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Effect of drying methods and pretreatments on the physical and antioxidant properties of prickly pear (*Opuntia stricta* and *Opuntia ficus-indica*)

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The invasive proliferation of prickly pear (*Opuntia stricta* [OS] and *Opuntia ficus-indica* [OFI]) in arid regions offers an opportunity to source a wide array of valuable bioactive and nutraceutical compounds. This study aimed to identify optimal drying and pretreatment strategies to preserve the quality of these fruits for commercial applications. Physical properties analyzed included moisture content, water activity, rehydration characteristics, and color. Antioxidant retention was determined using UV–VIS spectrophotometry to quantify betalains, total phenols, total flavonoids, total carotenoids, β -carotene, and antioxidant activity (DPPH assay). Results showed that freeze drying (FD) best preserved structural integrity, yielding the highest rehydration ratios (OS: 3.68–3.70; OFI: 4.27–4.52) and minimal color change ($\Delta E = 7.48$ –23.18), while oven drying (OD) and solar drying (SD) achieved lower final moisture content (6.99%–9.65%) and water activity (0.346–0.484). For antioxidant retention, FD was superior, but the efficacy of citric acid pretreatment was compound-specific: it was crucial for preserving flavonoids and β -carotene, marginally beneficial for phenols, and ineffective for betalains. Blanching consistently reduced antioxidant content. OFI exhibited higher carotenoid levels, whereas OS retained more phenols. These findings demonstrate that the optimal processing strategy is goal-dependent. Although FD is ideal for premium quality, oven-drying combined with citric acid pretreatment represents the most practical approach for industrial-scale processing, effectively balancing bioactive retention with shelf-stability and cost-effectiveness. This approach facilitates the transformation of an ecological threat into a sustainable source of functional food ingredients.

KEYWORDS

freeze-drying, bioactive compounds, rehydration ratio, color stability, food preservation

1 Introduction

Opuntia stricta (OS) and *Opuntia ficus-indica* (OFI), commonly known as prickly pear, belong to the Cactaceae family and the *Opuntia* genus (Giraldo Silva et al., 2023). In Kenya, prickly pear has become an invasive species in arid and semi-arid lands (ASALs), which constitute approximately 80% of the country's landmass. Its proliferation poses significant ecological and economic challenges, particularly in regions where livestock rearing is the primary source of livelihood. The invasion of prickly pear has led to the displacement of

native pasture, reduced grazing land, restricted livestock mobility, and negative impacts on both livestock and wildlife (Githae, 2018; 2019; Mugane et al., 2024). Moreover, its rapid spread threatens plant biodiversity, exacerbating land degradation in these fragile ecosystems.

In Kenya, consumption of prickly pear is most prevalent in the ASALs, where the cactus has proliferated as an invasive species, notably in counties such as Laikipia, Baringo, Kitui, Makueni, and Turkana (Githae, 2018). The fruit is a traditional food source in these regions, consumed fresh for its hydration and nutritional value. Its commercial presence is expanding, with trade observed from rural areas to urban markets in towns such as Nanyuki, Isiolo, and Nairobi, where vendors sell the fruit peeled and ready-to-eat, overcoming the handling challenges (Irungu, 2025). The growing recognition of its health benefits has stimulated market expansion, as reflected in the increased value addition and processing of prickly pear. Small and medium enterprises, including women's cooperatives in counties such as Laikipia and Kitui, are now processing a range of products such as juices, jams, jellies, and wine for local supermarkets and schools, while the cladodes are sold as crucial drought-resistant fodder, creating a dual income stream (Irungu, 2025). The strategic harvesting and processing of this invasive species for human and animal consumption presents a form of biocontrol through utilization. This approach transforms an ecological threat into a valuable bio-resource, offering a sustainable strategy for income generation, food security, and the management of invaded rangelands in Kenya's climate-vulnerable regions, with potential future opportunities in nutraceuticals and even export markets.

Despite its invasive nature, prickly pear has been reported to exhibit antioxidant activity twice as high as that of pears, apples, tomatoes, and white grapes, and comparable to red grapes and grapefruit (Yeddes et al., 2013). The bioactive compounds in prickly pear include phenolic acids, such as piscidic acid, gallic acid, and epicatechin (Zeghib et al., 2022), and flavonoids, including quercetin, kaempferol, and isorhamnetin derivatives, which provide strong antioxidant and anti-inflammatory effects (Chiteva and Wairagu, 2013; Feugang et al., 2006). It also contains betalain pigments—notably betacyanins and betaxanthins—that contribute both color and antioxidant activity (Gouws et al., 2019; Slimen et al., 2021). In addition, the fruit is rich in antioxidants including vitamin C, vitamin E, glutathione, taurine, and cysteine, which support its hypoglycemic, hypolipidemic, and anti-cancer potential (Feugang et al., 2006; Slimen et al., 2021). Carotenoids, including β -carotene, further enhance its antioxidant and provitamin A functions (Chiteva and Wairagu, 2013; Feugang et al., 2006). Together, these phytochemicals underscore the nutraceutical importance of prickly pear and highlight the need to preserve them through optimized drying and pretreatment processes.

The antioxidants in prickly pear collectively play a vital role in mitigating oxidative stress. Reactive oxygen species (ROS), although essential as secondary messengers in cell signaling, can trigger oxidative damage when produced in excess. This, in turn, leads to lipid peroxidation, protein modification, DNA damage, and activation of pathological signaling cascades. Antioxidants in prickly pear exert protective effects not only by directly scavenging ROS but also by modulating redox-sensitive signaling

pathways. They also regulate the mitogen-activated protein kinase (MAPK) pathway, which is involved in apoptosis, proliferation, and cellular stress responses (Zeghib et al., 2022). In addition, prickly pear bioactives enhance endogenous defense systems (Kensler et al., 2007). Moreover, prickly pear fruit bioactives contribute to cytoprotection and metabolic homeostasis. These molecular effects highlight the nutraceutical value of prickly pear, demonstrating that its antioxidants contribute not only to free radical scavenging but also to broader regulation of cellular homeostasis, inflammation, and disease prevention. This, therefore, highlights the need to preserve them through optimized drying and pretreatment processes.

Drying is a widely used preservation technique that reduces moisture, thereby inhibiting microbial growth and enzymatic activity while extending the shelf life of highly perishable fruits such as prickly pear (Abdulla et al., 2011; Mercer, 2014). The selection of drying methods in this study was guided by their relevance to both scientific outcomes and practical application in arid and semi-arid regions of Kenya. Among the available methods, solar, oven, and freeze drying were selected because they represent three distinct technological and cost spectrums with different implications for quality retention and adoption. Solar drying (SD) was chosen as a low-cost, renewable, and locally adaptable method, particularly suitable for rural communities, despite some risk of nutrient degradation under fluctuating environmental conditions (Omobowale et al., 2021). Oven drying (OD), although energy-intensive, provides a controlled environment that minimizes contamination and ensures uniform drying, making it a practical option for small-scale commercial processing (Norhadi et al., 2020). Freeze drying (FD), in contrast, is a high-cost but superior technology that operates at low temperatures, thereby preserving heat-sensitive nutrients, pigments, and antioxidants with minimal structural damage (Adeyeye et al., 2022). These three methods, therefore, provide a balanced comparison between cost, accessibility, and quality retention, making them more relevant than other traditional methods such as open sun drying, which poses risks of contamination and uneven drying, or more advanced industrial methods such as spray and vacuum drying, which are less accessible in ASAL contexts.

Similarly, pretreatments were included because they are critical in improving product quality before drying. Blanching was selected for its ability to inactivate enzymes responsible for enzymatic browning and quality deterioration while also reducing microbial load and improving carotenoid retention (Deng et al., 2017). Citric acid dipping was incorporated due to its effectiveness in lowering pH, inhibiting polyphenol oxidase activity, preserving color, and enhancing drying rates by modifying pectin structure (Deng et al., 2017). These methods were prioritized over other pretreatments, such as sulfiting or chemical preservatives, which may pose health risks and face regulatory restrictions, or alternative acid dips that are less readily available and costlier for local processors. Including a control (no pretreatment) ensures comparative evaluation of their effectiveness in preserving antioxidants, physical attributes, and overall product quality. Collectively, the chosen drying methods and pretreatments reflect both scientific rigor and practical feasibility while supporting the overarching aim of developing sustainable, safe, and high-quality dried prickly pear products.

Despite its nutritional richness in vitamins, antioxidants, and bioactive compounds, the fruit is highly perishable due to its high moisture content and seasonal availability, leading to postharvest losses and limited utilization.

The objective of this study was to investigate the effect of different pretreatments and drying methods on the antioxidant properties and physical attributes of *Opuntia stricta* and *Opuntia ficus-indica*. By examining rehydration characteristics, the study advances scientific understanding of drying dynamics, providing a basis for sustainable processing and value addition of *Opuntia* species. This study thus demonstrates the potential to transform prickly pear, an invasive species, from an ecological threat into a valuable source of stable, nutrient-rich food ingredients and nutraceuticals, supporting environmental management and economic resilience in the rangelands.

2 Materials and methods

2.1 Sample collection

Fresh fruits of OS were collected from Loisukut village in the Mayiannat Community Ranch, Laikipia County in August 2023, while OFI fruits were collected from Marigat in Baringo County in August 2024 at full physiological maturity. Maturity was determined using locally accepted indicators, including uniform dark purple skin color, glossy surface appearance, and ease of detachment from the cladodes. Sampling was carried out based on the availability of mature fruits across multiple sites within each location. Although precise mapping of sampling points was not conducted, efforts were made to collect fruits from a broad representation of plants in each area. The number of fruits per plant varied depending on fruiting intensity, typically ranging from 2 to 6 fruits per plant. This variability was considered acceptable for obtaining a representative sample of mature fruits for further analysis.

Spines and glochids were initially removed in the field using a traditional technique practiced by local harvesters. Fruits were transported to the fruits and vegetable workshop at the Jomo Kenyatta University of Agriculture and Technology (JKUAT) on the day of harvest. The fruits were placed in plastic crates lined with moistened carton boards and carried in a well-ventilated vehicle to minimize mechanical damage and moisture loss during transit.

The collection exercise was conducted twice for each species. The first round of sampling was carried out for preliminary analysis to assess key quality parameters and refine laboratory procedures. A second, more extensive collection was later conducted for the main experimental analysis. Both sampling exercises were carried out during the peak fruiting season of each species.

2.2 Sample preparation

Upon delivery to the fruits and vegetables workshop in JKUAT, the fresh prickly pear fruits were washed in a stainless-steel sink with plain, clear running water for 20 min. Additional spine removal was done using soft laboratory brushes. They were stored in a freezer at -20°C awaiting drying to prevent loss of antioxidants (Gouws et al., 2019).

2.3 Pretreatment

The fruits were divided into nine experimental batches based on a combination of pretreatments and drying methods. Three pretreatments were applied: no treatment (control), blanching (3 min in boiling water, followed by cooling in cold water for 5 min and draining for 20 min), and citric acid dip (40 min in 1% solution, followed by draining for 20 min). Each pretreated batch was then subjected to one of three drying methods (oven drying, solar drying, and freeze drying). This resulted in a total of nine treatment combinations (3 pretreatments $\times$ 3 drying methods).

2.4 Drying

Three drying methods were applied: oven drying, freeze drying, and greenhouse solar drying. For oven drying, the pretreated fruits were dried in a constant temperature and humidity chamber (TD-384KN, Tokyo, Japan) at 60°C and 25% relative humidity for 72 h (Bourhia et al., 2020; Lahsasni et al., 2004). Freeze drying was conducted in a freeze dryer (Model FDL-10N-50-TD-MM, Series no: YSFDL 16112836102, Israel) at -54°C and 1 kPa pressure for the same duration (72 h). For greenhouse solar drying, the fruits were placed in a solar drier at JKUAT's BED, where temperature and relative humidity were monitored continuously using a HUATO data logger. The average drying conditions in the greenhouse were 27°C and 56% relative humidity over the drying period (72 h).

2.5 Determination of physical properties

2.5.1 Moisture content

Moisture content was determined by the oven drying method at 105°C for 3 h according to the AOAC method 925.10 (AOAC, 2016). A measure of 5 g of fresh cactus fruits and 2.5 g of dried samples were weighed and then oven-dried. They were cooled in a desiccator and reweighed to a constant weight. This was carried out in six replicates ($n = 6$).

2.5.2 Water activity determination

Water activity for dehydrated cactus powder was determined using a HygroPalm Portable Water Activity Analyzer (Rotronic 8303, Bassersdorf). The samples with determined moisture content were sealed in a zip lock bag that ensured airtight conditions. A measure of 5 g of the samples was put into a sample cup. The water activity meter was set to quick mode, and sealed samples were kept at relatively constant temperatures that allowed temperature conditions of the samples and probe to stabilize before the displayed water activity was noted.

2.5.3 Color measurement

Color measurement of fresh and dried cactus berries was determined using an LAB color difference meter (Konica Minolta Spectrophotometer CM-23d). It was performed in triplicates at different positions of the sample. Values for L^* , a^* , and b^* were recorded for each sample portion produced by taking the color for three section readings of the samples. The calorimeter head was placed directly on the surface of the dried prickly pear powder, and

one reading was taken for every dried cactus berry. This procedure was repeated to obtain six values, which were averaged. Values displayed were used to calculate hue angle (Equation 1), chroma value (Equation 2) and total color difference (Equation 3) as follows:

$$\text{Hue angle} = \left[\tan^{-1} \left(\frac{b^*}{a^*} \right) \right], \quad (1)$$

$$\text{Chroma } c^* = \sqrt{a^{*2} + b^{*2}}, \quad (2)$$

$$\Delta E_{ab} = \sqrt{(L_2^* - L_1^*)^2 + (a_2^* - a_1^*)^2 + (b_2^* - b_1^*)^2}, \quad (3)$$

where 1 indicates fresh cactus berries and 2 indicates dried cactus berries.

2.5.4 Rehydration characteristics

Five grams of the dried cactus berries were weighed into 100 mL distilled water in a 250 mL beaker at ambient temperature. The solution was filtered using a funnel, excess water was removed, and the residue was weighed on a weighing balance. The rehydration ratio (Equation 4) and coefficient of rehydration (Equation 5) were calculated from the mass of the rehydrated and dried samples as described.

$$\text{Rehydration ratio} = \frac{C}{D}, \quad (4)$$

$$\text{Coefficient of rehydration (COR)} = \frac{C}{D} \times \frac{100 - A}{100 - B}, \quad (5)$$

where C is the final mass of the sample after 10 min of soaking (g), D is the initial test mass of the sample before soaking (g), A is the initial moisture content of the sample before drying (% wet basis), and B is the final moisture content for dried sample (% wet basis).

2.6 Analysis of antioxidants

2.6.1 Preparation of prickly pear fruit extracts

Samples for analysis of phytochemicals were prepared using the maceration method (Ainsworth and Gillespie, 2007). Fresh prickly pear (1 g) and 0.1 g of dried prickly pear samples were weighed into 100 mL centrifuge bottles, and 25 mL of methanol was added. The bottles were closed securely and covered with aluminum foil to prevent light penetration. The samples were shaken for approximately 3 h in a mechanical shaker (IKA Labortechnik KS250 Basic, Germany) at 200 rpm and kept in the dark to extract for 72 h. The samples were filtered using Whatman's filter paper, and the filtrate was made up to 25 mL. The samples were centrifuged at 2500 U/min using a centrifuge (Hettich Universal 16A, Germany) at room temperature, and the supernatant was collected. The extract was used for analysis of total phenols, total flavonoids, and betalains.

2.6.2 Determination of total polyphenol content

The Folin–Ciocalteu method was used according to Ainsworth and Gillespie (2007), where 0.5 mL of the extract was pipetted into a test tube lined with aluminum foil. A measure of 2 mL of 10% Folin–Ciocalteu reagent was added and vortexed prior to the addition of 4 mL of 0.7 M sodium carbonate to avoid air oxidation of the extract phenols. Each mixture was allowed to stand for 2 h at room temperature. Gallic acid was used to prepare concentrations of standards ranging from 5 to 50 µg/mL.

Absorbance was measured at approximately 760 nm against deionized water using a UV–VIS spectrophotometer (Shimadzu UV–VIS 1601 PC, Tokyo, Japan). The blank was run with gallic acid (10–50 µg/mL) and 0.5–80 mL of ethanol for calibration and standardization curves. The phenolic content was calculated based on the gallic acid calibration curve and expressed in grams of gallic acid equivalent per 100 g (Ainsworth and Gillespie, 2007).

2.6.3 Determination of total flavonoid

Total flavonoid content was determined following a method proposed by Maciel et al. (2011). The sample extract (0.5 mL) was transferred into test tubes containing 4 mL of distilled water. After 5 min, 0.3 mL of 5% sodium nitrate was added. This was vortexed and left to stand for 3 min. A 0.3 mL portion of 10% aluminum chloride was added, followed by 2 mL of 1 M sodium hydroxide after 1 min. After 2 min, 2.5 mL distilled water was added to the mixture, and the volume was adjusted to 10 mL. The resulting solution was left to stand at 25 °C for 30 min. Absorbance was measured at a 415 nm wavelength using a UV–VIS spectrophotometer (Shimadzu UV–VIS 1601 PC, Tokyo, Japan). Quercetin was used to prepare concentrations of standards ranging from 100 to 1000 µg/mL and used in generating the standard curve. The total flavonoid content was expressed as mg of quercetin equivalents per 100 g of extract.

2.6.4 Determination of total betalain content

The total betalain content (TBC) of the dried prickly pear methanolic extract was determined following a method proposed by Gouws et al. (2019). The absorbance of diluted methanolic extracts (10% v/v) was determined at 482, 532, and 600 nm using a UV–VIS spectrophotometer (Shimadzu UV–VIS 1601 PC, Tokyo, Japan). The betacyanin and betaxanthin contents were estimated relative to the maximum absorbance, molecular weight, and coefficient of extinction of betanin and indicaxanthin using the following formula. Betacyanin and betaxanthin content were calculated using Equation 6 below. The TBC was calculated as a sum of betacyanin and betaxanthin values and expressed as milligrams per 100 g (mg/100 g; dry weight).

betacyanin/betaxanthin (g/100g; dry weight)

$$= \frac{(A_{\max} - A_{600\text{nm}}) \times \text{Dilution factor} \times \text{MW} \times 10}{\epsilon \times 1}, \quad (6)$$

For betacyanin, $A_{\max} = 532 \text{ nm}$, $\text{MW} = 550 \text{ g/mol}$, and $\epsilon = 60,000 \text{ L mol}^{-1} \text{cm}^{-1}$ (betanin equivalent (BE)); and for betaxanthin, $A_{\max} = 482 \text{ nm}$, $\text{MW} = 308 \text{ g/mol}$, and $\epsilon = 43,000 \text{ L mol}^{-1} \text{cm}^{-1}$ (indicaxanthin equivalent (IE)) (Gouws et al., 2019).

2.6.5 Determination of β-carotene and total carotenoids

Total carotenoids and β-carotene were determined according to the method proposed by Sogi et al. (2012), with minor adjustments as follows: two grams of dried prickly pear powder samples and fresh samples were weighed on a digital balance and crushed using a pestle and mortar. A measure of 40 mL of acetone was used to extract carotene and transferred into a 50 mL volumetric flask. The extract was filtered using cotton wool, and the residue was washed with acetone until it was devoid of color, indicating that all the carotene had been extracted. The filtrate was filled up to the 50 mL mark. A

volume of 30 mL of petroleum ether was put into a clean separating funnel of 500 mL capacity. The 50 mL acetone extract was added slowly into the separating funnel without shaking. Washing was repeated by adding distilled water to the neck slowly to remove acetone. Two phases were allowed to separate for 3 min, i.e., acetone + water and petroleum ether + carotene extract. The lower aqueous layer was removed (acetone + water), while carotenoids remained with the petroleum ether fraction. This was collected into a conical flask by filtering through cotton wool containing 5% sodium sulfate to remove any traces of remaining water. Total carotenoids and β -carotene were measured at 450 nm and 440 nm, respectively, using a UV–VIS spectrophotometer (Shimadzu UV–VIS 1601 PC, Tokyo, Japan) with petroleum ether as a blank. The results were calculated in mg/100 g as shown by Equation 7 below:

$$\frac{A \times V (ml) \times 10^4}{A_{1cm}^{1\%} \times P (g)}, \quad (7)$$

where A is the absorbance; V is the total extract volume; P is the sample weight; and $A_{1cm}^{1\%} = 2592$, i.e., β -carotene coefficient in petroleum ether (Sogi et al., 2012).

2.6.6 Determination of antioxidant activity (DPPH assay)

Antioxidant activity was determined using DPPH assay according to Bey et al. (2014) method. With minor adjustments: a measure of 0.25 g of dried and fresh prickly pear fruit was weighed into centrifuge tubes lined with aluminum foil. Methanol (25 mL) was measured and added to the weighed sample. The centrifuge tubes were swirled in a mechanical shaker for 3 h to facilitate extraction. The extract was further extracted by keeping the samples in the dark for 72 h. The extract was filtered using Whatman filter paper No. 4, and the filtrate was concentrated in a rotary evaporator to approximately 20 mL. The extract was transferred into 50 mL Falcon tubes and tightly capped. Extract concentrations of 0.01, 0.1, 1.0, 2.0, and 5 mg/mL in methanol were prepared. A measure of 1 mL of the extract was placed in a test tube, to which 3 mL of methanol was added, followed by the addition of 0.5 mL of 1 mm 2, 2, diphenyl-1-picrylhydrazyl (DPPH) in methanol. Vitamin C was used as the antioxidant standard at concentration similar to that of the extract. Blank was prepared by adding 0.5 mL of DPPH to 4 mL of methanol. Radical scavenging activity was determined using a spectrophotometer at 517 nm.

The radical scavenging activity was calculated as shown by Equation 8 below:

$$\% \text{ inhibition of DPPH} = \frac{A_0 - A_1}{A_0} \times 100, \quad (8)$$

where A_0 is the absorbance measured for the control reaction, i.e., blank sample, and A_1 is the absorbance measured for the test compound (Bey et al., 2014).

2.7 Analytical method selection for antioxidants

The selection of UV–VIS spectrophotometry as the only analytical method for antioxidants in this research was guided by

the primary objective of this study: to comparatively evaluate the impact of drying and pretreatment on antioxidant retention. Well-established UV–VIS spectrophotometric assays were employed for the quantification of betalains, total phenolics, flavonoids, carotenoids, and antioxidant activity (DPPH assay). These methods were chosen for their proven specificity for the target compound classes, high-throughput capability necessary for our large sample set, and established use in similar matrices, ensuring the validity and comparability of our results. Although techniques such as HPLC provide detailed phytochemical profiles, the spectrophotometric methods used here are optimally suited for the robust comparative analysis central to this study's aims.

2.8 Statistical analysis

Statistical analysis was performed using R software (version 4.4.0). Data from triplicate measurements were expressed as the means $\pm$ standard deviations. ANOVA with Fisher's LSD post hoc tests ($p < 0.05$) was used to evaluate treatment effects on physical and antioxidant properties. Three-way ANOVA examined interactions between species, drying methods, and pretreatments, while regression analysis quantified relationships between variables.

3 Results and discussion

3.1 Physical properties

3.1.1 Moisture content and water activity

The initial moisture content of fresh OS and OFI fruits was high (82%–83% wb), characteristic of perishable fruits. All drying treatments successfully reduced the moisture content to below 12% (Table 1), a critical threshold for inhibiting microbial growth and ensuring shelf stability (Nyangena et al., 2020). A clear dichotomy was observed between the drying methods. OD and SD achieved superior moisture reduction (final moisture: 6.99%–9.65%), resulting in the lowest water activity (a_w) values (0.346–0.484). These a_w levels are well within the safe limits for suppressing mold, yeast, and bacterial growth (Tze et al., 2012), underscoring the practicality of OD and SD for producing shelf-stable products.

In contrast, freeze drying (FD) samples retained significantly higher moisture (10.30%–11.75%) and a_w (0.501–0.538) ($p < 0.05$). This is a known characteristic of freeze drying, where sublimation preserves a porous structure that can reabsorb moisture from the atmosphere if not properly packaged (Nowak and Jakubczyk, 2020). Therefore, while FD excels in quality preservation, it necessitates robust, airtight packaging to maintain stability, adding to the final cost.

The effects of pretreatments were species-specific but generally subtle compared to the predominant effect of the drying method. Citric acid dipping tended to facilitate slightly better moisture removal in some OD and SD treatments, potentially by modifying pectin structure and improving drying kinetics (Deng et al., 2017). The strong, direct relationship between moisture content and water activity (water activity $\sim$ moisture model; $R^2 = 0.929$, $p < 0.001$) confirms that moisture content is the primary

TABLE 1 Moisture content, water activity rehydration ratio, and coefficient of rehydration of *Opuntia stricta* and *Opuntia ficus-indica*.

Species	Pretreatment	Drying method	% Moisture content	Water activity	Rehydration ratio	Coefficient of rehydration
OS	Control	SD	9.48 ± 0.03	0.432 ± 0.007	2.28 ± 0.16	2.76 ± 0.03
		OD	9.65 ± 0.33	0.484 ± 0.012	2.56 ± 0.03	2.54 ± 0.03
		FD	10.72 ± 0.38	0.514 ± 0.008	3.68 ± 0.01	3.65 ± 0.01
	Blanched	SD	9.31 ± 0.16	0.460 ± 0.015	2.86 ± 0.07	2.84 ± 0.09
		OD	9.00 ± 0.14	0.421 ± 0.004	3.53 ± 0.11	2.51 ± 0.11
		FD	10.32 ± 0.12	0.505 ± 0.011	3.70 ± 0.09	3.67 ± 0.09
	Citric acid dip	SD	9.67 ± 0.25	0.472 ± 0.009	2.85 ± 0.10	2.83 ± 0.10
		OD	9.54 ± 0.05	0.466 ± 0.001	2.58 ± 0.04	2.56 ± 0.04
		FD	10.30 ± 0.05	0.501 ± 0.009	3.68 ± 0.01	3.65 ± 0.01
OFI	Control	SD	8.40 ± 0.44	0.382 ± 0.005	2.38 ± 0.02	2.36 ± 0.02
		OD	7.77 ± 0.06	0.387 ± 0.003	2.39 ± 0.01	2.37 ± 0.01
		FD	11.20 ± 0.08	0.538 ± 0.002	4.32 ± 0.04	4.29 ± 0.04
	Blanched	SD	7.43 ± 0.44	0.389 ± 0.002	2.25 ± 0.10	2.23 ± 0.10
		OD	7.48 ± 0.10	0.346 ± 0.001	2.61 ± 0.07	2.59 ± 0.07
		FD	11.69 ± 0.12	0.533 ± 0.003	4.27 ± 0.02	4.24 ± 0.02
	Citric acid dip	SD	6.99 ± 0.20	0.383 ± 0.005	2.30 ± 0.07	2.28 ± 0.07
		OD	7.49 ± 0.23	0.359 ± 0.007	2.68 ± 0.06	2.66 ± 0.06
		FD	11.75 ± 0.06	0.521 ± 0.002	4.52 ± 0.07	4.48 ± 0.07
p_Species (S)			***	***	***	***
p_Pretreatment (P)			***	***	***	***
p_Drying (D)			***	***	***	***
p_S x P			***	***	***	***
p_S x D			***	***	***	***
p_P x D			**	***	***	***
p_S x P x D			*	***	**	**

The data are expressed as the mean ± the standard deviation of three replicates. ***, significant at $p < 0.001$; **, significant at $p < 0.01$; *, significant at $p < 0.05$; and ns, –not significant at $p < 0.05$. Abbreviations: *Opuntia stricta* (OS), *Opuntia ficus-indica* (OFI), Solar drying (SD), Oven drying (OD) and Freeze drying (FD).

driver of stability, and from this perspective, OD and SD offer a distinct advantage for industrial applications where extended shelf life is a priority.

3.1.2 Rehydration characteristics

The rehydration ratio is a critical indicator of the cellular and structural damage inflicted during drying. The results demonstrate significant difference between drying methods, directly reflecting their impact on fruit microstructure (Table 1). FD yielded the highest rehydration ratios for both OS (3.68–3.70) and OFI (4.27–4.52), significantly outperforming other methods ($p < 0.001$). This superior performance is attributed to the sublimation process, which preserves the fruit’s porous, honeycomb-like structure, allowing for rapid and extensive water reabsorption (Vadivambal and Jayas, 2007). Conversely, OD resulted to the poorest rehydration characteristics (OS: 2.28–2.85; OFI: 2.25–2.38). This can be

attributed to severe case hardening and irreversible cellular collapse during the slow, variable drying process (Hameed et al., 2016). Oven drying (OD) on the other hand, led to intermediate values. Statistical analysis confirmed that the drying method was the principal factor, accounting for 78% of the variance in the rehydration ratio, while pretreatments had no significant overall effect. Pretreatment effects were notable. Blanching consistently impaired rehydration across all methods, likely by causing tissue softening and leaching of soluble solids, which leads to a more collapsed structure upon drying (Nyangena et al., 2019). Citric acid pretreatment, on the other hand, showed a slight positive effect, particularly in the OD–OFI (2.68 ± 0.06) sample, attributable to the strengthening of the cell wall matrix through cross-linking, thereby helping maintain capillary structures (Ismail and Göğüs, 2023). For applications where reconstitution is key (e.g., instant fruits and

beverage ingredients), FD is unequivocally the best method. In the case of thermal drying, citric acid pretreatment is preferable to blanching for better rehydration properties.

3.1.3 Color

Color stability is a vital quality attribute, directly influencing consumer acceptance. The total color difference (ΔE) values clearly ranked the drying methods. FD resulted in the smallest color change (OS: 7.48–9.86; OFI: 21.83–23.18), followed by OD (OS: 10.17–13.69; OFI: 26.16–29.59), while SD caused the most significant degradation (highest ΔE) (OS: 11.58–13.10; OFI: 27.44–31.24) for both species (Table 2). This hierarchy is directly linked to the exposure to heat, light, and oxygen. FD's low temperature and oxygen-limited environment minimized the degradation of pigments (betalains and carotenoids) and non-enzymatic browning reactions, leading to lower color difference (Ali et al., 2016).

The superiority of FD was further evidenced by its preservation of hue angle and chroma, indicating minimal shift in the actual color and intensity compared to the fresh fruit. Solar dried samples showed highest lightness (L^*) values (OS: 42.8–44.2; OFI: 55.04–58.84), indicative of darkening from Maillard reactions and pigment degradation (Vadivambal and Jayas, 2007). OFI was more susceptible to color change than OS, likely due to its different pigment profile and concentration.

Among pretreatments, citric acid dipping was effective in mitigating color loss, significantly reducing ΔE in SD and OD samples compared to blanched or control samples ($p < 0.05$). This is attributed to the ability of citric acid to lower pH and chelate metal ions, thereby inhibiting polyphenol oxidase activity and non-enzymatic browning (Deng et al., 2017). Blanching, while intended to inactivate enzymes, led to greater color change, possibly due to the leaching of water-soluble pigments and initiation of heat-induced reactions. Therefore, for optimal color preservation, FD is ideal. In thermal drying processes, a citric acid pretreatment is essential to maintain acceptable color quality.

3.2 Chemical properties

Antioxidants such as betalains, phenolics, flavonoids, carotenoids, and β -carotene are important indicators of nutritional quality and are sensitive to processing conditions. Table 4 provides the concentrations of these compounds across various treatments. The detailed findings and trends for each antioxidant are discussed individually in the following subsections.

3.2.1 Betalains

Betalains, the characteristic pigments of prickly pear, are highly sensitive to heat, light, and oxygen. Our results confirmed this, with drying method being the dominant factor influencing total betalain content (TBC) ($p < 0.001$, Table 3). freeze dried samples retained the highest TBC (OS: 5.54–6.54 g/100 g; OFI: 6.53–7.69 g/100 g), preserving over 50% of the fresh content, consistent with the findings of Alzaeem and Ebrahim (2022) on the efficacy of sublimation-driven preservation at low temperatures.

On the other hand, OD and SD resulted in severe degradation, retaining only 16%–38% and 8%–15% of the initial TBC,

respectively. The prolonged exposure to heat in OD and combined heat/light in SD accelerates betalain oxidation, as documented by Herbach et al. (2006) and Shofinita et al. (2023). A critical finding for industrial application is that neither blanching nor citric acid pretreatment offered a statistically significant benefit for betalain preservation ($p > 0.05$), contradicting the findings of Castellar et al. (2003) on citric acid dip benefits in OFI. The divergence could have stemmed from differences in tissue microstructure or endogenous enzyme activity between studies. This suggests that the degradation drivers (heat and light) are too intense for these pretreatments to counteract. Therefore, if betalain content is the primary goal, FD is the only suitable method.

3.2.2 Total phenols

The total phenol content (TPC) for fresh OS samples was 0.56 ± 0.02 g GAE/100 g DW, which was notably lower than the 0.61 ± 0.07 g GAE/100 g DW recorded for fresh OFI, as shown in Table 3. However, this aligns with the findings of Yeddes et al. (2013), who reported a 1.94-fold higher TPC in spiny OFI compared to OS, attributing this divergence to genetic variability and stress-adaptive responses. Such interspecies differences are further supported by Agostini-Costa (2022), who emphasized how environmental factors such as UV exposure and soil composition modulate phenolic biosynthesis in *Opuntia* species. The TPC values for both species in this study were lower than those reported by Fernández-López et al. (2010) (OS: 204.4 mg GAE/100 g FW; OFI: 218.8 mg GAE/100 g FW) and Albano et al. (2015) (OFI: 89.2 mg/100 g FW). These discrepancies likely stem from methodological variations in extraction protocols and differences in fruit developmental stages and growing conditions, as highlighted by del Socorro Santos Díaz et al. (2017).

The retention of TPC followed the same pattern as betalains, with FD being the most effective method. Interestingly, for OS, TPC in FD samples was higher than in fresh fruit (0.84–0.89 vs. 0.56 g GAE/100 g). This can be attributed to the release of bound phenolics through cell wall rupture during freezing and sublimation, enhancing extractability (Kamiloglu et al., 2015). For OFI, FD best preserved the original TPC.

Thermal drying methods (OD and SD) caused significant losses, with SD being the most detrimental. On the other hand, blanching pretreatment consistently reduced TPC across all drying methods, likely due to the leaching of water-soluble phenolic compounds into the blanching water (Guida et al., 2013). Citric acid dipping showed a marginal or no consistent advantage over the control. This indicates that the slightly acidic environment did not effectively stabilize phenolics in this matrix and may have even promoted slight leaching. The key conclusion for phenolics is that a gentle drying method is paramount, and pretreatments—particularly blanching—should be avoided as they reduce phenolic content without providing stabilizing benefits.

3.2.3 Flavonoids

While the drying method remained the most significant factor (FD > OD > SD), the effect of pretreatment was divergent and important. Similar to phenolics, blanching caused a significant reduction in total flavonoid content (TFC) by 18%–22% loss compared to control (OS: 1.17–1.57 g QE/100 g; OFI:

TABLE 2 L, a, b, Hue angle, chroma value, and ΔE of OS and OFI.

Species	Pretreatment	Drying method	L	a	b	Hue angle	Chroma value	ΔE
OS	Fresh		34.2 ± 0.001	8.90 ± 0.01	8.34 ± 0.13	6.86 ± 0.06	9.04 ± 0.12	
	Control	SD	44.2 ± 0.95	14.13 ± 0.74	7.77 ± 0.12	28.83 ± 1.08	16.13 ± 0.68	13.10 ± 0.47
		OD	42.37 ± 0.55	4.37 ± 0.42	11.07 ± 0.55	68.49 ± 1.31	11.90 ± 0.64	13.69 ± 0.57
		FD	40.50 ± 0.70	9.97 ± 0.49	5.00 ± 0.10	26.67 ± 1.29	11.15 ± 0.44	7.48 ± 0.55
	Blanched	SD	43.97 ± 1.10	12.47 ± 0.40	10.13 ± 1.64	40.01 ± 3.39	16.34 ± 1.38	14.10 ± 0.51
		OD	41.63 ± 0.25	11.03 ± 0.40	9.37 ± 0.29	40.33 ± 0.16	14.47 ± 0.49	11.31 ± 0.19
		FD	42.00 ± 0.90	13.30 ± 0.17	5.27 ± 0.50	21.59 ± 1.92	14.31 ± 0.23	9.86 ± 0.50
	Citric acid dip	SD	42.80 ± 0.36	12.10 ± 0.56	8.67 ± 0.29	35.63 ± 1.41	14.89 ± 0.51	11.88 ± 0.22
		OD	40.57 ± 0.50	10.97 ± 0.75	8.73 ± 0.45	38.56 ± 1.71	14.02 ± 0.77	10.17 ± 0.11
		FD	40.97 ± 0.12	12.37 ± 0.15	3.80 ± 0.10	17.08 ± 0.33	12.94 ± 0.17	8.02 ± 0.01 ^c
OFI	Fresh		28.5 ± 0.16	8.34 ± 0.11	−0.71 ± 0.14	−4.87 ± 0.43	8.37 ± 0.02	
	Control	SD	57.58 ± 0.32	6.49 ± 0.29	4.78 ± 0.31	36.34 ± 0.57	8.06 ± 0.42	29.20 ± 0.44
		OD	53.58 ± 0.32	4.98 ± 0.15	5.91 ± 0.18	49.88 ± 1.75	7.73 ± 0.05	26.16 ± 0.25
		FD	51.37 ± 0.1	10.03 ± 0.34	−1.47 ± 0.76	−8.38 ± 4.45	10.16 ± 0.26	22.96 ± 0.17
	Blanched	SD	58.84 ± 0.57	6.27 ± 0.01	6.45 ± 0.24	45.78 ± 1.09	9.00 ± 0.18	31.24 ± 0.61
		OD	57.00 ± 0.26	5.92 ± 0.13	6.89 ± 0.23	49.32 ± 0.85	9.08 ± 0.22	29.59 ± 0.31
		FD	50.33 ± 0.76	8.79 ± 0.15	−0.72 ± 0.13	−4.68 ± 0.85	8.12 ± 0.15	21.83 ± 0.75
	Citric acid dip	SD	55.04 ± 0.64	4.04 ± 0.15	4.77 ± 0.41	49.68 ± 1.39	6.25 ± 0.40	27.44 ± 0.67
		OD	54.12 ± 0.21	4.26 ± 0.06	5.32 ± 0.27	51.27 ± 1.33	6.81 ± 0.23	26.63 ± 0.25
		FD	51.55 ± 0.34	10.71 ± 0.15	−1.33 ± 0.06	−7.06 ± 0.42	10.80 ± 0.14	23.18 ± 0.35
p_Species (S)			***	***	***	***	***	***
p_Pretreatment (P)			ns	***	***	**	***	***
p_Drying (D)			***	***	***	***	***	***
p_SxP			**	***	***	***	***	***
p_SxD			***	***	***	***	***	***
p_PxD			ns	***	***	**	***	**
p_SxPxD			ns	**	**	*	**	ns
p_Species (S)			***	***	***	***	***	***

The data are expressed as the mean ± the standard deviation of three replicates. ***, significant at $p < 0.001$; **, significant at $p < 0.01$; *, significant at $p < 0.05$; and ns, –not significant at $p < 0.05$. Abbreviations: *Opuntia stricta* (OS), *Opuntia ficus-indica* (OFI), Solar drying (SD), Oven drying (OD) and Freeze drying (FD).

0.55–0.72 g QE/100 g) (Table 3), corroborating the findings of Ngungulu et al. (2024) on flavonoid leaching into blanching water.

However, in contrast to phenolics, citric acid dipping demonstrated a clear protective effect. This was particularly evident in FD samples, where citric acid-treated samples achieved the highest TFC values (OS: 2.90 g QE/100g; OFI: 2.34 g QE/100 g). This suggests that the acidic environment may help stabilize flavonoid glycosides, preventing their degradation or oxidation (Deng et al., 2017). Therefore, for optimal flavonoid retention, the combination of freeze drying with a citric acid pretreatment is recommended. If FD is not available, applying a citric acid dip before OD or SD can still help mitigate the significant losses expected from these harsher methods.

3.2.4 Total carotenoids and β-Carotene

Fresh OFI exhibited significantly higher total carotenoid content (12.3 ± 1.4 mg/100 g DW) than OS (5.67 ± 0.24 mg/100 g DW), as shown in Table 3. This inter-species variation likely stems from differential activation of carotenoid biosynthesis pathways, as suggested by Omar et al. (2021), who noted distinct metabolic profiles among *Opuntia* cultivars. The recorded TC values for fresh OS (1.02 mg/100 g FW) exceeded those reported by Kunyanga et al. (2014) (54–289 μg/100 g FW), potentially due to methodological differences in extraction solvents or spectrophotometric quantification protocols. For OFI, the dried powder values (1.52–8.45 mg/100 g) fell within the range (5.14–9.79 mg/100 g) documented by Bourhia et al. (2020),

TABLE 3 Effect of drying methods and pretreatment methods on total betalain content, total phenols, total flavonoids, total carotenoids, β-carotene, and DPPH IC₅₀.

Sample	Pretreatment	Drying method	Betalain content (g/100 g)	Total phenolic content (g GAE/100 g)	Total flavonoid content (g QE/100 g)	Total carotenoids (mg/100 g)	β-Carotene (mg/100 g)	DPPH IC ₅₀ (mg/mL)
OS	Fresh		9.68 ± 0.1	0.56 ± 0.02	0.25 ± 0.05	5.65 ± 0.24	4.57 ± 0.29	7.2 ± 0.2
	Control	SD	1.22 ± 0.04	0.68 ± 0.01	1.27 ± 0.07	0.68 ± 0.01	0.34 ± 0.03	5.9 ± 0.3
		OD	1.82 ± 0.05	0.79 ± 0.03	1.86 ± 0.22	1.43 ± 0.07	1.27 ± 0.05	3.6 ± 0.4
		FD	5.54 ± 0.23	0.88 ± 0.01	2.72 ± 0.14	1.84 ± 0.02	1.55 ± 0.01	0.55 ± 0.04
	Blanched	SD	1.46 ± 0.05	0.62 ± 0.01	1.17 ± 0.04	0.64 ± 0.004	0.3 ± 0.02	0.65 ± 0.05
		OD	1.74 ± 0.01	0.72 ± 0.0	1.57 ± 0.11	1.42 ± 0.05	0.56 ± 0.05	0.62 ± 0.02
		FD	6.39 ± 0.03	0.84 ± 0.02	2.53 ± 0.22	1.72 ± 0.07	1.5 ± 0.01	0.52 ± 0.02
	Citric acid dip	SD	0.92 ± 0.01	0.66 ± 0.02	1.35 ± 0.02	0.64 ± 0.004	0.32 ± 0.02	0.53 ± 0.03
		OD	1.61 ± 0.11	0.73 ± 0.01	1.61 ± 0.06	1.48 ± 0.04	0.94 ± 0.05	0.42 ± 0.03
		FD	6.54 ± 0.08	0.89 ± 0.01	2.9 ± 0.14	1.81 ± 0.01	1.78 ± 0.03	0.39 ± 0.03
OFI	Fresh		10.12 ± 0.53	0.61 ± 0.07	0.47 ± 0.04	12.3 ± 1.4	12.88 ± 0.82	2.33 ± 0.42
	Control	SD	0.73 ± 0.12	0.45 ± 0.01	0.7 ± 0.05	1.52 ± 0.3	2.47 ± 0.41	0.56 ± 0.05
		OD	3.88 ± 0.24	0.54 ± 0.01	0.88 ± 0.02	3.76 ± 0.15	4.24 ± 0.13	0.61 ± 0.01
		FD	6.87 ± 0.11	0.64 ± 0.02	2.01 ± 0.09	6.83 ± 0.55	7.34 ± 0.03	0.41 ± 0.02
	Blanched	SD	0.61 ± 0.13	0.38 ± 0.02	0.55 ± 0.02	3.66 ± 0.51	1.77 ± 0.25	0.56 ± 0.05
		OD	1.73 ± 0.07	0.47 ± 0.02	0.72 ± 0.14	2.06 ± 0.19	3.89 ± 0.39	0.51 ± 0.02
		FD	6.53 ± 0.12	0.63 ± 0.07	1.76 ± 0.14	5.94 ± 0.38	6.27 ± 0.49	0.4 ± 0.2
	Citric acid dip	SD	0.76 ± 0.33	0.44 ± 0.01	0.64 ± 0.04	2.02 ± 0.6	3.51 ± 0.04	0.55 ± 0.05
		OD	3.88 ± 0.06	0.53 ± 0.01	0.83 ± 0.14	4.38 ± 0.47	4.77 ± 0.04	0.61 ± 0.11
		FD	7.69 ± 0.08	0.71 ± 0.01	2.34 ± 0.1	8.45 ± 0.15	8.42 ± 0.16	0.41 ± 0.01
p_Species (S)			***	***	***	***	***	***
p_Pretreatment (P)			***	***	***	***	***	***
p_Drying (D)			***	***	***	***	***	***
p_SxP			***	***	***	***	***	**
p_SxD			***	*	**	***	***	ns
p_PxD			***	***	**	***	***	*
p_SxPxD			***	ns	*	***	***	ns

The data are expressed as the mean ± the standard deviation of three replicates. ***, significant at $p < 0.001$; **, significant at $p < 0.01$; *, significant at $p < 0.05$; and ns, not significant at $p < 0.05$. Abbreviations: *Opuntia stricta* (OS), *Opuntia ficus indica* (OFI), Solar drying (SD), Oven drying (OD), and Freeze drying (FD).

suggesting consistency in carotenoid retention across drying studies of this species.

Carotenoids are highly susceptible to isomerization and oxidation when exposed to heat and light. The data for total carotenoids (TC) and β-carotene vividly illustrated this, with FD again providing the best protection (Table 3). SD caused the most severe losses, retaining only 11%–30% of the initial content, consistent with observations in carrots and kale, where prolonged drying induced enzymatic oxidation of carotenoids (Piyarach et al., 2020). OFI, on the other hand, consistently contained higher

absolute levels of carotenoids than OS, highlighting a strong genetic predisposition (Agostini-Costa, 2022).

For the broader carotenoid class, pretreatments were ineffective; blanching caused leaching, and citric acid offered no significant stabilization. However, a critical distinction emerged for β-carotene specifically. Here, citric acid pretreatment showed a measurable protective effect, particularly in FD–OFI samples (8.42 mg/100 g vs. 7.34 mg/100 g in control). This indicates that β-carotene may be uniquely responsive to the antioxidant or enzyme-inhibiting properties of the acidic environment (Deng et al., 2017).

TABLE 4 Regression analysis for antioxidant species analysis.

Antioxidant	OS baseline (mean $\pm$ SE)	OFI vs. OS difference (β_1)	p-value	Conclusion
Betalains	3.69 $\pm$ 1.02	+0.588	0.689	No significant difference
Total phenols	0.737 $\pm$ 0.0344	-0.197	<0.001	OFI significantly lower
Flavonoids	1.72 $\pm$ 0.236	-0.633	0.074	Trend: OS > OFI
Total carotenoids	1.73 $\pm$ 0.823	+3.36	0.01	OFI significantly higher
β -Carotene	1.31 $\pm$ 0.870	+2.44	0.063	Trend: OFI > OS

Values in bold indicate statistically significant differences ($p < 0.05$) between *Opuntia ficus-indica* (OFI) and *Opuntia stricta* (OS) based on linear regression analysis. β represents the regression coefficient for the OFI vs. OS comparison; positive values indicate higher levels in OFI, and negative values indicate higher levels in OS.

Therefore, if preserving provitamin A activity through β -carotene is a target, combining FD with a citric acid dip is recommended.

3.2.5 Regression analysis for antioxidants

Table 4 shows linear regression analysis for antioxidant species analysis, which revealed significant interspecies differences in antioxidant profiles between OFI and OS. OFI exhibited markedly higher levels of total carotenoids ($\beta = +3.36$, $p = 0.010$) than OS, consistent with its known photoprotective adaptations. In contrast, total phenols were significantly lower in OFI ($\beta = -0.197$, $p < 0.001$), suggesting that OS may possess stronger phenolic-driven antioxidant capacity.

For flavonoids and β -carotene, trends emerged but did not reach statistical significance (flavonoids: $\beta = -0.633$, $p = 0.074$; β -carotene: $\beta = +2.44$, $p = 0.063$), indicating potential biological relevance warranting further investigation. Betalain content did not differ between species ($\beta = +0.588$, $p = 0.689$), implying conserved biosynthetic pathways.

These results reveal distinct antioxidant allocation patterns between OFI and OS species. OFI accumulates substantially higher carotenoid concentrations, while OS exhibits greater phenolic compound production. This divergence likely reflects evolutionary adaptations to differing environmental pressures, where carotenoids may offer OFI enhanced photoprotection in high-light habitats, while phenolics could provide OS with superior defense against biotic stressors.

3.2.6 DPPH

The DPPH radical scavenging activity provides an integrated measure of the overall antioxidant capacity. Lower IC_{50} values indicate higher activity. The results corroborate the trends observed in individual phytochemicals (Table 3). FD samples, particularly those pretreated with citric acid (CADFD), exhibited the strongest antioxidant activity (OS: 0.39 ± 0.03 mg/mL; OFI: 0.41 ± 0.01 mg/mL). The synergy between citric acid and FD likely stems from the combined effect of maximal retention of a wide range of antioxidants (betalains, phenolics, and flavonoids) and the acid's own stabilizing influence. This also aligns with the observations of Paredes-Lopez (2016), who observed that freeze-dried cactus cladodes retained a higher antioxidant capacity than those subjected to thermal drying, likely due to minimal thermal degradation of bioactive compounds.

Pretreatment with citric acid prior to drying further enhanced antioxidant activity across all drying methods when compared to

blanched and untreated controls. The improved stability of antioxidant compounds may be due to the acidic environment provided by citric acid, which likely inhibits enzymatic degradation and oxidation during drying (Kuyulu et al., 2018).

OFI consistently showed higher antioxidant activity than OS, correlating with its generally higher baseline levels of bioactive compounds. The strong antioxidant activity retained in citric-acid-dipped OD samples suggests that this combination is a viable, cost-effective alternative to FD for producing a functional ingredient with substantial antioxidant potential. This practical finding is significant for scale-up, positioning OD with citric acid as the most balanced approach for antioxidant preservation, where FD is not feasible.

4 Conclusion

This study demonstrates that drying methods and pretreatments exert a profound and interactive influence on the physical and antioxidant properties of OS and OFI fruits. A fundamental trade-off was observed: while freeze drying was optimal for preserving bioactive compounds, rehydration capacity, and color, it resulted in higher residual moisture. Conversely, oven drying and solar drying achieved superior moisture reduction for enhanced shelf stability but at the cost of significant degradation of nutrients and physical structure.

The key insight for the application is that the optimal process depends on the priority outcome. For a premium product, FD is recommended. However, for a practical, commercially viable ingredient, oven drying combined with a citric acid pretreatment is the most recommended strategy. This combination ensures adequate shelf stability while significantly improving the retention of key antioxidants such as flavonoids and β -carotene and maintaining better color than untreated or blanched samples. Solar drying and blanching generally led to the poorest quality outcomes.

Furthermore, notable interspecies variation was confirmed, with OFI being more suitable for carotenoid-rich products and OS for phenolic-focused applications. By providing this optimized processing framework, this research supports the transformation of invasive prickly pear into a valuable, shelf-stable functional food ingredient, aligning ecological management with economic development and improved nutrition in arid regions.

Data availability statement

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

Author contributions

RN: Validation, Conceptualization, Data curation, Investigation, Formal analysis, Writing – review and editing, Software, Writing – original draft. PK: Formal Analysis, Supervision, Writing – review and editing, Data curation. WO: Conceptualization, Writing – review and editing, Resources, Supervision, Funding acquisition, Project administration, Methodology.

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