DOI: http://doi.org/10.15446/ing.investig.104346

Research Article/Chemical, Food, and Environmental Engineering

Effect of Convective Drying and Far-Infrared Radiation on the Physical Properties and Microstructure of *Yacón* Chips (*Smallanthus sonchifolius*)

Efecto del secado convectivo y radiación infrarroja lejana sobre las propiedades físicas y microestructura de hojuelas de yacón (*Smallanthus sonchifolius*)

Edwin O. Baldeón[1], Álvaro Bracamonte-Herrera[2], Andrés Soto-Torres[3], Walter F. Salas-Valerio[4], and Julio Vidaurre-Ruiz[5]

ABSTRACT

Convective drying is widely used in the food industry due to its simplicity and versatility, as it allows for better temperature control and heat distribution, which is essential for maintaining product quality. However, this method can be slower compared to infrared drying. The aim of this research was to evaluate the effect of convective and infrared drying on the physical properties and microstructure of *yacón* chips. An infrared dryer and a convection dryer were used to this effect, setting temperatures of 60, 70, and 80 °C for both methods. The color and texture properties, as well as the microstructure, changed with the increase in temperature. The greatest color variation in the *yacón* samples was reported by infrared drying at a temperature of 80° C. Regarding texture, there were no differences between the two methods. The microstructure of the *yacón* samples dried by hot air exhibited more significant cell damage, especially at 60 °C, in comparison with infrared drying, which showed a more microporous and compact structure. The results indicate that the method used impacted shrinkage: infrared drying produced a higher level of shrinkage when compared to convective drying. It is important to note that this is a significant physical change that can adversely affect the quality of dehydrated food. Infrared drying produced greater rehydration in comparison with convective drying. Similarly, improved rehydration was observed at a temperature of 70 °C. In conclusion, the infrared drying method, coupled with appropriate drying conditions, constitutes a good alternative for drying *yacón* chips.

Keywords: heat transfer, internal structure, micropores, drying, hot air, infrared

RESUMEN

El secado convectivo es ampliamente utilizado en la industria alimentaria debido a su simplicidad y versatilidad, ya que permite un mejor control de la temperatura y distribución del calor, lo cual es esencial para mantener la calidad del producto. Sin embargo, este método puede ser más lento en comparación con el secado por infrarrojos. El objetivo de esta investigación fue evaluar el efecto del secado convectivo y por infrarrojos en las propiedades físicas y la microestructura de las rodajas de yacón. Para ello, se utilizaron un secador por infrarrojos y un secador de convección, estableciendo temperaturas de 60, 70 y 80 °C para ambos métodos. Las propiedades de color y textura, así como la microestructura, cambiaron con el aumento de la temperatura. La mayor variación de color en las muestras de yacón correspondió al secado por infrarrojos a una temperatura de 80 °C. En cuanto a la textura, no hubo diferencias entre los dos métodos. La microestructura de las muestras de yacón secadas con aire caliente mostró un daño celular más significativo, especialmente a 60 °C, en comparación con el secado por infrarrojos, que mostró una estructura más microporosa y compacta. Los resultados indican que el método utilizado impactó en la contracción: el secado por infrarrojos produjo un nivel de contracción más alto en comparación con el secado convectivo. Es importante señalar que este es un cambio físico significativo que puede afectar negativamente la calidad de los alimentos deshidratados. El secado por infrarrojos produjo una mayor rehidratación en comparación con el secado convectivo. De manera similar, se observó una mejor rehidratación a una temperatura de 70 °C. En conclusión, el método de secado por infrarrojos, en combinación con condiciones de secado adecuadas, constituye una buena alternativa para el secado de rodajas de yacón.

Palabras clave: transferencia de calor, estructura interna, microporos, secado, aire caliente, infrarrojo

[1]Food engineer, Universidad Nacional Agraria de la Selva, Peru. PhD. In Food Engineering, Universitat Politècnica de València, España. Affiliation: Senior professor, Universidad Nacional Agraria La Molina, Peru. E-mail: vidaurrejm@lamolina.edu.pe
[2]Food engineer, Universidad Nacional Agraria La Molina, Peru. Affiliation: Young research, Universidad Nacional Agraria La Molina, Peru. E-mail: 20141340@lamolina.edu.pe
[3]Food engineer, Universidad Nacional Agraria La Molina, Peru. Affiliation: Young research, Universidad Nacional Agraria La Molina, Peru. E-mail: 20141372@lamolina.edu.pe
[4] Food engineer, Universidad Nacional Agraria La Molina, Peru. MSc. In Agriculture Engineering, Michigan State University, United States of America. Affiliation: Senior professor, Universidad Nacional Agraria La Molina, Peru. E-mail: wfsalas@lamolina.edu.pe
[5] Food engineer, Universidad Nacional Pedro Ruiz Gallo, Peru. PhD. In Food Science, Universidad Nacional Agraria La Molina, Peru. Affiliation: Associate professor, Universidad Nacional Agraria La Molina, Peru. E-mail: vidaurrejm@lamolina.edu.pe

Received: April 4th, 2023
Accepted: January 11st, 2024

Introduction

Yacón is a native crop of the Andes region, grown at various altitudes in Peru, Bolivia, Ecuador, and Argentina. Due to its medicinal properties, it has been part of the Andean diet for centuries and has spread to other countries like New Zealand, Europe, the USA, and Japan. In Europe, the Czech Republic has pioneered its cultivation, while it is gaining importance in Brazil, particularly in the State of São Paulo. The name *yacón* comes from the Quechua term *yaku*, meaning 'water', but this crop has different names in various regions. It belongs to the genus Smallanthus, *i.e.*, *Smallanthus sonchifolius*, in the family Asteraceae. In recent years, *yacón* has gained popularity in other areas outside its native region, given its nutritional profile and potential health benefits. It has become an important crop in some South American areas and has been exported to other countries for consumption and use in the food and supplement industry (Žiarovská *et al.*, 2019; Choque Delgado *et al.*, 2013).

Yacón is an Andean natural resource, similar in appearance to potatoes, with a sweet flavor and crispy pulp (Bernstein and Noreña, 2014). It has been proven that the consumption of yacón has beneficial effects on health, since it has antioxidant properties, reduces blood sugar levels, and is a potential probiotic (Valentová and Ulrichová, 2003). This is due to its high content of fructooligosaccharides and inulin, which promote the development of the colonic microbiota (Choque Delgado *et al.*, 2013). Its consumption takes place after a period of exposure to the sun aimed at increasing its sweetness (Bernstein and Noreña, 2014). However, *yacón's* high water content (83-90%) and the presence of enzymes such as polyphenol oxidase and peroxidase make it a perishable food (Shi *et al.*, 2013). Its shelf life in fresh form is approximately seven days under ambient conditions, exhibiting constant depolymerization of the fructooligosaccharide compounds, which are of interest to consumers (Perussello *et al.*, 2014).

Different technological alternatives are being studied to preserve *yacón*, transforming the product into beverages, instant powders, sweets, purées, filters, and snacks, among others (Franco *et al.*, 2016; Choque Delgado *et al.*, 2013), always with the aim of not reducing its nutritional or bioactive compounds (Reis *et al.*, 2012; Campos *et al.*, 2016).

Convective drying is widely used in the food industry due to its simplicity and versatility. It allows for better temperature control and even heat distribution around the food, which is essential for maintaining product quality. However, this method can be slow in comparison with infrared drying, and high temperatures and extended drying times can adversely affect quality in terms of the taste, color, and texture of the food (Marques *et al.*, 2023). Convective drying is the simplest method to decrease the moisture content of a product, as heat and mass transfer occur in its surroundings (Reis *et al.*, 2012).

Recent research has shown that pretreatments such as osmotic dehydration or the application of organic acids improve the bioactive characteristics of *yacón*, even when dried at high temperatures (Khajehei *et al.*, 2018; Campos *et al.*, 2016; Perussello *et al.*, 2014). However, convective drying (CD) affects sensory properties such as the color and texture of foods, which is why some studies have sought alternatives to make drying processes less drastic and more economical. An example of this is vacuum drying, which has shown positive effects on *yacón* slices exhibiting low browning, a golden yellow color (Reis *et al.*, 2012).

Another alternative not yet studied in *yacón* is drying by infrared radiation, a type of non-contact heat transfer that harnesses the propagation of electromagnetic waves and does not require a medium. Infrared energy radiates to the heated surface and penetrates directly into the inner layer of the material. This energy is absorbed by molecules in different layers of the material, causing the vibrational energy level of the molecules to rise and fluctuate, generating heat and increasing the overall temperature. This is one of the most important advantages of infrared radiation, as it avoids energy losses and considerably maintains the original quality of the product. However, the initial acquisition and installation costs of infrared equipment are typically high, and precise temperature control can be a challenging task. Moreover, the limited penetration of infrared energy can affect the uniformity of dehydration in products with irregular geometries (D. Huang *et al.*, 2021; Zeng *et al.*, 2019).

Infrared drying provides faster dehydration by transferring energy directly to the food, helping to preserve product quality (*e.g.*, color and flavor). Additionally, it is more energy-efficient due to its shorter drying times.

Recent research has revealed the benefits of drying fruits using far-infrared radiation, as is the case of apples (El-Mesery and Mwithiga, 2015), kiwis (Zeng *et al.*, 2019), and mangoes (Yao *et al.*, 2020), among others. However, the effect of infrared drying on *yacón* chips at different temperatures has not yet been reported. Thus, the objective of this research was to evaluate the effects of convective and far-infrared radiation drying at three different temperature levels on the physical properties and microstructure of *yacón*.

This article consists of four sections. The first section covers the raw material conditioning process and provides a detailed description of the drying methods employed, as well as the analysis procedures conducted on the samples. The second section focuses on presenting the results obtained, encompassing the physical and microstructural properties of *yacón* chips. The third section of the article is devoted to discussing these results, which are analyzed and compared against those in the specialized literature. Finally, the fourth section provides the conclusions of this study and proposals for future research concerning the drying process of *yacón* chips. The results constitute a reference for studying the effects of far-infrared radiation drying on the physical quality components of *yacón*, aiming for a functional product with acceptable characteristics.

Materials and methods

Raw material conditioning

Yacón roots (*Smallanthus sonchifolius*) were purchased from the Santa Rosa market, located in the district of La Molina, Lima, Peru. The moisture content of the fresh *yacón* samples was analyzed via the 930.04 method (AOAC, 2005). The results showed a moisture content of 89,48 ± 0,72%, which is similar to the values reported in previous studies (Corrêa *et al.*, 2021). A selection process was carried out, eliminating the samples that exhibited physical damage, such as bruises or signs of microbial attack, evidenced in color changes on the surface. Then, the selected roots were washed with by immersion in potable water to eliminate any residues from the harvesting process. Disinfection was carried out with sodium hypochlorite (150 ppm). The water was removed from the outer part of the roots, and they were cut into 5 mm thick slices using a vegetable slicer (CL-52, Robot Coupe, United States). Chemical bleaching was performed by immersing the *yacón* slices in a 2% citric acid solution for 5 min at room temperature. This was done to inactivate the enzymes present in the *yacón* roots that are related to enzymatic browning (peroxidase and polyphenoloxidase).

Drying process

The *yacón* slices were placed on stainless steel mesh trays. They were dried in a convective cabin dryer (TAAC-PC, Edibon, Spain) at an air velocity of 0.91 m/s and in a far-infrared dryer (IRCDi8, IR Confort, Spain) at temperatures of 60, 70, and 80 °C. The temperature range for dehydrating *yacón* was selected while considering commercial working conditions; this range efficiently expedites the moisture removal process in *yacón*, saving both time and energy. The infrared dryer contained eight trays whose area and power were 0.24 m^2 and 221 W, respectively. Both drying operations ended when the product reached a humidity range of 8-10%. The dehydrated *yacón* samples were packed in polypropylene bags at room temperature for later characterization. An infrared moisture meter (MX-50, AND, Japan) was used to determine the moisture content of the dried *yacón* samples.

Yacón drying curves

The drying curve was constructed by plotting the moisture content *vs.* time, and the drying rate curve was plotted *vs.* the moisture content. The moisture content (X) was determined using Equation (1), which calculates the amount of water in kilograms per kilogram of dry matter.

$$X = \frac{W - W_{dm}}{W_{dm}} \quad (1)$$

where W represents the weight at a specific time, and W_{dm} denotes the weight of the dry matter.

The drying rate was calculated using Equation (2), which measures the amount of water removed in kilograms per kilogram of dry matter per hour.

$$\emptyset = -\frac{dX}{dt} = -\frac{\Delta X}{\Delta t} \quad (2)$$

where ϕ represents the drying rate ($kg_w/kg_{dm}h$), X is the free moisture (kg_w/kg_{dm}), and t represents the drying time (h).

Color determination

The color of the samples was expressed in accordance with the CIELAB parameters: L* (0=black; 100=white), a* (−a*=greenish, +a*=red), and b* (−b*=bluish, +b*=yellow). The colorimeter (CR-400, Konica Minolta, Japan) was placed vertically on the surface of the sample (laid on a white surface). Measurements were taken in three replicates. The total color difference (ΔE), indicating the color change between fresh and dry samples, was calculated using the following Equation (Yao *et al.,* 2020):

$$E^* = \sqrt{(L_0^* - L_1^*)^2 + (a_0^* - a_1^*)^2 + (b_0^* - b_1^*)^2} \quad (1)$$

Texture analysis

The methodology proposed by Egea *et al.* (2012) was used, with some modifications. A texturometer (Model 3345, Instron, USA) was used, equipped with a 0.25-inch diameter plunger. The speed of the penetration test was 1.0 mm/s. The breaking point (expressed in Newtons) of the dehydrated *yacón* was determined.

Volumetric shrinkage (Sh)

To determine the initial volume (V_0) of the *yacón* samples, their diameter and thickness were measured using a digital Vernier caliper with a precision of 0.01 mm. The area of each sample was digitally analyzed using the ImageJ software, and its thickness was measured at four different points using the digital Vernier. Four replicates of the measurements were performed. Sh was calculated with respect to the volume of the sample at each time (V) and its initial volume (V_0) according to Equation (3) (Senadeera *et al.*, 2020; Corrêa *et al.*, 2021).

$$Sh = \left(1 - \frac{V}{V_0}\right) * 100 \quad (3)$$

where V and V_0 are the volume of the sample at each time and the initial volume (m^3), respectively.

Rehydration

To measure the rehydration ratio, 5 g of dried *yacón* were soaked in 150 ml of distilled water in a 250 ml beaker at 25 °C. After 1 h, the samples were placed on a piece of paper towel to remove any excess water from the surface. The rehydrated mass was then determined three times to ensure accuracy. Three replicates of the measurements were performed. The rehydration ratio was calculated using Equation (2) (Mugodo and Workneh, 2021; Corrêa *et al.*, 2021).

$$\text{Rehydration ratio} = \frac{W_2}{W_1} \quad (4)$$

where the weights W_2 and W_1 (g) correspond to the drained and dried *yacón* samples, respectively.

Microstructure analysis

Photographs were taken using a scanning electron microscope (SEM). Fresh and dehydrated *yacón* chips were plated with gold under vacuum conditions using an automatic metallizer (Q150R, Quorum Technologies, England). The samples were subsequently analyzed using a SEM-Q250 from Thermo Scientific Analytical. The kV value was set as 15.00, and the gain was 300 μm.

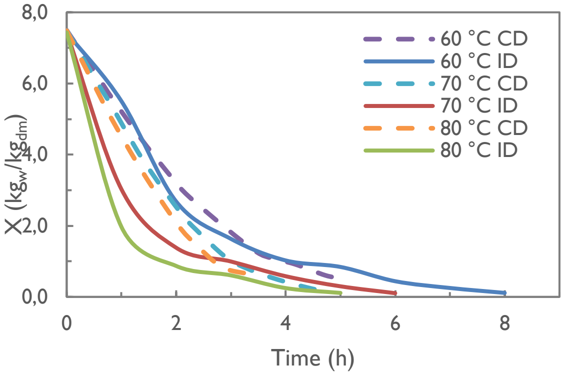
Statistical analysis

All experiments were performed in triplicate, and the treatments were analyzed within a completely randomized design (CDR). The results were averaged, and an analysis of variance (ANOVA) was performed for each determination. Then, a comparison of means was made, using the Tukey test at a significance level of 0.05. All statistical analyses were performed using the Statgraphics Centurion XVII statistical package.

Results

Figure 1 shows the moisture contents (experimental) *vs.* the drying time for the two methods. The results indicate that the technique used has an effect on the drying rates of *yacón*. Using the far-infrared drying (ID) method increases the drying rate and reduces the time required to achieve a certain moisture content.

a)



b)

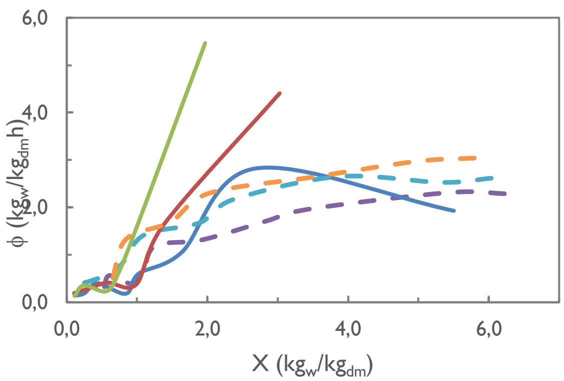


Figure 1. Drying curves of *yacón* for the two studied methods at different temperatures: a) moisture *vs.* time, b) drying rate curve. CD: convective drying, ID: far-infrared drying.

Figure 1 displays typical drying curves, characterized by two falling-rate periods and no apparent constant-rate period. However, it might be possible to have a very short constant-rate period at lower moisture values. The air temperature (60, 70, and 80 °C) impacted the drying kinetics of *yacón* (Figure 1a); increasing the temperature of the drying medium increased the drying potential and the moisture removal rates.

Table 1 shows the different color coordinates obtained for each drying treatment. In the case of CD, the luminosity of the *yacón* samples decreased as the drying temperature increased. This was also reported by ID. However, it should be noted that the greatest decrease in luminosity was obtained with ID at 80 °C. This phenomenon could be attributed to the duration of the process, since it was longer than 5 h, compared to 3 h for CD. This means that, at a temperature of 80 °C, the latter is faster than the former. The reduced values of the color coordinate a* caused yellowish tones in the *yacón* samples. In CD, the increase in a* was progressive as the drying temperature increased. In the case of ID, the increase in the value of a* was more abrupt, producing browner shades. As for b*, no significant changes were observed, indicating that the green tones remained constant.

Table 1. Physical properties (color coordinates and texture) of dehydrated *yacón*

	T (°C)	Physical properties				
		Color				Texture
		L*	a*	b*	ΔE	Force (N)
CD	60	62.31 ± 0.38^{a}	1.05 ± 0.13^{a}	23.74 ± 2.07^{a}	27.10 ± 0.56^{a}	18.54 ± 2.36^{a}
	70	58.89 ± 0.95^{ab}	2.97 ± 0.21^{b}	27.88 ± 3.57^{a}	30.42 ± 0.62^{ab}	14.57 ± 1.72^{ab}
	80	56.99 ± 1.25^{b}	3.61 ± 0.91^{bc}	25.90 ± 3.53^{a}	32.38 ± 0.70^{b}	12.78 ± 1.62^{b}
ID	60	61.74 ± 3.10^{a}	0.71 ± 0.02^{a}	22.82 ± 0.60^{a}	22.78 ± 3.17^{ab}	18.67 ± 2.01^{a}
	70	56.71 ± 2.18^{b}	4.18 ± 0.29^{c}	25.86 ± 0.58^{a}	32.54 ± 2.55^{b}	16.80 ± 2.02^{ab}
	80	42.94 ± 0.58^{c}	5.50 ± 0.42^{d}	24.28 ± 0.40^{a}	46.44 ± 0.83^{c}	13.85 ± 2.04^{b}

Different letters (a, b, c) within the same column show significant differences between values ($p<0.05$). Data are reported as the mean of three replicates (n=3) ± standard deviation (SD).

The results showed that the greatest color variations with respect to the fresh *yacón* sample occurred during ID at 80 °C. On the other hand, the smallest variations were evidenced during ID at 60 °C.

Table 1 also shows the force values required to break a *yacón* slice. It was observed that, as the drying temperature increases, the maximum breaking point decreases. This is due to the fact that higher temperatures entail a greater removal of water from the matrix, making the product more fragile.

Table 2 summarizes the shrinkage obtained for each drying treatment. The results indicate that the drying method affects shrinkage, but the temperature has no effect. ID produced a higher level of shrinkage when compared to CD. Shrinkage is a significant physical change that can adversely affect the quality of dehydrated food.

Table 2. Physical properties (shrinkage and rehydration) of dehydrated *yacón*

	T (°C)	Physical properties		
		Moisture (%)	Shrinkage (%)	Rehydration
CD	60	9.85 ± 0.74	72.68 ± 0.77^{a}	3.45 ± 0.06^{a}
	70	9.89 ± 1.02	74.97 ± 0.50^{a}	3.93 ± 0.04^{b}
	80	8.15 ± 0.35	75.32 ± 2.78^{a}	3.48 ± 0.07^{a}
ID	60	9.56 ± 0.74	82.14 ± 4.50^{b}	3.87 ± 0.09^{b}
	70	8.08 ± 1.89	79.64 ± 4.73^{b}	4.30 ± 0.13^{c}
	80	9.20 ± 1.13	81.60 ± 1.35^{b}	4.30 ± 0.16^{c}

Different letters (a, b, c) within the same column show significant differences between values ($p<0.05$).

Table 2 also shows the rehydration ratios. The data indicate a significant effect of both drying method and temperature. ID produced greater rehydration in comparison to CD. Similarly, improved rehydration was observed at a temperature of 70 °C.

Figure 2 shows the surface microstructure of the fresh and dried *yacón* samples under different drying conditions. The fresh sample (Figure 2a) exhibits round, elongated, compact, and well-structured parenchyma cells. CD produced severe surface shrinkage, manifesting as a brittle and poor-quality surface (Figures 2b and 2c). In contrast, ID showed more micropores and less shrinkage and deformation (Figures 2d and 2e).

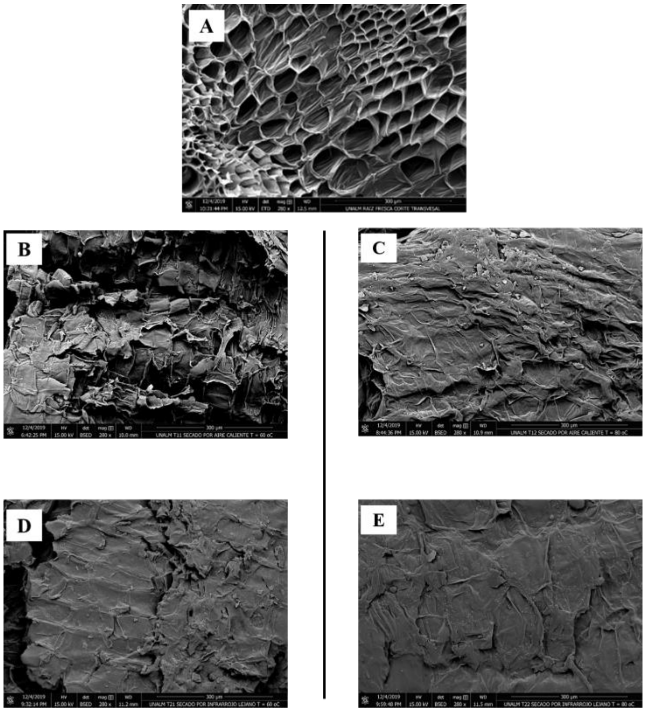


Figure 2. SEM of the surface of *yacón* root slices. A: control; B: convective drying at 60 °C; C: convective drying at 80 °C; D: infrared drying at 60 °C; E: infrared drying at 80 °C.

Discussion

ID was found to require shorter times than CD, as the dryer absorbs infrared radiation, causing heat to be released from the interior of the sample. As a result, water is carried from the inside of the sample to its surface, facilitating quick drying. The results were consistent with those of the specialized literature. For instance, during the drying process of *Ganoderma lucidum*, a study found that using an infrared dryer allowed reaching the desired moisture content faster and provided superior performance in comparison with CD (Naseri *et al.*, 2023). The *yacón* chips exhibited higher initial drying rates, potentially due to the evaporation of surface moisture. As the moisture content decreased, the drying rates also decreased, suggesting that moisture diffusion played a significant role. The high drying rates observed could be linked to internal heat generation. The absence of a constant drying rate period may be due to the fact that the thin slices did not provide a consistent supply of moisture during drying (Sadeghi*et al.*, 2020). Other studies have also reported increased drying rates with higher radiation intensity (Sadeghi *et al.*, 2020; Naseri *et al.*, 2023). Furthermore, the curve could indicate a constant drying rate stage if corrected for the actual exchange surface area of the sample (Marques *et al.*, 2023).

In this study, the total color variation (ΔE) is an indicator of treatment severity with regard to coloration of the initial sample (Bernstein and Noreña, 2014; Ning *et al.*, 2015). This can be attributed to the fact that infrared radiation generates rapid and intense heat inside the material, causing serious damage to cell tissues and increasing the likelihood of contact between the substrate and the enzymes, thereby darkening the *yacón*. However, Nowak and Lewicki (2005) state that drying with infrared technology can prevent the excessive browning of food, giving it a better appearance than that provided by traditional methods. The magnitudes of color variation were on the order of those reported by Bernstein and Noreña (2014), who blanched *yacón* slices for 4 min with steam at 100°C before subjecting them to a first drying period at 50°C for 5 h and a second drying period at 75°C for 5 h.

Several studies have observed that drying with infrared technology decreases hardness in comparison with CD. This is the result of the swelling of the matrix due to the heating of the starches and the solubilization of the pectin, which can produce infrared radiation (Nathakaranakule *et al.*, 2010; Qi *et al.*, 2014). However, this study noted no difference in this parameter between both drying technologies. As explained above, the infrared radiation exposure time is crucial to reap the benefits of this technology. Therefore, a correct selection of power and working conditions will be crucial to obtaining better results.

Studies on the drying of persimmon and *yacón* using hot air at varying temperatures showed that a value of 60°C results in minimal shrinkage (Senadeera *et al.*, 2020; Marques *et al.*, 2023). Furthermore, Yang *et al.* (2020) investigated the drying of mushrooms using different drying methods, including hot air and infrared technologies. They found that there is greater shrinkage in ID. This was also achieved in *yacón* slices. According to Mugodo and Workneh (2021), the techniques employed in drying mango slices significantly impact rehydration. This impact could include irreversible damage, causing cell rupture and shrinkage. This integrity loss and shrinkage subsequently decrease the hydrophilic properties of the cell. As a result, it cannot absorb enough water to fully hydrate the product (Corrêa *et al.*, 2021).

The dried *yacón* microstructure was similar to that of dried hemp, kiwi, and beet products (Junqueira *et al.*, 2018; Jiang *et al.*, 2018; Pham *et al.*, 2018). The observed shrinkage is due to the heat transfer caused by CD from the outside to the inside, causing the surface water to evaporate rapidly and forming hard membranes and surface cells with irregular contractions (Zhu *et. al*, 2022). In contrast, ID reported less shrinkage and more micropores, as one advantage of this technology is rapid heating, which causes the internal cell cavity to heat and expand, producing more micropores in the structure (X. Huang *et al.*, 2021). This benefits the surface since the cells are subjected to less structural stress, thus forming more open structures with good morphology in the dehydrated *yacón*. Similarly, Puente-Díaz *et al.* (2020) found changes in the microstructure of dried Physalis fruit puree using the infrared-assisted refractory window method at different temperatures, obtaining a rough surface with evident water loss. In their study, Marques *et al.* (2023) analyzed the microstructure of *yacón* to explain the shrinkage phenomenon during CD. They identified two distinct cell types: xylem vessels and parenchyma cells. These researchers found that xylem vessels have thicker cell walls than parenchyma cells, making them less susceptible to collapsing during drying. Their discovery sheds light on the cause behind the cell wall collapse observed in *yacón* slices dried at 60°C, and it demonstrates one of the advantages attributed to ID to improve the quality of *yacón* chips, in the form of enhancement in the physical structure and integrity of the product.

Conclusions

This research reported, for the first time, the effect of infrared drying on the physical and structural properties of *yacón* chips. It was found that a high temperature (80 °C) causes significant changes in the color and texture parameters of the product in both in infrared and convective drying. However, the most substantial changes were perceived at the structural level, as the infrared dried *yacón* chips showed a better morphology. Therefore, applying this technology cannot only increase the number of micropores in the internal structure. It can also improve the heat and mass transfer process, as well as the appearance of *yacón*. Although this work provides the first insight into the benefits of this technology, other aspects should also be explored, such as combined treatments using different technologies, pre-treatments to efficiently avoid browning, and the effect of different power levels during infrared drying.

Acknowledgements

The authors are grateful to the Vice-President for Research of Universidad Nacional Agraria La Molina for the financial support provided under the UNALM-MINEDU agreement (Resolution No. 0410-2019-R-UNALM).

Conflicts of interest

The authors of this paper declare that they have no conflicts of interest.

CRediT author statement

All authors: conceptualization, methodology, software, formal analysis, investigation, data curation, writing (original draft, review, and editing).

References

Bernstein, A., and Noreña, C. P. Z. (2014). Study of thermodynamic, structural, and quality properties of yacon (*Smallanthus sonchifolius*) during drying. *Food and Bioprocess Technology, 7*(1), 148-160. https://doi.org/10.1007/s11947-012-1027-y

Campos, D., Aguilar-Galvez, A., and Pedreschi, R. (2016). Stability of fructooligosaccharides, sugars and colour of yacon (*Smallanthus sonchifolius*) roots during blanching and drying. *International Journal of Food Science and Technology, 51*(5), 1177-1185. https://doi.org/10.1111/ijfs.13074

Choque Delgado, G. T., da Silva Cunha Tamashiro, W. M., Maróstica Junior, M. R., and Pastore, G. M. (2013). Yacon (*Smallanthus sonchifolius*): A functional food. *Plant Foods for Human Nutrition, 68*(3), 222-228. https://doi.org/10.1007/s11130-013-0362-0

Corrêa, J. L. G., Lopes, F. J., de Mello Junior, R. E., de Jesus Junqueira, J. R., de Angelis Pereira, M. C., and Salvio, L. G. A. (2021). Dried yacon with high fructooligosaccharide content. *Journal of Food Process Engineering, 44*(12), 13884. https://doi.org/10.1111/jfpe.13884

de Jesus Junqueira, J. R., Corrêa, J. L. G., de Mendonça, K. S., de Mello Júnior, R. E., and de Souza, A. U. (2018). Pulsed vacuum osmotic dehydration of beetroot, carrot and eggplant slices: Effect of vacuum pressure on the quality parameters. *Food and Bioprocess Technology, 11*(10), 1863-1875. https://doi.org/10.1007/s11947-018-2147-9

Egea, M. B., Borsato, D., Silva, R. S. dos S. F. da, and Yamashita, F. (2012). Osmo-dehydrated functional product containing fructo-oligosaccharides: Physical, chemical and sensorial characteristics. *Brazilian Archives of Biology and Technology, 55*(6), 927-936. https://doi.org/10.1590/S1516-89132012000600017

El-Mesery, H. S., and Mwithiga, G. (2015). Performance of a convective, infrared and combined infrared-convective heated conveyor-belt dryer. *Journal of Food Science and Technology, 52(5)*, 2721-2730. https://doi.org/10.1007/s13197-014-1347-1

Franco, T. S., Perussello, C. A., Ellendersen, L. N., and Masson, M. L. (2016). Effects of foam mat drying on physicochemical and microstructural properties of yacon juice powder. *LWT - Food Science and Technology, 66*, 503-513. https://doi.org/10.1016/j.lwt.2015.11.009

Huang, D., Yang, P., Tang, X., Luo, L., and Sunden, B. (2021). Application of infrared radiation in the drying of food products. *Trends in Food Science and Technology, 110*, 765-777. https://doi.org/10.1016/j.tifs.2021.02.039

Huang, X., Li, W., Wang, Y., and Wan, F. (2021). Drying characteristics and quality of Stevia rebaudiana leaves by far-infrared radiation. *LWT, 140*, 110638. https://doi.org/10.1016/j.lwt.2020.110638

Jiang, Y., Lawrence, M., Ansell, M. P., and Hussain, A. (2018). Cell wall microstructure, pore size distribution and absolute density of hemp shiv. *Royal Society Open Science, 5*(4), 171945. https://doi.org/10.1098/rsos.171945

Khajehei, F., Hartung, J., and Graeff-Hönninger, S. (2018). Total phenolic content and antioxidant activity of yacon (*Smallanthus sonchifolius* poepp. and endl.) chips: Effect of cultivar, pre-treatment and drying. *Agriculture, 8*(12), 183. https://doi.org/10.3390/agriculture8120183

Marques, B., Perré, P., Casalinho, J., Tadini, C. C., Plana-Fattori, A., and Almeida, G. (2023). Evidence of iso-volume deformation during convective drying of yacón: An extended van Meel model adapted to large volume reduction. *Journal of Food Engineering, 341*, 111311. https://doi.org/10.1016/j.jfoodeng.2022.111311

Mugodo, K., and Workneh, T. S. (2021). The kinetics of thin-layer drying and modelling for mango slices and the influence of differing hot-air drying methods on quality. *Heliyon, 7*(6), e07182. https://doi.org/10.1016/j.heliyon.2021.e07182

Naseri, M., Movagharnejad, K., and Nanvakenari, S. (2023). Comparison of the dried properties of Ganoderma lucidum produced by the convective dryer and infrared dryer. *Scientific Reports, 13*(1), 12636. https://doi.org/10.1038/s41598-023-39883-z

Nathakaranakule, A., Jaiboon, P., and Soponronnarit, S. (2010). Far-infrared radiation assisted drying of longan fruit. *Journal of Food Engineering, 100*(4), 662-668. https://doi.org/10.1016/j.jfoodeng.2010.05.016

Ning, X., Lee, J., and Han, C. (2015). Drying characteristics and quality of red ginseng using far-infrared rays. *Journal of Ginseng Research, 39*(4), 371-375. https://doi.org/10.1016/j.jgr.2015.04.001

Nowak, D., and Lewicki, P. P. (2005). Quality of infrared dried apple slices. *Drying Technology, 23*(4), 831-846. https://doi.org/10.1080/DRT-200054206

Perussello, C. A., Kumar, C., De Castilhos, F., and Karim, M. A. (2014). Heat and mass transfer modeling of the osmo-convective drying of yacon roots (*Smallanthus sonchifolius*). *Applied Thermal Engineering, 63*(1), 23-32. https://doi.org/10.1016/j.applthermaleng.2013.10.020

Pham, N. D., Martens, W., Karim, M. A., and Joardder, M. U. H. (2018). Nutritional quality of heat-sensitive food materials in intermittent microwave convective drying. *Food & Nutrition Research, 62*, 1-11. https://doi.org/10.29219/fnr.v62.1292

Puente-Díaz, L., Spolmann, O., Nocetti, D., Zura-Bravo, L., and Lemus-Mondaca, R. (2020). Effects of infrared-assisted refractance window™ drying on the drying kinetics, microstructure, and colour of Physalis fruit purée. *Foods, 9(3)*, 343. https://doi.org/10.3390/foods9030343

Qi, L.-L., Zhang, M., Mujumdar, A. S., Meng, X.-Y., and Chen, H.-Z. (2014). Comparison of drying characteristics and quality of shiitake mushrooms (*Lentinus edodes*) using different drying methods. *Drying Technology, 32*(15), 1751-1761. https://doi.org/10.1080/07373937.2014.929588

Reis, Felipe R., Lenzi, M. K., and Masson, M. L. (2012). Effect of vacuum drying conditions on the quality of yacon (*Smallanthus sonchifolius*) slices: Process optimization toward colour quality. *Journal of Food Processing and Preservation, 36*(1), 67-73. https://doi.org/10.1111/j.1745-4549.2011.00555.x

Reis, F. R., Lenzi, M. K., de Muñiz, G. I. B., Nisgoski, S., and Masson, M. L. (2012). Vacuum drying kinetics of yacon (*Smallanthus sonchifolius*) and the effect of process conditions on fractal dimension and rehydration capacity. *Drying Technology, 30*(1), 13-19. https://doi.org/10.1080/07373937.2011.611307

Sadeghi, E., Haghighi Asl, A., and Movagharnejad, K. (2020). Optimization and quality evaluation of infrared-dried kiwifruit slices.

Food Science & Nutrition, 8(2), 720-734. https://doi.org/10.1002/fsn3.1253

Senadeera, W., Adiletta, G., Önal, B., Di Matteo, M., and Russo, P. (2020). Influence of different hot air drying temperatures on drying kinetics, shrinkage, and colour of persimmon slices. *Foods, 9(1),* 101. https://doi.org/10.3390/foods9010101

Shi, Q., Zheng, Y., and Zhao, Y. (2013). Mathematical modeling on thin-layer heat pump drying of yacon (*Smallanthus sonchifolius*) slices. *Energy Conversion and Management, 71,* 208-216. https://doi.org/10.1016/j.enconman.2013.03.032

Valentová, K., and Ulrichová, J. (2003). *Smallanthus sonchifolius* and *Lepidium meyenii* - Prospective Andean crops for the prevention of chronic diseases. *Biomedical Papers, 147*(2), 119-130. https://doi.org/10.5507/bp.2003.017

Yang, R.-L., Li, Q., and Hu, Q.-P. (2020). Physicochemical properties, microstructures, nutritional components, and free amino acids of *Pleurotus eryngii* as affected by different drying methods. *Scientific Reports, 10*(1), 121. https://doi.org/10.1038/s41598-019-56901-1

Yao, L., Fan, L., and Duan, Z. (2020). Effect of different pretreatments followed by hot-air and far-infrared drying on the bioactive compounds, physicochemical property and microstructure of mango slices. *Food Chemistry, 305,* 125477. https://doi.org/10.1016/j.foodchem.2019.125477

Zeng, Y., Liu, Y., Zhang, J., Xi, H., and Duan, X. (2019). Effects of far-infrared radiation temperature on drying characteristics, water status, microstructure and quality of kiwifruit slices. *Journal of Food Measurement and Characterization, 13*(4), 3086-3096. https://doi.org/10.1007/s11694-019-00231-3

Žiarovská, J., Padilla-González, G. F., Viehmannová, I., and Fernández, E. (2019). Genetic and chemical diversity among yacon [*Smallanthus sonchifolius* (Poepp. et Endl.) H. Robinson] accessions based on iPBS markers and metabolomic fingerprinting. *Plant Physiology and Biochemistry, 14*, 183-192. https://doi.org/10.1016/j.plaphy.2019.05.020

Zhu, J., Liu, Y., Zhu, C., and Wei, M. (2022). Effects of different drying methods on the physical properties and sensory characteristics of apple chip snacks. *LWT, 154,* 112829. https://doi.org/10.1016/j.lwt.2021.112829