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Beetroot slices dried by refractance window dryer and conventional drying: drying kinetics, physicochemical properties and antioxidant capacity

Rodajas de betabel secadas mediante secador por ventana refractiva y secado convencional: cinética de secado, propiedades fisicoquímicas y capacidad antioxidante

E. Herman-Lara[1], C. E. Martínez-Sánchez[1], J. Rodríguez-Miranda[1], J. M. Juárez-Barrientos[2], C. Calderón-Chiu[3]*
[1]Departamento de Ingeniería Química y Bioquímica, Instituto Tecnológico Nacional de México/Tecnológico de Tuxtepec, Tuxtepec, Oaxaca, México.
[2]Instituto de Agroingeniería, Universidad del Papaloapan Campus Loma Bonita, Loma Bonita, Oax. México.
[3]Laboratorio Integral de Investigación en Alimentos, Tecnológico Nacional de México/Instituto Tecnológico de Tepic, Tepic, Nayarit, México.

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Abstract

This investigation evaluated the effect of drying methods, including tray drying (TD), fixed bed drying (FBD), and refractive window drying (RWD) of beetroot slices (1 mm thickness) at 60, 75, and 85 °C. Then, drying kinetics, color, texture, total polyphenol content (TPC), total flavonoid content (TFC), and antioxidant capacity (AC) were assessed. The moisture ratio and drying rate depended on temperature and method of drying. Beetroot slices processed on RWD showed lower moisture content and the highest drying rate than TD and FBD. For this reason, RWD required less time drying (60-100 min) in comparison to TD (100-150 min) and FBD (240-285 min) at temperatures evaluated. The color and firmness of dried beetroot slices by RWD were more similar to the control (fresh beetroot) than other drying methods. Similarly, the TPC, TFC, and AC were higher at low drying temperatures (60 °C) for the three methods evaluated. However, as the temperature increased, TPC, TFC, and AC were significantly reduced ($P<0.05$) for samples processed on TD and FBD. This study showed that RWD could effectively be used to dry thin layers of heat-sensitive products such as beetroot in a shorter time with minimum alteration in quality compared to conventional drying methods.

Keywords: beetroot, refractance window dryer, tray dryer, fixed bed dryer, physical properties, chemical properties.

Resumen

Se realizó el secado en bandeja (TD), lecho fijo (FBD) y por ventana refractiva (RWD) de rodajas de betabel (1 mm de espesor) a 60, 75 y 85 °C. Se evaluaron las cinéticas de secado, color, textura, contenido total de polifenoles (TPC) y flavonoides (TFC), y la capacidad antioxidante (CA) del betabel deshidratado. La eliminación de humedad y la velocidad de secado dependieron de la temperatura y método de secado. Las rodajas de betabel procesadas en RWD mostraron menor contenido de humedad y alta velocidad de secado que TD y FBD. RWD requirió menos tiempo de secado (60-100 min) que TD (100-150 min) y FBD (240-285 min) en las temperaturas evaluadas. El color y firmeza de betabel deshidratado por RWD fue más similar al control (betabel fresco). El TPC, TFC y AC fueron más altos a baja temperatura (60 °C) para los tres métodos evaluados. A medida que aumentó la temperatura, TPC, TFC y AC se redujeron significativamente ($P<0.05$) en muestras procesadas en TD y FBD. Este estudio demostró que el RWD podría utilizarse eficazmente para secar rodajas finas de productos sensibles al calor en tiempos más corto y mínimas alteraciones en comparación con los métodos de secado convencionales.

Palabras clave: betabel, secador por ventana refractiva, secador de bandeja, secador de lecho fijo, propiedades físicas, propiedades químicas.

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*Corresponding author. E-mail: carolinachiu@outlook.com;
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1 Introduction

Beetroot (*Beta vulgaris* L.) is a health-promoting food containing vitamins, minerals, phenolic compounds, carotenoids, and betalains (Chhikara *et al*., 2019). Bioactive compounds of beetroot have exhibited antioxidant, antimicrobial, anti-inflammatory, antiproliferative, and antiviral activities (Rehman *et al*., 2024), but the high moisture content of beetroot makes it susceptible to spoilage. Drying is a process that facilitates storage and prevents microbial contamination and other detrimental chemical reactions in fresh fruits and vegetables (Menon *et al*., 2020; García-Moreira *et al*., 2024). Hence, slices and powders of dried beetroot are currently available as functional foods (Preethi *et al*., 2020). Dried beetroot slices are consumed as a substitute for traditional snacks, and beetroot powder is an ingredient in instant beverages or a colorant alternative for food products (Seremet *et al*., 2020).

Conventional drying methods, including hot air drying (HAD) or convective drying (CD), generally produce slices and powders of dried beetroot. These drying methods are economical and widely implemented in the food industry but require extended drying times and high temperatures (Karam *et al*., 2016). Moreover, they negatively impact the physicochemical properties of dried beetroot (Figiel, 2010; Hamid and Mohamed, 2018). Indeed, Gokhale & Lele (2011) dehydrated beetroot pulp with a convective hot air laboratory tray dryer at different temperatures (50-120 °C). The drying process was optimized to produce beetroot powder as a natural food colorant, aiming at lower batch times (indirect benefits of reduced energy consumption and higher throughput) and maximum color retention. A sequential decreasing temperature profile (120 to 50 ºC) produced beetroot powder with 90% color retention in a 4 h drying period compared to the same color retention with a 6 h time under isothermal drying at 50 ºC. For its part, Hamid & Mohamed (2018) evaluated the drying of 2 mm thick beetroot slices in a convective oven at 70 °C for 24 h and freeze-drying (24 h). Oven drying of the slices significantly reduced total phenolics content, betalain and betacyanin but without considerable changes in the content of betaxanthin. The color of the powder of beetroot slices dried by a convective oven showed a decrease in lightness compared with freeze-drying, indicating that convective drying had adverse effects on the final product. Therefore, the appropriate drying method and conditions are indispensable for maintaining quality dried beetroot since it contains pigments sensitive to temperature, pH, oxygen, water activity, and light (Janiszewska, 2014).

Drying technologies with significant advantages have been developed, including shortened drying time, energy savings, and low-cost and high-quality end-products such as refractance window drying (Rodríguez *et al*., 2014; Nguyen *et al*., 2015). Refractance window drying (RWD) is a method for heat-sensitive products such as fruit and vegetable purees, slices, juices, or flakes (Ortiz-Jerez *et al*., 2015). RWD utilizes hot water to transfer thermal energy to a material placed on transparent plastic film (Mylar^{TM}). The thermal energy from hot water is transmitted to samples through the plastic film by radiation and conduction (Caparino *et al*., 2012; Calderón-Chiu *et al*., 2020). In RWD, the drying time is shorter, and the dried products are of higher quality than conventional drying methods (Raghavi *et al*., 2018). Fruit and vegetable powders such as mango (Caparino *et al*., 2012), anthocyanin (Celli et al., 2016), and chickpea protein isolate (Tontul *et al*., 2018), as well as slices of mango (Ochoa-Martínez *et al*., 2012), carrots (Hernández-Santos *et al*., 2016), and kiwifruit (Azizi *et al*., 2017) has been drying by RWD.

Previously, Preethi *et al*. (2020) used conductive hydro drying (CHD), a variant of the refractance window drying technology and tray drying to prepare flakes from a 1 mm thick layer of beetroot pulp at different temperatures (40, 50, and 60 °C). The authors found significantly lower drying time (90-180 min) and moisture content (below 5%) for CHD than tray drying (150-210 min) and better retention of color, total phenolic content, antioxidant properties, and betalain content. Likewise, Calderón-Chiu *et al*. (2020) dried 1 mm thicknesses of beetroot slices by RWD at 60 and 85 °C in relatively short times. Nevertheless, to our knowledge, the effect of conventional drying methods and RWD on the quality of beetroot slices dried is limited. Consequently, additional research is required to demonstrate that dried beetroot by RWD could be an efficient alternative to drying beetroot slices by conventional drying. Therefore, this study aimed to compare the effect of three different temperatures (60, 75 and 85 °C) and drying methods, including tray drying (TD), fixed bed drying (FBD), and refractance window drying (RWD), on drying kinetics, color, texture, total polyphenol (TPC) and flavonoid content (TFC), and antioxidant capacity (AC) of beetroot slices.

2 Materials and methods

2.1 *Plant material and chemical substances*

Beetroot with commercial maturity was obtained from the local market in Tuxtepec, Oaxaca, Mexico. Samples were selected to be uniform in color, shape, and size and cut into 3.5 cm diameter slices with a thickness of 1 mm.

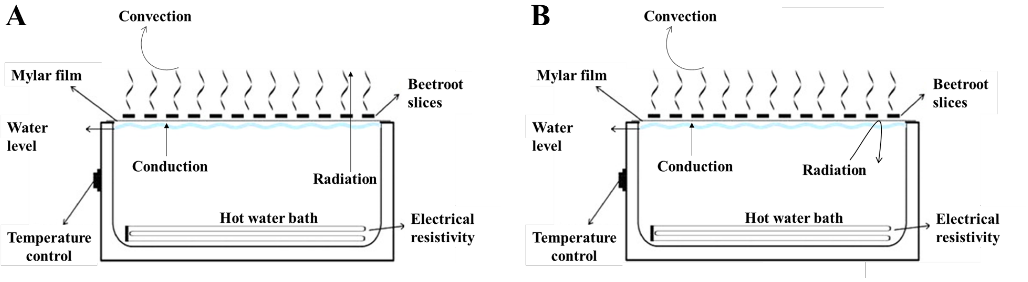

Figure 1. Schematic description of the Refractance windows dryer. Mode of heat transfer: (a) conduction, convection and radiation during the start of the drying process and (b) Conduction and convection at the end of the drying process, from hot water to drying product through Mylar film and convection heat transfer over product surface (adapted from Calderón-Chiu *et al*., 2020 and Kumar *et al*. 2022).

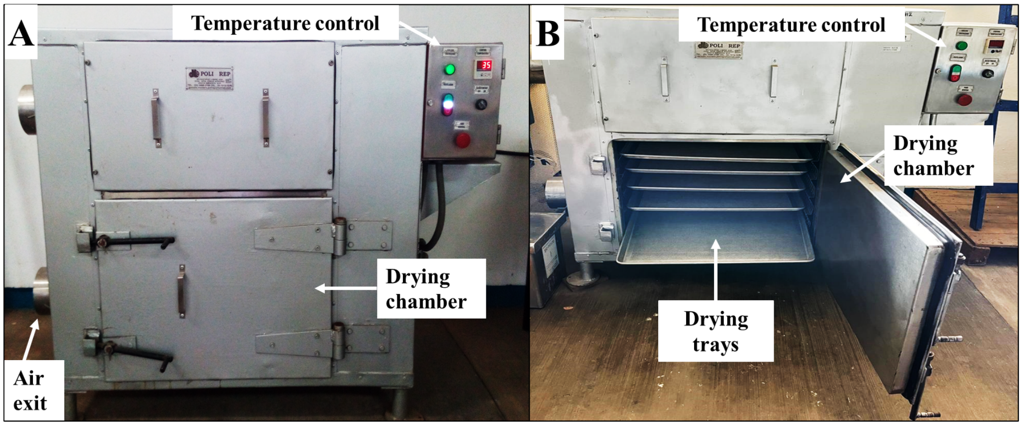

Figure 2. Tray dryer in its closed (A) and open form (B) showing the five trays with perforations.

The 1,1-diphenyl-2-picrylhydrazyl (DPPH+), Folin-Ciocalteu reagent, gallic acid, (+)-catechin, sodium carbonate, sodium nitrite, and aluminum chloride were purchased from Sigma-Aldrich (St. Louis, MO, USA). Acetone, methanol, and sodium hydroxide were obtained from Merck (Darmstadt, Germany).

2.2 *Drying methods*

2.2.1 *Refractance window drying (RWD)*

Beetroot slice drying was achieved on RWD manufactured by Hernández-Santos *et al*. (2016). The RWD was created in the laboratory by placing a Mylar film (0.017 mm thick) on the surface of a stainless-steel water bath, which allows the plastic film to rest directly above the water (Figure 1). Two electrical heaters (840 W) were used as the heating elements. The water bath temperature was controlled using a temperature controller (Johnson Controls, model A419, WI, USA). The water bath was maintained at 70 ± 2, 86 ± 2, and 98 ± 2 °C, which allowed for maintaining constant temperatures on the surface of the Mylar^{TM} film of 60, 75, and 85 °C, respectively; this film was removable to be continually weighed. The 1-mm thick slices were distributed in a monolayer on the surface of the Mylar^{TM} film, which was previously weighed (Calderón-Chiu *et al*., 2020).

2.2.2 *Tray drying (TD)*

Tray drying was accomplished in a pilot-scale TD (POLI-REP, Mexico). The dryer consisted of a steel drying chamber containing five perforated trays (length 64 cm and width 44 cm) through which the drying air flowed horizontally (Figure 2). The beetroot slices were placed on trays in the drying chamber and dried at 60, 75, and 85 °C at a constant airflow rate of 1.2 ± 0.2 m/s. The air velocity was measured with an omnidirectional anemometer (Extech Instrument Inc., 451112, Waltham, MA, USA) at the hot air outlet of the dryer.

2.2.3 *Fixed bed drying (FBD)*

Fixed bed drying was carried out using an experimental dryer described by Ruiz-López *et al*. (2008). The fixed bed dryer design is shown in Figure 3. The drying air was supplied from the bottom of the dryer, and the experiments were conducted using unidirectional airflow by closing valves A and B;

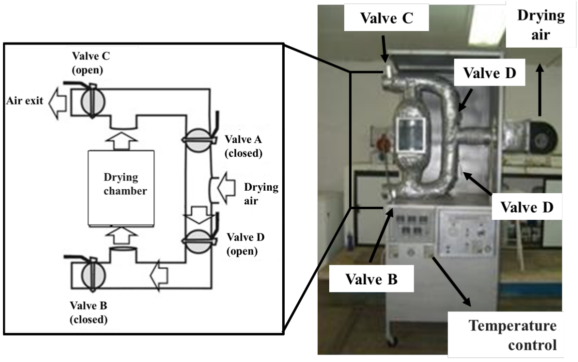

Figure 3. Fixed bed dryer (adapted from Ruiz-López *et al*., 2008).

valves C and D remained open, and the airflow was directed to the air exit. A monolayer of beetroot slices was placed on a wire mesh basket in the drying chamber and dried at 60, 75, and 85 °C at a constant airflow rate of 1.2 m/s.

Weight loss and moisture content (MC) of beetroot slices during the kinetics by RWD, TD, and FBD were recorded until a constant weight with an accuracy of 0.001 g (SERIE AB, VE-324, MEX.). The MC was determined using the 925.09 method (AOAC, 2005) based on sample (~3 g) weight loss after 24 h in a convective oven (Binder, ED 115, Germany) at 105 °C.

2.2.4 *Drying characteristics*

The moisture ratio (MR) of beetroot slices was calculated according to Eq. (1):

$$MR = \frac{M_t - M_e}{M_0 - M_e} \tag{1}$$

In which, M_t is the moisture content at t time of drying (kg water /kg dry solid); M_0 is the initial MC; M_e is the equilibrium moisture content. Moisture content was expressed on dry basis (d.b.) (Wang *et al*., 2018). Drying rate (DR) refers to moisture loss per unit time (g water/g dry solid · min) and was calculated according to Eq. (2):

$$DR = \frac{M_{t_1} - M_{t_2}}{t_2 - t_1} \tag{2}$$

In which, t_1 and t_2 are the drying times (min) at different times during drying, respectively; M_{t1} and M_{t2} are the moisture contents of beetroot slices at t_1 and t_2, respectively. M_{t1} and M_{t2} are expressed on dry basis (Zhang *et al*., 2019).

2.3 *Physical properties*

2.3.1 *Color*

Color was measured with a colorimeter (UltraScan Vis, Hunter Associates Laboratory Inc., USA) calibrated with a standard white filter (L*: 99.32, a*: -0.14 and b*: 0.04), reference to illuminant D65 and visual angle of 10°. The L* (lightness-darkness), a* (redness-greenness), and b* (yellowness-blueness) were recorded using the CIE Lab system. The total color difference (ΔE) in dried samples compared to fresh ones was calculated with Eq. (3):

$$\Delta E = \sqrt{\left(L^* - L_0^*\right)^2 + \left(a^* - a_0^*\right)^2 + \left(b^* - b_0^*\right)^2} \tag{3}$$

In which, ΔE is the total color difference between fresh and dried samples; $L_0{}^*$, $a_0{}^*$, $b_0{}^*$ and L^*, a^*, b^* are the color parameters of fresh and dried samples, respectively (Y. Zhang *et al*., 2020).

2.3.2 *Texture*

The puncture strength of beetroot slices was measured using a Texture Analyzer (TA-XT Plus, Stable Microsystems Inc., UK). Penetration tests with a 2 mm cylindrical probe (P/2N) were performed, expressing the maximum penetration force in Newtons (N). Pre-test and test speeds were set to 2 mm/s, while post-test speed was set to 10 mm/s with a contact force of 0.01 N and compression distance of 8 mm (Calderón-Chiu *et al*., 2020). Fresh beetroot slice was the control.

2.4 *Chemical properties*

2.4.1 *Obtaining of extracts*

The sample extracts were obtained using the methodology described by Jiratanan and Liu (2004). The dried beetroot slices were reduced in size using a mill (Osterizer, Oster-4655, Mexico), and five grams of sample were placed in an Erlenmeyer flask with an 80% acetone-water mixture (sample-solvent ratio of 1:10, w/v). The mixture was thoroughly mixed employing a homogenizer (Virtis, Gardiner, New York) at 6000 rpm for 3 min in darkness, and the supernatant was recovered. Finally, the solvent was evaporated (Rotary evaporator R-100, Büchi Labortechnik, DEU), and the extract was recovered and stored for further analysis. Control was the extract of fresh beetroot slices.

2.4.2 *Total phenolic content*

The total polyphenol content (TPC) was determined using the Folin-Ciocalteu method (Calderón-Chiu *et al*., 2020). Briefly, 125 μL of sample extract (distilled water for blank) were mixed with 500 μL of distilled water, followed by 125 μL of Folin-Ciocalteu reagent. The mixture was incubated in the dark for 6 min. Subsequently, 1.25 mL of 7% Na_2CO_3 solution and 1 mL of distilled water were added and incubated for 90 min in the dark at room temperature. Then, the absorbance at 760 nm was read using a spectrophotometer (Cary 60 UV-Vis, Agilent Technologies Inc., Italy). TPC was expressed as equivalent micrograms of gallic acid (GAE) per g of dry solids (μg GAE/g dry solids). A calibration curve with gallic acid at 20–500 μg/mL concentrations was used.

2.4.3 *Total flavonoids content*

The total flavonoid content (TFC) of the extract was performed according to Calderón-Chiu *et al.* (2020). At 250 μL of sample extract (distilled water for blank), 75 μL of 5% $NaNO_2$ solution, 150 μL of freshly prepared solution of 10% $AlCl_3$, and 500 μL of 1M NaOH were added. The volume was adjusted to 2.5 mL with deionized water and incubated for 5 min. The absorbance at 510 nm was read using a spectrophotometer, and the TFC was expressed as equivalent micrograms of catechin (CE) per g of dry solids (μg CE/g dry solids). A calibration curve with catechin at 20–500 μg/mL concentration was used.

2.4.4 *Antioxidant capacity*

The *in vitro* antioxidant capacity was evaluated as the $DPPH^+$ radical scavenging activity according to Alañón *et al.* (2017) with modifications. Briefly, 100 μL of extract (methanol for blank) were added to 2.9 mL 0.06mM of $DPPH^+$ methanolic solution. The samples were shaken (Vortex 2 IKA, ABATEC, Mexico) for 15 s and incubated for 30 min at room temperature. Subsequently, the absorbance was read at 515 nm in a spectrophotometer, and the $DPPH^+$ scavenging activity of the extract was calculated with Eq. (4), A_{Sample} is the absorbance of the sample, and A_{Blank} is the absorbance of the blank.

$$DPPH^+ \ radical \ scavenging \ activity \ (\%) = \left[1 - \frac{A_{Sample}}{A_{Blank}}\right] \times 100 \quad (4)$$

2.5 *Statistical analysis*

Results were presented as means ± SD (n=3). Data analysis was performed using one-way analysis of variance (ANOVA), followed by an LSD mean comparison test (P<0.05) with the STATISTICA version 10.2 software (Stat Soft Inc., Tulsa, OK).

3 Results and discussion

3.1 *Effect of drying methods on the moisture ratio and drying rate*

The MR and DR depended on the temperature and drying method (Figure 4). The MR decreased rapidly during the initial drying stage due to free water evaporation with a falling rate period characterized by slow moisture removal. The higher temperature produced a higher heat transfer rate, and according to Li *et al.* (2019) and Mandale *et al.* (2023), this promotes high moisture diffusion from the interior to the surface for evaporation, reducing drying times. This behavior was similar to those reported in RWD-dried carrot slices (Hernández-Santos *et al.*, 2016), in hot air-dried okra (Li *et al.*, 2019), in convective dried beetroot slices (Calderón-Chiu *et al.*, 2020) and purple yam powder obtained by RWD (Santos *et al.*, 2022).

The drying rate for RWD was higher (0.21-0.56 g water/g dry solid · min) as compared to TD (0.13-0.23 g water/g dry solid · min) and FBD (0.04-0.09 g water/g dry solid · min). Furthermore, only in the RWD was a constant period of high DR observed at the three temperatures (Figures 1B, 1D and 1F), especially at 85 °C at which point the MC was reduced from 7.25 to 2.7 g water/g dry solid to a constant DR of 0.56 g water/g dry solid · min. On the other hand, for RWD at 75°C, the MC was reduced from 7.25 to 3.79 g water/g dry solid to a relatively constant DR of 0.25-0.22 g water/g dry solid · min, and for RWD at 60°C, the MC was reduced from 7.6 to 5.45 g water/g dry solid to a constant DR of 0.21 g water/g dry solid · min. These periods of constant DR are due to heat and mass transfer of free water on the product surface. However, as the MC was reduced, the DR decreased due to the falling rate period dependent on internal heat and mass transfer, especially the infrared radiation produced by the Mylar film in this type of drying.

Concerning drying methods, the MC for TD at 85 °C was reduced from 7.25 to 3.67 g water/g dry solid to a DR of 0.23 g water/g dry solid · min while that for FDB, a period of constant DR was not observed, but the MC was considerably reduced from 7.13 to 4.21 g water/g dry solid at 0.09 and 0.06 g water/g dry solid · min, respectively. A lower temperature (60 °C) implied lower DR for beetroot slices dried in TD and FBD. However, FBD showed the lowest DR compared to the other drying methods at all the temperatures evaluated. For this reason, RWD required less time drying (100, 70, and 60 min) in comparison to TD (150, 120, and 100) and FBD (285, 270, and 240 min) at temperatures of 60, 75, and 80 °C, respectively. The reduction in drying time will undoubtedly impact the physical and chemical properties of the dried product. Regarding moisture content, RWD (0.09-0.02 g water/g dry solid) showed lower MC than TD (0.14-0.058 g water/g dry solid) and FBD (0.11-0.06 g water/g dry solid) at temperatures 60, 75, and 85 °C, respectively. The results showed that high drying temperatures influence the drying rate, drying time, and MC of the final product. El Broudi *et al.* (2022) mentioned that the high drying temperature positively correlates with improved effective moisture diffusivity of biological and food products.

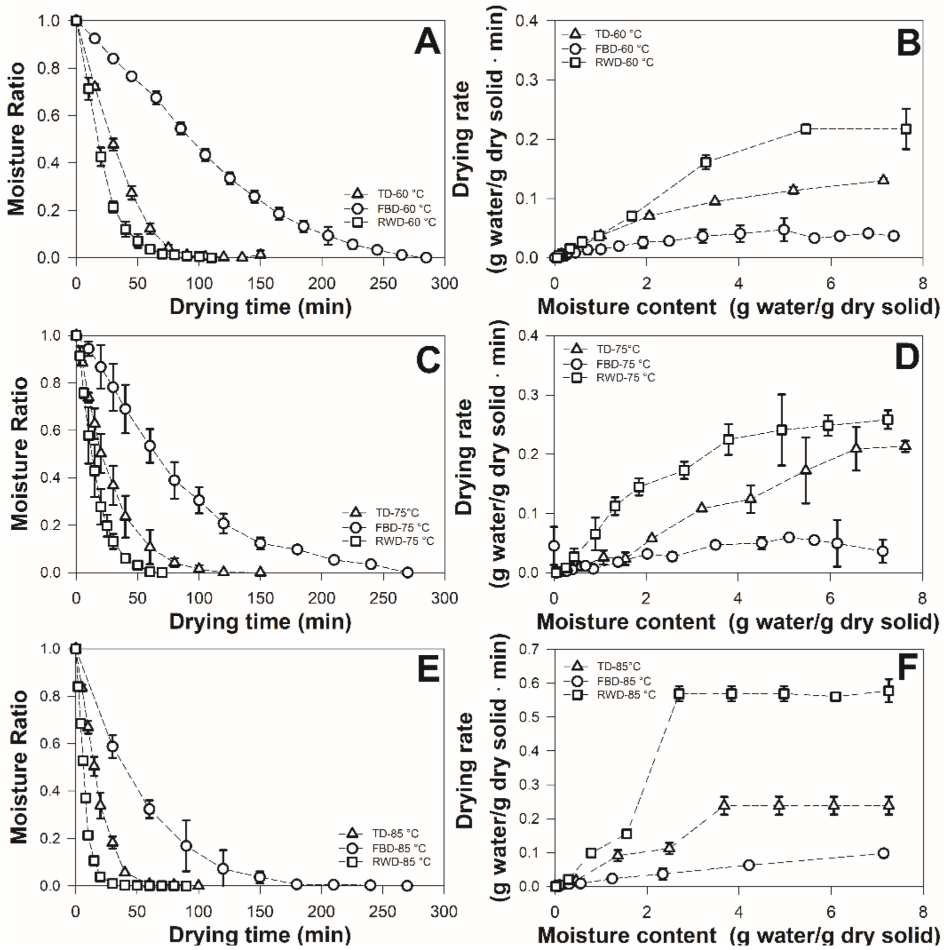

Figure 4. Curves of drying kinetics under tray drying (Δ), Fixed bed drying (o), and Refractance windows drying (□) drying processes: A, C, and E are moisture ratios, while B, D, and F are drying rates of beetroot slices at 60, 75 and 85 °C, respectively.

Similarly, García-Moreira *et al.* (2024) found that high drying temperatures produced sliced peaches with the lowest moisture and shorter drying due to the high moisture transfer.

However, RWD allowed the obtainment of beetroot slices with noticeably lower water content at all evaluated temperatures (mainly high temperature) with shorter drying times due to more extended periods of high DR observed during RWD drying than in the other methods. Preethi et al.(2020) found a similar behavior when drying a 1 mm thick layer of beetroot pulp at 40, 50, and 60 °C by conductive hydro drying (a variant of RWD) and TD. The authors reported that 90-180 min were required for drying beetroot in conductive hydro drying while TD required longer drying times (210-150 min). They attributed this to the participation of the three heat transfer modes in conductive hydro drying, which produced greater DR than in TD. RWD is a drying technique that combines modes of heat transfer: conduction, radiation, and convection (hot air circulates over film). The simultaneous heat transfer modes for water evaporation throughout the whole system lead to obtaining an energy-efficient drying method(Calín-Sánchez *et al.*, 2020; Calderón-Chiu *et al.*, 2020; Mahanti *et al.*, 2021; Kumar *et al.*, 2022). In RWD equipment, convection and conduction modes occur when thermal energy from the hot water is transferred to the film of Mylar and from film to product when the solid is partially moist-dry. However, a great part of the thermal energy of hot water is directly transferred to the product in radiation infrared mode when the solid is entirely moist (refractance window method). The transmission of infrared radiation energy through film depends on the refractive index of the water-film-food system. Lower short drying times by RWD than conventional drying methods for carrot slices (Hernández-Santos *et al.*, 2016), okra samples (Li *et al.*, 2019), apple slices (Rajoriya *et al.*, 2019), and banana slices (Dadhaneeya *et al.*, 2023) by other researchers have been reported.

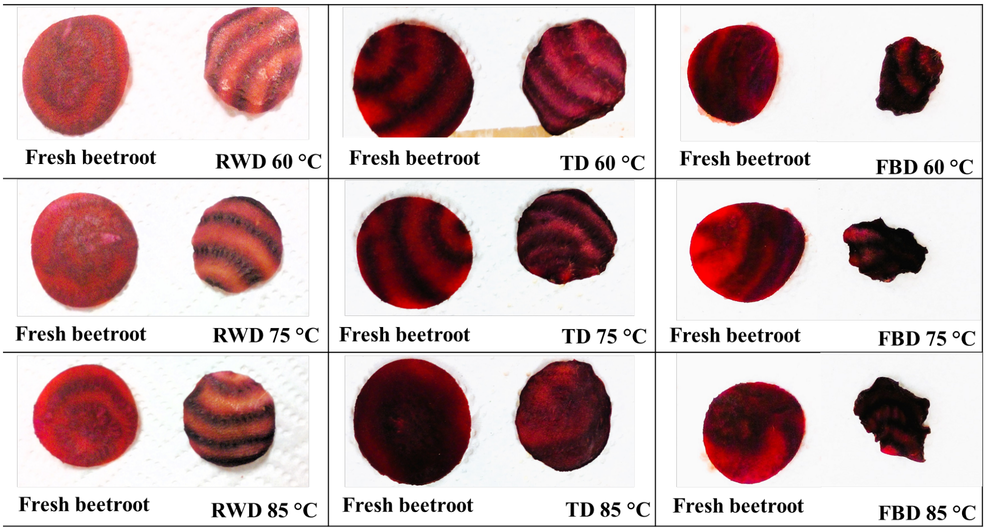

Figure 5. Comparison of beetroot slices before and after drying at different temperatures. TD: tray drying; FBD: Fixed bed drying; RWD: Refractance windows drying.

3.2 *Physical properties*

3.2.1 *Color*

Food color influences customer preferences and may be used to indicate chemical and quality changes caused by thermal processing. Color parameters were affected by temperature and drying method. Figure 5 shows the beetroot slices before and after drying by different processes. The L^* increased as a function of drying temperature for RWD and FBD, while in TD significantly decreased (Table 1, $P<0.05$). Notwithstanding, the luminosity of most treatments remained relatively similar or higher than the control, especially at 85 °C ($P<0.05$).

The parameter a^* was reduced in all drying methods concerning the control ($P<0.05$). Regarding this, betalains (red pigment) are water-soluble pigments, and during the constant drying rate period, surface moisture evaporates, lowering the surface color of the sample (Gokhale & Lele, 2011). However, the increase in temperature drying did not significantly affect the redness of samples, except for FBD due to a longer drying time. Indeed, the samples dried in RWD showed more similarity to the control than TD and FBD, and the high drying temperature in RWD intensified a^* parameter due to moisture and water-soluble pigments diffusing to the surface, leading to a significant increase in redness during the falling rate period, which was shorter in RWD than other drying methods at the three temperatures evaluated (Gokhale & Lele, 2011). Preethi *et al.* (2020) also reported that a^* value was better in beetroot slices dried in conductive hydro drying (a variant of RWD), indicating better retention of pigments, whereas in TD-dried samples, a^* value was lower. The b^* values were significantly lower at temperatures of 60 and 75 °C in all types of drying used with respect to the temperature of 85 °C, except in TD at 75 °C with the highest value ($P<0.05$). However, all b^* results did not show a significant difference ($P>0.05$) with the control at 85 °C in all drying methods. This behavior is due to the formation of yellow products (neobetacyanins, betalamic acid, and newly formed betaxanthins) derived from the exposition of betacyanins from beetroot at high temperatures (Sadowska-Bartosz & Bartosz, 2021). The formation of yellow compounds at high temperatures could explain the higher L^* for the samples than the control at 85 °C.

Some variations in color parameters were observed during its measurement and attributed to the heterogeneity of the beetroot slice surfaces caused by the cut. The drying methods significantly affected the ΔE, especially at low drying temperatures (60 and 75 °C). Low drying temperature implies that the falling rate period requires longer drying; therefore, the samples were exposed to heat for longer. This prolonged time can cause the degradation of some beetroot pigments, leading to more significant total color differences. Nonetheless, samples dried RWD showed lower ΔE than those dried by TD and FBD, indicating that RWD showed better color maintenance even at high temperatures. Then, lower ΔE could be due to the formation of undesirable pigments due to drying. This is because the parameter a^*, associated with the presence of betalains, was less affected by RWD than other drying methods.

Mandale *et al.* (2023) found a minimum color difference (5.53–6.29) of beet slices of 0.5, 1, and 1.5 mm dried at 75, 80, and 85°C by solar-assisted continuous refractance window drier, which were similar to those reported in this study even though both dryers have different configurations. Similarly, the authors stated that at 85 °C, the color difference value decreased, and the ΔE showed the closeness

Table 1. Color parameters of dried beetroot slices by different drying methods and temperatures.

Parameter	Drying method	Temperature (°C) 60	75	85
L^*	RWD	26.73 ± 0.72^{a,A}	27.36 ± 1.13^{a,A}	29.38 ± 0.49^{b,B}
	TD	28.23 ± 0.34^{ab,A}	27.92 ± 2.54^{a,A}	25.13 ± 1.22^{a,A}
	FBD	29.11 ± 1.35^{b,A}	22.85 ± 3.70^{b,B}	30.72 ± 0.24^{b,A}
	C	26.78 ± 1.24^{a}	26.78 ± 1.24^{ab}	26.78 ± 1.24^{a}
a^*	RWD	15.52 ± 1.83^{b,A}	14.09 ± 4.17^{ab,A}	17.49 ± 0.71^{b,A}
	TD	8.66 ± 0.72^{c,A}	12.90 ± 3.99^{b,A}	9.83 ± 0.75^{c,A}
	FBD	8.28 ± 0.44^{c,A}	13.89 ± 3.35^{ab,B}	12.33 ± 0.72^{d,B}
	C	19.86 ± 1.81^{a}	19.86 ± 1.81^{a}	19.86 ± 1.81^{a}
b^*	RWD	4.68 ± 0.5^{b,A}	5.13 ± 0.28^{b,AB}	5.97 ± 0.83^{a,B}
	TD	6.25 ± 0.72^{c,A}	10.23 ± 0.58^{c,B}	6.01 ± 0.77^{a,A}
	FBD	5.94 ± 0.17^{c,A}	2.51 ± 0.81^{d,B}	6.98 ± 1.74^{a,A}
	C	7.23 ± 0.36^{a,}	7.23 ± 0.36^{a}	7.23 ± 0.36^{a}
ΔE	RWD	5.19 ± 2^{b,A}	6.53 ± 3.33^{b,A}	4.09 ± 0.36^{b,A}
	TD	11.43 ± 2.28^{c,A}	9.07 ± 2.73^{b,A}	10.28 ± 1.71^{c,A}
	FBD	11.96 ± 1.15^{c,A}	9.64 ± 2.83^{b,A}	8.75 ± 0.79^{c,A}
	C	0 ± 0^{a}	0 ± 0^{a}	0 ± 0^{a}

RWD, Refractance windows drying; TD, Tray drying; FBD, Fixed bed dryer; C, Control: Fresh beetroot. Results represent mean ± SD. $^{a-d}$*Different lowercase letters in the same column indicate significant differences among drying methods at the same temperature and the control (P<0.05).* $^{A-B}$*Different capital letters in the same row indicate significant differences with increasing temperature (P<0.05).*

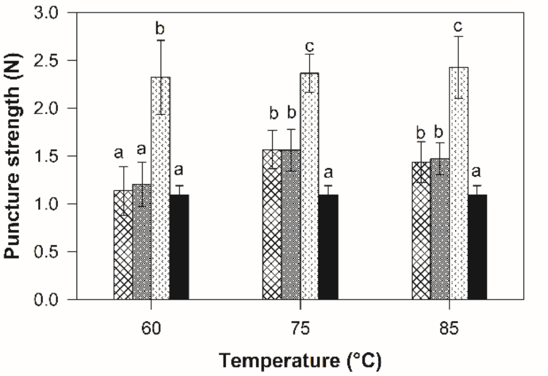

Figure 6. Puncture strength of beetroot slices dried at 60, 75, and 85 ° C by RWD (▨), TD (▩), FBD (⬚), and control (■). $^{a-c}$Different lowercase letters indicate significant differences among drying methods at the same temperature and the control (P<0.05). Control: Fresh beetroot.

of color to fresh beetroot, a trend also observed in this research (Table 1). Rajoriya *et al.* (2019) also found that an increase in drying temperature from 60 to 90 °C resulted in lower values of ΔE due to the shorter drying time required in apple slices for RWD. Improved results of ΔE for RWD compared with the conventional drying were also shown for mango powder (Caparino *et al.*, 2012) and apple slices (Franco *et al.*, 2019).

3.2.2 Texture

Textural properties are a crucial aspect of dried samples. The maximum hardness was obtained in FBD samples concerning RWD, TD, and control, even at the lowest drying temperature (Figure 6). Temperatures >60 °C significantly increased puncture strength for the three drying methods, but in FBD, the hardness of the samples was drastically increased. The above indicated that the mechanism of moisture transfer in RWD, TD and FBD differed, leading to different appearances and texture characteristics (Jia *et al.*, 2019). The poor texture of FBD beetroot slices was caused by slow water evaporation and migration of solutes to the surface during drying. The solutes were concentrated and precipitated as the surface moisture evaporated, leaving hard and dry skin (Jia *et al.*, 2019). The high hardness of the beetroot slices processed by FBD indicated tissue collapse and shrinkage were revealed in their rigid appearance (Rajoriya *et al.*, 2019). Increased hardness and energy consumption due to extended drying times in FBD indicate that this

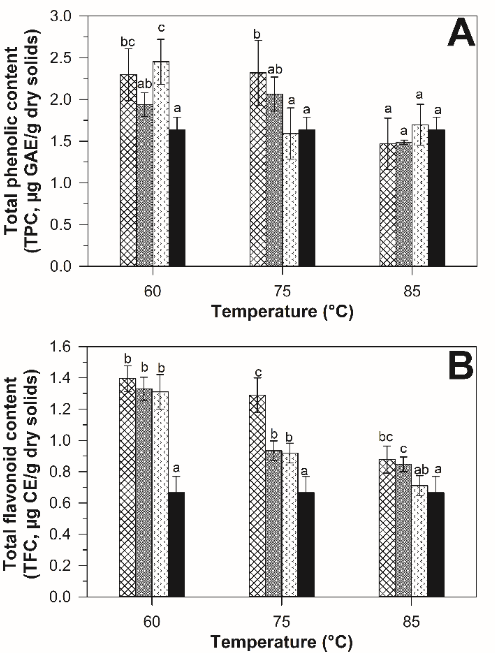

Figure 7. Total polyphenol content (A) and total flavonoid content (B) of beetroot slices dried at 60, 75, and 85 ° C by RWD (▨), TD (▩), FBD (⬚) and control (■). $^{a-c}$Different lowercase letters indicate significant differences among drying methods at the same temperature and the control (P<0.05). Control: Fresh beetroot.

drying method is unsuitable for producing snack foods (Gong *et al*., 2019).

Although RWD and TD showed very similar puncture strength, RWD was better for obtaining dried beetroot slices because it reduced the drying time, and the hardness was similar to the control. Rajoriya *et al*. (2019) stated that RW-dried apple slices showed a porous structure similar to fresh tissue but with slight shrinkage compared to conventional methods. The porous with well-connected cell structures would explain the higher mass transfer rate and shorter drying time observed during RWD (Figures 1B, 1D and 1F). The above suggests that in RWD, the sample dried quite effectively, maintaining the structure of the fresh material to a greater extent. The structure maintenance could indicate that the compounds bound to the plant matrix have been less affected by heat exposure and retain greater biological activity. Franco *et al*. (2019) also reported lower hardness in RWD-dried apple slices than in conventional drying. Mandale *et al*. (2023) reported firmness values in 1-mm thick beetroot slices dried by a solar-assisted continuous refractance window dryer at 75 °C (2.39-2.66 N) and 85 °C (2.25-2.38 N) higher than those recorded in this study. The differences observed could be due to the different configurations of the RWD equipment used for drying.

3.3 Chemical properties

3.3.1 Total polyphenol and flavonoid content

Retaining greater phenols, flavonoid, and glycoside content is essential when evaluating a drying method (ElGamal *et al*., 2023). In most treatments, the TPC and TFC of the control (fresh beetroot) were lower than those of dried beetroot slices (Figure 7). Sometimes, dried plants contain higher polyphenolics and flavonoid compounds than fresh material because drying can break down the cellular constituents and release compounds from the food matrix (Pinela *et al*., 2012; Roshanak *et al*., 2016). Also, active enzymes in the fresh sample lead to the degradation of phenols and flavonoid compounds (Pinela *et al*., 2012). Peroxidases and tyrosinases are responsible for the oxidation of betaxanthin in fresh beetroot (Sadowska-Bartosz & Bartosz, 2021). However, due to the low water activity, destructive enzymes inactivated in the dried samples, and the extract had high levels of phenolic and flavonoid compounds (Hossain *et al*., 2010; Pinela *et al*., 2012).

In dry samples, RWD showed the highest retention of phenolic and flavonoid compounds at low temperatures (60 and 75 °C) followed by TD and FBD (Figure 7). Nevertheless, TPC was reduced at 85 °C, but there were no significant differences with the control (Figure 7A).

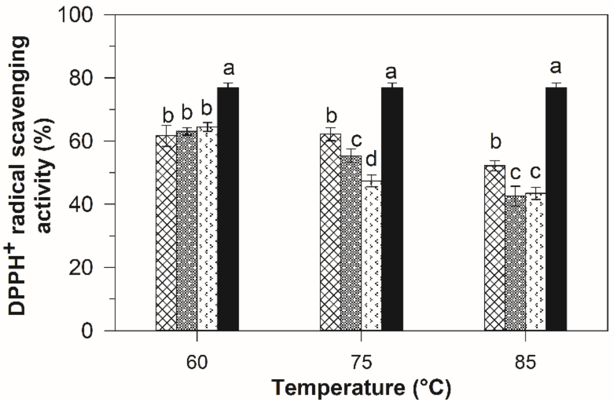

Figure 8. DPPH$^+$ radical scavenging activity of beetroot slices dried at 60, 75, and 85 °C by RWD (▩), TD (▦), FBD (⬚), and control (■).$^{a\text{-}c}$Different lowercase letters indicate significant differences among drying methods at the same temperature with the control (P<0.05). Control: Fresh beetroot.

The reduction of TPC of dried beetroot slices at 85 °C was 36.6% for RWD, 27.9% for TD, and 30.8% for FBD, as compared to TPC at 60 °C. These results show that slices dried at 85 °C for FBD show greater retention of polyphenols. This behavior is because of the decomposition of betaxanthin to phenolic compounds for the prolonged exposure of the sample to the high temperature (Sadowska-Bartosz & Bartosz, 2021), which were responsible for increasing the TPC and the high values of *L** for FBD mentioned above (Table 1).

On the other hand, the TFC at 85 °C for RWD and TD were significantly higher than the control (Figure 7B), while the FBD was similar (P>0.05). The loss of flavonoids in beetroot slices due to RWD, TD and FBD at 85 °C was 37.0, 36.3 and 45.7%, respectively, concerning TFC at 60 °C. RWD and TD treatments affect flavonoid compounds to a lesser extent at high temperatures. Contrary to TPC, approximately 45.7% of the CFT were affected during drying by FBD at 85 °C (Figure 7B). The continuous drying time, low drying efficiency, and large oxygen exposure area of samples in FBD would significantly aggravate the loss of heat-sensitive compounds (Hu *et al.*, 2023). The main reason for this difference is the ideal drying temperature of these compounds, which is related to the molecular structure. Indeed, in order to ensure high content of phenols and flavonoids in dried products, the samples are usually dried at a temperature of 55–60 °C and 60–70 °C, respectively (ElGamal *et al.*, 2023), which is consistent with the results in this study for the drying methods evaluated.

It is worth highlighting that RWD showed the highest phenolic and flavonoid compounds at 60 and 75 °C. Although a similar loss of flavonoid compounds at high temperatures for TD and RWD was recorded, RWD required less drying time than TD. The above is an excellent advantage for sample processing because it would imply lower energy consumption and better quality in the final product, as reported by Zotarelli *et al.* (2015), Ochoa-Martínez *et al.* (2012) and Preethi *et al.* (2020) in mango pulp, mango slices and beetroot slices, respectively. The adverse effect of FBD on flavonoid compounds was due to prolonged exposure to heat, which affects the integrity of the cells, resulting in their extensive degradation (Preethi *et al.*, 2020).

3.3.2 Antioxidant capacity

The phenols and flavonoids are heat-dependent biomolecules; therefore, parameters and methods of drying influence the antioxidant capacity of these compounds. Similar to TPC and TFC, the antioxidant capacity of dried beetroot was higher at low drying temperatures (60 °C) for the three drying methods evaluated (Figure 8). As the temperature increased, antioxidant capacity was significantly reduced (P<0.05), with more significant adverse effects for samples processed on TD and FBD. Regarding the control, the loss of antioxidant capacity for RWD, TD and FBD ranged from 19.7-32.07%, 17-44.5% and 16.1-43.49%, respectively.

Although FBD showed a greater retention of polyphenols at 85 °C than other drying methods, the antioxidant capacity of these samples was significantly reduced. According to the literature, prolonged exposure of beetroot to high temperatures forms betaxanthin derivatives. Betaxanthins and their derivatives are weaker antioxidants, contributing to the antioxidant capacity of red beetroot to a lesser extent (Sadowska-Bartosz & Bartosz, 2021), which explains the low antioxidant capacity of these samples despite maintaining a higher phenolic content than RWD and TD at 85 °C. Hence, it was inferred that the antioxidant capacity was related to the flavonoid content of the samples rather than polyphenols. Moreover, some of the oxidation products of phenols by heat are flavonoid compounds (ElGamal *et al*., 2023), which could contribute to this statement. Nevertheless, further studies are required to identify compounds by HPLC compounds in the beetroot slices after drying.

Even so, RWD showed better retention of antioxidant capacity at all temperatures evaluated. In RWD, water removal occurs quickly, so there is less exposure time to heat. Besides, samples dried by RWD showed lower ΔE and better firmness than other drying methods, indicating maintenance of the structure. Hence, the phenolic and flavonoid compounds bound with the cellular matrix show lower degradation (Calderón-Chiu *et al*., 2020) and better antioxidant capacity. Rajoriya *et al*. (2019) indicated that RWD is an efficient technique for retaining more ascorbic acid and their capacity antioxidant in apple slices than conventional methods.

Conclusions

The effect of refractance window drying, tray drying, and fixed bed drying of 1 mm thick beetroot slices at 60, 75, and 85 °C was evaluated. The temperature and drying method influenced the reduction of moisture ratio and rate drying. Notwithstanding, refractance window drying required less time to reduce the moisture ratio due to a higher drying rate than other drying methods at temperatures evaluated. Beetroot slices dried by refractance windows showed relatively minimum differences in color and puncture strength than the control, indicating that the cellular structure is maintained and less degradation of the pigments occurred during drying. For this reason, the greater retention of polyphenols, flavonoids, and antioxidant capacity by beetroot slices processed on refractance windows compared to other drying methods was observed. So, refractance window drying could be considered an effective method for quickly obtaining beetroot snacks of reasonable quality. Beetroot powder could also be obtained from dried slices and used as a colorant in the food industry for liquid foods. Nonetheless, future research must evaluate the impact of drying on powders' morphological, functional, thermal, and rheological properties.

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Nomenclature

AC:	Antioxidant capacity
DR:	Drying rate
FBD:	Fixed bed drying
MC:	Moisture content
MR:	Moisture ratio
RWD:	Refractance window drying
TD:	Tray drying
TFC:	Total flavonoid content
TPC:	Total polyphenol content.

References

Alañón, M. E., Alarcón, M., Marchante, L., Díaz-Maroto, M. C., & Pérez-Coello, M. S. (2017). Extraction of natural flavorings with antioxidant capacity from cooperage by-products by green extraction procedure with subcritical fluids. *Industrial Crops and Products*, *103*, 222–232. `https://doi.org/10.1016/j.indcrop.2017.03.050`

AOAC. (2005). Official Methods of Analysis of AOAC International. In *Association of Official Analysis Chemists International*.

Azizi, D., Jafari, S. M., Mirzaei, H., & Dehnad, D. (2017). The influence of refractance window drying on qualitative properties of kiwifruit slices. *International Journal of Food Engineering*, *13*(2). `https://doi.org/10.1515/ijfe-2016-0201`

Calderón-Chiu, C., Martínez-Sánchez, C. E., Rodríguez-Miranda, J., Juárez-Barrientos, J. M., Carmona-García, R., & Herman-Lara, E. (2020). Evaluation of the combined effect of osmotic and Refractance Window drying on the drying kinetics, physical, and phytochemical properties of beet. *Drying Technology*, *38*(12), 1663–1675. `https://doi.org/10.1080/07373937.2019.1655439`

Calín-Sánchez, Á., Lipan, L., Cano-Lamadrid, M., Kharaghani, A., Masztalerz, K., Carbonell-Barrachina, Á. A., & Figiel, A. (2020). Comparison of traditional and novel drying techniques and its effect on quality of fruits, vegetables and aromatic herbs. *Foods*, *9*(9), 1261. `https://doi.org/10.3390/foods9091261`

Caparino, O. A., Tang, J., Nindo, C. I., Sablani, S. S., Powers, J. R., & Fellman, J. K. (2012). Effect of drying methods on the physical properties and microstructures of mango (Philippine 'Carabao' var.) powder. *Journal of Food*

Engineering, *111*(1), 135–148. https://doi.org/10.1016/j.jfoodeng.2012.01.010

Celli, G. B., Khattab, R., Ghanem, A., & Brooks, M. S.-L. (2016). Refractance Window^{TM} drying of haskap berry – Preliminary results on anthocyanin retention and physicochemical properties. *Food Chemistry*, *194*, 218–221. https://doi.org/10.1016/j.foodchem.2015.08.012

Chhikara, N., Kushwaha, K., Sharma, P., Gat, Y., & Panghal, A. (2019). Bioactive compounds of beetroot and utilization in food processing industry: A critical review. In *Food Chemistry*. https://doi.org/10.1016/j.foodchem.2018.08.022

Dadhaneeya, H., Nayak, P. K., Saikia, D., Kondareddy, R., Ray, S., & Kesavan, R. krishnan. (2023). The impact of refractance window drying on the physicochemical properties and bioactive compounds of malbhog banana slice and pulp. *Applied Food Research*, *3*(1), 100279. https://doi.org/10.1016/j.afres.2023.100279

El Broudi, S., Zehhar, N., Abdenouri, N., Boussaid, A., Hafidi, A., & Benkhalti, F. (2022). Investigation of drying kinetics and drying conditions on biochemical, sensory, and microstructural parameters of "Sefri" pomegranate arils (*Punica granatum* L. a Moroccan variety). *Revista Mexicana de Ingeniería Química*, *21*(3), 1–25. https://doi.org/10.24275/rmiq/Alim2813

ElGamal, R., Song, C., Rayan, A. M., Liu, C., Al-Rejaie, S., & ElMasry, G. (2023). Thermal degradation of bioactive compounds during drying process of horticultural and agronomic products: A comprehensive overview. *Agronomy*, *13*(6), 1580. https://doi.org/10.3390/agronomy13061580

Figiel, A. (2010). Drying kinetics and quality of beetroots dehydrated by combination of convective and vacuum-microwave methods. *Journal of Food Engineering*, *98*(4), 461–470. https://doi.org/10.1016/j.jfoodeng.2010.01.029

Franco, S., Jaques, A., Pinto, M., Fardella, M., Valencia, P., Núñez, H., Ramírez, C., & Simpson, R. (2019). Dehydration of salmon (*Atlantic salmon*), beef, and apple (*Granny Smith*) using Refractance window^{TM}: Effect on diffusion behavior, texture, and color changes. *Innovative Food Science & Emerging Technologies*, *52*, 8–16. https://doi.org/10.1016/j.ifset.2018.12.001

García-Moreira, D. P., Moreno, I., Irigoyen-Campuzano, J. R., Martín-Domínguez, I., García-Valladares, O., & López-Vidaña, E. C. (2024). Effect of convective drying on color, water activity, and browning index of peach slices. *Revista Mexicana de Ingeniería Química*, *23*(1), 1–18. https://doi.org/10.24275/rmiq/Alim24188

Gokhale, S. V., & Lele, S. S. (2011). Dehydration of red beet root (*Beta vulgaris*) by hot air drying: Process optimization and mathematical modeling. *Food Science and Biotechnology*, *20*(4), 955–964. https://doi.org/10.1007/s10068-011-0132-4

Gong, X., Huang, X., Yang, T., Wen, J., Zhou, W., & Li, J. (2019). Effect of drying methods on physicochemical properties and antioxidant activities of okra pods. *Journal of Food Processing and Preservation*, *43*(12). https://doi.org/10.1111/jfpp.14277

Hamid, M. G., & Mohamed, N. A. A. A. (2018). Effect of different drying methods on quality attributes of beetroot (*Beta vulgaris*) slices. *World Journal of Science, Technology and Sustainable Development*, *15*(3), 287–298. https://doi.org/10.1108/WJSTSD-11-2017-0043

Hernández-Santos, B., Martínez-Sánchez, C. E., Torruco-Uco, J. G., Rodríguez-Miranda, J., Ruiz-López, I. I., Vajando-Anaya, E. S., Carmona-García, R., & Herman-Lara, E. (2016). Evaluation of physical and chemical properties of carrots dried by Refractance Window drying. *Drying Technology*. https://doi.org/10.1080/07373937.2015.1118705

Hossain, M. B., Barry-Ryan, C., Martin-Diana, A. B., & Brunton, N. P. (2010). Effect of drying method on the antioxidant capacity of six *Lamiaceae* herbs. *Food Chemistry*, *123*(1), 85–91. https://doi.org/10.1016/j.foodchem.2010.04.003

Hu, D., Liu, X., Qin, Y., Yan, J., Li, R., & Yang, Q. (2023). The impact of different drying methods on the physical properties, bioactive components, antioxidant capacity, volatile components and industrial application of coffee peel. *Food Chemistry: X*, *19*, 100807. https://doi.org/10.1016/j.fochx.2023.100807

Janiszewska, E. (2014). Microencapsulated beetroot juice as a potential source of betalain. *Powder Technology*, *264*, 190–196. https://doi.org/10.1016/j.powtec.2014.05.032

Jia, Y., Khalifa, I., Hu, L., Zhu, W., Li, J., Li, K., & Li, C. (2019). Influence of three different drying techniques on persimmon chips' characteristics: A comparison study among hot-air, combined hot-air-microwave, and vacuum-freeze drying techniques. *Food and Bioproducts Processing*, *118*, 67–76. `https://doi.org/10.1016/j.fbp.2019.08.018`

Jiratanan, T., & Liu, R. H. (2004). Antioxidant activity of processed table beets (*Beta vulgaris var*, conditiva) and green beans (*Phaseolus vulgaris* L.). *Journal of Agricultural and Food Chemistry*, *52*(9), 2659–2670. `https://doi.org/10.1021/jf034861d`

Karam, M. C., Petit, J., Zimmer, D., Baudelaire Djantou, E., & Scher, J. (2016). Effects of drying and grinding in production of fruit and vegetable powders: A review. In *Journal of Food Engineering*. `https://doi.org/10.1016/j.jfoodeng.2016.05.001`

Kumar, M., Madhumita, M., Prabhakar, P. K., & Basu, S. (2022). Refractance window drying of food and biological materials: Status on mechanisms, diffusion modelling and hybrid drying approach. *Critical Reviews in Food Science and Nutrition*, 1–24. `https://doi.org/10.1080/10408398.2022.2132210`

Li, H., Xie, L., Ma, Y., Zhang, M., Zhao, Y., & Zhao, X. (2019). Effects of drying methods on drying characteristics, physicochemical properties and antioxidant capacity of okra. *LWT*, *101*, 630–638. `https://doi.org/10.1016/j.lwt.2018.11.076`

Mahanti, N. K., Chakraborty, S. K., Sudhakar, A., Verma, D. K., Shankar, S., Thakur, M., Singh, S., Tripathy, S., Gupta, A. K., & Srivastav, P. P. (2021). Refractance WindowTM-Drying vs. other drying methods and effect of different process parameters on quality of foods: A comprehensive review of trends and technological developments. *Future Foods*, *3*, 100024. `https://doi.org/10.1016/j.fufo.2021.100024`

Mandale, N. M., Attkan, A. K., Kumar, S., & Kumar, N. (2023). Drying kinetics and quality assessment of refractance window dried beetroot. *Journal of Food Process Engineering*, *46*(7). https://doi.org/10.1111/jfpe.14332Menon, A., Stojceska, V., & Tassou, S. A. (2020). A systematic review on the recent advances of the energy efficiency improvements in non-conventional food drying technologies. *Trends in Food Science & Technology*, *100*, 67–76. `https://doi.org/10.1016/j.tifs.2020.03.014`

Nguyen, V. T., Van Vuong, Q., Bowyer, M. C., Van Altena, I. A., & Scarlett, C. J. (2015). Effects of different drying methods on bioactive compound yield and antioxidant capacity of *Phyllanthus amarus*. *Drying Technology*, *33*(8), 1006–1017. `https://doi.org/10.1080/07373937.2015.1013197`

Ochoa-Martínez, C. I., Quintero, P. T., Ayala, A. A., & Ortiz, M. J. (2012). Drying characteristics of mango slices using the Refractance Window^{TM} technique. *Journal of Food Engineering*, *109*(1), 69–75. `https://doi.org/10.1016/j.jfoodeng.2011.09.032`

Ortiz-Jerez, M. J., Gulati, T., Datta, A. K., & Ochoa-Martínez, C. I. (2015). Quantitative understanding of Refractance Window^{TM} drying. *Food and Bioproducts Processing*. `https://doi.org/10.1016/j.fbp.2015.05.010`

Pinela, J., Barros, L., Dueñas, M., Carvalho, A. M., Santos-Buelga, C., & Ferreira, I. C. F. R. (2012). Antioxidant activity, ascorbic acid, phenolic compounds and sugars of wild and commercial *Tuberaria lignosa* samples: Effects of drying and oral preparation methods. *Food Chemistry*, *135*(3), 1028–1035. `https://doi.org/10.1016/j.foodchem.2012.05.038`

Preethi, R., Deotale, S. M., Moses, J. A., & Anandharamakrishnan, C. (2020). Conductive hydro drying of beetroot (*Beta vulgaris* L.) pulp: Insights for natural food colorant applications. *Journal of Food Process Engineering*, *43*(12). `https://doi.org/10.1111/jfpe.13557`

Raghavi, L. M., Moses, J. A., & Anandharamakrishnan, C. (2018). Refractance window drying of foods: A review. *Journal of Food Engineering*. `https://doi.org/10.1016/j.jfoodeng.2017.11.032`

Rajoriya, D., Shewale, S. R., & Hebbar, H. U. (2019). Refractance window drying of apple slices: Mass transfer phenomena and quality parameters. *Food and Bioprocess Technology*, *12*(10), 1646–1658. `https://doi.org/10.1007/s11947-019-02334-7`

Rehman, S., Mufti, I. U., Ain, Q. U., & Ijaz, B. (2024). *Bioactive Compounds and Biological Activities of Red Beetroot (Beta vulgaris L.)* (pp. 1–31). `https://doi.org/10.1007/978-3-031-29006-0_42-1`

Rodríguez, J., Mulet, A., & Bon, J. (2014). Influence of high-intensity ultrasound on drying kinetics in fixed beds of high porosity. *Journal of Food Engineering*, *127*, 93–102. `https://doi.org/10.1016/j.jfoodeng.2013.12.002`

Roshanak, S., Rahimmalek, M., & Goli, S. A. H. (2016). Evaluation of seven different drying treatments in respect to total flavonoid, phenolic, vitamin C content, chlorophyll, antioxidant activity and color of green tea (*Camellia sinensis* or *C. assamica*) leaves. *Journal of Food Science and Technology*, *53*(1), 721–729. `https://doi.org/10.1007/s13197-015-2030-x`

Ruiz-López, I. I., Martínez-Sánchez, C. E., Cobos-Vivaldo, R., & Herman-Lara, E. (2008). Mathematical modeling and simulation of batch drying of foods in fixed beds with airflow reversal. *Journal of Food Engineering*, *89*(3), 310–318. `https://doi.org/10.1016/j.jfoodeng.2008.05.009`

Sadowska-Bartosz, I., & Bartosz, G. (2021). Biological properties and applications of betalains. *Molecules*, *26*(9), 2520. `https://doi.org/10.3390/molecules26092520`

Santos, S. de J. L., Canto, H. K. F., da Silva, L. H. M., & Rodrigues, A. M. da C. (2022). Characterization and properties of purple yam (*Dioscorea trifida*) powder obtained by refractance window drying. *Drying Technology*, *40*(6), 1103–1113. `https://doi.org/10.1080/07373937.2020.1847140`

Seremet, L., Nistor, O.-V., Andronoiu, D. G., Mocanu, G. D., Barbu, V. V., Maidan, A., Rudi, L., & Botez, E. (2020). Development of several hybrid drying methods used to obtain red beetroot powder. *Food Chemistry*, *310*, 125637. `https://doi.org/10.1016/j.foodchem.2019.125637`

Tontul, I., Kasimoglu, Z., Asik, S., Atbakan, T., & Topuz, A. (2018). Functional properties of chickpea protein isolates dried by refractance window drying. *International Journal of Biological Macromolecules*. `https://doi.org/10.1016/j.ijbiomac.2017.11.135`

Wang, J., Law, C.-L., Nema, P. K., Zhao, J.-H., Liu, Z.-L., Deng, L.-Z., Gao, Z.-J., & Xiao, H.-W. (2018). Pulsed vacuum drying enhances drying kinetics and quality of lemon slices. *Journal of Food Engineering*, *224*, 129–138. `https://doi.org/10.1016/j.jfoodeng.2018.01.002`

Zhang, X.-L., Zhong, C.-S., Mujumdar, A. S., Yang, X.-H., Deng, L.-Z., Wang, J., & Xiao, H.-W. (2019). Cold plasma pretreatment enhances drying kinetics and quality attributes of chili pepper (*Capsicum annuum* L.). *Journal of Food Engineering*, *241*, 51–57. `https://doi.org/10.1016/j.jfoodeng.2018.08.002`

Zhang, Y., Zhu, G., Li, X., Zhao, Y., Lei, D., Ding, G., Ambrose, K., & Liu, Y. (2020). Combined medium- and short-wave infrared and hot air impingement drying of sponge gourd (*Luffa cylindrical*) slices. *Journal of Food Engineering*, *284*, 110043. `https://doi.org/10.1016/j.jfoodeng.2020.110043`

Zotarelli, M. F., Carciofi, B. A. M., & Laurindo, J. B. (2015). Effect of process variables on the drying rate of mango pulp by Refractance Window. *Food Research International*, *69*, 410–417. `https://doi.org/10.1016/j.foodres.2015.01.013`