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Simultaneous application of refractance window and microwave drying: A novel hybrid technique for fruit dehydration to reducing drying time and improve bioactive compound retention

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ABSTRACT

Refractance window (RW™) and microwave (MW) are two drying technologies characterized by short drying time and high-quality retention. This study investigated the effect of drying apple slices (as a model food), using a novel system: RW™ assisted with microwaves (RW-MW). Drying time, moisture content, water activity (a_w), total polyphenol content, antioxidant capacity and color change were determined. The study also aimed to model the drying process through Fick's second law and anomalous diffusion model based on fractional calculus. Drying was performed with RW™, and RW-MW using two power densities: 815 W/kg and 1165 W/kg. RW™ and RW-MW were set at 98 °C. In both cases, the drying process was performed until the apple slices reached a moisture content lower than 0.097 g of water/ g sample (wet basis) and a_w below 0.4. Bioactive compound retention was assessed by measuring total polyphenol content (TPC), and antioxidant capacity (AC). The results showed that applying microwave power densities of 815 W/kg and 1165 W/kg simultaneously during RW™ drying allowed reduced drying time by up to 66 % compared to RW™ alone, maintaining the retention of TPC and AC. This study demonstrated that RW-MW is a technology that allows for reduced drying times while maintaining high bioactive compound retention compared to RW™ drying.

1. Introduction

The consumption of fresh fruits is desirable to obtain the most significant health benefits. However, the short shelf life of this raw product has encouraged research on the processing of the fruit into a dry form to extend its availability throughout the year, thereby promoting the consumption of many essential nutrients with bioactive functions (Akther et al., 2023; Nowacka et al., 2023; Retamal et al., 2025)

Drying is arguably the most important unit operation in industrial processes because of its impact on food preservation and energy consumption during its application. Moreover, it presents challenges in obtaining final products with optimal sensory and nutritional qualities (Mahanti et al., 2021; Morais et al., 2018). Food drying is a complex process that involves mass and heat transfer phenomena and structural changes coupled with the physical and chemical transformations of various compounds present in the food matrix (Asrate and Ali, 2025; Morais et al., 2018). Therefore, finding an appropriate equilibrium between drying temperature and time is crucial to enhance quality retention in the process design. Therefore, higher temperatures are expected to reduce drying time and nutrient exposure to high temperatures. Shorter drying times allow better preservation of bioactive compounds than prolonger drying processes (Franco et al., 2019; Morais et al., 2018; Núñez et al., 2023). This observation is consistent with technologies such as drum driers (Galaz et al., 2017) and refractance windows (RW™) (Baeghbali et al., 2016), known for their short drying times and improved retention of bioactive compounds.

A critical aspect to maximize bioactive compound retention is ensuring that drying kinetics are sufficiently faster than the degradation kinetics of the bioactive compounds (Morais et al., 2018). Therefore, RW™ technology emerges as a promising alternative, especially when coupled with other technologies such as microwaves. This combination could produce high-nutrition dried fruits with a high bioactive compound content, positively impacting people's health.

Refractance window, also called hydro-conductive drying, (Baeghbali et al., 2016) has been studied in recent years, mainly in pulps and fruits, as an interesting alternative that preserves food properties

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(Mahanti et al., 2021). This drying technique utilizes the principle of refraction of the water surface to create a window for the passage of infrared energy (Rurush et al., 2022; Sabarez, 2019). The RW™ technique uses hot water between 55 °C to 100 °C as an energy source and an infrared transparent plastic film (Mylar) as the drying surface. When there is no product to be dehydrated, the energy transferred by the radiation mechanism is reduced; however, if there is a fresh product (with a high moisture content), the amount of energy transferred by the radiation mechanism increases, allowing the food to be dehydrated in a short time, a phenomenon known as the refractance window (Franco et al., 2019; Ortiz-Jerez et al., 2015). Nevertheless, other heat transfer mechanisms such as conduction and convection are present during the drying process, with conduction being the most dominant mechanism (Raghavi et al., 2018). This technology exhibits a relatively high thermal efficiency (52–77 %), the equipment is easy to operate, and the product quality can be compared with that of freeze-dried products (Brennan, 2011). Several researchers have investigated the RW™ technique for the dehydration of fruits and vegetables (Franco et al., 2019; Hernández et al., 2019). Franco et al. (2019) concluded that RW™ technology for drying apple slices (*Granny Smith*) could reduce the drying time by 50 % with minor damage to the final product quality compared with conventional hot-air drying. According to Dadhaneeya et al. (2023), drying banana slices and pulp with RW™ at 70 °C showed retention values of phenolic compounds comparable to those obtained by freeze-drying and higher than those of hot-air drying.

Refractance window using coupled drying technologies has been less frequently studied. For example, Puente et al. (2020) studied the coupled effect of RW™ with infrared light, revealing a significant reduction in drying time compared with RW™ alone (close to 60 %) when both technologies worked together. Baeghbali et al. (2019) reported on the application of RW™ coupled with ultrasound. The results showed the positive effect of these technology combinations on reducing processing time and retaining quality in apple slices.

However, drying can be accelerated by applying microwaves (MW) that operate industrially at 915 MHz and 2.45 GHz (Chandrasekaran et al., 2013; Chen et al., 2021; Zahoor et al., 2023). The electromagnetic field established in the MW system propagates in the surrounding space. Inside the food, polar molecules (water molecules) continuously reorient themselves according to the electromagnetic field displacement, which generates molecular friction and thus heat, promoting water migration and drying (Gaikwad et al., 2022). Microwave heating of food is often non-uniform, leading to potential hot spots and burning. One way to overcome this drawback is to keep the dried product in constant motion during microwave application, ensuring that all parts receive approximately the same dose of energy, or to use low levels of microwave power density (W/g of material). Time reduction and high quality are important characteristics of this technology (Monteiro et al., 2015; Bhagya Raj and Dash, 2020). However, exploring the effects of applied power is necessary, considering that higher power levels are expected to increase drying efficiency but may also negatively impact total phenol content and cause structural damage (Bhagya Raj and Dash, 2020).

This work aimed to study the effect of drying apple slices using RW™ and RW™ coupled with microwaves (RW-MW) on drying time and bioactive compound retention, as well as to model the drying process through Fick's second law and the anomalous diffusion model of apple slice drying.

2. Materials and methods

2.1. Sample preparation

Fresh apples (Granny Smith cv.) were obtained from a local market and stored at 5 °C until use. The ripeness of the apples was assessed by measuring soluble solids content (°Brix) using a digital refractometer. The °Brix values of the apples used in the experiments ranged from 12.2 to 14.7, which is within the typical range for commercially mature apples suitable for harvest and export, as reported in Chilean apple production (Yuri et al., 2019). A few hours before use, the apples were removed from refrigeration and left to equilibrate at room temperature. Apple were cut into slices 3 mm of thickness and 40 mm in diameter with an average mass of 3.873 ± 0.400 g and a moisture content of 0.893 ± 0.006 g water/g of sample (wet basis). The slices were obtained exclusively from the parenchymatic tissue based on the work of Ramírez et al. (2011). The samples were immersed in a solution containing 1.00 g ascorbic acid/100 g and 2.00 g citric acid/100 g for 3 min to prevent enzymatic browning.

2.2. Refractance window (RW™)

The RW™ comprised a thermoregulated water bath (MEMMERT, model WNB22, Germany). The water surface was covered with a Mylar film, an infrared-transparent plastic film of 0.1 mm thickness (Clear polyester film type D, Professional Plastics, Inc., USA) with an area of 15 × 47 cm^2 on which 45 samples were placed, evenly spaced, for each test. The temperature of the thermoregulated water bath was set at 98.0 ± 1.0 °C, chosen based on preliminary tests. All experimental work was carried out in the laboratory at room temperature (25 °C and 48 % RH). Drying time was set at 60 min based on previous studies (non-reported here), to assure a moisture content below 0.03 g water/ g of sample (wet basis) and water activity a_w <0.4.

2.3. Drying with RW™ coupled to microwave (RW-MW)

The diagram of the RW-MW drying system is presented in Fig. 1. For RW™, a rectangular glass container with internal dimensions of 31 cm (length) × 20 cm (width) × 5 cm (height) was filled with 800 *g* of hot water and a plastic Mylar film was placed on the surface, in direct contact with the water. The RW™ was centrally positioned inside the microwave oven chamber (RW-MW), which has internal dimensions of 33 cm (length) × 32 cm (width) × 20 cm (height). The amount of 15 apple slices were weight initially (average initial sample weight of 58.155 ± 0.273 g) and dried in the lab-scale RW-MW dryer system at 98 °C with an exhaust system to avoid the accumulation of water vapor in the microwave chamber. The microwave oven (Prowat, WA70002SLA, China) of 2450 MHz has a maximal power of 1000 W. Water temperature and sample temperature were monitoring during RW™ and RW-MW drying with polyimide optic fibers of 1 mm of diameter (Technica, AY-231,017–1Re) connected to sensing instrument (Luna Hyperion platform, Si155, USA). The RW-MW system was operated at two output power levels: 700 W (power density of 815 W/kg) and 1000 W (power density of 1165 W/kg), maintaining the water temperature at 98 °C throughout the experiment. The total mass of water and samples inside the chamber was approximately 858 g. Drying times were set to 35 min and 20 min for RW-MW 700 and RW-MW 1000, respectively. These drying times were chosen based on preliminary, unpublished tests to ensure that the final moisture content and water activity would remain below 0.10 g water/g sample (wet basis) and 0.4, respectively.

To determine the water loss curves during the drying process, sequential sampling was performed in triplicate. At each time interval, a sample was taken from the RW™ and RW-MW, immediately weighed, and then returned to the drying equipment. This procedure was repeated throughout the entire drying period, with a new sample collected at each defined time point. Each sample was identified and its weight recorded, allowing for the estimation of the remaining water content in the material over time.

2.4. Determination of moisture content and water activity

Moisture content was determined using the standard procedures of the AOAC (method no. 934.06) (AOAC, 2016). Water activity was determined using a dew-point hygrometer (Hygropalm Rotronic HP23-AW-A; Shanghai, China).

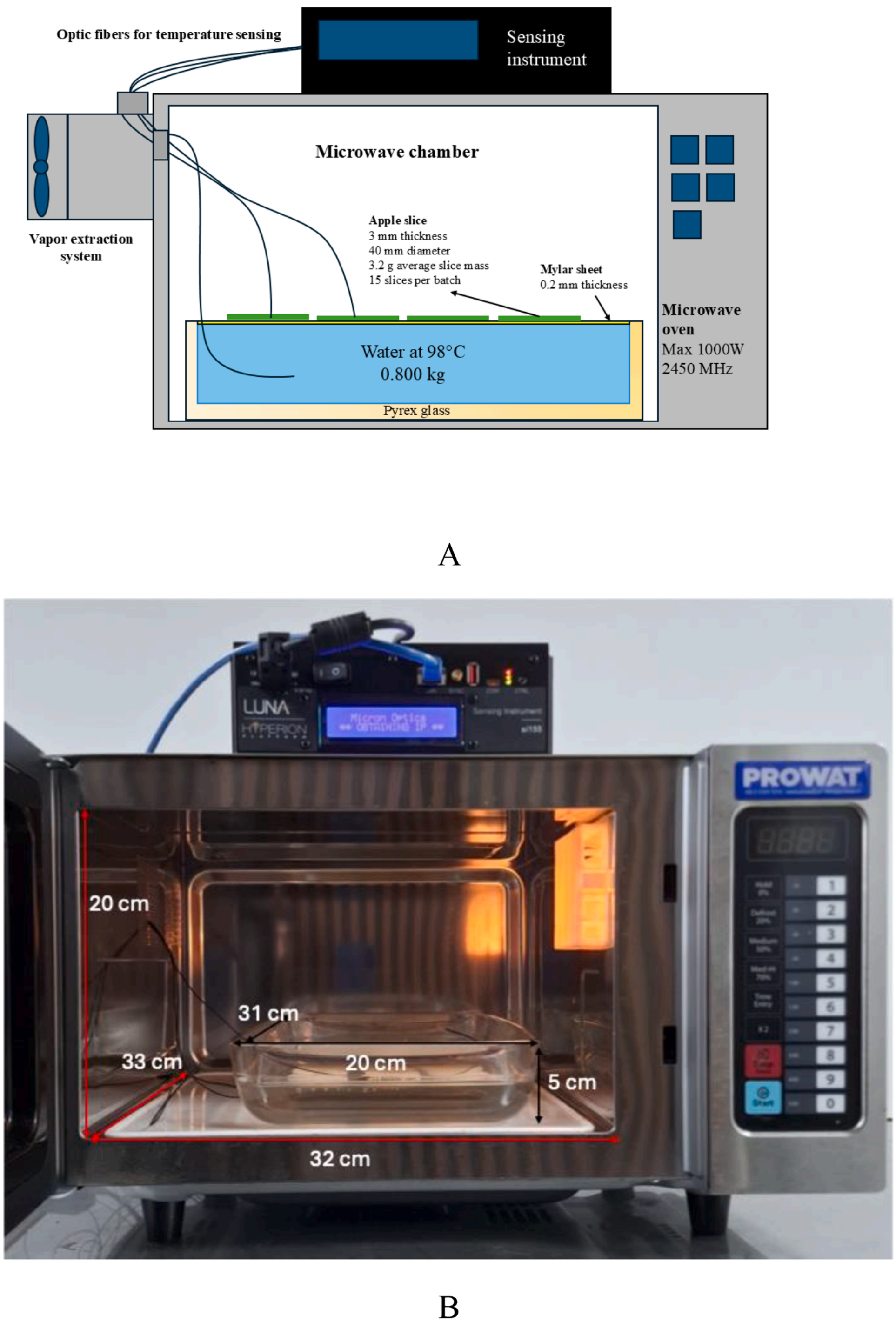

Fig. 1. Refractance window–microwave (RW-MW) drying system: A) schematic diagram of the experimental setup, and B) photograph of the RW-MW system during operation.

2.5. *Determination of color change (ΔE)*

The colors of the samples were evaluated using a colorimeter (model CR-410, Konica Minolta, Tokyo, Japan) to measure the coordinates of the CIEL*a*b* uniform color space, where L^* is luminosity, a^* is red/green hue, and b^* is yellow/blue hue. The illuminant type was D65, and the degree of the observer was 2° Measurements were performed on at least five randomly selected samples at three positions per sample. The total color difference (ΔE) in fresh, pretreated, and dehydrated samples was calculated using Eq. (1).

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}} \quad (1)$$

2.6. *Determination of total polyphenol content (TPC) and antioxidant activity*

Polyphenols were extracted by mixing two grams of the ground sample (fresh or dried) with 20 mL of an 80 % methanol solution using a homogenizer at room temperature, protected from light for 1 h. The supernatant was filtered through Whatman paper No. 2 and stored at −20 °C. TPC was determined using the Folin–Ciocalteu method (Galaz et al., 2017) and expressed as gallic acid equivalent (GAE) in mg/g dry matter. Antioxidant activity was determined using the DPPH assay, following the procedure of Galaz et al. (2017). The results were expressed as Trolox equivalents (TE) in µmol/g dry matter. The total polyphenol content and antioxidant capacity were determined using a Genesys 5 spectrophotometer (Spectronic Instrument, Inc., model 336, 001, New York, NY, USA) by measuring the absorbance at 765 nm and 517 nm, respectively.

2.7. Mathematical models

2.7.1. Fick's second law

From the analytical solution of Fick's second law proposed by Crank (1975) and experimental considerations, the following assumptions were made: a) apple slices correspond to an infinite slab geometry; b) the ambient temperature is constant; c) the diffusion coefficient is constant; and d) there is no sample deformation.

The model is given in Eq. (2):

$$MR_t = \frac{W_t - W_e}{W_0 - W_e} = \frac{8}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{(2i-1)^2}e^{\left(\frac{-(2i-1)^2\pi^2 D_{eff} t}{4L^2}\right)} \tag{2}$$

where MR_t corresponds to the dimensionless moisture ratio, W_t is the moisture content at any time t (g water/g dry basis), W_e is the moisture content at equilibrium (g water/g dry basis), and W_0 is the initial moisture content (g water/g dry basis). D_{eff} is the effective moisture diffusion coefficient (m^2/s), t is the drying time (s), and L is the half-thickness of a slice (m). The value of W_e was obtained by checking the asymptotic values of the moisture profiles. (Ramírez et al., 2017; Simpson et al., 2017)

2.7.2. Anomalous or non-fickian diffusion model based on fractional calculus

Simpson et al. (2013) proposed an anomalous diffusion model for food matrices based on a fractional calculus approach. The model is given in Eq. (3):

$$\frac{\partial^\alpha W}{\partial t^\alpha} = D_{eff}\frac{\partial^\beta W}{\partial t^\beta} \tag{3}$$

where W corresponds to the food water concentration (g water/g dry basis), D_{eff} corresponds to the effective diffusion coefficient (m^2/s^α), a is related to anomalous waiting times between jumps, and fractional differentiation order b is related to anomalous jump lengths.

In food matrices, the space component converges to two, and the temporal component has a fractional order (Ramírez et al., 2017; Simpson et al., 2013; Simpson et al., 2015). Thus, Eq. (4) can be represented as follows:

$$\frac{\partial^\alpha W}{\partial t^\alpha} = D_{eff}\frac{\partial^2 W}{\partial t^2} \tag{4}$$

Then, the solution for the anomalous diffusion model is shown in Eq. (5)

$$MR_t = \frac{W_t - W_e}{W_0 - W_e} = \frac{8}{\pi^2}\sum_{i=1}^{\infty}\frac{1}{(2i-1)^2}E_\alpha\left(\frac{-(2i-1)^2\pi^2 D^*_{eff} t^\alpha}{4L^2}\right) \tag{5}$$

where E_α corresponds to a Mittag-Leffler function, which is commonly used to solve equations with derivatives of fractional order and reduces to the exponential function when $\alpha = 1$. The α parameter is dimensionless, and D^*_{eff} is the effective anomalous diffusion coefficient (m^2/s^α). The α-value indicates that the transport mechanism is dominating the mass transfer process. Then, if $0<\alpha<1$, the diffusion mechanisms can be assumed to be sub-diffusive, whereas the mechanisms can be considered super-diffusive for $\alpha > 1$. If α converges to the unit, the anomalous diffusion model tends to follow Fick's second law. In practical terms, the *α-value* has been related to the microstructure of the food matrix, and changes during drying contribute to the non-Fickian behavior of water diffusion (Simpson et al., 2017)

The drying data were fitted to diffusion models using a routine code implemented in MATLAB R2022A (MathWorks, Inc., Natick, MA, USA). The developed code allowed us to obtain the values of the effective diffusion coefficients (D_{eff} and D_{eff}*), coefficient of determination (R^2), and parameter alpha (α) of the anomalous model.

2.8. Statistical analysis

The results were analyzed using one-way ANOVA at a 95 % probability level. In the case of significant effects ($p < 0.05$), the means were compared using the Duncan's test. STATGRAPHIC Centurion XVIII software (Statgraphics Technologies, Inc., Virginia, USA) was used for statistical analysis.

3. Results and discussion

3.1. Effect of RW™ and RW-MW on drying time, processing temperature, moisture content, water activity, total polyphenol content, antioxidant capacity and color change

The results obtained for RW™ and RW-MW respect to average processing temperature, power density, drying time, average temperature inside the apple slice, moisture content and water activity are summarized in Table 1. The average processing temperature was set at 98 °C for both RW™ and RW-MW drying methods. The main difference between them was the variability observed. The RW™ method maintained a more stable water temperature, while the RW-MW method exhibited fluctuations, with the standard deviation reaching up to ± 3.6 °C when the microwave oven was set at 700 W. Regarding the temperature measured in the apple slices after 5 min of drying, the results showed that under RW™ conditions, the average sample temperature was 64.52 ± 5.14 °C. For the RW-MW system, the average temperatures ranged from 68.39 ± 7.61 °C to 71.97 ± 6.99 °C for RW-MW 700 and RW-MW 1000, respectively. These results confirm that microwave application increases the internal temperature of the product, with higher power intensifying the effect. It is also important to note that part of the water used in the system is evaporated during drying, with losses of approximately 25 % at 700 W and 38 % at 1000 W. This vapor is continuously removed from the chamber through the exhaust system

The moisture content at the end of drying processes were: 0.088 ± 0.003 g water/g sample (wet basis) for RW™, 0.099 ± 0.001 g water/g sample (wet basis) for RW-MW 700 and 0.097 ± 0.002 g water/g sample (wet basis) when RW-MW 1000 was used. These results were attained considering drying time of 60, 35 and 20 min, respectively. At the same time, water activity attained by the samples was below 0.4 for all experiments (water activity ranged between 0.317 ± 0.011 to 0.311 ± 0.013). In Table 2 are presented the result obtained for polyphenols content (TPC), antioxidant capacity (AC), color parameters and color change (*ΔE*). In terms of bioactive compound retention, the results showed that TPC, in general, decreased during drying compared to non-treated samples (control), which presented a TPC of 10.334 ± 0.146 mg of gallic acid equivalent/g of sample (dry basis). This value is lower than reported by Núñez et al. (2023) for apple (16.79 mg of gallic acid equivalent/g of sample (dry basis)) and, Heras-Ramírez et al. (2012) who reported a value close to 12 mg of gallic acid equivalent/g of sample (dry basis) for fresh apple. For samples dried at 98 °C using RW™, the TPC values were 9.164 ± 0.086 mg of gallic acid equivalent/g of sample (dry basis)

With respect to the TPC in case of RW-MW, the results showed an increase in the retention of TPC compared with RW™, attaining a retention close to 96 % when RW-MW using 700 W was applied and close to 86 % when 1000 W were used. Then, the TPC obtained for samples dried using RW-MW was dependent on the applied power. As

Table 1
Summary of results of average processing temperature, power density, drying time, average temperature inside the apple slice, moisture content and water activity obtained for apple slices drying using RW™ at 98 °C and RW-MW at power levels of 700 and 1000 W.

Drying method	Average processing temperature			Power density	Drying time	Average temperature inside the sample			Moisture Content			Water activity		
	°C			W/kg	min	°C			g water/g sample$_{wb}$					
Apple slices		–		–	–		–		0.893	±	0.006[a]	0.997	±	0.001[a]
RW™	98.6	±	0.7	0	60	64.518	±	5.141	0.088	±	0.003[b]	0.317	±	0.011[b]
RW-MW_700	98.6	±	3.6	815	35	68.390	±	7.610	0.099	±	0.001[b]	0.311	±	0.013[b]
RW-MW-1000	98.2	±	2.3	1165	20	71.970	±	6.990	0.097	±	0.002[b]	0.312	±	0.017[b]

*Different lowercase letters indicate significant differences ($p < 0.05$).

Table 2
Results of polyphenols content, antioxidant capacity, Lab color parameters and color change obtained for apple slices drying using RW™ at 98 °C and RW-MW at power levels of 700 and 1000 W. .

Drying method	Total polyphenols content			Antioxidant Capacity			Color											
	mg of GAE/gdb			μmol of Trolox/g db			L^*			a^*			b^*			ΔE		
Apple slices	10.334	±	0.146[a]	84.122	±	7.124[a]	69.98	±	1.84	−6.210	±	1.03	16.68	±	2.62		–	
RW™	9.164	±	0.086[b]	34.118	±	2.256[b]	77.15	±	3.00	0.008	±	1.06	24.44	±	1.71	12.8	±	2.6[a]
RW-MW 700	9.950	±	0.412[a]	46.117	±	0.458[c]	80.21	±	1.47	−1.480	±	1.31	19.32	±	1.42	12.0	±	1.9[a]
RW-MW 1000	8.914	±	0.306[b]	40.842	±	1.305[c]	76.77	±	1.79	−1.400	±	0.96	20.83	±	0.23	9.7	±	2.0[a]

[*] Different lowercase letters indicate significant differences ($p < 0.05$).

the power increased from 700 to 1000 W, the TPC was reduced, from 9.950 ± 0.412 to 8.914 ± 0.306 mg of gallic acid/ g $_{(}$dry basis).

Respect to AC, the result showed for non-treated sample an AC of 84.122 ± 7.124 μmol of Trolox/g of sample (dry basis). For this case, the value obtained in the present work is higher than reported by Nuñez et al. (2023), where the value of 15.08 μmol Trolox/g (dry basis) was reported. However, Heras-Ramírez et al. (2012), reported values close to 40 μmol Trolox/g (dry basis). When samples were dried with RW™, the AC decreased to values of 34.118 ± 2.256 μmol of Trolox/g of sample (dry basis), attaining an AC percentage retention of 40.6 %

Interestingly, when RW-MW was used as drying system, the AC was much larger ($p < 0.05$) respect to RW™ alone, attaining an AC percentage retention until 54 %. If we compared the RW-MW process, the results showed that as the power increased, the AC was diminished, presenting the same tendency observed in TPC. As the power increased from 700 to 1000 W the AC was reduced from 46.117 ± 0.485 to 40.842 ± 1.305 μmol of Trolox/g (dry basis).

The highest values of both TPC and AC achieve for RW-MW 700, followed by RW-MW 1000 and RW™. This trend can be attributed to the drying time and the average temperature attained in the sample during drying process. Several studies have reported similar findings regarding the application of RW™ drying to enhance the drying process and the retention of bioactive compounds in fruits. For example, Rajoriya et al. (2020) demonstrated that coupling RW™ drying with far-infrared (FIR) drying for apple slices significantly reduced the drying time by approximately 50 %, while also increasing the total polyphenol content. The authors attributed this improvement to the rapid heating characteristic of the combined drying process, which facilitates the release of bound phenolic compounds from the cellular matrix of the apple tissue.

In a related study, Rajoriya et al. (2019) investigated the drying of apple slices using RW™ drying and quantified the retention of ascorbic acid. Their results indicated that as the RW™ drying temperature increased, the drying time decreased, and the retention of ascorbic acid increased to as much as 80 %.

Moreover, studies on other fruits, such as goldenberry pulp dried using RW™, reported an increase in total polyphenol content (TPC) and antioxidant capacity when compared to the fresh sample. However, in the case of infrared drying, although the highest TPC value was observed, the antioxidant capacity was found to be the lowest (Puente et al., 2020).

Regarding color, the results showed that RW-MW using 1000 W resulted in lower color differences with ΔE of 9.7 ± 2.0. While in the case of RW™ and RW-MW using 700 W the ΔE was similar with values of 12.8 ± 2.6 and 12.0 ± 1.9, respectively. Independent of the during system, de ΔE reported were higher, and showed a non-significantly color difference respect to non-treated sample.

3.2. Drying kinetics of apple slices dried with RW™ and RW-MW

The drying curves obtained during the drying process performed with RW™ and RW-MW, along with the fit of Fick's second law model and the anomalous model, are presented in Fig. 2A and B. In general, the drying curves show that the drying process using RW-MW was faster than using RWTM alone. When comparing RW-MW 700 W and RW-MW 1000 W, the main differences were observed after 10 min of drying, during which RW-MW 1000 W showed a rapid drop in MR values.

In terms of the mathematical analysis of the drying curves, the data were fit to Fick's second law (Fig. 2A) and anomalous diffusion model (Fig. 2B), observing that for both models the values of R^2 were over 0.98, which could indicate that the diffusion of water molecules though the sample has a Fickean behavior. According to Table 3, the values of R^2 ranged from 0.9893 to 0.9985. From the fit to RW™ data, it was possible to obtain the values of D_{eff} of 4.92 • 10^{-9} m^2/s. Additionally, the values of D_{eff} were affected by the microwave power. So, the D_{eff} obtained for RW-MW were higher than the D_{eff} obtained for RW™ alone, presenting the highest value of D_{eff} at 700 W, with 12.75 • 10^{-9} m^2/s. But as the power increased the D_{eff} becomes to be low, attaining values of 11.94 • 10^{-9} m^2/s, without present significance differences between them.

When the drying data were modeled using an anomalous diffusion model based on fractional calculus, the results showed a time exponent alpha higher than one, implying a super-diffusion process for the RW™ and RW-MW 1000 cases, with an α-value of 1.10 and 1.06, and the R^2 of 0.9954 and 0.9967, respectively. In general, α-values higher than 1 suggest that microstructural changes during drying promote the diffusion of water molecules through the matrix in a more channeled pattern (Olivares et al., 2021). Similar super-diffusive behavior (α-value of 1.23) during RW™ drying of apple slices was reported by Franco et al. (2019) and Rajoriya et al. (2019) In case of RW-MW 700, the α-value calculated was of 0.95, and R^2 of 0.9967, which suggest a sub-diffusive behavior.

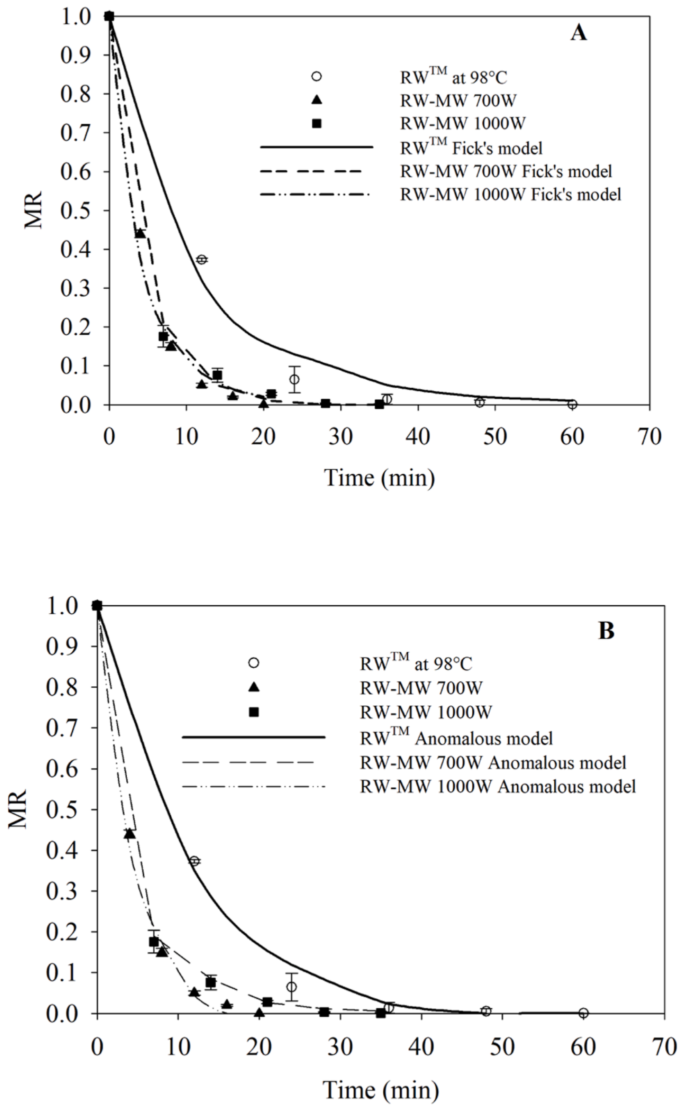

Fig. 2. Drying curves obtained from the drying process using RW™ and RW-MW and fit to a) Fick 'second law model; b) anomalous diffusion model.

4. Conclusions

Refractance window is a powerful technology known for producing high-quality dried products. However, this process can be improved in terms of processing time or quality retention by integrating technologies that promote faster water migration from food structures, such as microwaves.

Data obtained from this preliminary study on food drying using RW-MW indicate that it was possible to shorten the drying time up to 66 % compared with RW™ alone. Additionally, an increase in the retention of bioactive compounds (over 66 % retention of TPC respect to fresh sample) compared with RW™ (50 % retention of TPC respect to fresh sample) was observed. Color change was not significantly affected by application of microwave during RW™ drying. These findings suggest that improvements in drying time and bioactive compound retention when the drying was performed with the simultaneous application of RW™ and MW.

Ethical statement for solid state ionics

Hereby, I Cristian Ramírez consciously assure that for the manuscript Simultaneous Application of Refractance Window and Microwave Drying: A Novel Hybrid Technique for Fruit Dehydration to reducing drying time and improve bioactive compound retention the following is fulfilled:

1) This material is the authors' own original work, which has not been previously published elsewhere.
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3) The paper reflects the authors' own research and analysis in a truthful and complete manner.
4) The paper properly credits the meaningful contributions of co-authors and co-researchers.
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I agree with the above statements and declare that this submission follows the policies of Solid State Ionics as outlined in the Guide for Authors and in the Ethical Statement.

CRediT authorship contribution statement

C. Ramírez: Writing – original draft, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **H. Núñez:** Supervision, Investigation, Data curation. **R. Vallejos:** Investigation, Formal analysis. **K. Belmonte:** Writing – review & editing, Supervision, Data curation. **S. Almonacid:** Writing – review & editing, Supervision. **F Marra:** Writing – review & editing, Methodology, Formal analysis.

Table 3
Effective diffusion coefficient obtained during drying of apple slices using RW™ at 98 °C and RW-MW at power levels of 700 and 1000 W through mathematical analysis based on Fick's second law and the anomalous diffusion model based on fractional calculus.

					Fick's Second Law					Anomalous diffusion based on fractional calculus							
Drying method	Processing Temperature			Power density	D_{eff} x 10^9				R^2	D_{eff} x 10^9				α-value			R^2
				W/kg	m^2/s					m^2/s^α							
RW™	98.6	±	0.7	0	4.92	±	0.26	a	0.9904	2.38	±	0.09	a	1.10	±	0.12	0.9954
RW-MW 700	98.6	±	3.6	815	12.75	±	1.46	b	0.9981	17.95	±	7.65	b	0.95	±	0.03	0.9997
RW-MW 1000	98.2	±	2.3	1165	11.94	±	0.05	b	0.9915	8.55	±	4.41	b	1.06	±	0.09	0.9967

*Different lowercase letters indicate significant differences ($p < 0.05$).

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data availability

Data will be made available on request.

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