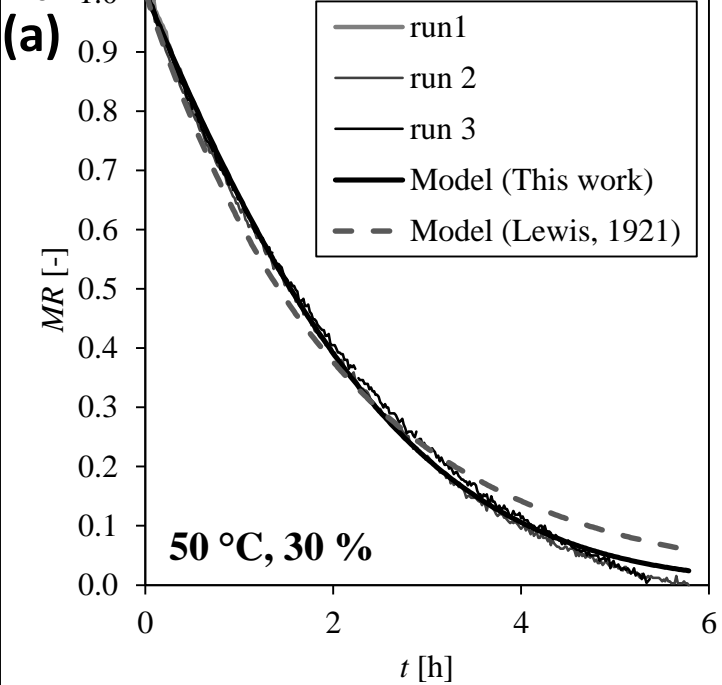
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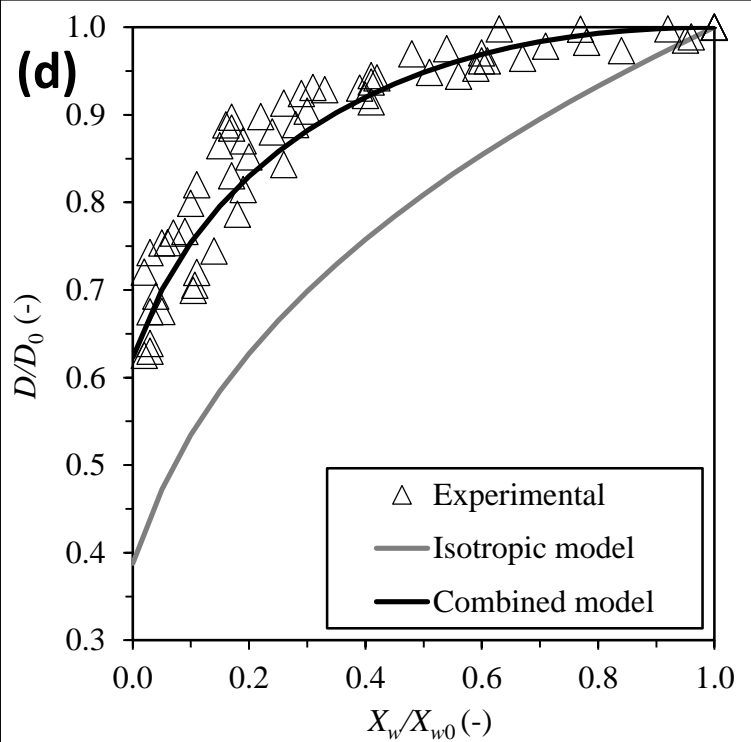
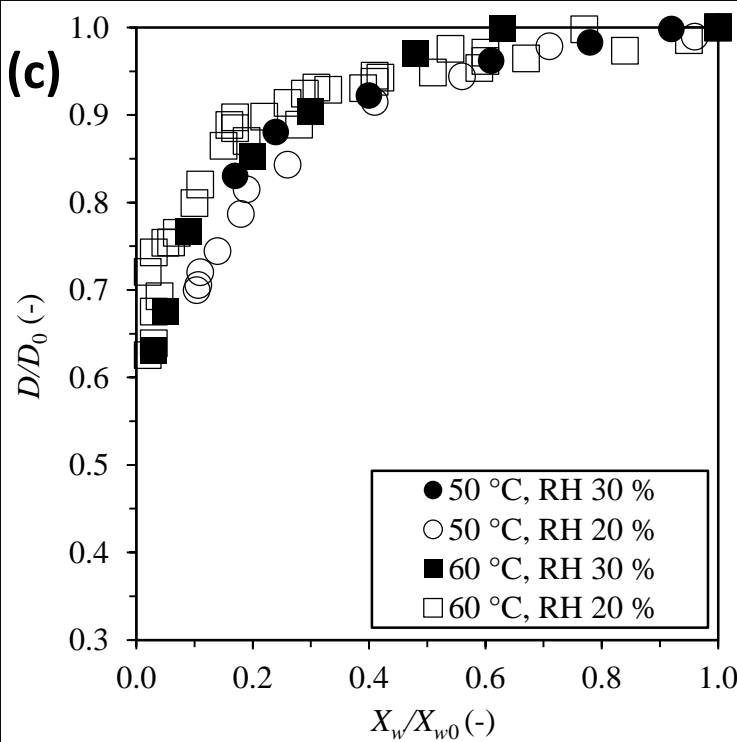
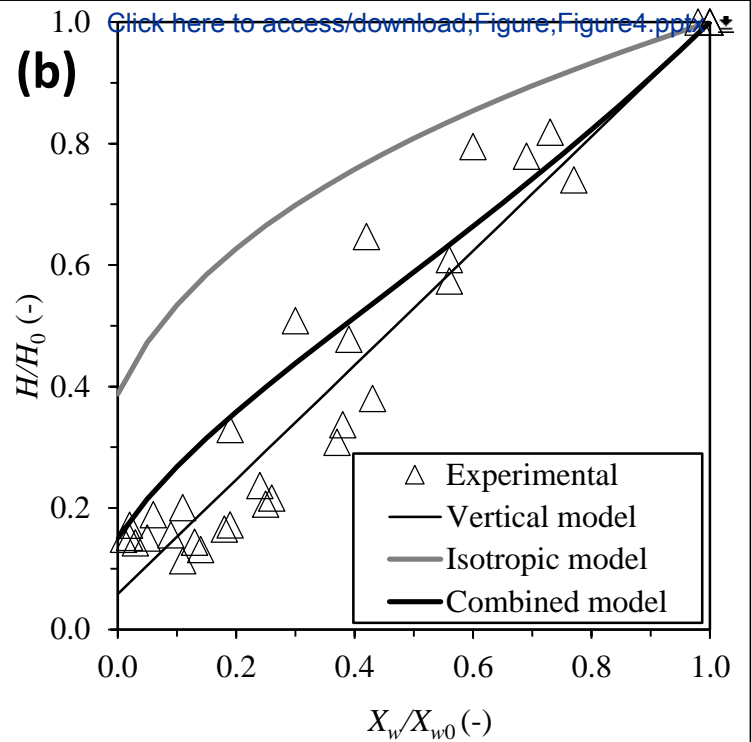
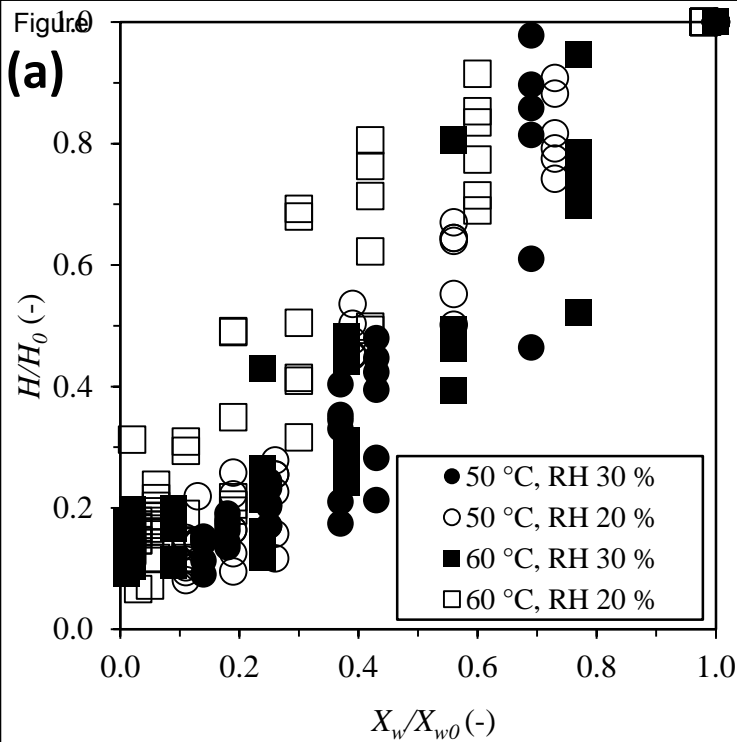
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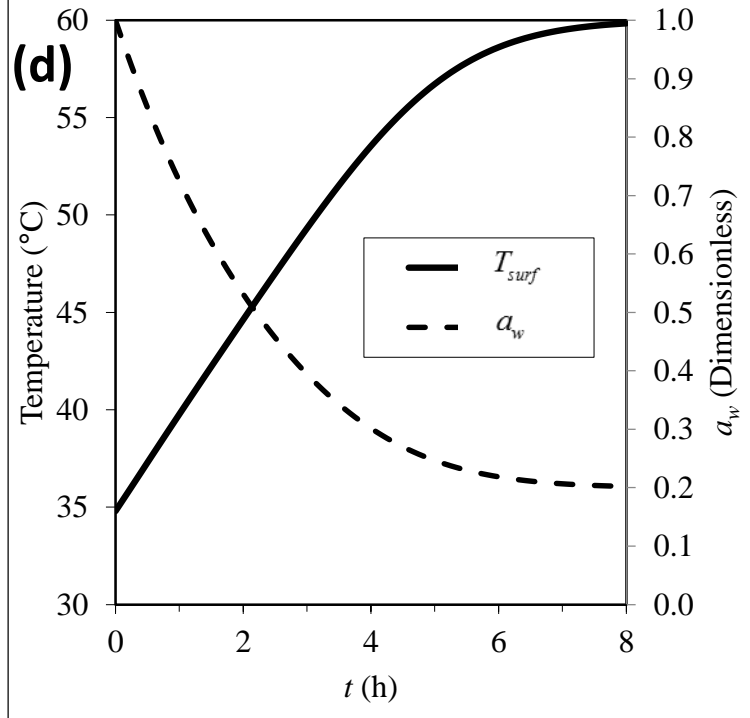
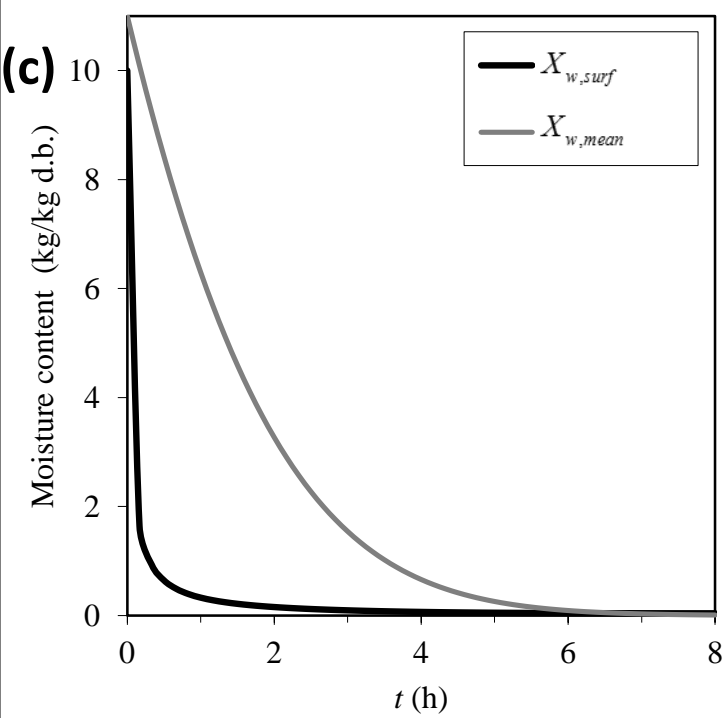
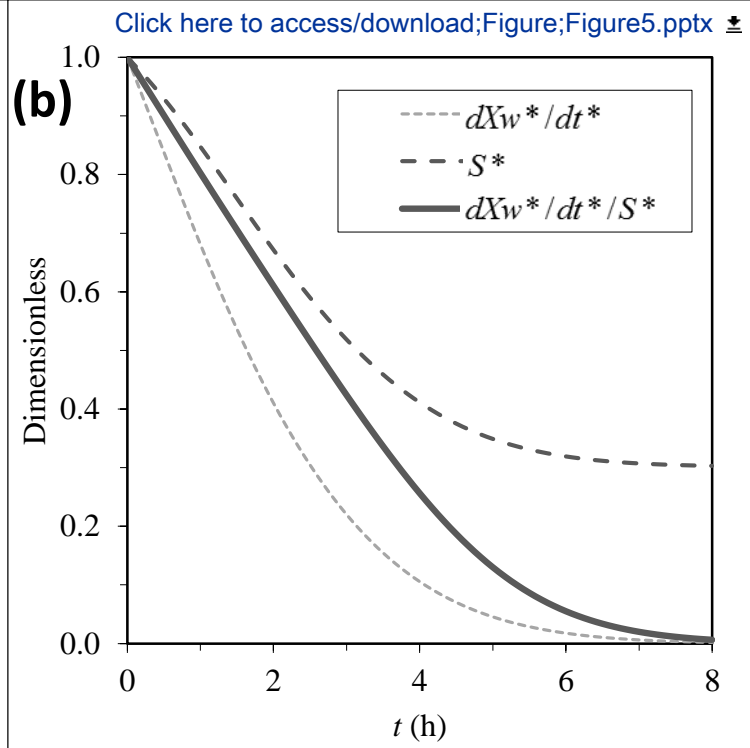
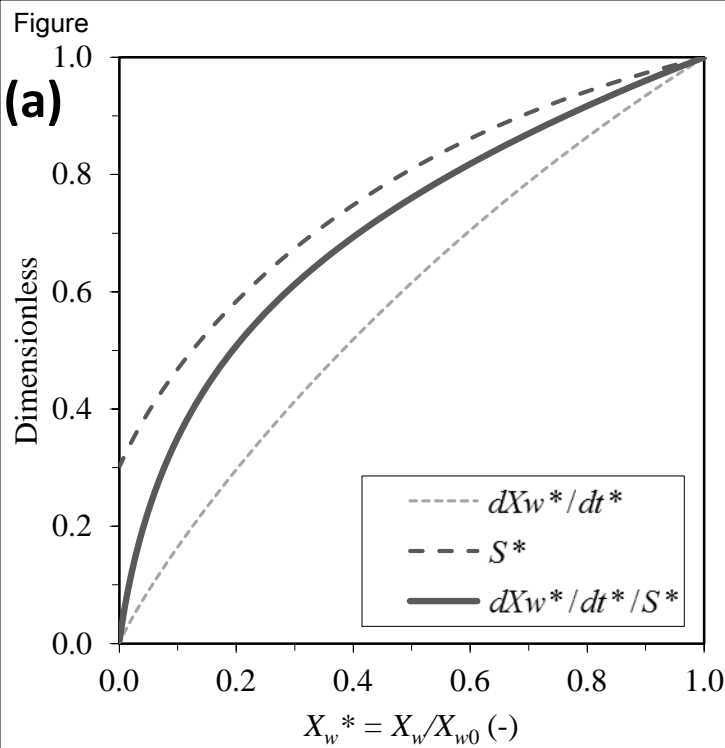


- DDI 50 °C
- DVS 50 °C
- GAB model
- DDI 60 °C
- DVS 60 °C









Conflict of Interest and Authorship Conformation Form

Please check the following as appropriate:

All authors have participated in (a) conception and design, or analysis and interpretation of the data; (b) drafting the article or revising it critically for important intellectual content; and (c) approval of the final version.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript

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