

Effects of Erythritol and Ultrasound-Assisted Osmotic Dehydration on Drying Kinetics, Bioactive Retention, and Quality of Semi-Dried Red-Fleshed Dragon Fruit

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This study explored the potential of osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD) as pretreatment strategies for semi-dried red-fleshed dragon fruit (RFDF) by evaluating their impact on drying kinetics, quality attributes, and sensory preference. Erythritol and sucrose solutions of 30°Brix and 50°Brix were evaluated as osmotic agents, demonstrating distinct effects on process efficiency and product quality. The application of USOD significantly enhanced mass transfer, where a 10-min treatment yielded water loss comparable to 120 min of conventional OD. These modifications translated into accelerated drying kinetics, specifically in reducing the predicted drying time from 12.62 h (control) to 9.92 h (USOD with 30°Brix erythritol, USOD_30E), representing a 21.4% increase in efficiency. While a high sucrose concentration (50°Brix) improved initial water loss, it led to structural modifications that increased internal resistance, resulting in longer drying duration (12.38 h). Physicochemical analysis revealed that USOD_30E best preserved functional attributes, maintaining betacyanin content (12.93 mg/100 g), total phenolic content (47.09 mg gallic acid equivalent/100 g), and antioxidant capacity nearly identical to the control. Microstructural stability of this sample was significantly improved, characterized by reduced shrinkage (from 28.28% to 16.84%) and higher color vibrancy, with the total color difference value of 7.19 indicating a distinct visual enhancement. Sensory evaluation supported these findings, revealing that the USOD_30E obtained high acceptability in terms of color, texture, and taste with average scores of >7.0 over 9.0. The findings proved that the combination of ultrasound and erythritol could be effectively employed to produce high-value semi-dried dragon fruit rich in bioactive compounds while maintaining its sensory quality.

Keywords: antioxidant, drying model, intermediate moisture food, mass transfer, sensory scores, sugar alcohol

INTRODUCTION

Dragon fruit (*Hylocereus* spp.) is widely cultivated in tropical and subtropical regions. Two major cultivars are predominantly grown, namely white-fleshed dragon fruit (*Hylocereus undatus*) and red-fleshed dragon fruit (*Hylocereus polyrhizus*) [Luu *et al.*,

2021]. The latter is particularly favored due to its intense red flesh color and superior nutritional value. The fruit is characterized by a high moisture content and appreciable levels of carbohydrates, dietary fiber, vitamin C, and essential minerals (K, Mg, and Ca) [Luu *et al.*, 2021]. It also contains various bioactive compounds,

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including phenolic compounds and betacyanins, the latter being responsible for its characteristic pigmentation and strong antioxidant activity [Lim *et al.*, 2025].

Vietnam is one of the world's leading producers of dragon fruit [Chen *et al.*, 2024a], with a cultivated area exceeding 55,000 hectares and an annual production of over 1 million tonnes recorded in 2018 [Luu *et al.*, 2021]. Approximately 80–85% of the total production is exported while only a minor proportion is consumed domestically [Luu *et al.*, 2021]. This strong export orientation renders the dragon fruit sector highly sensitive to fluctuations in international market demand and trade conditions. Moreover, due to its high moisture content and fragile tissue structure, dragon fruit is highly perishable after harvest, resulting in a limited postharvest shelf life [Bassey *et al.*, 2022]. Therefore, the development of appropriate processing strategies is essential to mitigate postharvest losses, stabilize product quality, and enhance added value. Among various processed fruit products, semi-dried ones have attracted increasing attention owing to their desirable sensory properties and improved storability compared to fresh fruit. Semi-dried fruits, also known as intermediate-moisture fruit products, are generally characterized by a moisture content of approximately 20–30% [Özkan-Karabacak *et al.*, 2022]. At this moisture level, the products retain a soft, pliable, and chewy texture while maintaining microbiological stability. All these features distinguish them from fully dried fruits, which are generally hard, brittle, and crispy [Le *et al.*, 2026].

Semi-dried fruit is typically produced by convective hot-air drying at temperatures of 40 to 80°C [Gomez *et al.*, 2022; Mahayothee *et al.*, 2019]. However, prolonged drying durations may induce color degradation and losses of heat-sensitive bioactive compounds [Mahayothee *et al.*, 2019]. To address these limitations, pretreatment methods, such as osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD), have received considerable attention due to their ability to accelerate moisture removal, reduce drying time, and better preserve structural and quality attributes [Bozkir *et al.*, 2019]. OD is a non-thermal pretreatment in which plant materials are immersed in a hypertonic solution (typically sugar- or salt-based), generating an osmotic pressure gradient that drives water diffusion from the tissue into the surrounding medium, followed by partial solute uptake. As a result, OD could partially reduce moisture content prior to drying, shorten subsequent drying time, and contribute to improved texture and sensory quality [Bozkir *et al.*, 2019; Mari *et al.*, 2024]. The application of ultrasound during OD (USOD) may further enhance mass transfer efficiency through acoustic cavitation, which could generate microchannels within cell structures, increase membrane permeability, and promote water migration. Consequently, ultrasound-assisted osmotic dehydration may improve dehydration efficiency and product quality while further reducing processing time and energy consumption [Bozkir *et al.*, 2019]. Recent studies have demonstrated the effectiveness of USOD

in a wide range of fruits, including apple [Kroehnke *et al.*, 2021], kiwifruit [Kroehnke *et al.*, 2021; Prithani & Dash, 2020], papaya [Chandra *et al.*, 2023], strawberry [Amami *et al.*, 2017], persimmon [Bozkir & Ergün, 2020; Bozkir *et al.*, 2019], melon [Fernandes *et al.*, 2008], and white-fleshed dragon fruit [Bhagya Raj & Dash, 2022], with enhanced water loss, moisture diffusivity, accelerated dehydration, and shortened drying time being reported. In addition, several studies have recorded improved retention of bioactive compounds, antioxidant activity, color, and texture in fruits subjected to ultrasound-assisted osmotic dehydration [Amami *et al.*, 2017; Bhagya Raj & Dash, 2022; Chandra *et al.*, 2023; Kroehnke *et al.*, 2021].

In both OD and USOD processes, the choice of an osmotic agent plays an important role in determining dehydration efficiency and product quality. Sucrose is commonly employed to this end due to its availability and effectiveness, whereas erythritol has gained attention because of its high stability, good heat resistance, low caloric value, and digestive safety [Kroehnke *et al.*, 2021; Wojtyś *et al.*, 2024]. Furthermore, Kroehnke *et al.* [2021] demonstrated that erythritol could be successfully applied as an alternative osmotic agent during ultrasound-assisted osmotic dehydration of kiwifruit, resulting in greater retention of carotenoids and polyphenols than sucrose.

To the best of our knowledge, the application of osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD) as pretreatment strategies for the production of semi-dried red-fleshed dragon fruit (*H. polyrhizus*) has not yet been systematically investigated. Moreover, studies evaluating erythritol as an osmotic agent during these treatments for red-fleshed dragon fruit are still limited. Therefore, this study aimed to evaluate the effects of OD and USOD pretreatments using sucrose and erythritol solutions on the drying kinetics of red-fleshed dragon fruit, as well as on the physicochemical and quality characteristics of the resulting semi-dried products.

MATERIALS AND METHODS

■ Materials and chemicals

Red-fleshed dragon fruits (RFDF) harvested from plants cultivated in Lam Dong Province (Vietnam) were purchased from local supermarkets (Ho Chi Minh City, Vietnam). Sucrose was purchased from Quang Ngai Sugar Joint Stock Company (Quang Ngai City, Vietnam), and erythritol was acquired from Ringo Natural Materials Co., Ltd. (Ha Noi, Vietnam). Other analytical-grade chemicals were purchased from Xilong Scientific Co., Ltd. (Shantou, Guangdong, China) and Sigma-Aldrich (St. Louis, MO, USA) via local distributors in Ho Chi Minh City, Vietnam.

■ Red-fleshed dragon fruit preparation

RFDF of uniform ripeness and free from visible defects were selected by visual inspection. They were washed to remove adhering impurities and foreign materials. After manual peeling, the flesh was cut into rectangular slices (4 × 4 × 0.75 cm), with

an average mass of 17.5 ± 0.5 g *per slice*, prior to pretreatment and drying.

■ Osmotic dehydration and ultrasound-assisted osmotic dehydration pretreatment

Three osmotic solutions were prepared by dissolving sucrose (S) or erythritol (E) in distilled water to obtain concentrations of 30°Brix (30S), 50°Brix (50S), and 30°Brix (30E). Regarding osmotic dehydration (OD) pretreatment, RFDF slices (approximately 17.5 g each) were immersed in 30S, 50S, or 30E solutions for 120 min at room temperature, with a sample-to-solution ratio of 1:4 (w/w). The pretreated samples were designated as OD_30S, OD_50S, and OD_30E, respectively. For ultrasound-assisted osmotic dehydration (USOD), RFDF slices were similarly immersed in the respective osmotic solutions (30S, 50S, and 30E) in glass beakers, which were subsequently placed in an ultrasonic bath (Elmasonic S 30 H, Elma Schmidbauer GmbH, Singen, Germany). Ultrasonic treatment was performed at a frequency of 37 kHz and an effective ultrasonic power of 80 W for 10 min at 30°C. The resulting RFDF slices were denoted as USOD_30S, USOD_50S, and USOD_30E.

After pretreatment, the samples were briefly rinsed with water to eliminate surface-adhered solutes, and the excess surface water was gently removed by absorbent paper. The weight of the pretreated RFDF slices was recorded, and their moisture content was determined by drying at 105°C using a universal UF260 oven (Memmert, Schwabach, Germany) to a constant weight according to the AOAC International method [AOAC, 2005]. Water loss (WL) and solid gain (SG) were subsequently calculated using Equation (1) and Equation (2), respectively:

$$WL (\%) = \frac{m_i z_i - m_f z_f}{m_i} \times 100 \quad (1)$$

$$SG (\%) = \frac{m_f s_f - m_i s_i}{m_i} \times 100 \quad (2)$$

where: m_i is the initial mass of the RFDF slices before pretreatment (g), m_f is the mass after osmotic pretreatment (g); z_i and z_f are the corresponding initial and final moisture contents (g water/100 g); and s_i and s_f are the corresponding initial and final dry matter contents (g solid/100 g).

■ Determination of drying kinetics

After OD and USOD pretreatments, the RFDF slices were subjected to convective drying at 60°C (UF260 oven, Memmert) until equilibrium moisture content was reached. Untreated samples were used as controls. During drying, sample mass was recorded at 15-min intervals during the first 3 h and at 1-h intervals thereafter. A total of seven treatments were evaluated, and all experiments were performed in triplicate. The moisture ratio (MR) was calculated using Equation (3):

$$MR = \frac{MC_t - MC_e}{MC_0 - MC_e} \quad (3)$$

where: MC_0 , MC_t , and MC_e represent the initial, time-dependent, and equilibrium moisture contents (g water/g dry matter), respectively.

Drying curves were achieved by plotting moisture ratio (MR) against drying time. The drying kinetics were analyzed by fitting the experimental data to several thin-layer drying models summarized in Table 1 [Alara *et al.*, 2019; Erbay & Icier, 2010; Midilli *et al.*, 2002]. Model fitting was performed using LAB Fit software (Wilton and Cleide Pereira da Silva, Federal University of Campina Grande, Campina Grande, PB, Brazil), and the drying time required to achieve a final moisture content of 22 g/100 g was determined from the fitted curves.

■ Product quality assessment

Based on the drying kinetics models, the pretreated RFDF slices were semi-dried to a final moisture content of 22 g/100 g and subsequently used for quality and sensory evaluations. The quality of semi-dried products was evaluated in terms of betacyanin content, total phenolic content, antioxidant capacity, color change, and shrinkage ratio. For chemical analyses, 1 g of semi-dried RFDF slices was extracted with 10 mL methanol for 30 min at room temperature and centrifuged at $3,630 \times g$ for 20 min. The supernatant was used for subsequent analyses.

Betacyanin content was determined according to the spectrophotometric method described by Ramli *et al.* [2014]. The absorbance of the extract was measured at 538 nm using a UV-Vis spectrophotometer (UH5300, Hitachi, Tokyo, Japan). Betacyanin content (BC) was expressed as mg/100 g of semi-dried RFDF slices and calculated according to Equation (4):

$$BC = \frac{A \times DF \times MW \times V \times 100}{\epsilon \times L \times W_d} \quad (4)$$

where: A is the absorbance at 538 nm, DF is the dilution factor, V is the extraction volume (mL), MW is the molecular weight of betanin (550 g/mol), ϵ is the molar extinction coefficient of betanin (65,000 L/(mol $\times$ cm)), L is the cuvette path length (cm), and W_d is the semi-dried RFDF slice weight used for extraction (g).

Table 1. Mathematical models applied to drying curves.

Model	Equation
Henderson and Pabis	$MR = a \exp(-kt)$
Page	$MR = \exp(-kt^n)$
Logarithmic	$MR = a \exp(-kt) + c$
Midilli-Kucuk	$MR = a \exp(-kt^n) + bt$

MR, moisture ratio; a, b, c, k and n, empirical model constants.

The total phenolic content (TPC) of the samples was determined using the Folin-Ciocalteu method described by Singleton & Rossi [1965] with slight modifications. Briefly, 500 µL of extract were mixed with 2.5 mL of a 10% (v/v) Folin-Ciocalteu reagent. After 5 min, 2 mL of 7.5% (w/v) sodium carbonate solution were added, and the mixture was left in the dark for 120 min. The absorbance was then measured at 765 nm. TPC was expressed as mg gallic acid equivalents *per* 100 g of semi-dried RFDF slices (mg GAE/100 g).

The antioxidant capacities of samples were determined based on 2,2-diphenyl-1-picrylhydrazyl (DPPH) radical scavenging activity [Huang *et al.*, 2005] and reducing power [Xiao *et al.*, 2020]. Regarding the DPPH assay, 0.2 mL of extract was mixed with 3.8 mL of a 0.1 mM DPPH radical methanolic solution. The mixture was left in the dark for 30 min at room temperature, and the absorbance was measured at 515 nm. Antioxidant capacity was calculated using an ascorbic acid calibration curve and expressed as mg ascorbic acid equivalents *per* 100 g of semi-dried RFDF slices (mg AAE/100 g). Regarding the reducing power assay, 200 µL of extract were mixed with 600 µL of 1% (w/v) potassium ferricyanide and 600 µL of phosphate buffer (pH 6.6). The mixture was incubated at 50°C for 20 min, followed by the addition of 600 µL of 10% (w/v) trichloroacetic acid. Subsequently, 2,000 µL of distilled water and 400 µL of 0.1% (w/v) FeCl₃ were added, and the absorbance was measured at 700 nm. Results were expressed as mg AAE/100 g of semi-dried RFDF slices based on an ascorbic acid calibration curve.

The color parameters L^* (lightness), a^* (red–green), and b^* (yellow–blue) of semi-dried RFDF slices were measured using a colorimeter (CR-400, Konica Minolta, Tokyo, Japan). The total color difference (ΔE) between the pretreated semi-dried RFDF slices and the control (without OD or USOD pretreatment) was calculated according to Equation (5) [Robertson, 1977]:

$$\Delta E = \sqrt{(L_S^* - L_C^*)^2 + (a_S^* - a_C^*)^2 + (b_S^* - b_C^*)^2} \quad (5)$$

where: the subscripts S and C represent the pretreated sample and control, respectively.

Shrinkage was evaluated based on the change in the surface area of the RFDF slices after drying. The images of fresh and semi-dried RFDF slices were captured in a closed box equipped with a fixed smartphone camera (Galaxy S9+, Samsung Electronics Co., Ltd., Suwon, South Korea) to ensure consistent imaging conditions. The surface area of each sample was determined using ImageJ software (U.S. National Institutes of Health, Bethesda, MD, USA). The shrinkage ratio was determined according to Equation (6):

$$\text{Shrinkage ratio (\%)} = \frac{S_0 - S}{S_0} \times 100 \quad (6)$$

where: S_0 is the surface area of the fresh slices, and S is the surface area of the semi-dried slices.

Sensory evaluation

Sensory evaluation was conducted to assess the sensory attributes (color, texture, taste, and overall acceptability) of semi-dried RFDF slices. The test was performed by 50 untrained panelists including students and staff of Ho Chi Minh City University of Technology and Engineering (Ho Chi Minh City, Vietnam), aged 19–55 years, using a nine-point hedonic scale. Individuals with known food allergies or dietary restrictions were excluded. Samples were served on coded plates, and the presentation order was randomized using a Williams Latin square design to minimize positional bias. Panelists evaluated the samples sequentially, and water was provided for palate cleansing between samples. The sensory evaluation was conducted in a standard sensory laboratory with individual booths equipped with adequate lighting. Prior to the evaluation, participants received a detailed briefing regarding the testing protocols and the ingredients used in the samples, including sucrose and erythritol; subsequently, informed verbal consent was secured from all panelists.

Statistical analysis

Data were statistically analyzed using Minitab software (version 21.0, Minitab, LLC, State College, PA, USA). Results were expressed as mean values with standard deviation, derived from triplicate determinations. Mean comparisons were performed by Fisher's least significant difference (LSD) or Tukey's test (for sensory analysis), and significance was established at $p < 0.05$. Pearson correlation analysis was conducted to evaluate the linear relationships among total phenolic content, betacyanin content, and antioxidant capacities. The Pearson correlation coefficient (r) was calculated using Equation (7) [Asuero *et al.*, 2006]:

$$r = \frac{n\sum xy - (\sum x)(\sum y)}{\sqrt{[n\sum x^2 - (\sum x)^2][n\sum y^2 - (\sum y)^2]}} \quad (7)$$

where: n is the number of paired observations, and x and y are the values of the two variables being correlated.

RESULTS AND DISCUSSION

Effects of different osmotic dehydration pretreatments on water loss and solid gain of red-fleshed dragon fruit

The mass transfer properties of RFDF during OD and USOD were evaluated using water loss (WL) and solid gain (SG) as indicators of efficiency, and results are shown in Table 2. Regarding RFDF slices subjected to OD alone, increasing the sucrose concentration of osmotic solution from 30 to 50°Bx enhanced both WL and SG. This could be attributed to the increment in osmotic pressure gradient between the fruit tissue and the surrounding solution, which promoted both water diffusion and solute penetration. This aligned with the findings of Song *et al.* [2020], who reported that increasing the sugar concentration enhanced mass transfer during OD of blackberries. Notably, the WL values of OD_50S and OD_30E showed no significant ($p \geq 0.05$) difference and were approximately twofold higher as compared

Table 2. Water loss and solid gain of red-fleshed dragon fruit slices subjected to different osmotic dehydration pretreatments.

Pretreatment	Water loss (%)	Solid gain (%)
OD_30S	7.88±0.16 ^b	3.01±0.30 ^c
OD_50S	15.27±1.17 ^a	4.44±0.19 ^a
OD_30E	16.39±1.65 ^a	3.10±0.13 ^c
USOD_30S	7.72±1.34 ^b	3.52±0.97 ^{bc}
USOD_50S	8.68±1.62 ^b	4.00±0.34 ^{ab}
USOD_30E	9.32±1.72 ^b	4.14±0.34 ^{ab}

Values are presented as mean ± standard deviation ($n=3$). Values in the same column with different letters are significantly different ($p<0.05$). OD_30S, OD_50S, and OD_30E, samples pretreated by osmotic dehydration in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by ultrasound-assisted osmotic dehydration in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively.

to that of OD_30S, suggesting that a 50°Bx sucrose solution provided dehydration efficiency comparable to that of a 30°Bx erythritol solution. This behavior could be explained by the lower molecular weight of erythritol (122.1 g/mol) compared to sucrose (342.3 g/mol), which provided higher osmotic pressure difference and hence accelerated water diffusion from plant tissues. It has also been reported that solute molecular size strongly influenced diffusion behavior and mass transfer efficiency [Wojtyś *et al.*, 2024]. However, no significant difference ($p\geq 0.05$) in SG was observed between OD_30S and OD_30E, indicating that while erythritol could enhance water removal, its overall solid uptake remained limited under these conditions. This may be

related to differences in solute-matrix interactions and spatial restriction and size exclusion effects within the dense matrix of the plant cell wall. These results suggest that erythritol could be a promising alternative osmotic agent for the development of reduced-sugar dried fruit products, as it is a low-calorie sweetener capable of providing dehydration efficiency comparable to that of higher-concentration sucrose solutions.

Regarding USOD-treated RFDF slices, no significant differences ($p\geq 0.05$) in WL and SG were observed among the three pretreatments (Table 2). It should be emphasized that USOD pretreatment for only 10 min produced a WL comparable to that of OD_30S after 120 min with only slight increment in SG (from 3.01% to 3.52–4.14%). This WL acceleration could be attributed to acoustic cavitation, which disrupted cell structures and formed microchannels, hence facilitating solute diffusion [Prithani & Dash, 2020]. Consequently, ultrasounds could increase effective moisture diffusivity and markedly reduce processing time, leading to improved dehydration efficiency even at shorter immersion durations [Salehi, 2023]. The present results further indicate that erythritol could be effectively combined with ultrasound-assisted osmotic dehydration, maintaining mass transfer performance comparable to that achieved with conventional sucrose solutions while offering the additional benefit of reduced caloric content of products.

■ Effects of osmotic dehydration and ultrasound-assisted osmotic dehydration pretreatments on convective drying kinetics of red-fleshed dragon fruit

RFDF slices were dried at 60°C following OD or USOD pretreatment. The drying curves, expressed as the moisture ratio (MR)

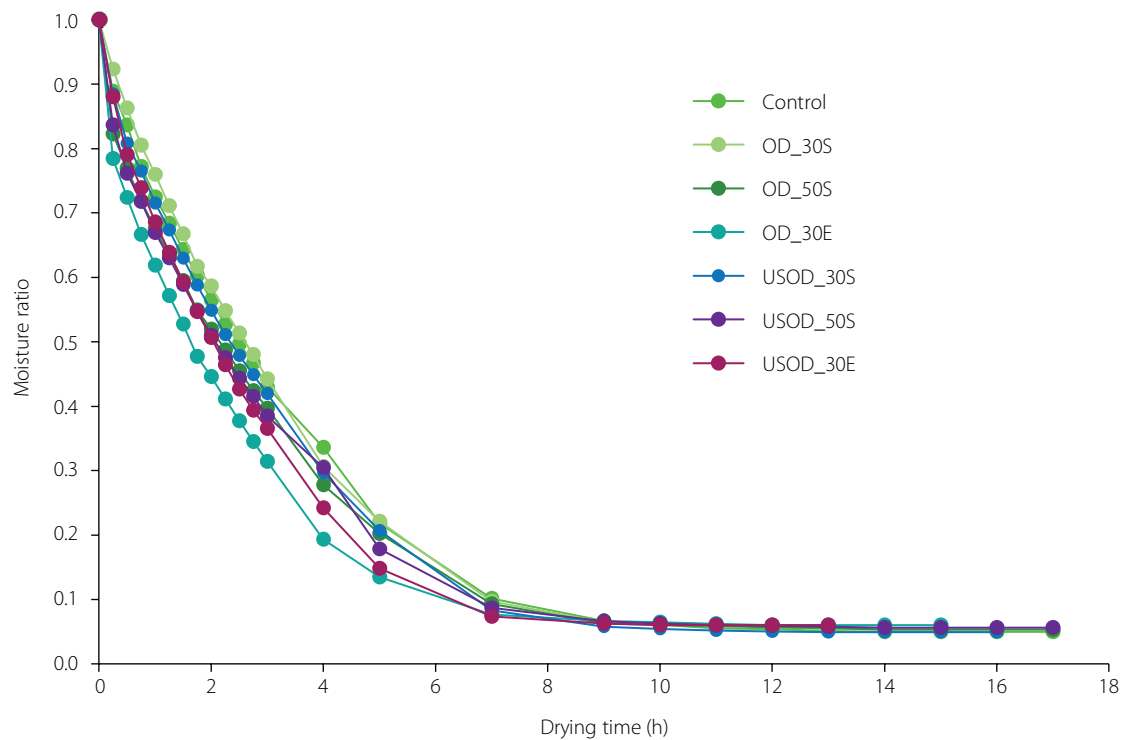


Figure 1. Experimental drying curves at 60°C for red-fleshed dragon fruit (RFDF) slices subjected to different osmotic dehydration pretreatments. Control, sample dried without osmotic dehydration (OD) or ultrasound-assisted osmotic dehydration (USOD) pretreatment; OD_30S, OD_50S, and OD_30E, samples pretreated by OD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by USOD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively.

Table 3. Statistical parameters of different drying models fitted to the experimental data for drying of red-fleshed dragon fruit (RFDF) slices pretreated by osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD).

RFDF slice	Henderson and Pabis model		Page model		Logarithmic model		Midilli-Kucuk model	
	R ²	RMSE	R ²	RMSE	R ²	RMSE	R ²	RMSE
Control	0.9963	0.0208	0.9960	0.0206	0.9971	0.0170	0.9976	0.0153
OD_30S	0.9963	0.0210	0.9964	0.0210	0.9968	0.0183	0.9986	0.0121
OD_50S	0.9928	0.0283	0.9933	0.0247	0.9946	0.0218	0.9951	0.0206
OD_30E	0.9883	0.0357	0.9917	0.0258	0.9922	0.0244	0.9940	0.0214
USOD_30S	0.9959	0.0213	0.9955	0.0216	0.9965	0.0185	0.9971	0.0169
USOD_50S	0.9921	0.0302	0.9932	0.0248	0.9944	0.0220	0.9951	0.0205
USOD_30E	0.9952	0.0225	0.9951	0.0213	0.9964	0.0178	0.9969	0.0166

Control, sample dried without OD or USOD pretreatment; OD_30S, OD_50S, and OD_30E, samples pretreated by OD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by USOD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; R², coefficient of determination; RMSE, root mean square error.

Table 4. Parameters of the Midilli–Kucuk model and predicted drying time of red-fleshed dragon fruit (RFDF) slices pretreated by osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD) to reach moisture content of 22 g/100 g.

RFDF slice	<i>a</i>	<i>k</i>	<i>n</i>	<i>b</i>	Drying time (h)
Control	0.9640	0.2667	1.0572	0.0023	12.62
OD_30S	0.9736	0.2386	1.1507	0.0031	11.41
OD_50S	0.9483	0.3305	0.9493	0.0022	12.38
OD_30E	0.9600	0.4513	0.8663	0.0030	10.63
USOD_30S	0.9595	0.2791	1.0596	0.0023	11.65
USOD_50S	0.9552	0.3456	0.9349	0.0024	12.20
USOD_30E	0.9682	0.3372	1.0297	0.0033	9.92

Control, sample dried without OD or USOD pretreatment; OD_30S, OD_50S, and OD_30E, samples pretreated by OD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by USOD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; *a*, *b*, *k* and *n*, empirical model constants.

as a function of time, are presented in **Figure 1**. In all cases, MR decreased progressively over time, with a rapid reduction during the first 3 h followed by a slower decline. The trend followed the typical drying curve of agricultural products [Onwude *et al.*, 2016], where an initial slope of decrease occurred as pure water evaporated, followed by falling rate periods, where moisture removal was controlled by combined external-internal resistances. Afterward, the curve reached a plateau when steady-state equilibrium had been achieved. These observations were consistent with previous findings regarding dragon fruit drying [Bassey *et al.*, 2022]. Among the samples, the fastest MR reduction was observed for OD_30E and USOD_30E during the first 5 h of drying (**Figure 1**). The infiltration of erythritol during osmotic dehydration was reported to expand the intercellular space, modifying the macro-texture [Wang *et al.*, 2025], which could facilitate the moisture diffusion and evaporation during drying.

To characterize the drying behavior, MR data were fitted to four commonly used drying models (**Table 1**), which are widely applied to agricultural products [Akpınar, 2006; Alara *et*

al., 2019]. Model performance was assessed by using the coefficient of determination (R²) and root mean square error (RMSE), where higher R² and lower RMSE reveal better goodness of fit. As shown in **Table 3**, the Midilli-Kucuk model provided the best fit, yielding the highest R² values (>0.994) and the lowest RMSE (0.0121–0.0214), confirming its suitability for describing the drying kinetics of RFDF slices. The corresponding model parameters (*a*, *k*, *n*, and *b*) are presented in **Table 4** and varied among treatments, indicating that drying behavior was influenced by pretreatment method, sugar concentration, and sweetener type. The agreement between predicted and experimental data was illustrated in **Figure S1** in Supplementary Materials.

Consequently, the Midilli-Kucuk model was selected to predict the drying time required for 7.5 mm-thick slices to reach a target final moisture content of 22 g/100 g in a convective dryer. The results provided in **Table 4** showed that the drying durations of OD_30S and OD_30E samples were significantly reduced compared to the control, with reductions of 9.6% and 15.8%, respectively. Notably, although OD_50S exhibited higher WL

than the other samples during pretreatment, *i.e.*, a lower initial moisture content prior to drying, its predicted drying time was longer and comparable to that of the untreated sample. The prolonged drying duration was similarly observed for the sample USOD_50S. This behavior could be attributed to severe structural modifications induced by excessive solute uptake, which may increase internal resistance to moisture diffusion by partially blocking microchannels within the tissue, hence reducing drying rates during subsequent hot-air drying [Fernandes *et al.*, 2009]. Similar effects of high solute impregnation on tissue structure and mass transfer limitations have also been reported in a recent study [Cheng *et al.*, 2023]. Overall, these findings suggest that a reasonable solute content used in osmotic dehydration was required to provide better effectiveness in reducing drying time.

On the other hand, USOD shortened the drying process despite a short pretreatment time of only 10 min (Table 4). The drying durations of USOD_30S and USOD_30E were reduced by 7.7% and 21.4%, respectively, compared to the control. This improvement was likely due to ultrasound-induced structural modifications, such as the formation of microscopic channels that could enhance water diffusivity and facilitate moisture removal during drying. Similar findings have been reported for persimmon, where ultrasound-assisted osmotic pretreatment significantly reduced drying time [Bozkir & Ergün, 2020; Bozkir *et al.*, 2019]. Among all treatments, USOD_30E exhibited the shortest drying duration, which may be attributed to the combined positive effects of ultrasound and erythritol as discussed above.

■ Effects of osmotic dehydration and ultrasound-assisted osmotic dehydration pretreatments on the quality attributes of semi-dried red-fleshed dragon fruit

■ Betacyanin content, total phenolic content, and antioxidant capacity

The betacyanin content and total phenolic content (TPC) of semi-dried RFDF slices are shown in Table 5. The results indicate that the control sample retained the highest levels of both betacyanins and phenolics, despite having the longest drying

duration. In contrast, the OD-pretreated samples exhibited an insignificant ($p \geq 0.05$) difference among themselves but showed a reduction of 18.8–21.3% in betacyanin content and 7.6–9.1% in TPC compared to the control. This decline may be attributed to the leaching of water-soluble bioactive compounds into the osmotic solution during the 2-h immersion, particularly betacyanin due to its high solubility. Furthermore, the prolonged osmotic dehydration time and exposure to light may accelerate the degradation of betacyanins [de Jesus Junqueira *et al.*, 2018].

The USOD_30S and USOD_50S semi-dried samples exhibited higher retention of betacyanins and phenolics than their respective OD samples, and only slightly lower than the control (Table 5). This enhancement was primarily linked to the significantly shorter immersion time of USOD (10 min) compared to OD (120 min), which limited the leaching of bioactive compounds. Interestingly, the USOD_30E sample showed no significant difference in betacyanin content and TPC compared to the control. This retention could be explained by the synergistic effect of the rapid dehydration facilitated by ultrasound and the protective role of erythritol, both of which could contribute to the shorter subsequent convective drying duration. These results demonstrate that erythritol may offer advantages over sucrose in USOD treatments. These findings were consistent with those reported by Kroehnke *et al.* [2021], who observed greater carotenoid retention in dried kiwifruit when sugar alcohols were used in OD or USOD prior to ultrasound-assisted drying.

The antioxidant capacity of semi-dried RFDF samples, measured *via* DPPH and reducing power assays, followed a trend consistent with the retention of betacyanins and phenolics. Particularly, the control sample exhibited the highest antioxidant capacity, while the OD-pretreated samples exhibited significantly lower values. In contrast, the USOD pretreatments allowed for significantly better preservation of antioxidant potential of dried slices; specifically, USOD_30E displayed DPPH radical scavenging activity and reducing power (39.94 and 5.62 mg AAE/100 g, respectively) comparable to the control ($p \geq 0.05$). Pearson correlation analysis was performed to further elucidate these

Table 5. Betacyanin content, total phenolic content (TPC), and antioxidant capacity of semi-dried red-fleshed dragon fruit (RFDF) slices pretreated by osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD).

RFDF slice	Betacyanin content (mg/100 g)	TPC (mg GAE/100 g)	DPPH radical scavenging activity (mg AAE/100 g)	Reducing power (mg AAE/100 g)
Control	13.06±0.06 ^a	47.68±0.30 ^a	40.95±0.52 ^a	5.74±0.09 ^a
OD_30S	10.41±0.13 ^{de}	43.35±0.41 ^{de}	35.99±0.37 ^d	4.64±0.14 ^{de}
OD_50S	10.28±0.15 ^e	42.54±1.28 ^e	35.35±1.04 ^d	4.63±0.17 ^e
OD_30E	10.61±0.11 ^d	44.07±0.25 ^d	36.42±0.32 ^d	4.84±0.07 ^d
USOD_30S	12.76±0.15 ^{bc}	46.64±0.29 ^{bc}	39.03±1.16 ^{bc}	5.45±0.10 ^{bc}
USOD_50S	12.62±0.13 ^c	45.99±0.34 ^c	37.85±0.39 ^c	5.30±0.09 ^c
USOD_30E	12.93±0.09 ^{ab}	47.09±0.39 ^{ab}	39.94±1.02 ^{ab}	5.62±0.12 ^{ab}

Values are presented as mean ± standard deviation ($n=3$). Values in the same column with different letters are significantly different ($p < 0.05$). Control, sample dried without OD or USOD pretreatment; OD_30S, OD_50S, and OD_30E, samples pretreated by OD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by USOD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; GAE, gallic acid equivalent; AAE, ascorbic acid equivalent.

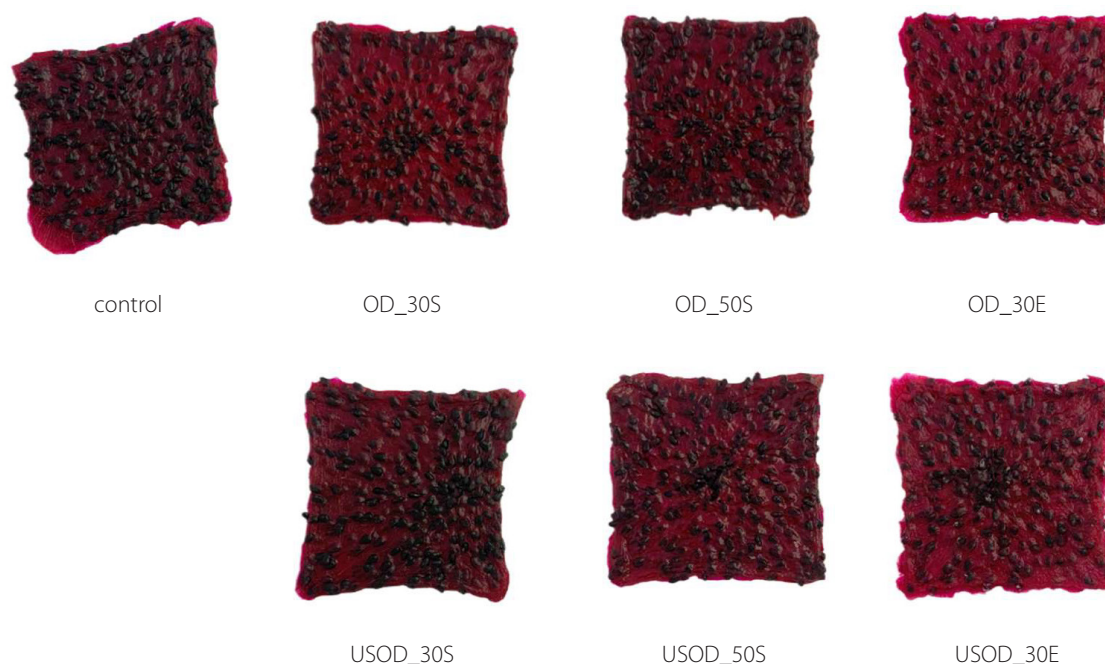


Figure 2. Appearance of semi-dried red-fleshed dragon fruit (RFDF) slices subjected to different osmotic dehydration pretreatments. Control, sample dried without osmotic dehydration (OD) or ultrasound-assisted osmotic dehydration (USOD) pretreatment; OD_30S, OD_50S, and OD_30E, samples pretreated by OD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by USOD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively.

Table 6. Shrinkage ratio and color parameters of semi-dried red-fleshed dragon fruit (RFDF) slices pretreated by osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD).

RFDF slice	Shrinkage ratio (%)	L^*	a^*	b^*	ΔE
Control	28.28±0.11 ^a	28.23±1.85 ^d	26.79±0.95 ^{bc}	3.87±0.50 ^c	–
OD_30S	21.77±0.53 ^c	31.41±0.9 ^a	32.55±2.82 ^a	4.89±0.79 ^{bc}	6.90±1.60 ^a
OD_50S	24.87±1.46 ^b	30.82±1.21 ^{abc}	29.80±1.83 ^{ab}	3.66±0.96 ^c	4.16±0.90 ^b
OD_30E	22.52±1.17 ^c	31.05±0.08 ^{ab}	26.13±2.14 ^c	5.87±0.83 ^b	4.02±0.90 ^b
USOD_30S	17.75±0.42 ^{de}	28.93±0.80 ^{cd}	29.58±1.64 ^{ab}	3.86±1.00 ^c	3.53±0.80 ^b
USOD_50S	19.16±0.75 ^d	29.43±0.42 ^{bcd}	29.62±1.65 ^{ab}	4.44±0.20 ^c	3.52±1.00 ^b
USOD_30E	16.84±0.69 ^e	31.66±1.26 ^a	31.82±1.95 ^a	7.21±0.25 ^a	7.19±1.20 ^a

Values are presented as mean ± standard deviation ($n=3$). Values in the same column with different letters are significantly different ($p<0.05$). Control, sample dried without OD or USOD pretreatment; OD_30S, OD_50S, and OD_30E, samples pretreated by OD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by USOD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; L^* , lightness; a^* , red–green; b^* , yellow–blue; ΔE , total color difference.

relationships. The results reveal a remarkably strong positive correlation between betacyanin content and antioxidant capacity ($r=0.935$ for DPPH assay and $r=0.978$ for reducing power). Similarly, TPC showed a near-perfect correlation with reducing power ($r=0.992$) and DPPH radical scavenging activity ($r=0.978$). These high correlation coefficients indicate that betacyanins and phenolic compounds were major contributors to the antioxidant capacity of the dragon fruit.

■ Shrinkage ratio and color parameters

Shrinkage reflects structural changes arising from mass transfer between fruit tissue and the drying medium and is strongly influenced by the rate and extent of moisture removal [Mahiuddin *et*

al., 2018]. **Figure 2** provides the photographs of semi-dried RFDF slices, which could visualize their shrinkage after drying. Their shrinkage ratios relative to fresh samples are shown in **Table 6**. The control sample exhibited significantly ($p<0.05$) higher shrinkage ratio (28.28%) than all pretreated samples, which could be attributed to its high initial moisture content prior to drying, with water distributed across intracellular, intercellular, and cell wall environments [Khan & Karim, 2017]. During drying, the removal of intracellular water reduced turgor pressure and weakened cellular structure, leading to tissue collapse. This effect was further exacerbated by prolonged drying (12.62 h at 60°C, **Table 4**), which increased structural deformation and resulted in greater shrinkage.

All pretreated samples showed reduced shrinkage, indicating improved structural stability during drying. Notably, USOD samples resulted in greater volume retention than the OD-pretreated RFDF slices, with USOD_30E showing the lowest shrinkage ratio (16.84%). This improvement could be attributed to ultrasound-induced structural modifications, including the formation of microchannels and the sponge effect associated with acoustic cavitation [Hamed *et al.*, 2018]. These changes likely facilitated a more uniform redistribution of internal moisture and solutes within the tissue, hence reducing localized stress and minimizing structural deformation during subsequent convective drying. In addition, the shorter drying time of the USOD-treated samples, particularly USOD_30E (9.92 h), may limit prolonged thermal and mechanical loads, hence reducing damage of tissue structures. Furthermore, the relatively higher solid gain in USOD_30E (4.14%) may contribute to partial filling of intercellular spaces, providing mechanical support that could limit tissue collapse as moisture was removed.

The color parameters (L^* , a^* , b^*) and the total color difference (ΔE) of semi-dried RFDF, which could provide essential information regarding the impact of pretreatments on visual quality, are shown in **Table 6**. The color is governed by various factors such as the retention of pigments (*i.e.*, betacyanins) [Gokhale & Lele, 2014] after osmotic dehydration and drying, and the chemical changes over drying (*e.g.*, Maillard reaction) [Chen *et al.*, 2024b]. In addition, as illustrated in **Figure 2**, a greater extent of sample shrinkage could lead to a higher quantity of black seeds *per* surface area, hence significantly influenced color measurement. In our study, while the control sample retained the highest amount of betacyanin (red pigments), it exhibited relatively lower a^* and L^* values compared to most pretreated samples. This was due to the fact that color perception of the control was also influenced by its high shrinkage ratio (28.28%). As shown in **Figure 2**, high shrinkage led to a “concentration effect” of the black seeds and the pigmented tissue, resulting in a darker, less vibrant appearance. In contrast, the USOD_30E sample maintained the highest a^* (31.82) and L^* (31.66) values, likely due to its high betacyanin retention (12.93 mg/100 g) and significantly lower shrinkage (16.84%), which may help maintain the natural brightness of the flesh.

In addition, the type of osmotic agent and the resulting solid gain also significantly influenced the lightness (L^*) and total color difference (ΔE). The samples treated with a higher concentration of sucrose, such as OD_50S and USOD_50S, showed higher SG values (4.00–4.44%) (**Table 2**). The presence of sucrose, a precursor for reducing sugars upon inversion, may slightly promote the Maillard reaction during drying at 60°C, leading to a more muted color profile. Conversely, erythritol, a sugar alcohol, is chemically stable and does not participate in Maillard browning. This attribute, combined with the shortest drying duration of USOD_30E (**Table 4**), may have limited thermal degradation and browning, resulting in the highest L^* , a^* and b^* values (**Table 6**). Moreover, a notable correlation was observed between

the shrinkage ratio and the visual distribution of seeds (**Figure 2**). As the fruit tissue collapsed, the density of black seeds *per* unit of surface area increased. This “seed crowding” masked the red pigments of the pulp, contributing to the lower a^* values observed in the control and OD_30E. The USOD treatments may alleviate this effect through ultrasound-induced structural modifications, which could help maintain tissue integrity during drying. As a result, the seeds appeared less densely distributed on the product surface, allowing the vibrant red color of the pulp to remain more visually prominent.

The total color difference (ΔE) represents the magnitude of the color shift in the pretreated samples relative to the control (**Table 6**). An ΔE value exceeding 3.5 indicates a clear difference that is easily recognizable by the untrained human eye [Mokrzycki & Tatol, 2011]. In this study, all treatments surpassed this threshold, with OD_30S and USOD_30E exhibiting the highest values (6.90 and 7.19, respectively). These high ΔE values suggested a substantial departure from the appearance of the control sample. Rather than indicating quality loss, these shifts reflected a significant enhancement in color quality, moving from the dark, brownish-red appearance of the control toward a more vibrant, saturated red profile. These results suggest that the combination of ultrasound and osmotic agents, particularly erythritol, may influence the optical properties of the dried RFDF, resulting in a product that was visually distinct and significantly brighter than the untreated one.

■ Sensory attribute scores

The sensory perception of semi-dried RFDF slices is a multidimensional attribute influenced by the fruit’s visual appearance, structural integrity, and the balance of flavors induced by osmotic agents. The mean scores for color, texture, taste, and overall acceptability are shown in **Table 7**. The sensory scores for color were highest for OD_30E (8.16) and USOD_30E (8.04), which significantly outperformed the control (5.78) ($p < 0.05$). These results strongly correlated with the objective colorimetric data in **Table 6**, where these treatments exhibited the high L^* (lightness), a^* (redness) (for USOD_30E), and b^* (yellowness) values. This result suggests that panelists preferred the vibrant, bright crimson hue of the erythritol-treated samples over the dark, brownish-red appearance of the control. The lower score for the control was likely a result of the high shrinkage ratio and prolonged drying time, which led to a denser distribution of seeds and a less appealing, shriveled surface.

Regarding texture, most pretreated samples received significantly higher scores ($p < 0.05$) than the control. The lowest score of the control (5.66) was attributed to the extensive shrinkage during the prolonged convective drying process. This resulted in a tough, leather-like texture that was less appealing to the panelists. Similarly, the OD_50S sample also received a relatively low texture score (6.34) due to its second highest shrinkage ratio (**Table 6**). In contrast, all other pretreated samples, including both OD and USOD treatments at 30°Brix and USOD at 50°Brix,

Table 7. Sensory attribute scores of semi-dried red-fleshed dragon fruit (RFDF) slices pretreated by osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD).

RFDF slice	Color	Texture	Taste	Overall acceptability
Control	5.78±1.74 ^c	5.66±1.41 ^c	5.70±1.33 ^d	5.71±0.93 ^c
OD_30S	7.04±1.23 ^b	7.16±1.22 ^a	7.60±1.07 ^{ab}	7.27±0.73 ^a
OD_50S	7.14±1.21 ^b	6.34±0.82 ^{bc}	6.52±1.00 ^c	6.67±0.64 ^b
OD_30E	8.16±0.98 ^a	7.22±1.39 ^a	7.78±0.9 ^a	7.72±0.69 ^a
USOD_30S	7.46±1.25 ^{ab}	7.24±1.02 ^a	7.48±1.30 ^{ab}	7.39±0.72 ^a
USOD_50S	7.66±1.35 ^{ab}	7.00±1.39 ^{ab}	7.40±1.33 ^{ab}	7.35±0.97 ^a
USOD_30E	8.04±0.79 ^a	7.62±1.28 ^a	7.02±1.35 ^{bc}	7.57±0.74 ^a

Values are presented as mean ± standard deviation ($n=50$). Values in the same column with different letters are significantly different ($p<0.05$). Control, sample dried without OD or USOD pretreatment; OD_30S, OD_50S, and OD_30E, samples pretreated by OD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively; USOD_30S, USOD_50S, and USOD_30E, samples pretreated by USOD in sucrose (30°Bx), sucrose (50°Bx), and erythritol (30°Bx) solutions, respectively.

received higher scores ranging from 7.00 to 7.62. Notably, there were no statistically significant differences ($p\geq 0.05$) among these samples, indicating that they all provided a similarly desirable semi-dried texture. The use of lower sugar concentrations (30°Brix) or the application of ultrasound effectively preserved the fruit's structural integrity and reduced excessive toughening. The acoustic cavitation from ultrasound (USOD) could maintain a more porous internal structure as discussed above, resulting in a product that was perceived as softer and more tender compared to the conventionally dried control.

The sensory scores for taste followed a similar trend to those observed for texture (except USOD_30E). The control sample and OD_50S received the lowest taste scores, at 5.70 and 6.52, respectively. This suggested a possible correlation between physical deformation and flavor perception. The high shrinkage ratio of these two samples likely led to a condensed taste profile. While concentration could enhance flavor in certain food, the excessive structural collapse and hardening associated with these samples may hinder the pleasant release of flavors during mastication, leading to a less balanced sensory experience. In contrast, the other pretreated samples received higher taste scores ($p<0.05$) of 7.40 to 7.78, except USOD_30E. The infusion of osmotic agents at a moderate concentration may provide a desirable balance between the fruit's natural acidity and added sweetness. Interestingly, although USOD_30E exhibited the best color and lowest shrinkage, its taste score (7.02) was slightly lower than its OD counterpart. This might be attributed to its higher solid gain facilitated by ultrasound (Table 2), where the specific flavor profile of erythritol with its distinct cooling effect became more perceptible to the panelists, potentially deviating from the traditional sweetness expected in dried fruit products. As a result of the combined sensory perception of color, texture and taste, the overall acceptability of panelists towards the control and OD_50S was significantly lower ($p<0.05$) while the scores

for all other treated samples did not differ significantly ($p\geq 0.05$) (Table 7).

CONCLUSIONS

This study established that the integration of ultrasound-assisted osmotic dehydration (USOD) with erythritol served as an efficient technical solution for producing high-quality semi-dried RFDF slices. The experimental results demonstrated that the USOD method not only significantly improved mass transfer efficiency and reduced pretreatment time but also created a favorable condition for subsequent convective drying. A moderate solute concentration (30°Brix) yielded better drying efficiency than higher concentrations (50°Brix), as it could avoid severe structural modifications that increased internal resistance to moisture diffusion. Regarding quality attributes, erythritol provided better results and preserved the fruit's natural pigmentation. The USOD_30E treatment resulted in a product with good brightness and redness while maintaining betacyanin levels and antioxidant capacity comparable to the control. Furthermore, the minimization of the shrinkage ratio through ultrasound-induced acoustic cavitation helped disperse the black seeds across the surface, significantly improving both the visual appearance and the tender, semi-dried texture. As a result, the USOD pretreatment with 30°Brix erythritol solution could not only enhance processing efficiency by reducing total drying time but also helped meet sensory acceptability and preserve antioxidant properties. This protocol may represent a promising model for the processing of tropical fruits that are sensitive to heat and rich in natural pigments.

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CONFLICT OF INTERESTS

The authors declare no conflict of interests.

SUPPLEMENTARY MATERIALS

The following are available online at <https://journal.pan.olsztyn.pl/Effects-of-Erythritol-and-Ultrasound-Assisted-Osmotic-Dehydration-on-Drying-Kinetics,240491,0,2.html>; **Figure S1**. Experimental and predicted moisture ratio (MR) during drying of red-fleshed dragon fruit (RFDF) slices pretreated by osmotic dehydration (OD) and ultrasound-assisted osmotic dehydration (USOD) as described by the Midilli–Kucuk model: (A) Control without OD or USOD pretreatment; (B) OD in a sucrose (30°Bx) solution, OD_30S; (C) OD in a sucrose (50°Bx) solution, OD_50S; (D) OD in an erythritol (30°Bx) solution, OD_30E; (E) USOD in a sucrose (30°Bx) solution, USOD_30S; (F) USOD in a sucrose (50°Bx) solution, USOD_50S; and (G) USOD in an erythritol (30°Bx) solution, USOD_30E.

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