Cut orientation and drying temperature effect on drying and rehydration kinetics of yacon (*Smallanthus sonchifolius*)

Lester De Los Santos Pazos, Bach.[1], Danny Chávez Novoa, MSc.[2], Alexander Vega Anticona, Dr.[2], Guillermo Linares, Dr.[3], Jesús Sánchez-González, MSc.[3], Alberto Claudio Miano Dr.[4], Meliza Lindsay Rojas, Dr.[4]*
[1]Escuela de Ingeniería Agroindustrial, Universidad Nacional de Trujillo, Perú, ldelossantosp@unitru.edu.pe.
[2] Departamento de Ingeniería de Materiales, Universidad Nacional de Trujillo, Perú, dchavez@unitru.edu.pe, avega@unitru.edu.pe.
[3] Departamento de Ciencias Agroindustriales, Universidad Nacional de Trujillo, Perú, glinares@unitru.edu.pe, jsanchezg@unitru.edu.pe.
[4]Dirección de Investigación y Desarrollo, Universidad Privada del Norte, Perú, alberto.miano@upn.edu.pe, meliza.rojas@upn.edu.pe.
*Corresponding author: meliza.rojas@upn.edu.pe; Av. Del Ejército 920, Trujillo, Perú.

Abstract*– Yacon (Smallanthus sonchifolius) is commonly consumed fresh and is known for its nutritional and functional properties, however, this raw material still needs an added value that allows greater stability and availability. Against this, drying is a good processing alternative. This study aimed to evaluate for the first time the influence of temperature and the orientation of cut on drying and rehydration behavior of Yacon cylinders with longitudinal (L) and transversal (T) cut. Drying was performed at 50 and 60 °C and rehydration was performed with water at 30 °C. Drying and rehydration kinetics were described by the Page and Peleg models, respectively. As results, the effects of drying temperature are greater than the effects of the type of cut. The Page's model parameters indicated that the treatment with T cut dried at 60 °C was the treatment that dehydrated fast, while the water transfer during the process followed a super-diffusive mechanism. Regarding rehydration, the kinetics of water gain indicate that there was no difference between the rate of water gain among the treatments. However, the T cut samples dried at 50 °C presented a lower amount of water gained at the end of rehydration. In conclusion, the present work demonstrates the influence of temperature on accelerating water transfer as well as the non-isotropicity of food matrices. In addition, drying is presented as a good alternative for the processing of yacon, either in snacks or for subsequent processes such as making flour.

***Keywords*-- Yacon (Smallanthus sonchifolius), food drying, rehydration, kinetics, mass transfer.**

I. INTRODUCTION

Yacon (*Smallanthus sonchifolius*) is considered an Andean root [1], it is a perennial plant that grows in the Andean regions (from 1800 to 3500 m above sea level), especially in countries like Bolivia, Peru, Ecuador. The sweet and juicy yacon roots are known as a source of fructooligosaccharides (FOS) or inulin-type fructans, antioxidant and phenolic compounds. FOS have low caloric value and have prebiotic functions, reducing blood lipid and glucose levels, improving the intestinal balance. For example, it improves the growth of bifidobacteria in the colon and promotes beneficial effects on the intestinal health of animals. Furthermore, promotes a positive modulation of the immune system, improving resistance to infections and allergic reactions [2-8].

Despite the advantages of the composition of this raw material, its properties can degrade rapidly. Fructo-oligosaccharides has been reported to hydrolyze after harvest [3]. On the other hand, its seasonal production restricts its availability throughout the whole seasons of the year. By considering this, from an academic and industrial point of view, it is necessary to study processing methods that allow its compounds to be preserved, as well as making the product available and accessible to consumers. Since yacon present high-water activity of 0.994 ± 0.001 [9], a good alternative of processing raw yacon and promote their preservation is the drying process, for example, to obtain flour or snacks [6, 10].

Drying is one of the most applied preservation techniques, which consists of reducing water activity in order to increase food shelf life. Mechanistically, this process is complex since involves mass, heat and momentum transfer [11]. The drying process is affected by many extrinsic factors such as temperature, air velocity, air humidity and charge load [12]. However, there are intrinsic factors: structure and composition of the food matrix, which are specific for each one. Although the same process conditions are used, the intrinsic factors are complex to control during drying processing and did not allow to generalize effects or results among types of food material. And even if it is the same material, within the matrix there are different structural elements (tissues, cells, organelles) whose orientation in which they are located can change the behavior observed during processes such as drying and rehydration [13]. That is, food materials are non-isotropic whose behavior will depend on the position or direction in which they are processed and evaluated.

The behavior during drying or other mass transfer phenomena is usually described by evaluating the loss or gain of a certain compound along with time processing, in the case of drying, water loss, or in the case of rehydration, the water

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gain is evaluated. To describe drying or rehydration kinetics, different mathematical models could be used from theoretical, semi-empiric, or empirical models [14, 15]. In yacon, the behavior of the drying and rehydration kinetics, as well as the influence of the orientation of the structural elements in the transfer of water, has not yet been explored.

In the present work, it was proposed to study the drying and rehydration processes. The effect of two types of cutting (longitudinal and transverse) - through which differently oriented tissue are obtained, and the effect of two levels of drying temperature on the drying and rehydration kinetics of yacon cylinders were evaluated.

II. MATERIAL AND METHODS

A. *Raw material*

The fresh yacon (*Smallanthus sonchifolius*) samples were obtained from market number 2 - Chepen, which are grown in Cajamarca, Peru (about 2700 m above sea level). The samples were washed with tap water and dried with towel paper before being cut. The flesh part was cut using a cylinder corer to obtain cylinders of 2 cm diameter x 0.4 cm height with two cut orientations: transverse (T), and longitudinal (L) cut, as observed in Fig.1. Longitudinal cuts were parallel to the tuber stalk and vascular tissue, the transverse cut was perpendicular to the longitudinal cut.

B. *Drying process*

Hot-air drying experiments were performed at 50 °C and 60 °C using a convective drying oven (ODG-9030ª, Kert Lab, USA). In each drying process, cylinders with transverse (T) or longitudinal (L) cut were randomly placed inside the drying chamber. Therefore, four treatments: L-50°C, T-50°C, L-60°C and T-60°C, were evaluated.

Sample weight was recorded along the drying time. Drying experiments were stopped when samples showed a constant weight in the last consecutive three measurements. The drying process was replicated at least 12 times.

The initial moisture content of the samples was determined by placing samples into small pieces at 105 °C until constant weight. The sample moisture content at different process time during drying was obtained by mass balance to study the drying kinetics.

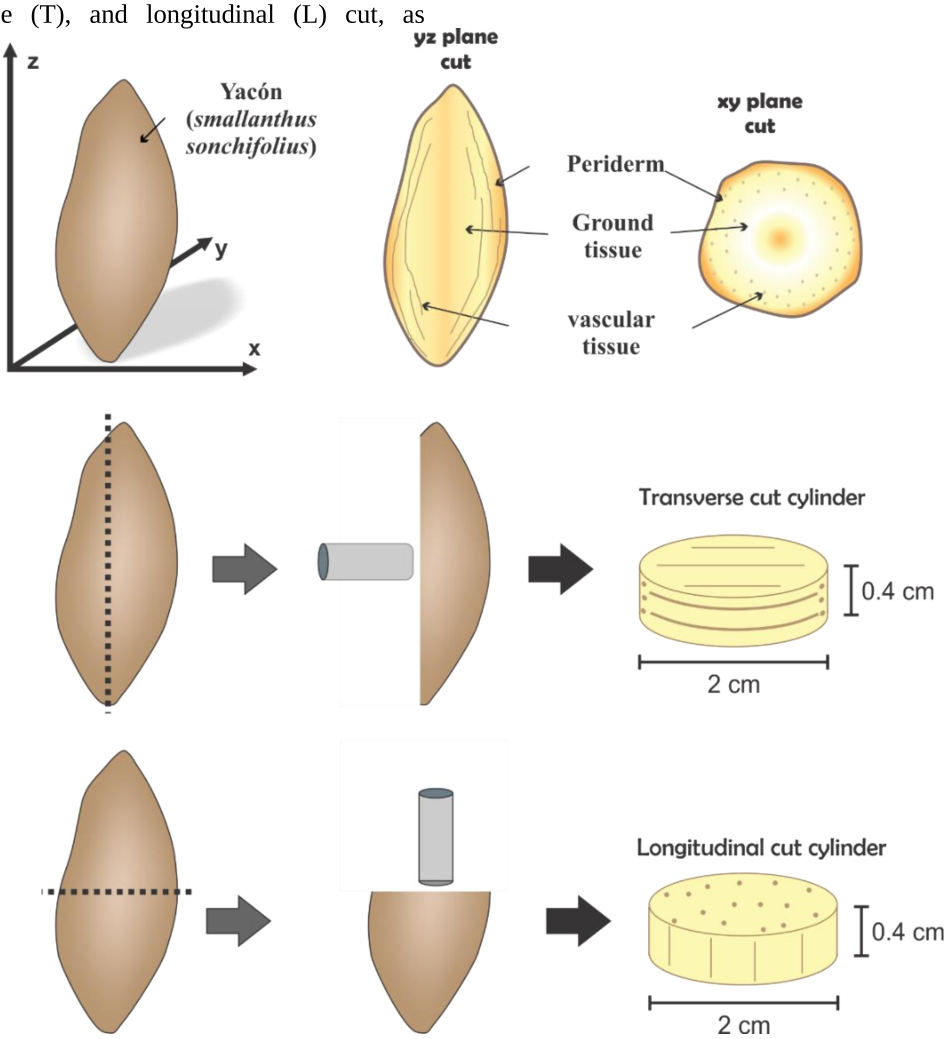

Fig.1 representation of yacón cylinders obtention with two cut orientations (transverse and longitudinal)

For evaluating the drying kinetics, dimensionless moisture content (MR_t) was considered (1), where M_t is the moisture content of the sample at different drying times, M_0 is the initial moisture content of the sample (fresh) and M_∞ is the equilibrium moisture content (in this case, the final moisture content after drying was considered as M_∞).

$$MR_t = \frac{M_t - M_\infty}{M_0 - M_\infty} \tag{1}$$

C. *Rehydration process*

For rehydration evaluation, five cylinders were used for each replicate, which were soaked in water at 30 °C by using a thermostat bath (CDK-S22, Kert Lab, USA). The rehydration kinetics was evaluated by recording the mass of samples each 10 min until 1h. For this, the cylinders were removed, superficially dried using towel paper, weighed and returned to the water. Then, considering the initial moisture content of the dried cylinders, the moisture content at each time was obtained by mass balance.

D. *Kinetics description*

The drying kinetics data were modeled using the equation of Page [16] (2), whose parameters interpretation was proposed by Simpson, et al. [17]. Indeed, parameter "*k*" could be related to the drying rate and geometry of the sample, "*n*" is related to the "type of diffusion" and sample microstructure. When *n*=1, means that the mass transfer is diffusional, otherwise when *n* <1 is considered as "sub-diffusion" and when *n*>1 is considered as a "super-diffusion", indicating that other transfer mechanisms are involved.

$$MR_t = \exp(-k \cdot t^n) \tag{2}$$

Rehydration kinetics was described assuming negligible solid loss by using an equation (3) based on the Peleg model [18] considering the water gain ($WG = \frac{(m_t - m_0)}{m_0}$) during rehydration time (t) instead of the moisture content [19]. Regarding the two parameters: k_1 (WG^{-1}·min) is related to the reciprocal of WG rate and k_2 (WG^{-1}), which is related to the reciprocal of maximum WG capacity.

$$WG = \frac{t}{k_1 + k_2 \cdot t} \tag{3}$$

The equations (2) and (3) were fitted to the respective drying and rehydration experimental data by identifying their parameter values that minimize the sum of squared errors (SSE, (4)) between the experimental and the predicted values. The Generalized Reduced Gradient method implemented in the 'Solver' tool of software Excel 2016 (Microsoft, USA) was used for this purpose.

$$\mathrm{SSE} = \sum_{\mathrm{i}=1}^{\mathrm{x}} ((\mathrm{predicted}) - (\mathrm{experimental}))_{\mathrm{i}}^{2} \tag{4}$$

E. *Statistical analysis*

A factorial design 2^2 with 12 replicates was conducted. For evaluating the statistical effect of the factors on the response variables (Page model and Peleg model parameters), ANOVA with 5% of significance was performed. In addition, Tukey's test was performed for mean comparisons among treatments. All these analyses were conducted using IBM SSPS Statistics V.23 (IBM Corp., USA) software.

III. RESULTS AND DISCUSSION

A. *Drying description*

In Fig.2 is showed the drying kinetics of each performed treatment. Of the two factors evaluated (cut orientation-drying temperature), drying temperature effects (Fig. 2 (A and B)) were more evident than the cut orientation effects (Fig. 2 (C and D)) on drying kinetics. In all drying curves (Fig. 2), is observed that the moisture decreases rapidly during the first 100 min of drying. This behavior was also reported by Scher, et al. [9] during drying of yacon slices at 50 °C, 60 °C and 70 °C. In fact, the temperature effect on the drying behavior of yacon was also described by Shi, et al. [3], where, as expected, the higher the temperature, the shorter the drying time. In this work, when drying was performed at 60 °C, the drying time was reduced ~ 60% compared to drying at 50 °C.

The importance of exploring different drying temperatures in yacon is that, in addition to improving the drying process (reducing time), the temperature should not alter the composition and properties of yacon. It was reported that temperatures of drying below 60 °C did not alter the FOS content [9], however, other authors as Campos, et al. [20] reported that higher temperatures of drying (80 °C) did not affect the FOS and allowed to obtain yacon flour with excellent characteristics. Therefore, the effect of temperature should be better studied in terms of its effect on the composition and properties of dehydrated yacon.

Drying kinetics showed in Fig. 2 were described through the Page model (2), which parameters are showed in Table I.

TABLE I
PAGE MODEL (2) PARAMETERS AND R^2 VALUE OBTAINED FROM DRYING KINETICS MODELLING

Treatment		Page model parameters		
		k (min^{-n})	n (-)	R^2
50 °C	L	0.006±0.004 ^{a}	1.213±0.079 ^{a}	≥ 0.991
	T	0.006±0.002 ^{a}	1.197±0.059 ^{a}	≥ 0.993
60 °C	L	0.009±0.003 ^{a}	1.298±0.061 ^{a}	≥ 0.996
	T	0.015±0.011 ^{b}	1.207±0.165 ^{a}	≥ 0.994

*Different superscript letters indicate significant differences among treatments.

Regarding k parameter of the Page model, it is related to the drying rate. The treatment that showed the higher k value than the others was the transversal cut dried at 60 °C (T-60 °C), that is, this treatment dried faster than the others. Probably the tissue orientation of this cut (T) combined with a higher temperature (60 °C) promoted the exit of water from inside samples.

On the other hand, regarding parameter n, this was greater than 1 for all treatments. Similar results were reported by Reis, et al. [21] who evaluated drying kinetics of yacon slices obtaining in all treatments values of $n > 1$. It means that, according to Simpson, et al. [17], the mechanism of water transfer during yacon drying could be related to a super-diffusive behavior. This behavior means that other mass transfer mechanisms, apart from diffusion, are important such as capillarity.

In conclusion, it was probably not evidenced great effects among treatments during drying since simultaneously to the drying process, composition, physical and structural modifications occur. For example, shrinkage occurs simultaneously with water loss during drying [22, 23]. Although the shrinkage is a consequence of drying, as the drying process is carried out, the shrinkage can at the same time influence the drying kinetics.

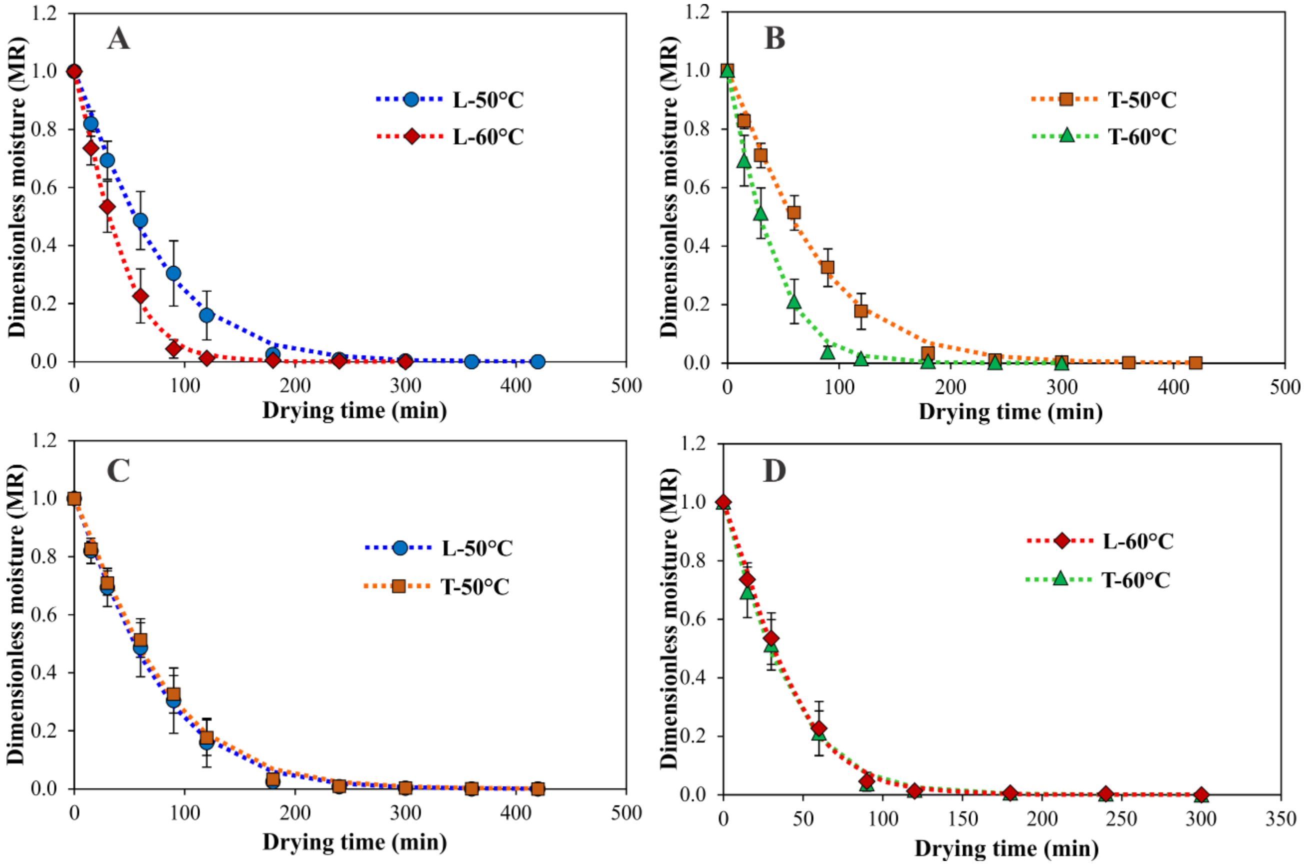

Fig.2 Drying kinetics of yacón samples with transversal and longitudinal cut dried at 50 °C and 60 °C. Dots are experimental data and dotted lines are the calculated data by Page model (2). Comparison between drying temperatures for longitudinal cut (A) and transversal cut (B). Comparison between cut orientations dried at 50 °C (C) and 60 °C (D).

B. *Rehydration description*

The water gain (WG) kinetics during rehydration of samples with different cut orientation dried at 50 °C and 60 °C are showed in Fig.3. By analyzing the drying kinetics behavior, apparently, the temperature at which the samples were dried only influenced the rehydration of transverse cut samples (Fig. 3, B). On the other hand, analyzing the influence of the type of cut on rehydration, it seems that there is a difference only when drying was carried out at 50 °C (Fig. 3, C). In addition, it can be inferred that the sample with transverse cut orientation dried at 50 °C (T-50°C) showed poor rehydration properties. Through rehydration, the aim is to recover the original appearance and properties of the yacon samples [21]. So, a greater amount of water gained and greater retention of that gained water at the end of the rehydration process is required, and in general, is the main target of the rehydration process.

The rehydration kinetics were modeled using the Peleg model (3), whose parameters (k_1, k_2) (Table II) allowed describing the rehydration properties. The inverse of the parameter k_1 is associated with the maximum water gain rate. Consequently, the lower the value of k_1 is, the faster the rehydration process will be. On the other hand, the reciprocal of the parameter k_2 is associated with the equilibrium gained water amount. Therefore, the lower the value of k_2 is, the higher the amount of gained water will be.

TABLE II
PELEG MODEL (3) PARAMETERS AND R^2 VALUE OBTAINED FROM REHYDRATION KINETICS MODELLING

Treatment		Peleg model parameters		
		k_1 (WG^{-1}.min)	k_2 (WG^{-1})	R^2
50 °C	L	3.013±0.764 ^{a}	0.182±0.034 ^{a}	≥ 0.952
	T	3.752±1.109 ^{a}	0.246±0.091 ^{b}	≥ 0.903
60 °C	L	3.223±1.351 ^{a}	0.170±0.025 ^{a}	≥ 0.763
	T	3.084±0.533 ^{a}	0.167±0.021 ^{a}	≥ 0.916

*Different superscript letters indicate significant differences among treatments.

Regarding k_1 value, no significant differences (p>0.05) were observed among treatments. This means that neither the type of cut nor the drying temperature influenced the water absorption rate. It was also previously reported where drying temperature has little effect on the rehydration rate of yacon slices [3]. In contrast, in other types of raw material, during rehydration of samples with different cut orientation, more pronounced differences were reported. For example, pumpkin samples with the analogous cut to transversal orientation presented the highest rehydration rate (lowest k_1 value) [13]. It could be explained due to the orientation of the microstructural elements which promote the water inlet during rehydration.

On the other hand, regarding k_2 value, differences between L and T cut orientations only were evidenced at 50 °C. The treatment T-50 °C showed higher k_2 values compared to L-50 °C which was similar to other treatments dried at 60 °C. It means that transverse cut dried at 50 °C in the equilibrium presented less amount of water gained than the others, this also is evidenced in Fig.3. The observed behavior could be explained by the structural elements, principally by the vascular tissue length and alignment, which plays an important role during water transfer [13]. However, as evidenced in the present work, the influence of temperature also is important.

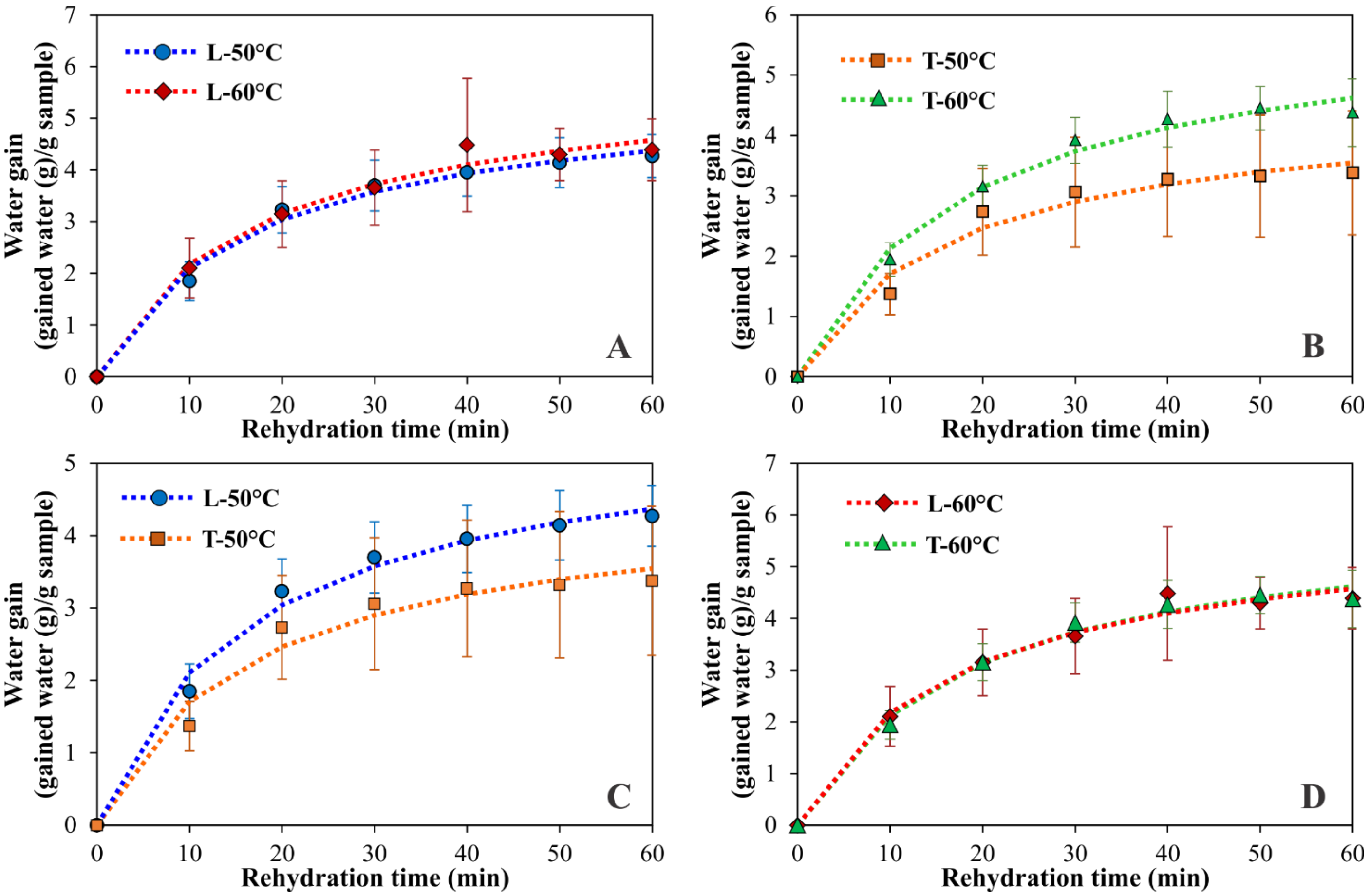

Fig.3 Rehydration kinetics (at 30 °C) of yacon samples with a longitudinal and transversal cut, which were previously dried at 50 °C and 60 °C. Dots are experimental data and dotted lines are the calculated data by Peleg model (3). Comparison between rehydration behavior of samples that were dried at different temperatures for longitudinal cut (A) and transversal cut (B). Comparison between rehydration of samples with different cut orientations dried at 50 °C (C) and 60 °C (D).

Therefore, since this is the first work evaluating in a combined way the effect of the type of cut and drying temperature on drying and rehydration kinetics of yacon, it is recommended to evaluate the microstructure, as well as other physical characteristics such as the shrinkage level. In fact, a good correlation among microstructure, drying kinetics, rehydration kinetics and shrinkage was reported in pumpkin [13].

V. CONCLUSION

In this work, the influence of the types of cut (which allow obtaining samples with different tissue orientation), as well as the drying temperature, on the drying and rehydration kinetics of yacon was evaluated for the first time. As results, it was obtained that in the drying kinetics, the effects of temperature are greater than the effects of the type of cut. The drying kinetics was described using the Page model, where its parameters k indicated that the transversal cut samples dried at 60 °C dehydrated fast, while the transfer of water during the drying process followed a super-diffusive mechanism (obtaining in all treatments values of n >1). On the other hand, the kinetics of water gain during rehydration was described using the Peleg model. No difference between the rate of water gain among the treatments was found. However, the samples with transversal cut dried at 50 °C presented a lower amount of water gained in the equilibrium (higher k_2 value). It is recommended to evaluate the microstructural elements that compose the yacon matrix to better describe the changes they experience and their effect during processing.

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