

ORIGINAL ARTICLE

Encapsulation of Andean Berry puree by ionic gelation: Drying kinetics and bioactive retention using Refractance Window® Technology

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Abstract

Andean blueberry (mortiño) (*Vaccinium meridionale* Swartz), valued for its high vitamin and bioactive content, was subjected to ionic gelation encapsulation (IGE) using amidated low-methoxyl pectin (3% to 5%) crosslinked with calcium chloride, combined with Refractance Window® (RW) drying (70 °C to 90 °C) to evaluate physicochemical and functional properties. Results demonstrated increased diffusion coefficients at elevated temperatures and pectin concentrations, specifically at 5%. Mortiño color remained stable across all treatments ($p > 0.05$). Water activity (a_w) values were consistently below 0.6 in all samples. Anthocyanin and total phenolic compounds (TPC) concentrations were significantly higher in IGE samples compared to non-encapsulated puree. These results demonstrated that combining ionic gelation with RW drying constitutes a high-potential technology for preserving physicochemical and bioactive properties in dehydrated mortiño puree.

Keywords: Encapsulation; *Vaccinium meridionale* Swartz; Low-methoxyl pectin; Anthocyanins; Color; Phenolic compounds.

Highlights

- Ionic gelation encapsulation combined with Refractance Window® preserves anthocyanins and total phenolic compounds of Andean berry puree
- Andean berry encapsulated by ionic gelation encapsulation and dried using Refractance Window® maintains a stable color
- High anthocyanin content is achieved with 5% pectin and 90 °C drying

1 Introduction

Andean blueberry (*Vaccinium meridionale* Swartz), also known as mortiño or agraz, is a wild fruit native to the high-altitude Andean regions of Colombia, Venezuela, Ecuador, and Peru. It is recognized for its intense purple color and high concentration of bioactive compounds (Quintero-Quiroz et al., 2019).



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This berry is a source of anthocyanins, flavonols, and phenolic compounds with significant potential benefits for human health (Howard et al., 2024; Quintero-Quiroz et al., 2019), thus qualifying as a functional food that distinguishes itself from other fruits and holds considerable potential for consumption. It is typically consumed fresh or processed into jellies, sauces, nectars, desserts, and other products (Howard et al., 2024; Quintero-Quiroz et al., 2019). Due to its high water activity, mortiño is highly perishable, rendering it susceptible to microbiological, enzymatic, and physicochemical deterioration. It limits its shelf life and commercial distribution in fresh form (Gallego-Peláez et al., 2021; Naranjo-Durán et al., 2021; Quintero-Quiroz et al., 2019). Therefore, this fruit requires preservation techniques that extend its shelf life without compromising its physicochemical and bioactive properties. One widely used approach is drying or dehydration, which reduces water activity (aw), inhibits microbial growth, and extends product shelf life. In the case of mortiño, this process preserves its physicochemical and functional characteristics, particularly its anthocyanin and phenolic compound content. However, not all drying technologies are optimal regarding final product quality, environmental footprint, or other factors. Thus, to prevent degradation of the product's physicochemical properties and bioactive compounds, encapsulation using wall materials such as food-grade biopolymers (e.g., pectin) must be employed to create an effective barrier against environmental factors (light and oxygen). In this context, ionic gelation encapsulation (IGE) represents a potential alternative for protecting mortiño pulp. This technique enables the formation of stable particles using biopolymers such as low-methoxyl pectin, which undergoes gelation in the presence of divalent ions (e.g., calcium chloride), forming three-dimensional networks that immobilize the core material and reduce its exposure to degrading factors. Characterized by employing moderate temperatures, this method minimizes the loss of heat-sensitive compounds (e.g., anthocyanins and phenolic compounds). It has been successfully utilized for encapsulating plant extracts and pulps to enhance their stability during processing and storage (Moura et al., 2018, 2019; Naranjo-Durán et al., 2021).

Particles produced through ionic gelation have a high moisture content, making a drying process essential to enhance their stability during storage and to broaden their potential applications and commercial viability (Santos et al., 2025; Silveira et al., 2023). Generally, particles obtained via ionic gelation are dried using either air drying or lyophilization. However, both methods have limitations. For instance, air drying often involves high temperatures that can degrade thermosensitive compounds such as betalains. Conversely, using lower temperatures for drying can extend the process to as long as 24 hours (Otálora et al., 2016). Lyophilization, on the other hand, can only be performed in batches and also requires higher energy consumption (Hosseini et al., 2013). Therefore, utilizing a less thermally aggressive drying technology that substantially preserves the physicochemical characteristics of mortiño serves as a complementary approach to encapsulation for maintaining its functional properties. One such technique is Refractance Window® drying (RW), characterized by short drying times and high retention of nutritional quality and bioactive compounds. Furthermore, it operates through conduction and infrared radiation mechanisms, enabling an efficient process with minimal thermal degradation of heat-sensitive compounds (Leiton-Ramírez et al., 2020). The purpose of this study was to assess the influence of IGE (using varying concentrations of amidated low-methoxyl pectin (ALMP) and calcium chloride) and processing temperature on the drying kinetics and physicochemical/functional quality of mortiño puree dried via RW technology.

2 Materials and methods

Mortiño fruits (*Vaccinium meridionale* Swartz) with °Brix levels between 9.3 and 10.5 were utilized. The fruits were procured from a market in Cali, Colombia. ALMP and calcium chloride were sourced from specialized chemical reagent suppliers.

2.1 Obtention of mortiño puree

The fruit was washed and disinfected, then liquefied using a commercial blender (Oster Pro 1200, USA) at medium speed (~9,000 rpm) for 1 min. Finally, the fruit was filtered with the help of a strainer to obtain the puree.

2.2 Encapsulation process by ionic gelation

The encapsulation of the mortiño puree by ionic gelation was performed following the methodology proposed by Otálora et al. (2016), with some modifications. The process was represented schematically (Figure 1), and details for production are described below. ALMP was used as a gelling agent, and calcium chloride (CaCl_2) served as a cross-linking agent. Initially, 3% and 5% (w/w) pectin solutions were prepared in distilled water at 25 °C. These solutions were homogenized using a constant magnetic stirrer (Polco, USA) for 30 minutes to achieve a lump-free consistency. For gelation, the mortiño puree was mixed with the prepared pectin solution in a 2:1 (w/w) ratio (mortiño puree to pectin solution) while stirring continuously for 15 minutes at 25 °C. The homogenized mixture was then transferred into a 60-ml syringe fitted with a 2.5 mm diameter catheter tip. The mixture of mortiño puree and pectin solution was added dropwise into a 3% (w/w) CaCl_2 solution, with constant stirring for 30 minutes. The resulting particles were then collected, rinsed with distilled water to remove excess CaCl_2 , and stored in Petri dishes at 4 °C. After crosslinking completion, gels were transferred onto Mylar sheets of the RW dryer for dehydration. Particle size was standardized using a digital vernier caliper (Mitutoyo, Japan), with gels measuring approximately 2 mm in diameter selected to ensure homogeneous drying distribution, process reproducibility, efficient heat transfer during RW dehydration, and structural integrity preservation.

2.3 Refractance window drying

Encapsulated (PE) and non-encapsulated (PNE) mortiño puree samples underwent drying using a pilot-scale RW system (Cei Robots, Colombia). The apparatus consisted of a water tank overlaid with a 0.25-mm Mylar® polyester membrane (metalized polyethylene terephthalate) that was transparent to infrared radiation (Mosquera-Vivas et al., 2024; Puente-Díaz et al., 2020). Water was recirculated at 2.70 L/min and heated to three experimental temperatures (70 °C, 80 °C, and 90 °C) (Ayala-Aponte et al., 2021a; Shende & Datta, 2020). Both PE and PNE samples were positioned on the Mylar® membrane for dehydration. Moisture content (x_w) was determined gravimetrically at timed intervals to construct drying curves, expressed as moisture ratio (g water/g dry matter) versus processing time (min). Physicochemical properties (color, water activity (a_w), total phenolic content (TPC), and anthocyanins) of dehydrated samples were analyzed at ~10% moisture content (dry basis) to standardize comparisons.

2.4 Moisture content and water activity

The moisture content of the agraz puree and coacervates was gravimetrically determined using a vacuum oven at 60 °C and 10 kPa until a constant mass was achieved (Association of Official Analytical Chemists, 1995). Water activity (a_w) was measured at 25 °C with a temperature-controlled hygrometer (Acualab, CX-1, US), accurate to 0.001. Measurements were performed at the beginning and the end of each drying kinetic experiment.

2.5 Diffusion coefficient and activation energy

The effective diffusion coefficient (D_{ef}) was determined using the analytical solution of Fick's second law for an infinite slab geometry. This approach employs the moisture ratio (MR), defined by Equation 1.

$$MR = \frac{x_t - x_e}{x_0 - x_e} \quad (1)$$

Where: x_t , x_0 , and x_e represent moisture content (dry basis) at time t , initial state, and equilibrium, respectively.

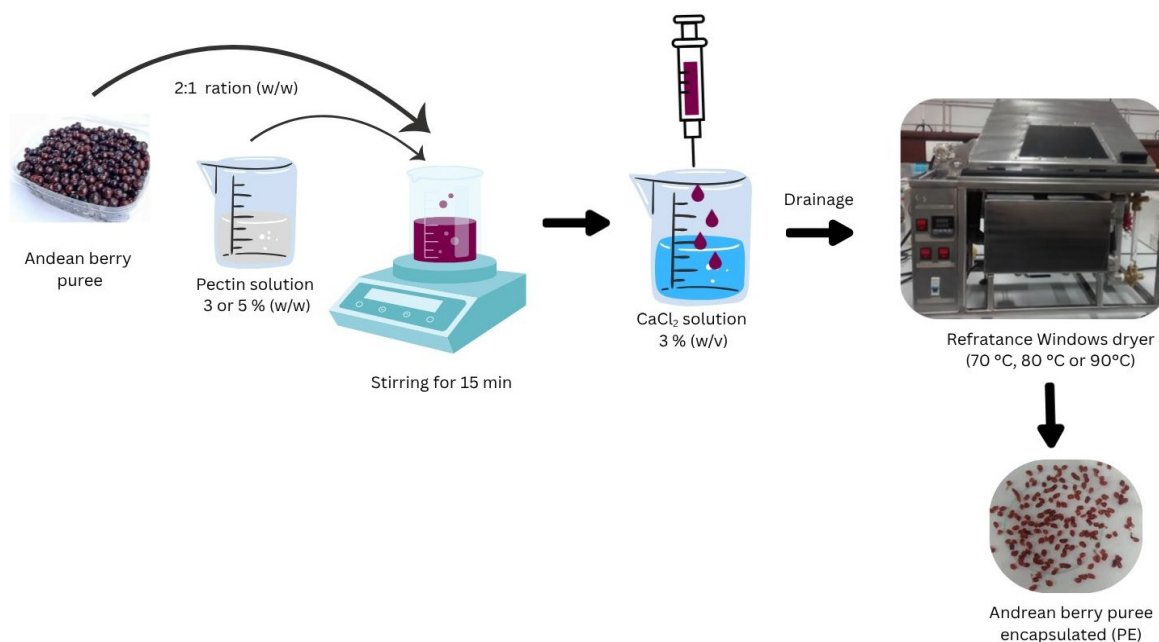


Figure 1. Schematic representation of the encapsulation by ionic gelation and drying in a refractance window of the Andean Berry puree.

Given the Refractance Window® system's lack of controlled air humidity, MR was simplified to Equation 2. The complete solution (Equation 3) was truncated to its first term (Equation 4), enabling (D_{ef}), calculation from processing time t and characteristic length (L). This approximation remains valid exclusively during the falling-rate period, where internal moisture diffusion dominates the drying mechanism.

$$MR = \frac{X_t}{X_o} \quad (2)$$

$$MR = \sum_{i=0}^{\infty} \frac{8}{(2i+1)^2} \cdot \exp\left(\frac{-D_{ef}(2i+1)\pi^2 t}{4L^2}\right) \quad (3)$$

$$MR = \frac{8}{\pi^2} \exp\left(\frac{-D_{ef}\pi^2 t}{4L^2}\right) \quad (4)$$

To calculate the activation energy (E_a), the Arrhenius equation was applied. This equation describes the temperature dependence of the moisture diffusion coefficient (D_{ef}) as a function of temperature (Equation 5).

$$D_{ef} = D_0 \exp\left(\frac{-E_a}{R(T+273.15)}\right) \quad (5)$$

Where D_{ef} is the effective moisture diffusivity, D_0 ($m^2 \cdot s^{-1}$) is the Arrhenius pre-exponential factor, R is the universal gas constant ($kJ \cdot kmol^{-1} \cdot K^{-1}$), T ($^{\circ}C$) is the temperature, and E_a ($kJ \cdot mol^{-1}$) is the activation energy.

2.6 Anthocyanin content

Anthocyanin content was measured following the methodology proposed by Martynenko & Chen (2016). Monomeric anthocyanins were extracted using an acidified methanol:acetone: water solution (2:2:1 v/v) containing 0.1% formic acid. Quantification employed the differential pH spectrophotometric method, with sample pH adjusted to 1.0 using 0.025 M potassium chloride buffer and 4.5 using 0.04 M sodium acetate buffer.

Absorbance measurements at 520 and 700 nm were conducted using an Ultraviolet-visible (UV-VIS) spectrophotometer (UV-3000, Mapada Instruments Co., Ltd., Shanghai, China). The total anthocyanin content was calculated according to Equation 6. All analyses were performed in triplicate.

$$\text{Total Anthocyanin (mgC3G)} = \frac{A \cdot MW \cdot DF \cdot 1000}{\epsilon \cdot l} \quad (6)$$

Where ϵ is the molar extinction coefficient ($26.900 \text{ L} \cdot \text{mol}^{-1} \cdot \text{cm}^{-1}$ for cyanidin-3-O-glucoside, C3G). l : is the cuvette path length (1 cm). MW is the molecular weight of C3G ($449.2 \text{ g} \cdot \text{mol}^{-1}$). DF is the dilution factor, and A represents absorbance (Equation 7):

$$A = (A_{pH\ 1.0} - A_{pH\ 4.5})_{525nm} - (A_{pH\ 1.0} - A_{pH\ 4.5})_{700nm} \quad (7)$$

2.7 Total phenolic compound content

Samples were homogenized in methanol: water solution (50:50 v/v) and reacted with Folin-Ciocalteu reagent. Absorbance was measured at 725 nm using an UV-VIS spectrophotometer (UV-3000, Mapada Instruments Co., Ltd., Shanghai, China). Quantification employed a gallic acid standard calibration curve (0–500 mg/L), with results expressed as milligrams of gallic acid equivalents per gram of dry sample (mg GAE/g). All analyses were performed in triplicate.

2.8 Statistical analysis

Experimental data were analyzed using analysis of variance (ANOVA) with Statgraphics Centurion XVI software, supplemented by Tukey's honestly significant difference (HSD) post hoc test for multiple comparisons. For all analyses, significant differences between means were determined at a 95% confidence level ($p < 0.05$).

3 Results and discussion

3.1 Drying kinetics

Figures 2 and 3 present the drying kinetics at different temperatures for non-encapsulated mortiño puree (PNE) and mortiño puree encapsulated (PE) with pectin at 3% and 5% concentrations and calcium chloride, respectively. The initial moisture content of the fresh, PNE samples was $7.93 \pm 0.11 \text{ g water/g dry solid (d.b)}$. This moisture content is within the mortiño moisture levels reported by Martín-Gómez et al. (2020) and Rurush et al. (2022). Conversely, the initial moisture content of PE with 3% and 5% pectin was 16.23 ± 0.16 and $14.20 \pm 0.15 \text{ g water/g dry solid (dry basis)}$, respectively. ANOVA revealed that temperature exerted a significant effect ($p < 0.05$) on moisture content for both PE and PNE samples. All treatments demonstrated reduced drying times with increasing temperature to achieve specific moisture levels, with 90°C requiring the shortest duration and 70°C the longest. For PNE to reach 10% moisture (dry basis), drying times of 85, 96, and 125 minutes were required at 90°C , 80°C , and 70°C , respectively. A similar trend was observed for PE with 3% and 5% pectin, consistent with the established inverse relationship between temperature and processing time reported in drying literature (Ayala-Aponte et al., 2021a; Pinheiro et al., 2022). This reduction in drying time due to temperature elevation can be attributed to the increased thermal gradient between the water bath (heat source) and the PNE and PE samples, which accelerates water removal from the food matrix through enhanced heat transfer. It has been established that higher temperatures intensify heat conduction, evaporation rates, and migration of moisture from the product's interior to its surface (Beigi, 2019). When comparing the PNE treatments (Figure 2) and the PE treatments (3% and 5%) (Figure 3), significant differences ($p < 0.05$) were observed in drying times. It is noted that the PE samples had the shortest drying times compared to the PNE samples. These results were not as expected, since the ionic gelation formed by the pectin and calcium chloride is an additional barrier. Two factors can explain this behavior:

the PNE samples may have developed a crusting phenomenon during drying, which is the formation of a hard layer on their surface due to the concentration of their solutes as the water is eliminated. On the other hand, ionic gelation forms a porous structure that facilitates water diffusion during the drying process. Furthermore, rapid evaporation of water from the surface can lead to high porosity and crack formation (Santos et al., 2025; Silveira et al., 2023). Regarding the 3% and 5% pectin concentrations, significant differences ($p < 0.05$) were observed in moisture loss in the ionic gelation of the PE treatments (Figure 3). The 5% PE samples had shorter drying times than the 3% samples.

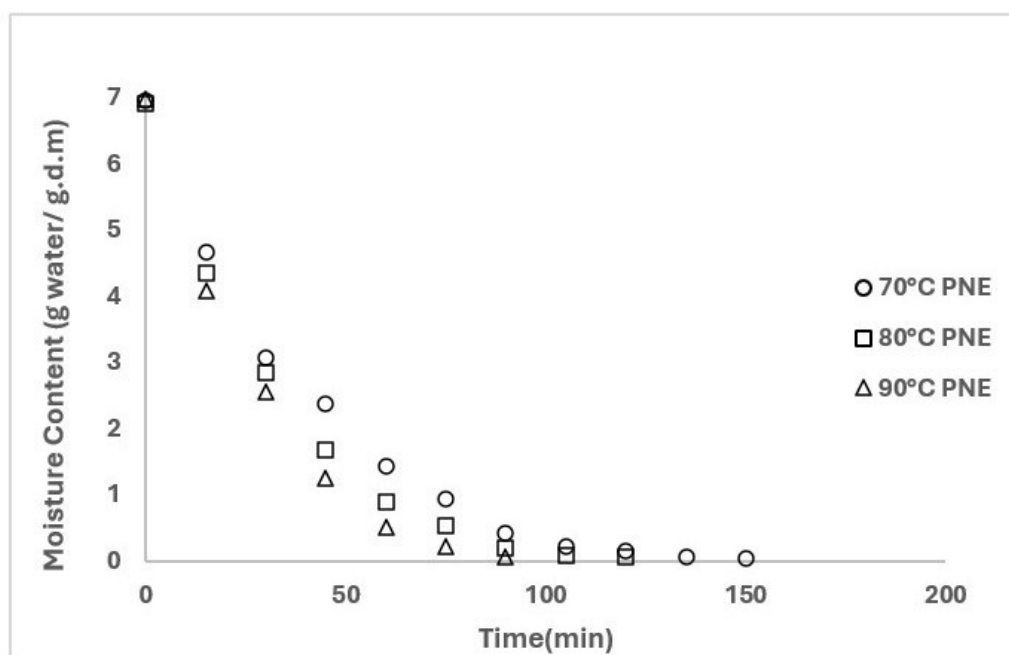


Figure 2. Drying curves of non-encapsulated mortiño puree (PNE) at 70, 80, and 90 °C using Refractance Window® drying.

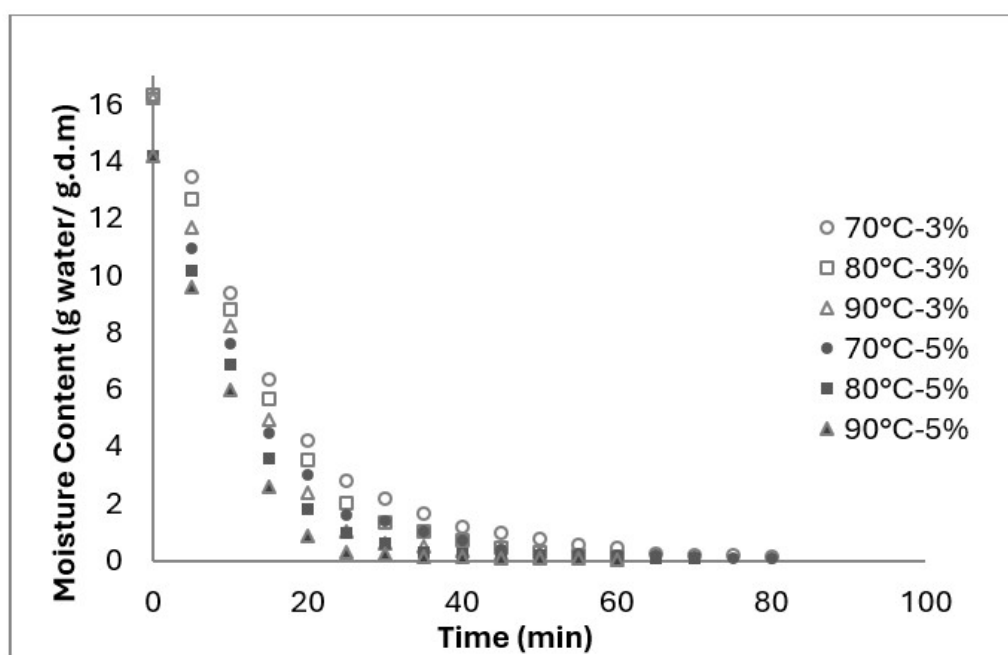


Figure 3. Drying curves of mortiño puree encapsulated (PE) with 3% and 5% pectin at 70, 80, and 90 °C using Refractance Window® drying.

3.2 Water diffusion coefficient and activation energy

Table 1 presents the effective moisture diffusivity (D_{ef}) values for PE and PNE mortiño samples dried via Refractance Window® (RW). ANOVA revealed significant effects ($p < 0.05$) of encapsulation treatment, temperature, and pectin concentration on diffusivity. Encapsulated treatments (3%-PE and 5%-PE) exhibited higher values than PNE samples across all temperatures. Ionic gelation-encapsulated samples at 3% pectin concentration showed D_{ef} ranging from 2.43 to 2.85 $\times 10^{-10}$ m²/s, while 5% PE ranged from 2.41 to 2.36 $\times 10^{-10}$ m²/s. In contrast, PNE samples demonstrated lower diffusivity from 1.49 to 2.10 $\times 10^{-10}$ m²/s. These values align with the typical moisture diffusivity range for food drying 10⁻¹¹ to 10⁻⁹ m²/s (Beigi, 2019). Furthermore, Pereira Silveira et al. (2023) reported that pectin beads produced using ionic gelation exhibited a value of 3.67 $\times 10^{-10}$ m²/s. This behavior aligns with the earlier drying kinetics, where PE treatments exhibited accelerated moisture removal rates, and this behavior also increased with rising temperatures in both PE and PNE treatments. Elevated D_{ef} values at higher temperatures are attributed to enhanced kinetic energy and molecular mobility of water molecules. This phenomenon accelerates molecular displacement, thereby facilitating more efficient moisture diffusion through the product matrix (Xiao et al., 2010).

Furthermore, elevated temperatures reduce water viscosity, enhancing molecular mobility through the material's capillary networks. This phenomenon accelerates moisture diffusion by facilitating the transport of water molecules within the product matrix (Sabat et al., 2018).

This identical temperature-dependent behavior has been documented in other food dehydration processes, exemplified by banana (Zhou et al., 2022) and Aloe vera drying (Ayala-Aponte et al., 2021b). Regarding pectin concentration, higher-concentration treatments (5%-PE) exhibited greater D_{ef} values than 3%-PE. This behavior aligns with the drying kinetics, where elevated pectin concentrations accelerated moisture release.

Table 1. Effective Moisture Diffusivity (D_{ef}) Values for Encapsulated (PE) and Non-Encapsulated (PNE) Mortiño Puree Dried via Refractance Window® (RW).

Treatments	Temperature (°C)	D_{ef} (m ² /s)
PNE	70	1.49 $\times 10^{-10}$
	80	1.80 $\times 10^{-10}$
	90	2.10 $\times 10^{-10}$
3%-PE	70	2.33 $\times 10^{-10}$
	80	2.58 $\times 10^{-10}$
	90	2.85 $\times 10^{-10}$
5%-PE	70	2.41 $\times 10^{-10}$
	80	3.08 $\times 10^{-10}$
	90	3.68 $\times 10^{-10}$

Table 2 demonstrates that activation energy (E_a) values for PNE and PE treatments ranged from 8.24 and 17.79 kJ/mol. These values align with typical E_a ranges reported for food systems (Yamchi et al., 2024). ANOVA indicated significant differences ($p < 0.05$) in E_a attributable to both encapsulation (between PNE and PE) and pectin concentration effects.

Table 2. Activation energy (E_a) values for non-encapsulated (PNE) and encapsulated (PE) treatments.

Pectin Concentration	E_a (kJ/mol)
PNE	17.79 ^a
PE-3%	10.26 ^b
PE-5%	8.24 ^c

Means within the same column that share the same lowercase letter did not exhibit significant differences at $p \leq 0.05$, according to Tukey's test.

The PNE treatments exhibited the highest E_a , 17.79 kJ/mol, while PE samples showed the lowest values. Notably, the 5% pectin concentration yielded the minimal E_a 8.24 kJ/mol. It indicates that higher ionic gelation concentrations (5% pectin) reduce the energy required for water extraction. The activation energy represents the minimum energy water molecules must possess to initiate diffusion through the food matrix during drying. Therefore, the lower E_a observed in the 5%-PE treatment indicates that this material wall provides a greater protective effect, making the matrix less susceptible to changes by temperature (Ling et al., 2015).

3.3 Water activity

Table 3 presents water activity a_w values for PNE and PE samples in the fresh state and after RW at 0.100 ± 0.002 g water/g dry solid (10% d.b). Total color change (ΔE) between fresh and dried samples is concurrently reported. Fresh mortiño puree exhibited a_w values of 0.9532–0.9916 (PNE and PE), attributable to high initial moisture content (7.93 ± 0.11 g water/g dry solid, d.b.), consistent with findings by Vivas-Álzate et al. (2025) for untreated mortiño. Post-drying a_w reduction (0.4331–0.5148) confirms storage stability against microbial proliferation, as most spoilage organisms require $a_w > 0.61$ for metabolic activity due to restricted water availability below this threshold.

Table 3. Water activity (a_w) and total color change (ΔE) values of encapsulated (PE) and non-encapsulated (PNE) mortiño puree dried by Refractance Window®.

Pectin Concentration	Temperature (°C)	a_w Fresh samples	a_w Dried samples (10%, db)	ΔE (Measured between fresh and dry samples)
PNE	70	$0.9641^a \pm 0.008$	$0.4681^d \pm 0.009$	$3.88^a \pm 0.04$
	80	$0.9578^a \pm 0.010$	$0.4831^b \pm 0.007$	$3.75^a \pm 0.05$
	90	$0.9532^a \pm 0.009$	$0.5148^a \pm 0.010$	$3.59^a \pm 0.03$
PE 3%	70	$0.9916^b \pm 0.007$	$0.4342^c \pm 0.009$	$2.95^b \pm 0.04$
	80	$0.9876^b \pm 0.009$	$0.4331^c \pm 0.010$	$3.28^{ba} \pm 0.05$
	90	$0.9847^b \pm 0.008$	$0.4942^b \pm 0.008$	$2.92^b \pm 0.02$
PE 5%	70	$0.9725^c \pm 0.009$	$0.4929^b \pm 0.010$	$2.60^c \pm 0.03$
	80	$0.9703^c \pm 0.010$	$0.4772^{bd} \pm 0.007$	$2.55^c \pm 0.04$
	90	$0.9782^c \pm 0.008$	$0.4939^b \pm 0.009$	$2.31^c \pm 0.03$

The results are presented as the mean ($n = 3$) $\pm$ standard deviation. Means within the same column that share the same lowercase letter did not exhibit significant differences at $p \leq 0.05$, according to Tukey's test (measured between fresh and dry samples).

Regarding total color change (ΔE), temperature exhibited no significant influence ($p > 0.05$), whereas encapsulation and pectin concentration significantly impacted results ($p < 0.05$). All treatments demonstrated low ΔE values (2.31–3.88), indicating excellent color retention in hue, chroma, and luminosity. In fact, fresh mortiño purée showed narrow ranges of L^* (11.47–12.20), a^* (0.14–0.25), and b^* (−0.65 to −0.44), while after refractance window drying, the values ranged from L^* (9.92–11.09), a^* (−1.03 to −0.55), and b^* (−1.23 to −1.71). These small variations confirm that the differences observed were minimal and consistent with the low ΔE values obtained. These changes represent noticeable differences to human observers (Ayala-Aponte et al., 2021b), confirming minimal visual degradation. PNE and PE mortiño puree maintained their reddish-purple hue during RW drying, demonstrating exceptional optical stability with this dehydration technology.

Encapsulation significantly enhanced color retention, with PE samples exhibiting lower ΔE values than PNE. All pectin-calcium chloride treatments (3% and 5%) demonstrated superior protection against thermal color degradation during drying. It aligns with Pan et al. (2022), who reported improved anthocyanin stability in pectin-encapsulated mortiño, and Mora et al. (2023), who reported documenting similar protective effects with alternative encapsulation matrices. Although this study utilized encapsulated puree rather than pure anthocyanins, both works confirm encapsulation's critical role in shielding pigments from thermal degradation. Higher pectin concentrations (5%) yielded the lowest ΔE values (2.31–2.60), indicating enhanced color stability. This phenomenon is attributed to denser, more cohesive ionic gelation matrices that

reduce oxygen and light penetration, thereby limiting phenolic pigment degradation. The optimized barrier properties at 5% pectin concentration minimize photochemical and oxidative damage while improving pigment retention.

3.4 Anthocyanins and total phenolic compounds

Table 4 presents anthocyanin and total phenolic compound (TPC) concentrations for PE and PNE mortiño puree. Fresh samples contained 1.428 mg cyanidin-3-glucoside equivalents/g and 3.135 ± 0.689 mg GAE/g, consistent with Howard et al. (2024) and Garzón et al. (2010). ANOVA indicated significant effects ($p < 0.05$) of temperature and encapsulation on bioactive retention. Anthocyanin content increased with rising RW drying temperatures across all treatments, potentially due to shorter thermal exposure limiting degradation and enhanced bioaccessibility from thermally disrupted cellular structures that liberate bound compounds before degradation (Martín-Gómez et al., 2020). Other studies support this finding; for instance, Celli et al. (2016) also found a greater retention of anthocyanins when drying haskap berries at 95 °C. Encapsulation further improved retention, with PE samples showing 23% to 37% higher anthocyanins than PNE at 90 °C, as pectin matrices minimize oxidative loss through controlled compound release (Tan et al., 2023; Zielinska & Michalska, 2016).

Table 4. Total anthocyanin content and total phenolic compounds of unencapsulated puree (PNE) and puree encapsulated (PE) with 3% or 5% pectin.

Samples	Temperature (°C)	Anthocyanins (mg cyanidin-3-glucoside equivalents/g)	TPC (mg gallic acid equivalents/g)
PNE	70	$0.3420^g \pm 0.0700$	$3.7050^i \pm 0.7480$
	80	$0.4560^f \pm 0.0440$	$6.4190^h \pm 0.1630$
	90	$0.5916^d \pm 0.0103$	$7.3498^g \pm 0.0531$
PE 3%	70	$0.6150^e \pm 0.0400$	$11.8950^b \pm 0.3099$
	80	$0.8780^c \pm 0.0148$	$10.1115^d \pm 0.3882$
	90	$1.0150^b \pm 0.0160$	$8.4376^f \pm 0.0433$
PE 5%	70	$0.6129^e \pm 0.0133$	$13.9900^a \pm 0.9360$
	80	$0.8885^c \pm 0.0055$	$11.2840^c \pm 0.8570$
	90	$1.0490^a \pm 0.0163$	$9.4450^e \pm 0.1640$

The results are expressed as the mean ($n = 3$) $\pm$ standard deviation. Means with the same lowercase letter in the same column did not differ significantly at $p \leq 0.05$ according to Tukey's test.

According to Tan et al. (2023) and Zielinska & Michalska (2016), anthocyanin liberation is optimized when drying combines limited oxygen exposure with moderate cellular structural collapse. This mechanism was validated in convective blueberry drying by Zia & Alibas (2021), where temperature elevation from 50 °C to 90 °C increased anthocyanin content by 88% (4.04 to 7.61 mg/g). These findings demonstrate that controlled thermal energy enhances compound release without significant degradation through two synergistic effects: reduced oxidative stress via oxygen-limited environments and preferential disruption of cellular matrices that liberate bound pigments before thermal decomposition dominates.

Regarding TPC, elevated temperatures increased TPC concentrations in PNE samples but decreased them in encapsulated treatments (PE-3% and PE-5%). While high-temperature exposure rapidly inactivates degradative enzymes (e.g., polyphenol oxidase) and protects polyphenols from extended decomposition in brief processes, the observed TPC reduction in PE systems reflects the thermo-oxidative vulnerability of specific phenolic fractions, particularly phenolic acids and flavonols predominant in mortiño, which degrade readily under oxygen exposure at elevated temperatures (Pan et al., 2022; Prencipe et al., 2014). This phenomenon primarily stems from thermally induced structural collapse within the pectin-calcium matrix, which accelerates localized TPC degradation through enhanced oxygen permeability at fracture sites and microscale thermal accumulation exceeding bulk temperature measurements (Fang et al., 2008; Zielinska & Michalska, 2016).

The TPC concentrations increased significantly during mortiño drying compared to fresh samples (6.335 ± 0.689 mg GAE/g). PNE samples exhibited TPC increases to 3.7050, 6.4190, and 7.3498 mg GAE/g at 70 °C, 80 °C, and 90 °C, respectively, while encapsulated treatments (3%-5% PE) reached 8.4376–13.990 mg GAE/g. This enhancement is attributed to thermally induced cellular structural rupture, which liberates bound phenolic compounds from the plant matrix (Zia & Alibas, 2021). Concurrently, the thermal inactivation of oxidative enzymes like polyphenol oxidase (PPO), whose activity decreases by >90% at 90 °C (Li et al., 2018), preserves liberated phenolics. These mechanisms are complemented by microstructural modifications during dehydration that physically trap polyphenols within the fruit tissue (Zielinska & Michalska, 2016), collectively explaining the 45-121% TPC elevation observed across treatments relative to fresh material.

Encapsulation using low-methoxyl pectin (3% and 5%) and calcium chloride significantly enhanced bioactive retention, with PE samples demonstrating superior preservation of anthocyanins and TPC across all temperatures compared to PNE. At 70 °C, TPC concentrations reached 11.8950 and 13.9900 mg GAE/g in 3%-PE and 5%-PE, respectively, with identical protection trends observed for anthocyanins. This thermoxidative shielding is attributed to the pectin-calcium matrix's ability to form progressively ordered “egg-box” structures through calcium-mediated monocomplexation and interchain dimerization (Fang et al., 2008). The three-dimensional networks formed within this structure stabilize encapsulated bioactive compounds by reducing their exposure to heat and oxygen during drying, consistent with findings by Norcino et al. (2022) in pectin-microencapsulated grape anthocyanins, where encapsulation outperformed unencapsulated controls. Silva Júnior et al. (2023) and Gaćina et al. (2022) further validate encapsulation's efficacy in enhancing phenolic compound retention through therm-oxidative protection, while broader studies confirm pectin's capacity to shield sensitive bioactive compounds even under gastrointestinal conditions (Hartini et al., 2021; Nájera-Martínez et al., 2023; Žugić et al., 2025). Comparative analysis of pectin concentrations revealed significantly higher TPC retention at 5% than at 3% ($p < 0.05$). Anthocyanins also exhibited marginally higher retention at 5%, though this difference was not statistically significant ($p > 0.05$). These results demonstrated that increased pectin concentration enhances bioactive protection during RW of mortiño puree by strengthening matrix integrity and mass transfer barriers, and also highlighted the significant potential of RW for processing mortiño puree. The scientific literature confirms RW's superiority over traditional drying methods in retaining bioactive compounds in *Vaccinium* berries. PNE samples dried via RW exhibited anthocyanin concentrations of 0.3420–0.5916 mg C3G/g (wb) and TPC of 3.7050–7.3498 mg GAE/g (wb). These values significantly exceed those reported by Zia & Alibas (2021) using microwave drying (0.0290 mg C3G/g w.b; 1.4287 mg GAE/g w.b), as well as those obtained by Narváez & Carrión (2022) with forced convection drying (0.0474–0.0512 mg C3G/g w.b; 2.610–3.080 mg GAE/g w.b) and by Zielinska & Michalska (2016) employing combined microwave-assisted technologies (0.252 mg C3G/g w.b). These results confirm that RW technology can effectively preserve anthocyanins and TPC in mortiño (*Vaccinium* spp.), positioning it as a high-potential alternative for processing fruits with thermosensitive bioactive compounds.

4 Conclusions

This study demonstrated that IGE using amidated low-methoxyl pectin (3% and 5%) and calcium chloride yielded the shortest drying times during RW processing compared to non-encapsulated samples at identical temperatures, alongside higher effective diffusion coefficients (D_{eff}) and lower activation energy (E_a). Furthermore, encapsulated samples exhibited superior retention of anthocyanins and TPC, confirming the protective capacity of the pectin-calcium matrix. The 5% pectin concentration achieved bioactive preservation and color stability, evidenced by the lowest ΔE values. For PE, the elevated drying temperatures increased the anthocyanin content, which was attributed to the liberation of bound pigments. In contrast, the TPC decreased marginally due to thermo-oxidative sensitivity. These findings collectively validate ionic gelation combined with RW as a promising technology for producing dehydrated fruits with significant retention of physicochemical and functional quality attributes.

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Data Availability Statement

Data will be made available on request.

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