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Evaluating the nutritional, physicochemical, and quality characteristics of different treated freeze-dried Barhi dates

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Introduction: Barhi dates at the Khalal stage exhibit high perishability, which results in considerable post-harvest losses. Implementing freeze-drying, either independently or combined with pre-treatments, represents a promising strategy and enhances the product's quality. Therefore, the current study evaluated the impact of freeze-drying alone or combined with various pre-treatments on the nutritional, physico-chemical, and quality characteristics of fresh Barhi dates.

Methods: The pre-treatments included soaking in sodium metabisulfite (Met-D) 1 g L⁻¹, ascorbic acid (Asc-D) 1 g L⁻¹, and citric acid (Cit-D) 1 g L⁻¹ for 2 min, blanching (Bla-D) for 5 min, and blanching followed by ascorbic acid soaking (BAs-D) 1 g L⁻¹ for 2 min, compared to untreated freeze-dried samples (RD). The freeze-dried dates were then analyzed for proximate composition, mineral content, total phytochemicals and polyphenolics, antioxidant activity (DPPH, ABTS), sugar profile (HPLC-RID), instrumental color (Hunter Lab), water activity (*a_w*), and *in vitro* glycemic index (GI) and glycemic load (GL).

Results: Freeze-drying consistently reduced moisture content to a stable range of 6.21–7.16% without a remarkable effect on proximate composition or mineral content. All treatments yielded stable products with low *a_w* (0.22–0.26). Asc-D and Cit-D treatments significantly enhanced the retention of total phenolic compounds (TPC) and flavonoids, with BAs-D exhibiting the highest TPC and most potent antioxidant activity. HPLC analysis observed that Met-D and Cit-D treatments had the highest extractable polyphenols, whereas *p*-hydroxybenzoic acid was quantified as the predominant phenolic acid. The glycemic index (GI) and glycemic load (GL) remained low 39.72–39.80 and 35.32–35.63, respectively. Color analysis demonstrated that Met-D and Asc-D preserved lightness, while blanching induced browning.

Discussion: Freeze-drying combined with ascorbic or citric acid pre-treatments effectively preserves bio-active compounds, antioxidant activity, and shelf stability while maintaining a low glycemic index, providing a viable approach to reduce post-harvest losses and enhance the commercial value of Barhi dates. These findings provide a robust framework for industrial applications, supporting nutrient-dense date products and contributing to sustainable agricultural practices.

KEYWORDS

Barhi dates, nutritional, quality, freeze-drying, healthy snacks, food supply, sustainability

1 Introduction

The dates market reached USD 31.03 billion globally in 2024 and is forecast to grow 5.99% annually, from USD 32.70 billion in 2025 to USD 49.14 billion by 2032. The Middle East and Africa controlled 85.24% of the market in 2024, while the U.S. market is expected to expand significantly to USD 1.16 billion by 2032, driven by growing health consciousness regarding dried fruits (Insights, 2025). However, date fruit producers have valid concerns about the potential loss of a substantial amount of freshly picked dates during harvest, storage, or processing stages, which is caused by the enormous increasing trend in output (Hussien et al., 2018). Typically, when fruits reach the Khalal stage, they are suitable for being sold as “fresh” date fruits. Several date cultivars, such as Barhi, Bereim, and Khalas, are ideal for marketing when they reach the Khalal stage (Glasner et al., 1999). The Barhi cultivar is among the most satisfactory cultivars for worldwide marketing at the Khalal stage. Unfortunately, fresh dates like Barhi are subject to biological processes such as respiration, ripening, and senescence, which can rapidly influence their quality characteristics by reaching the overripening stage rapidly (Mehyar et al., 2014). Due to the climacteric nature of Barhi dates, they produce ethylene and undergo a series of physiological changes during maturation that lead to full ripeness (Al-Qurashi and Awad, 2011; Ghafoor et al., 2022).

The over-maturation of Barhi dates, particularly during the commercially optimal Khalal phase, causes accelerated quality degradation that generates substantial financial losses throughout processing and distribution operations (Selim et al., 2020; Abdelkhalek et al., 2022). Barhi dates are highly perishable at this stage, and improper post-harvest handling accelerates overripening, causing texture, color, and firmness changes, diminishing their market value and consumer acceptability (Selim et al., 2020; Abdelkhalek et al., 2022). Economic losses associated with Barhi dates during the marketing phase are notable, as reports that the average post-harvest loss for Barhi (often grouped with Sukkari, a similarly handled variety) is about 5–10% in most regions, with some locations reporting losses exceeding 20% during handling and marketing (El-Habbab et al., 2017). The primary causes of these losses include cuts and bruises (54%), small fruit size (30%), and insect damage (12%) for Barhi dates (El-Habbab et al., 2017). These losses translate directly into reduced returns for producers and threaten the sustainability of Barhi cultivation, despite its relatively high benefit–cost ratio (BCR of 5.75) compared to other cultivars (Rizk et al., 2020).

Overripening in Barhi causes significant changes in their nutritional, physico-chemical, and mechanical properties. As Barhi dates progress from the Khalal (crisp., yellow) to the Rutab (soft, brown) stage, moisture content drops sharply from about 63.3 to 32.6%, leading to a reduction in fruit size, mass, and flesh thickness (Hassan et al., 2025). This dehydration also increases sugar concentration, reflected in higher total soluble solids (TSS), but prolonged storage or overripening can eventually reduce TSS due to senescence and degradation (Abdelkarim et al., 2022). Mechanically, Barhi dates become much softer: the modulus of elasticity decreases dramatically from 548.8 kPa at Khalal to 16.7 kPa at Rutab, and both bioyield and rupture stress decline, indicating a loss of firmness and structural integrity (Hassan et al., 2025). Nutritionally, overripening and longer storage reduce total phenolic content (TPC) and antioxidant activity, as higher temperatures and longer durations accelerate the breakdown of these bioactive compounds (Abdelkarim

et al., 2022). These combined changes diminish the fruit’s textural quality, nutritional value, and marketability.

In contrast, the soluble solids, total sugars, and reducing sugars consistently increase throughout the ripening process, increasing the sweetness. On the contrary, hardness gradually decreases and reaches its lowest point during the Rutab stage of fruit development (Selim et al., 2020). Utilizing the modified atmosphere packaging (MAP) technique can effectively reduce post-harvest losses and preserve the quality of fresh fruits and vegetables (Mphahlele et al., 2016). Few studies have been carried out to enhance the storage period of Barhi dates, such as MAP, ultrasonic treatments, coating, cold storage, and canning (Abu-Shama et al., 2020; Abdelkarim et al., 2022; Ghafoor et al., 2022). Interestingly, all treatments to reduce overripening and associated economic losses are still unsatisfactory, because the perishable nature of Barhi dates at the Khalal stage continues to pose a significant challenge for producers and marketers. In fact, freeze-drying is still innovative, and to our knowledge, not enough trials have been established yet. Recent research on freeze-dried Barhi dates highlights their potential for extended shelf life while preserving nutritional and sensory qualities (Ibrahim et al., 2024; Alqahtani et al., 2025). Freeze-drying concentrates nutrients and flavors, with 20 grams of freeze-dried Barhi equivalent to about 60 grams of fresh fruit, maintaining natural sweetness, dietary fiber, and energy content without additives. This method effectively retains fruit’s natural flavor and freshness over time, making it suitable for convenient consumption and long-term storage (Abdelkarim et al., 2022; Alhamdan, 2024).

Recent research demonstrates that various pre-treatment methods significantly enhance freeze-drying efficiency across different fruits, though specific studies on dates remain limited. Osmotic dehydration using sugar solutions effectively reduces initial moisture content, with studies showing reductions of up to 15.2% in pineapple samples, leading to potential drying time reductions of 35.01% (Yan et al., 2025). Combined ultrasound and osmotic pre-treatment prove even more effective, reducing moisture content by up to 37.5% and decreasing drying time by up to 6 h in citrus fruits. These pre-treatments improve drying efficiency and preserve nutritional quality, with better retention of vitamin C, total phenolic content, and antioxidant properties (Hossain et al., 2025). Blanching pre-treatments effectively inactivate browning enzymes and enhance food quality across various products (Ijod et al., 2025). Microwave blanching showed promising results, increasing phenolic compounds and anthocyanins (Pinchao-Yandun et al., 2025). Ultrasonic pre-treatment of pineapple slices can reduce drying time by up to 35% and improve quality in microwave-assisted vacuum freeze-drying (Yan et al., 2025). Freeze-drying consistently showed superior preservation of bioactive compounds compared to other drying methods (Mejias et al., 2025). Similarly, freeze-dried hop leaves retained higher total polyphenol and flavonoid content than oven-dried samples, with multivariate analysis revealing that drying processes accounted for 37.1% of variation in phytochemical profiles (Carbone and Macchioni, 2025).

Given the perishability of fresh Barhi dates, freeze-drying offers a promising application for the food industry to reduce post-harvest losses and provide a stable, high-quality product for markets beyond local fresh date availability. Implementing freeze-drying in Barhi date processing to extend shelf life, preserve nutritional integrity, and expand market opportunities requires a comprehensive assessment of the nutritional, physicochemical, and quality attributes of the treated and untreated samples. Therefore, the primary objective of this study is to determine the effect of freeze-drying alone or combined with

different treatments on the nutritional, physicochemical, and mechanical properties of fresh Barhi dates.

2 Materials and methods

2.1 Raw materials and pre-dipping pre-treatments of Barhi date fruits

Fresh Barhi dates (*Phoenix dactylifera* L.) at the Khalal stage were obtained from the Kingdom dates Co. at Buraydah, Qassim region, KSA (<https://kdc.sa>) from the yield of the 2024 season. Upon arrival, the dates were sorted thoroughly and cleaned to remove any adhering dust or debris, washed 3 times, and air dried at room temperature in the lab. Consequently, homogeneous dates in shape and maturity were carefully selected and divided into experimental group batches. The fruits were cut manually in halves, and the kernels were removed. The yield was calculated as flesh pulp%, kernels%, flesh/kernel ratio, and the TSS% was determined. To measure TSS% in fresh date samples, fresh Barhi dates were homogenized into a pulp, then centrifuged at $3,000 \times g$ for 10 min. Clear juice was measured by placing 1–2 drops on the prism of the refractometer, then the temperature equilibrated to 20 °C, and the °Brix reading was recorded in triplicate according to AOAC method No. 932.12 (AOAC, 2012).

Immediately, batch 1, nominated as untreated freeze-dried samples (RD), was packaged in foam plates, sealed into polyethylene packages, and then frozen at -80°C . Later on, batches 2, 3, and 4 were soaked in aqueous solutions of sodium metabisulfite (Merck KGaA, Darmstadt, Germany) 1 g L^{-1} (Met-D), ascorbic acid (Sigma-Aldrich, St. Louis, USA) 1 g L^{-1} (Asc-D), and citric acid (Fisher Scientific, Loughborough, UK) 1 g L^{-1} (Cit-D) for 2 min, then removed and left for 10 min under air flow at room temperature in the lab. Subsequently, all batches were separately packaged in foam plates, sealed into polyethylene packages, and then frozen at -80°C . For batches 5 and 6, dates were blanched under live steam for 3 min, then cooled down, and batch 5 (Bla-D) was packaged in foam plates, sealed into polyethylene packages, while batch 6 was soaked in 1 g L^{-1} ascorbic acid (BAs-D), left for 10 min under air flow at room temperature, packaged in foam plates, sealed into polyethylene packages, and then both of them were frozen at -80°C for 48 h. All batches were freeze-dried in a (CHRIST Alpha 1–2 LD plus, Osterode am Harz, Germany) freeze-dryer at 0.06 mbar for 72 h. The freeze-dried dates (Figure 1) were placed aseptically into dark glass flasks and stored at 5°C in the dark until appropriate analysis.

2.2 Proximate chemical composition and mineral content

Moisture, crude protein, crude lipids, ash, and total carbohydrates (calculated by difference) were determined in various treated freeze-dried Barhi dates following AOAC protocols (2012). Sodium and potassium levels were analyzed using flame photometry (P. F. P. 7, Model Jenway 8,515, England) according to the AOAC method 956.01. Calcium, magnesium, iron, copper, manganese, and zinc concentrations were measured with an atomic absorption spectrometer (Perkin-Elmer, 2,380, England) in line with AOAC method 968.08 (2012). Phosphorus content was quantified through a standard colorimetric procedure described by Borah et al. (2009).

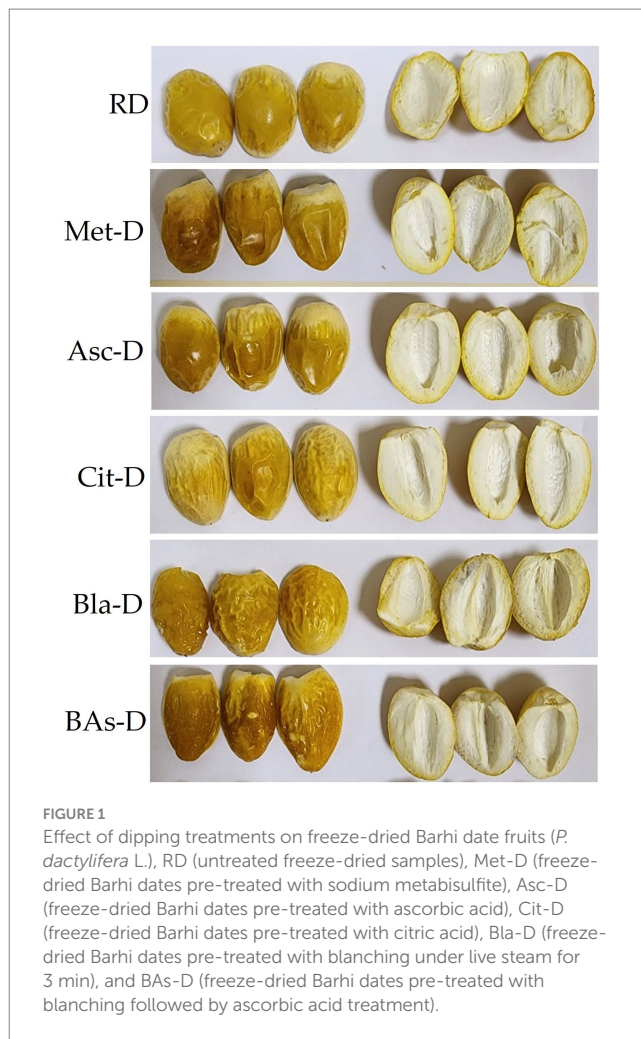


FIGURE 1

Effect of dipping treatments on freeze-dried Barhi date fruits (*P. dactylifera* L.), RD (untreated freeze-dried samples), Met-D (freeze-dried Barhi dates pre-treated with sodium metabisulfite), Asc-D (freeze-dried Barhi dates pre-treated with ascorbic acid), Cit-D (freeze-dried Barhi dates pre-treated with citric acid), Bla-D (freeze-dried Barhi dates pre-treated with blanching under live steam for 3 min), and BAs-D (freeze-dried Barhi dates pre-treated with blanching followed by ascorbic acid treatment).

2.3 Phytochemicals analysis of freeze-dried Barhi dates

Using the Folin-Ciocalteu method, the total phenolic compounds (TPC) in different treated freeze-dried Barhi dates were quantified and expressed as mg gallic acid equivalents (mg GAE 100 g^{-1}) following Bettaieb et al. (2010). The modified method from Khalifa et al. (2016) was used to determine the total carotenoids (TCs) content through a colorimetric assay. The concentrations of total flavonoids (TFs) (Barakat and Almundarij, 2020) and total flavonols (TFLs) (Kumaran and Karunakaran, 2007) were quantified, and the findings were expressed as mg quercetin equivalent (mg QE g^{-1}).

2.4 Antioxidant activity of freeze-dried Barhi dates

Freeze-dried Barhi date samples were milled, and exactly 1.0 g of each sample was extracted with 20 ml of 70% (v/v) aqueous methanol by shaking at 200 rpm for 3 h at ambient temperature, then centrifuged at $5,000 \times g$ for 15 min. Aliquots of each extract were applied to measure the antioxidant activity (AOA) colorimetrically by measuring the scavenging capacity against 2,2-diphenylpicrylhydrazyl (DPPH) radicals to evaluate DPPH radical scavenging activity (DPPH-RSA),

and against 2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) radicals to determine ABTS radical scavenging activity (ABTS-RSA). Results were calibrated using a Trolox standard curve and expressed as μmol Trolox equivalents per 100 grams ($\mu\text{mol TE } 100 \text{ g}^{-1}$) (Zhang and Hamauzu, 2004). For the DPPH assay, the standard curve was linear between 10 and 100 μmol Trolox ($y = 0.0123x + 0.0054$, $R^2 = 0.9991$), and linearity was observed from 20 to 200 μmol Trolox ($y = 0.0107x + 0.0021$, $R^2 = 0.9985$) for the ABTS assay.

2.5 Sugar profile of freeze-dried Barhi dates

The sugar profile of freeze-dried Barhi dates was analyzed using HPLC (Smartline, Knauer, Germany) equipped with a Refractive Index Detector (RID), following validated procedures reported in the literature. Approximately 0.5 g of freeze-dried date powder was accurately weighed and dissolved in 10 ml of distilled water. The mixture was vortexed for 5 min and then sonicated for 15 min to ensure complete sugar extraction. The extract was centrifuged at 5,000 rpm for 10 min, and the supernatant was filtered through a 0.45 μm membrane filter before injection. A 20 μl sample was separated using HILIC NH_2 , 250 $\times$ 4.6 mm, 5 μm particle size column at 35 °C. The mobile phase consisted of acetonitrile and HPLC water (80/20, v/v) delivered isocratically at a flow rate of 1.3 ml min^{-1} . RID detected sugars including fructose, glucose, sucrose, and maltose at 20 °C and 29% Humidity. Quantification was achieved by comparing the peak areas of samples with those of standard sugar solutions prepared at known concentrations. Calibration curves for each sugar showed excellent linearity ($R^2 > 0.989$) over the concentration range tested (Limpanich et al., 2022).

2.6 Quantification of phenolic and flavonoids in different treated freeze-dried Barhi dates

The phenolics and flavonoids in different treated freeze-dried Barhi dates were analyzed using the HPLC system Agilent 1,260 Infinity Series (Agilent Technologies, Palo Alto, CA, USA), which is equipped with a Quaternary pump, an autosampler, and a Variable Wavelength Detector (VWD, Hewlett Packard 1,050) according to Becerra-Herrera et al. (2014). The system uses a column (Phenomenex, USA) and operates at 30 °C. Automatically inject 20 μl of sample extract, set the flow rate to 1 ml/min , and undergo separation at 30 °C. The separation was achieved using a ternary linear elution gradient with (A) HPLC-grade water, 0.1% Trifluoroacetic acid (TFA), (B) Acetonitrile, and (C) HPLC-grade methanol. Peaks of the phenolic compound were quantified as mg/kg using a library providing external calibration curves of relevant standard solutions.

2.7 Instrumental color measurements of different treated freeze-dried Barhi dates

The color attributes of freeze-dried Barhi date samples were determined using a Hunter Lab colorimeter (ColorFlex, Reston, VA, USA). Before measurement, the instrument was calibrated using a standard white calibration tile according to the manufacturer's instructions. Each freeze-dried sample was measured by placing the sample on both the bottom and the crust of the date, covered with the black measurement cup of the Hunter Lab colorimeter to ensure

consistent light shielding and minimize external light interference during color assessment. Color was expressed in the CIE Lab. color, where L^* represents lightness, a^* indicates the red-green axis, and b^* corresponds to the yellow-blue axis. The hue angle (H°), chroma (C), color changes (ΔE), and browning index (BI), compared with the values of the control, were then calculated according to Lavelli et al. (2011).

2.8 Water activity (a_w) of different treated freeze-dried Barhi dates

The a_w of freeze-dried Barhi date samples was measured using a water activity meter (AquaLab model 3TE, Pullman, WA, USA). Immediately after freeze-drying, samples were milled using a high-speed grinder (Homelec, HC-G-350 N) for 1 min into homogeneous date powder. Approximately 2 g of freeze-dried date powder was placed in a sealed sample chamber of the instrument at room temperature (25 ± 1 °C). The sample was allowed to equilibrate for 10–15 min until a stable reading was obtained. Measurements were performed in triplicate for each sample, and the mean value was reported according to Tapia et al. (2020).

2.9 *In vitro* glycemic index (GI) and glycemic load (GL) analysis in different treated freeze-dried Barhi dates

In vitro GI and GL determination in different treated freeze-dried Barhi dates was applied using the method described by Aribas et al. (2020) and modified by Barakat and Almutairi (2024). A 0.1 g freeze-dried date powder was mixed with 2 ml of 0.05 M HCl containing pepsin (0.117 g/ml; Sigma) and incubated at 37 °C with shaking for 30 min. Subsequently, 1 ml of enzyme solution containing pancreatin (0.243 g; Sigma) and amyloglucosidase (14.45 U, 260 U/ml; Sigma) was added. The mixture was incubated in a horizontal water bath at 37 °C with continuous stirring. Aliquots of 100 μl were withdrawn every 20 min up to 180 min, mixed immediately with 1 ml of 100% ethanol to stop the reaction, and centrifuged at $800 \times g$ for 10 min. Glucose concentration in the supernatant was determined using the GOD-PAP assay (FDL, UK), with absorbance measured at 500 nm by a Shimadzu UV-1800 spectrophotometer.

2.10 Statistical analysis

The data were analyzed using one-way ANOVA using the Statistical Package for the Social Sciences (SPSS) software at a significance level of 0.05, followed by multiple comparisons using Tukey's test as outlined by Steel et al. (1997).

3 Results and discussion

3.1 Yield and total soluble solid content of fresh Barhi date

Data in Table 1 showed the yield and total soluble solids (TSS%) of fresh Barhi date (*P. dactylifera*). Analysis of fresh Barhi date

(*P. dactylifera*) samples revealed that the fruit consists predominantly of pulp, accounting for 88.45% of the total fresh weight, while the kernel comprises 11.55%. Interestingly, the flesh/kernel ratio was 7.96, and the TSS content was 35.11%, indicating a high level of sugars and dissolved solids in the fresh pulp. Abdelkarim et al. (2022) reported the Barhi dates at the Khalal stage with a pulp content exceeding 85%, and TSS values ranging from 27 to 36%, depending on orchard conditions and post-harvest handling. El-Beltagi et al. (2023) indicated that the fresh Barhi date juice at the Khalal stage typically registers around 20–30 °Brix as reviewed by Alqahtani et al. (2025). Abdul-Hamid et al. (2018) found that the kernel/weight mass ratio ranged from 4.56 to 17.42 in nine Algerian date palm fruit varieties. Alqahtani et al. (2025) reported TSS values for Barhi dates in Oman at 34–36% at the Khalal stage, with pulp content above 87%, confirming the high edible portion and sweetness. Technologically, a high proportion of pulp (88.45%) in fresh Barhi dates underscores their suitability for direct consumption and processing, as the edible portion is maximized relative to the inedible kernel. This pulp-to-kernel ratio is consistent with the desirable characteristics of premium date cultivars, where consumer preference is closely linked to the amount of flesh available for eating and culinary use (Abdul-Hamid et al., 2018). The TSS value of 35.11% reflects the notable sweetness and rich flavor profile of Barhi dates at the Khalal stage. Collectively, these findings confirm the commercial and nutritional advantages of the Barhi cultivar, supporting its reputation as a premium date variety with high edible yield and superior sensory qualities (Selim et al., 2020; Abdelkarim et al., 2022; Ghafoor et al., 2022).

3.2 Effect of dipping treatments on the proximate composition of freeze-dried Barhi date fruits

The proximate composition of freeze-dried Barhi date fruits subjected to different treatments is presented in Table 2. The results reveal significant variations in moisture, ash, and carbohydrate content, while crude protein and fat remained relatively stable across all treatments. Moisture content varied significantly ($p < 0.05$) among treatments. The highest moisture was observed on the blanched date, followed by raw samples, while the lowest moisture was recorded in the blanched and dipped in ascorbic acid. Intermediate moisture levels were found in dipping in sodium metabisulfite and citric acid. The reduction in moisture in ascorbic acid-treated samples may be attributed to its osmotic and antioxidant properties, which enhance water loss during processing (Al-Farsi et al., 2005).

Conversely, steam blanching alone retained higher moisture, possibly due to gelatinization of cell wall polysaccharides, reducing water loss (Mirhosseini et al., 2008). No significant differences

($p > 0.05$) were observed in crude protein or fat content across all treatments. This stability suggests that dipping and blanching do not significantly degrade proteins or lipids, consistent with findings in other date varieties. Regarding ash content, the representing mineral retention was highest in dipping in sodium metabisulfite (1.89 g 100 g⁻¹) and lowest in blanching with steam (1.68 g 100 g⁻¹). The sulfite treatment likely preserved minerals by inhibiting enzymatic browning (Li et al., 2023), whereas steam blanching may have leached some minerals. Blanching with steam and dipping in ascorbic acid showed the highest carbohydrate content, while untreated and steam-blanching samples had the lowest. As reported in dried fruits, this increase may result from moisture loss and concentrated sugars. Hussain et al. (2023) indicated that blanching methods did not significantly affect dried pear slices' chemical or sensory properties. In comparison, blanching and ascorbic acid dipping can impact nutrient retention and color change during drying (Korese and Achaglinkame, 2024). These findings highlight the importance of optimizing pre-treatments and drying techniques to maintain product quality and safety in dried fruits and vegetables. Unlike other date varieties, where treatments like osmotic dehydration or acid dipping significantly changed composition (Al-Farsi et al., 2005; Mounir et al., 2020), Barhi dates maintained their nutritional integrity after all treatments. Freeze-drying effectively preserved macronutrients, as seen in similar studies (Kulkarni and Vijayanand, 2010; Sapkota et al., 2023), with no single treatment outperforming others. Protein, fat, and ash contents remained stable, consistent with previous findings (Sapkota et al., 2023).

3.3 Effect of dipping treatments on mineral content of freeze-dried Barhi date fruits

The mineral content of freeze-dried Barhi date fruits as influenced by different treatments is presented in Table 3. No significant differences ($p > 0.05$) were observed among treatments for Ca, with values ranging from 52.71 mg 100 g⁻¹ (Bla-D) to 58.20 mg 100 g⁻¹ (Asc-D). The Met-D treatment had the highest Na content (120.07 mg 100 g⁻¹), while BAs-D had the lowest (86.64 mg 100 g⁻¹), which were statistically significant. The highest K content was found in Asc-D (900.18 mg 100 g⁻¹) and Cit-D (898.84 mg 100 g⁻¹), while BAs-D (812.10 mg 100 g⁻¹) had the lowest, but differences were not significant. Regarding P content, significant differences ($p < 0.05$) were observed, with RD (27.83 mg 100 g⁻¹) having the highest P content, while Bla-D (17.33 mg 100 g⁻¹) and BAs-D (16.89 mg 100 g⁻¹) had the lowest. RD (79.44 mg 100 g⁻¹) exhibited the highest Mg content, while BAs-D (63.97 mg 100 g⁻¹) had the lowest, showing a significant decline ($p < 0.05$). No significant differences were found among treatments for Mn, with values ranging from 0.36 mg 100 g⁻¹ (BAs-D) to 0.44 mg 100 g⁻¹ (Cit-D). Significant differences ($p < 0.05$) were observed, with RD (5.52 mg 100 g⁻¹) having the highest Fe content, while BAs-D (3.59 mg 100 g⁻¹) had the lowest. For Zn, no significant differences were detected, with values ranging from 0.85 mg 100 g⁻¹ (BAs-D) to 1.09 mg 100 g⁻¹ (RD). Significant differences ($p < 0.05$) were noted, with RD (0.35 mg 100 g⁻¹) having the highest Cu content, while Bla-D (0.28 mg 100 g⁻¹) and BAs-D (0.28 mg 100 g⁻¹) had the lowest.

Dipping treatments, with varying effects on macro- and microminerals, influenced the mineral composition of freeze-dried

TABLE 1 Yield and total soluble solids (TSS%) of fresh Barhi date (*P. dactylifera*), mean $\pm$ SE, $n = 4$.

Fresh Date	Content %
Fresh Pulp	88.45 $\pm$ 0.41
Kernels	11.55 $\pm$ 0.41
Flesh/Kernel Ratio	7.96 $\pm$ 0.30
TSS %	35.11 $\pm$ 0.10

TABLE 2 Effect of dipping treatments on proximate composition of freeze-dried Barhi date fruits (*P. dactylifera*) mean ± SE, n = 3.

Proximate composition	g 100 g ⁻¹					
	RD	Met-D	Asc-D	Cit-D	Bla-D	BA-s-D
Moisture	6.82 ± 0.05 ^a	6.43 ± 0.05 ^d	6.66 ± 0.03 ^c	6.46 ± 0.03 ^d	7.01 ± 0.08 ^a	6.02 ± 0.01 ^c
Crude Protein	2.12 ± 0.06 ^a	2.11 ± 0.04 ^a	2.08 ± 0.05 ^a	2.12 ± 0.07 ^a	2.04 ± 0.03 ^a	2.09 ± 0.03 ^a
Crude Fat	0.44 ± 0.01 ^a	0.47 ± 0.05 ^a	0.49 ± 0.09 ^a	0.53 ± 0.04 ^a	0.41 ± 0.04 ^a	0.47 ± 0.06 ^a
Ash	1.76 ± 0.03 ^{abc}	1.89 ± 0.03 ^a	1.84 ± 0.02 ^{ab}	1.87 ± 0.07 ^{ab}	1.68 ± 0.04 ^c	1.73 ± 0.06 ^{bc}
Total carbohydrates	88.86 ± 0.11 ^c	89.11 ± 0.11 ^b	88.92 ± 0.04 ^{bc}	89.00 ± 0.07 ^{bc}	88.86 ± 0.03 ^c	89.70 ± 0.06 ^a

^{a,b,c,d,e}No significant difference ($p > 0.05$) exists between any two means within the same row with the same superscript letters.

TABLE 3 Effect of dipping treatments on mineral content of freeze-dried Barhi date fruits, mean ± SE, n = 3.

Minerals	mg 100 g ⁻¹					
	RD	Met-D	Asc-D	Cit-D	Bla-D	BA-s-D
Calcium	57.83 ± 0.32 ^a	56.16 ± 3.55 ^a	58.20 ± 3.18 ^a	56.91 ± 10.4 ^a	52.71 ± 2.56 ^a	53.32 ± 0.94 ^a
Sodium	104.61 ± 6.67 ^{bc}	120.07 ± 9.99 ^a	111.06 ± 9.98 ^a	105.14 ± 15.93 ^a	97.21 ± 14.47 ^{bc}	86.64 ± 1.32 ^d
Potassium	836.97 ± 59.67 ^a	839.36 ± 26.35 ^a	900.18 ± 51.70 ^a	898.84 ± 47.94 ^a	824.77 ± 53.58 ^a	812.10 ± 7.53 ^a
Phosphorus	27.83 ± 2.2 ^a	21.63 ± 3.56 ^{ab}	23.83 ± 1.65 ^{ab}	20.09 ± 0.38 ^{ab}	17.33 ± 1.04 ^b	16.89 ± 3.55 ^b
Magnesium	79.44 ± 4.96 ^a	74.53 ± 1.73 ^{ab}	75.78 ± 0.89 ^{ab}	69.19 ± 7.09 ^{ab}	70.62 ± 0.36 ^{ab}	63.97 ± 2.65 ^b
Manganese	0.43 ± 0.04 ^a	0.38 ± 0.01 ^a	0.42 ± 0.04 ^a	0.44 ± 0.01 ^a	0.37 ± 0.02 ^a	0.36 ± 0.02 ^a
Iron	5.52 ± 0.09 ^a	5.21 ± 0.40 ^{ab}	4.96 ± 0.08 ^{ab}	4.74 ± 0.26 ^{bc}	4.23 ± 0.05 ^{cd}	3.59 ± 0.22 ^d
Zinc	1.09 ± 0.18 ^a	1.03 ± 0.00 ^a	1.06 ± 0.05 ^a	0.96 ± 0.15 ^a	0.92 ± 0.06 ^a	0.85 ± 0.04 ^a
Copper	0.35 ± 0.00 ^a	0.31 ± 0.03 ^{abc}	0.34 ± 0.01 ^{ab}	0.30 ± 0.01 ^{abc}	0.28 ± 0.01 ^c	0.28 ± 0.03 ^c

^{a,b,c,d,e}No significant difference ($p > 0.05$) exists between any two means within the same row with the same superscript letters.

Barhi dates. The lack of significant differences in Ca and K suggests that these minerals were relatively stable across treatments. However, P and Mg significantly reduced Bla-D and BA-s-D, likely due to leaching during blanching (Al-Farsi et al., 2005). The higher K content in Asc-D and Cit-D may be attributed to the protective effect of organic acids against mineral loss (El Hadrami and Al-Khayri, 2012). Fe and Cu showed significant declines in treated samples, particularly in Bla-D and BA-s-D, likely due to thermal degradation and solubility in water (Dong et al., 2022). The stability of Mn and Zn across treatments suggests their lower susceptibility to leaching, possibly due to their binding with organic compounds (Abdelkarim et al., 2022; Korese and Achaglinkame, 2024). However, the findings align with studies indicating that blanching reduces mineral content due to leaching (Al-Farsi et al., 2005). The retention of K in Asc-D and Cit-D supports the role of antioxidants in preserving minerals. The decline in Fe and Cu in blanched samples is consistent with reports on thermal processing effects (Abdelkarim et al., 2022; Ghafoor et al., 2022). Interestingly, deep treatments, particularly blanching, significantly reduced P, Na, Mg, Fe, and Cu content, while Ca, K, Mn, and Zn remained stable. Ascorbic acid and citric acid treatments were more effective in preserving certain minerals. The preservation of minerals during processing is essential, as dates are often consumed for their health benefits, including their contribution to daily mineral intake (Vayalil, 2012). The results also highlight the suitability of freeze-drying as a method for producing high-quality dried fruit products with minimal loss of essential nutrients (Ratti, 2001). In conclusion, the data demonstrate that the deeping treatments applied in this study do not dramatically affect the mineral content of freeze-dried Barhi date fruits.

3.4 Effect of dipping treatments on phytochemical content of freeze-dried Barhi date fruits

The study investigated the effects of different dipping treatments on the phytochemical content of freeze-dried Barhi date fruits Table 4. The results revealed significant variations in phytochemical levels across treatments, as summarized in Table 4. TPC ranged from 331.32 mg GAE 100 g⁻¹ in Cit-D to 396.13 mg GAE 100 g⁻¹ in BA-s-D, with Bla-D and BA-s-D showing the highest values (381.19 and 396.13 mg GAE 100 g⁻¹, respectively). Statistical analysis indicated that Bla-D and BA-s-D were significantly different ($p < 0.05$) compared to the others. This aligns with previous studies suggesting that blanching in Bla-D and BA-s-D treatments enhanced phenolic compound extraction due to cell ruptures (Jomlaperatikul et al., 2023). Similarly, carotenoid content was lowest in RD (2.19 mg 100 g⁻¹) and highest in Bla-D (3.86 mg 100 g⁻¹). The significant increase in Bla-D and Cit-D treatments ($p < 0.05$) may be attributed to increasing the extractability and protective effect of acidic conditions against oxidative degradation, as reported (Ahmed et al., 2021). In the context, TF was highest in BA-s-D (32.58 mg QE 100 g⁻¹), while TFL peaked in Asc-D (18.81 mg QE 100 g⁻¹). Several factors influence the variability in flavonoid retention during processing. Notably, Bla-D showed reduced TFL (12.20 mg QE 100 g⁻¹), suggesting potential degradation under this treatment.

Extraction methods, chemical structure, and sugar moieties significantly affect flavonoid stability (Biesaga, 2011). Heat processing impacts flavonoid stability differently, with glycosylated flavonoids showing higher resistance than aglycones. However, the antioxidant

TABLE 4 Effect of dipping treatments on phytochemicals content of freeze-dried Barhi date fruits (*P. dactylifera*) mean $\pm$ SE, $n = 3$.

Phytochemicals	Treatments					
	RD	Met-D	Asc-D	Cit-D	Bla-D	BA-s-D
TPC (mg GAE 100 g ⁻¹)	349.21 $\pm$ 8.59 ^b	353.03 $\pm$ 8.34 ^b	356.95 $\pm$ 7.05 ^b	331.32 $\pm$ 4.93 ^b	381.19 $\pm$ 3.89 ^a	396.13 $\pm$ 13.72 ^a
Carotenoid (mg 100 g ⁻¹)	2.19 $\pm$ 0.07 ^c	3.46 $\pm$ 0.11 ^b	3.63 $\pm$ 0.10 ^{ab}	3.65 $\pm$ 0.11 ^{ab}	3.86 $\pm$ 0.12 ^a	3.42 $\pm$ 0.10 ^b
TF (mg QE g ⁻¹)	25.85 $\pm$ 0.44 ^c	26.27 $\pm$ 0.79 ^c	30.99 $\pm$ 1.58 ^{ab}	28.99 $\pm$ 1.41 ^{bc}	30.32 $\pm$ 1.31 ^{ab}	32.58 $\pm$ 0.69 ^a
TFL (mg QE g ⁻¹)	15.51 $\pm$ 0.46 ^{bc}	16.79 $\pm$ 0.37 ^b	18.81 $\pm$ 0.73 ^a	16.94 $\pm$ 0.31 ^b	12.20 $\pm$ 0.23 ^d	14.19 $\pm$ 1.09 ^c
DPPH (μ mol of TE 100 g ⁻¹)	230.28 $\pm$ 23.44 ^d	301.87 $\pm$ 13.04 ^c	450.43 $\pm$ 36.32 ^b	400.63 $\pm$ 34.14 ^b	557.71 $\pm$ 7.14 ^a	589.57 $\pm$ 12.22 ^a
ABTS (μ mol of TE 100 g ⁻¹)	299.37 $\pm$ 30.47 ^d	386.39 $\pm$ 16.69 ^c	540.52 $\pm$ 43.58 ^b	480.75 $\pm$ 40.97 ^b	658.10 $\pm$ 8.42 ^a	707.49 $\pm$ 14.67 ^a

^{a,b,c,d}No significant difference ($p > 0.05$) exists between any two means within the same row with the same superscript letters.

activity of flavonoids varies during processing, with some compounds maintaining activity even after degradation (Chaaban et al., 2017). Regarding antioxidant activity, Bla-D and BA-s-D exhibited the highest antioxidant activity (DPPH: 557.71 and 589.57 μ mol TE 100 g⁻¹; ABTS: 658.10 and 707.49 μ mol TE 100 g⁻¹, respectively). These results correlate with the elevated TPC and carotenoid levels, reinforcing the role of phenolic compounds in antioxidant capacity (Baliga et al., 2011). The strong performance of Bla-D and BA-s-D suggests their potential for enhancing the extractability of bioactive compounds. These findings demonstrate that Bla-D and BA-s-D treatments are particularly effective in strengthening phytochemical content and antioxidant activity in Barhi dates due to cell rupture, which obviously increased their determined contents. In addition, Asc-D and BA-s-D exhibited high antioxidant activity, likely influenced by the addition of ascorbic acid which should be considered when comparing results among the formulations.

3.5 Effect of dipping treatments on the sugar profile of different treated freeze-dried Barhi date fruits

The sugar profile (g 100 g⁻¹) of freeze-dried Barhi date fruits subjected to different treatments is presented in Table 5. The data indicate that the concentrations of individual sugars—glucose, fructose, and sucrose—varied depending on the treatment. In all samples, glucose and fructose were the predominant sugars, while sucrose was present in Bla-D and BA-s-D treatments. The results revealed significant variations in the concentrations of fructose, glucose, sucrose, and maltose across the treatments. Fructose levels ranged from 11.16 g 100 g⁻¹ in the BA-s-D treatment to 44.20 g 100 g⁻¹ in the Cit-D treatment. RD exhibited fructose content of 40.84 g 100 g⁻¹, with slight increases observed in Met-D, Asc-D, and Cit-D treatments. Notably, Bla-D and BA-s-D treatments showed a marked reduction in fructose content compared to RD. Glucose followed a similar trend, with the highest concentration observed in the Cit-D treatment (46.90 g 100 g⁻¹) and the lowest in the BA-s-D treatment (4.30 g 100 g⁻¹). RD had a glucose content of 43.57 g 100 g⁻¹, with minimal variations in Met-D and Asc-D treatments. Sucrose was undetectable in RD, Met-D, Asc-D, and Cit-D treatments but was significant in Bla-D (39.17 g 100 g⁻¹) and BA-s-D (65.10 g 100 g⁻¹) treatments. Maltose was below the detection limit in all treatments. The absence of maltose in all treatments indicates that maltose is either not present in significant amounts in Barhi dates or is degraded

during processing. Specifically, the dipping treatments significantly influenced the sugar profile of Barhi date fruits, as evidenced by the variations in fructose, glucose, and sucrose concentrations. The higher fructose and glucose levels in Cit-D, Asc-D, and Met-D treatments compared to the control (RD) suggest that these treatments may enhance the retention or solubilization of monosaccharides during processing. Citric acid (Cit-D) and ascorbic acid (Asc-D) are known to stabilize sugars by inhibiting enzymatic browning and oxidative degradation, which could explain their higher sugar contents (Al-Farsi et al., 2005).

The observed variations in the sugar profile of freeze-dried Barhi date fruits following different dipping treatments can be attributed to the chemical and enzymatic reactions during processing. The predominance of glucose and fructose aligns with the enzymatic hydrolysis of sucrose by the invertase enzyme during processing and freeze-drying (Pitombo et al., 1994). Additionally, dipping treatments, particularly those involving acidic solutions, can enhance the hydrolysis of sucrose into glucose and fructose, leading to undetectable sucrose levels in unblanched samples. On the contrary, blanched samples showed sucrose due to inactivated invertase by thermal treatment. Higher levels of glucose and fructose contribute to dates' characteristic sweetness and flavor profile. At the same time, the reduction or absence of sucrose may affect texture and crystallization properties during storage. Results demonstrate that dipping treatments significantly influence the sugar profile of freeze-dried Barhi date fruits, primarily by promoting sucrose hydrolysis and modifying the balance between glucose and fructose.

3.6 Effect of dipping treatments on individual polyphenols and flavonoids of freeze-dried Barhi date fruits

The HPLC analysis of freeze-dried Barhi date fruits revealed significant variations in individual polyphenols and flavonoid concentrations across dipping treatments (Table 6). The RD exhibited a total polyphenol content of 370.32 mg Kg⁻¹, predominantly composed of gallic acid (334.72 mg Kg⁻¹), catechol (11.29 mg Kg⁻¹), and resveratrol (11.41 mg Kg⁻¹). In contrast, treated samples showed marked increases in total polyphenols, with Met-D (3004.84 mg Kg⁻¹), Cit-D (2745.36 mg Kg⁻¹), and BA-s-D (1433.45 mg Kg⁻¹) demonstrating the most pronounced effects. Notably, *p*-hydroxybenzoic acid was the dominant phenolic compound in Met-D (2851.33 mg Kg⁻¹), Cit-D (2679.70 mg Kg⁻¹),

TABLE 5 Sugar profile (g 100 g⁻¹) of different treated freeze-dried Barhi date fruits.

Sugar profile	Chemical formula	g 100 g ⁻¹ FW					
		RD	Met-D	Asc-D	Cit-D	Bla-D	BA-D
Fructose	C ₆ H ₁₂ O ₆	40.84 ± 0.25 ^b	41.25 ± 0.75 ^b	43.23 ± 0.57 ^a	44.20 ± 0.61 ^a	16.02 ± 0.27 ^c	11.16 ± 0.87 ^c
Glucose	C ₆ H ₁₂ O ₆	43.57 ± 0.58 ^c	43.25 ± 0.85 ^c	45.00 ± 0.42 ^b	46.90 ± 0.82 ^a	20.03 ± 0.99 ^d	4.30 ± 0.35 ^d
Sucrose	C ₁₂ H ₂₂ O ₁₁	-	-	-	-	39.17 ± 0.53 ^b	65.10 ± 0.85 ^a
Maltose	C ₁₂ H ₂₂ O ₁₁	-	-	-	-	-	-

–: Lower than the detection limit, the presented data are mean values of duplicate analysis, ^{a,b,c,d}No significant difference ($p > 0.05$) exists between any two means within the same row with the same superscript letters.

and BA-D (1400.19 mg Kg⁻¹), suggesting that these treatments enhanced the extraction or stability of this compound.

The detection of chlorogenic acid in Met-D (49.47 mg Kg⁻¹), Cit-D (41.87 mg Kg⁻¹), and BA-D (27.61 mg Kg⁻¹) aligns with findings by Al-Farsi et al. (2005), who reported similar phenolic profiles in date fruits subjected to enzymatic treatments. The absence of chlorogenic acid in RD and Bla-D may indicate that certain dipping treatments selectively preserve or degrade specific polyphenols. Ferulic acid, though present in low concentrations in Met-D (6.45 mg Kg⁻¹) and Bla-D (5.42 mg Kg⁻¹), was undetectable in other treatments, consistent with its sensitivity to processing conditions as noted by Borochov-Neori et al. (2015).

Flavonoids such as quercetin (67.64 mg Kg⁻¹ in Met-D) and myricetin (5.00–6.53 mg Kg⁻¹ in Met-D and Bla-D) were detected only in treated samples, highlighting the potential of dipping treatments to liberate bound flavonoids. This observation corroborates the work of Hong et al. (2006), who demonstrated that chemical treatments could enhance flavonoid accessibility in plant matrices. The presence of rutin (1.52 mg Kg⁻¹) and hesperidin (2.38 mg Kg⁻¹) exclusively in Cit-D suggests a treatment-specific effect, possibly due to citrate's ability to chelate metals and stabilize these compounds (White and Kottler, 2002).

The total polyphenol content in treated samples exceeded that of RD, with Met-D showing the highest levels. This trend is consistent with studies by Al-Shahib and Marshall (2003), who noted that methanolic extraction significantly boosts phenolic yields in dates. However, the lower polyphenol content in Asc-D (923.59 mg Kg⁻¹) compared to other treatments may reflect ascorbate's role as an antioxidant, which could reduce oxidative degradation and limit phenolic release (Mansouri et al., 2005).

In conclusion, dipping treatments, particularly Met-D and Cit-D, markedly enhanced the polyphenol and flavonoid profiles of Barhi dates, with *p*-hydroxybenzoic acid emerging as a key phenolic compound. These findings underscore the importance of selecting appropriate extraction treatments to optimize the bioactive potential of date fruit extracts. Future research should explore the mechanisms underlying these treatment-specific effects and their implications for nutritional quality.

3.7 Effect of dipping treatments on instrumental color of freeze-dried Barhi date fruits

The instrumental color measurements of freeze-dried Barhi date fruits subjected to different treatments are summarized in Table 7 (flesh

color) and Table 8 (crust color). For both flesh and crust, the color parameters L* (lightness), a* (red-green), and b* (yellow-blue) were evaluated. For flesh, the L* values varied significantly among treatments, with the highest lightness observed in the Met-D (81.38) and Ascorbic (80.28) treatments, while the RD samples exhibited the lowest lightness (71.55). The a* values were negative across all treatments. The b* values were highest in the RD (19.03) and BA-D (17.47) treatments, while the Asc-D resulted in the lowest yellowness (13.44). Chroma (C) followed a similar trend to b*, with the highest value in untreated (19.13) and the lowest in Asc-D (13.59) samples. The hue angle (H°) was highest in Met-D (98.85) and lowest in Bla-D (−80.76), indicating a shift in color tone. The ΔE, representing total color difference, was highest in Met-D (12.43) and lowest in Bla-D (4.57), suggesting that processing treatments significantly altered the flesh color compared to the untreated sample.

The results demonstrate that dipping treatments significantly influenced the instrumental color parameters of both the flesh and crust of freeze-dried Barhi date fruits. For flesh color changes, the higher L* values in Met-D and Asc-D treatments suggest that they helped retain lightness, possibly due to their antioxidant properties inhibiting browning reactions. The RD sample exhibited the highest b* and C, likely due to the absence of processing-induced degradation of carotenoids and other pigments. The Bla-D and BA-D treatments showed the lowest H°, indicating a shift toward redder tones, possibly due to thermal degradation of pigments. The high ΔE in treated samples confirms that processing significantly alters flesh color, with Bla-D and BA-D treated samples showing the most pronounced change.

For crust color (Table 8), the L* values for the crust were highest in the Met-D (60.48) and Cit-D (56.76) treatments, while the Bla-D samples had the lowest lightness (46.24). The a* values were positive, indicating redness, with the highest value in BA-D (6.22) and the lowest in Met-D (1.20). The b* values were highest in RD (36.64) and BA-D (36.79), while Bla-D had the lowest yellowness (30.57). Chroma (C) was highest in RD (37.08) and lowest in Bla-D (30.91). The hue angle (H°) was highest in Met-D (267.90) and lowest in Bla-D (81.67), indicating a shift toward redder tones in some treatments. The ΔE was highest in Asc-D (28.62), confirming that treatments significantly modified crust color. The results demonstrate that dipping treatments significantly influenced the instrumental color parameters of both the flesh and crust of freeze-dried Barhi date fruits. For crust color, the Met-D treatment resulted in the highest L* in the crust, suggesting minimal browning, while Bla-D darkened significantly. The a* values indicate that BA-D enhanced redness, possibly due to caramelization or non-enzymatic browning. The RD sample had the highest b* and C, indicating strong yellowness, which decreased in treated samples due to pigment degradation. The ΔE values confirm that all treatments modified crust color, with Ascorbic

TABLE 6 Effect of dipping treatments on individual polyphenols and flavonoids of freeze-dried Barhi date fruits (*P. dactylifera*) fractionated by HPLC.

Parameters	mg Kg ⁻¹					
	RD	Met-D	Asc-D	Cit-D	Bla-D	BAs-D
Gallic acid	334.72	9.41	4.20	8.50	6.44	5.65
Catechol	11.29	-	-	-	-	-
<i>p</i> -hydroxybenzoic	-	2851.33	898.03	2679.70	1255.28	1400.19
Chlorogenic acid	-	49.47	16.98	41.87	-	27.61
Syringic acid	3.78	-	-	-	-	-
Ferulic acid	-	6.45	-	-	5.42	-
O-Coumaric	4.43	-	-	-	-	-
Rosmarinic acid	4.69	-	4.38	5.56	-	-
Catechin	-	-	-	5.83	-	-
Rutin	-	-	-	1.52	-	-
Hesperidin	-	-	-	2.38	-	-
Resveratrol	11.41	13.54	-	-	15.14	-
Myricetin	-	5.00	-	-	6.53	-
Quercetin	-	67.64	-	-	-	-
Apigenin	-	-	-	-	0.17	-
Kaempferol	-	2.00	-	-	2.26	-
Total	370.32	3004.84	923.59	2745.36	1291.24	1433.45

-: Not detected.

TABLE 7 Effect of dipping treatments on instrumental color measurements of the flesh of freeze-dried Barhi date fruits (*P. dactylifera*) mean $\pm$ SE, $n = 3$.

Parameters	Treatments					
	RD	Met-D	Asc-D	Cit-D	Bla-D	BAs-D
L*	71.55 $\pm$ 1.54 ^b	81.38 $\pm$ 1.70 ^a	80.28 $\pm$ 1.07 ^a	80.38 $\pm$ 0.30 ^a	68.80 $\pm$ 2.76 ^b	76.73 $\pm$ 1.52 ^a
a*	-1.95 $\pm$ 0.12 ^a	-2.61 $\pm$ 0.12 ^{bc}	-2.00 $\pm$ 0.13 ^a	-2.27 $\pm$ 0.14 ^{ab}	-2.71 $\pm$ 0.24 ^{bc}	-2.87 $\pm$ 0.12 ^c
b*	19.03 $\pm$ 0.05 ^a	16.67 $\pm$ 0.16 ^{bc}	13.44 $\pm$ 0.38 ^d	16.11 $\pm$ 0.40 ^c	16.63 $\pm$ 0.37 ^{bc}	17.47 $\pm$ 0.34 ^b
C	19.13 $\pm$ 0.05 ^a	16.88 $\pm$ 0.17 ^{bc}	13.59 $\pm$ 0.40 ^d	16.27 $\pm$ 0.42 ^c	16.85 $\pm$ 0.34 ^{bc}	17.70 $\pm$ 0.34 ^b
b/a	-9.82 $\pm$ 0.62 ^b	-6.41 $\pm$ 0.24 ^a	-6.76 $\pm$ 0.23 ^a	-7.13 $\pm$ 0.26 ^a	-6.27 $\pm$ 0.73 ^a	-6.10 $\pm$ 0.24 ^a
H°	95.82 $\pm$ 0.35 ^b	98.85 $\pm$ 0.35 ^a	98.39 $\pm$ 0.29 ^a	97.96 $\pm$ 0.29 ^a	-80.76 $\pm$ 0.95 ^c	-80.71 $\pm$ 0.35 ^c
BI	28.06 $\pm$ 0.69 ^a	19.95 $\pm$ 0.58 ^c	16.02 $\pm$ 0.45 ^d	19.68 $\pm$ 0.44 ^c	24.09 $\pm$ 1.76 ^b	22.37 $\pm$ 0.90 ^{bc}
ΔE	0.0 $\pm$ 0.0 ^d	12.43 $\pm$ 1.67 ^a	12.42 $\pm$ 0.92 ^a	11.57 $\pm$ 0.25 ^a	4.57 $\pm$ 0.57 ^c	7.77 $\pm$ 1.51 ^b

^{a,b,c,d,e}No significant difference ($p > 0.05$) exists between any two means within the same row with the same superscript letters.TABLE 8 Effect of dipping treatments on instrumental color measurements of the crust of freeze-dried Barhi date fruits (*P. dactylifera*) mean $\pm$ SE, $n = 3$.

Parameters	Treatments					
	RD	Met-D	Asc-D	Cit-D	Bla-D	BAs-D
L*	48.79 $\pm$ 1.17 ^b	60.48 $\pm$ 0.83 ^a	46.54 $\pm$ 1.27 ^b	56.76 $\pm$ 2.18 ^a	46.24 $\pm$ 0.48 ^b	48.68 $\pm$ 0.36 ^b
a*	5.71 $\pm$ 0.33 ^{ab}	1.20 $\pm$ 0.17 ^d	3.74 $\pm$ 0.32 ^c	4.52 $\pm$ 0.51 ^{bc}	4.51 $\pm$ 0.53 ^{bc}	6.22 $\pm$ 0.27 ^a
b*	36.64 $\pm$ 1.85 ^a	32.00 $\pm$ 0.82 ^b	35.26 $\pm$ 1.37 ^a	36.15 $\pm$ 0.47 ^a	30.57 $\pm$ 0.27 ^b	36.79 $\pm$ 0.28 ^a
C	37.08 $\pm$ 1.87 ^a	32.02 $\pm$ 0.82 ^b	35.46 $\pm$ 1.39 ^a	36.44 $\pm$ 0.51 ^a	30.91 $\pm$ 0.34 ^b	37.31 $\pm$ 0.32 ^a
b/a	6.43 $\pm$ 0.22 ^b	27.58 $\pm$ 3.45 ^a	9.53 $\pm$ 0.58 ^b	8.20 $\pm$ 0.85 ^b	6.95 $\pm$ 0.74 ^b	5.93 $\pm$ 0.21 ^b
H°	261.19 $\pm$ 0.31 ^c	267.90 $\pm$ 0.27 ^a	264.01 $\pm$ 0.35 ^b	262.94 $\pm$ 0.74 ^b	81.67 $\pm$ 0.90 ^d	80.45 $\pm$ 0.34 ^d
BI	131.47 $\pm$ 6.61 ^a	73.38 $\pm$ 2.03 ^c	130.28 $\pm$ 3.79 ^a	101.22 $\pm$ 7.30 ^b	107.5 $\pm$ 3.93 ^b	133.58 $\pm$ 1.76 ^a
ΔE	0 $\pm$ 0 ^d	16.10 $\pm$ 0.46 ^c	28.62 $\pm$ 0.36 ^a	22.34 $\pm$ 1.51 ^b	26.54 $\pm$ 0.66 ^a	28.41 $\pm$ 0.25 ^a

^{a,b,c,d,e}No significant difference ($p > 0.05$) exists between any two means within the same row with the same superscript letters.

acid causing the most significant deviation from the untreated sample, likely due to its impact on oxidation and browning reactions.

The findings suggest that sodium metabisulfite and ascorbic acid treatments were more effective in preserving lightness, while blanching induced more pronounced color changes, particularly in the crust. The differences in H° and ΔE highlight that thermal treatments (e.g., blanching) and chemical treatments (e.g., citric acid) have distinct effects on color attributes. The results are aligned with previous studies showing that antioxidants (e.g., ascorbic acid) can mitigate browning, while thermal treatments accelerate pigment degradation. Previous studies have shown that freeze-drying is generally effective in preserving the color and overall quality of fruits due to the low processing temperatures and minimal exposure to oxygen, which limit enzymatic and non-enzymatic browning reactions (Ratti, 2001; Ciurzyńska and Lenart, 2011). For dates, sodium metabisulfite and/or ascorbic acid treatments were most effective in preserving lightness and overall color quality (Al-Amrani et al., 2020; Shawky et al., 2020). These treatments also helped maintain higher levels of functional components, such as ascorbic acid, carotenoids, and phenolics (Chaethong and Pongsawatmanit, 2015). In contrast, blanching treatments, particularly steam blanching, resulted in more pronounced color changes and date deterioration (Al-Amrani et al., 2020). The studies highlight the importance of appropriate pre-treatments in maintaining the quality and appearance of processed fruits and vegetables during storage.

3.8 Effect of dipping treatments on a_w of freeze-dried Barhi date fruits

The effect of different pre-treatments on the a_w of freeze-dried Barhi dates is shown in Figure 2. The results indicate significant

differences among the treatments, as denoted by letters above the bars. The Bla-D treatment resulted in the highest a_w , significantly greater than all other treatments. Cit-D treatment produced the lowest a_w , indicating the most effective reduction of a_w among the tested pre-treatments. BAs-D and RD treatments showed intermediate a_w values, statistically similar but significantly lower than Bla-D. Asc-D and Met-D treatments also resulted in intermediate a_w values, which were not significantly different.

The a_w is critical in determining dried fruit products' shelf-life and microbial stability. Lower a_w values are generally desirable as they inhibit microbial growth and enzymatic reactions, contributing to product stability during storage. The observed differences in a_w can be attributed to the nature of pre-treatments. The Cit-D was most effective in reducing a_w , which aligns with previous findings where citric acid dips help disrupt cellular integrity, facilitating more efficient moisture removal during freeze-drying (Jomlaperatikul et al., 2023). The Bla-D resulted in the highest a_w . This is consistent with studies showing that blanching can sometimes cause cell wall swelling, leading to moisture retention and less efficient drying. The other treatments, such as Asc-D, Met-D, Bas-D, and RD, yielded intermediate results, suggesting moderate effects on cell structure and drying efficiency. These findings are consistent with earlier research on Barhi dates and other fruits (Jomlaperatikul et al., 2023). Microwave scalding resulted in higher a_w than acid pre-treatments in Barhi dates, supporting the current observation that Bla-D yields higher a_w than Cit-D. Citric acid pre-treatment (Cit-D) is recommended for maximizing shelf-life and safety of freeze-dried Barhi dates due to its superior ability to reduce a_w (Ahmed et al., 2021). Blanching, while useful for enzyme inactivation, may not be optimal if the primary goal is to minimize a_w . However, the study demonstrates that pre-treatment choice significantly affects the a_w of

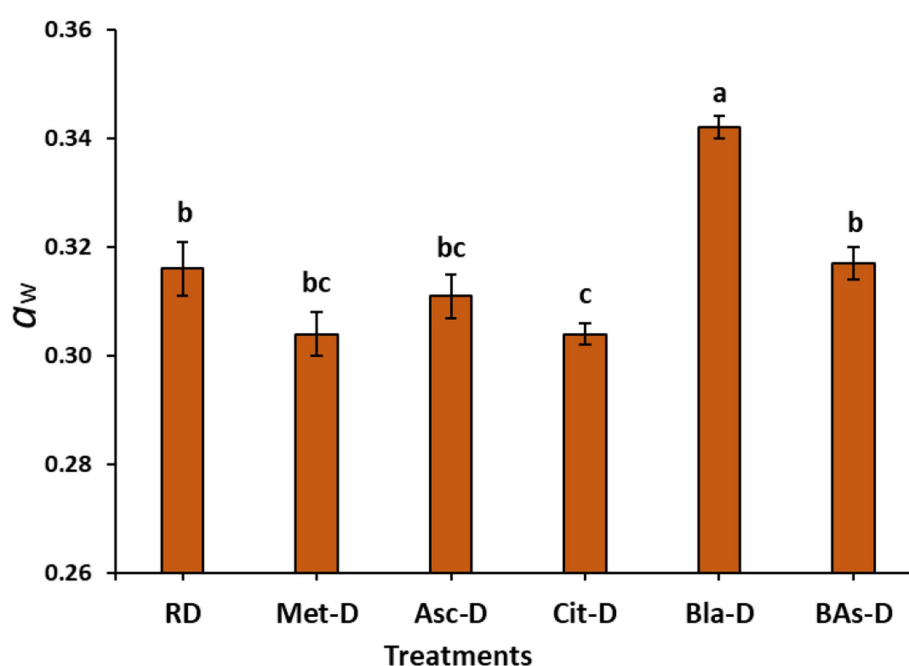


FIGURE 2

Effect of dipping treatments on a_w of freeze-dried Barhi date fruits (*P. dactylifera*) mean ± SE, $n = 3$. ^{a,b,c}: Bars not sharing similar letters are significantly different ($p > 0.05$).

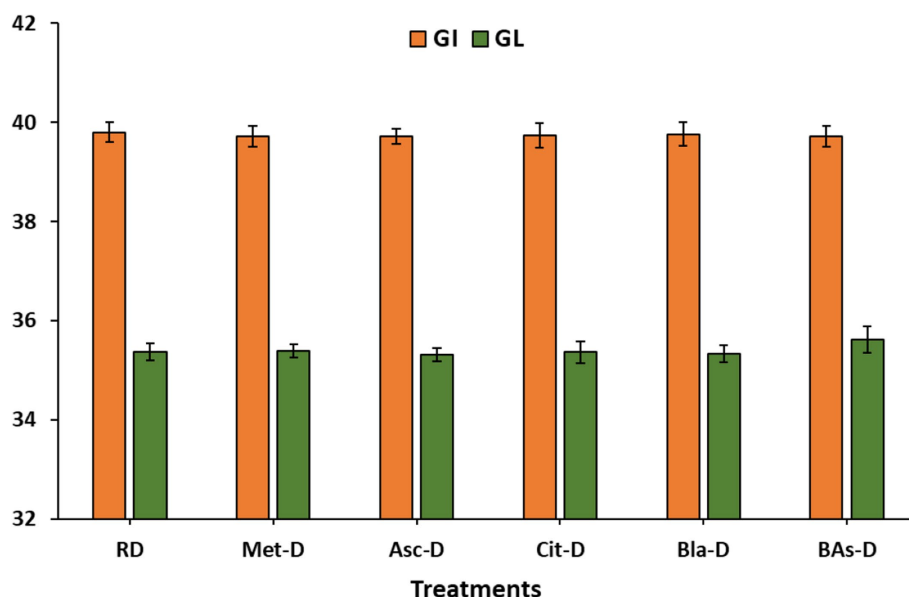


FIGURE 3

Effect of dipping treatments on glycaemic index and glycaemic load of freeze-dried Barhi date fruits (*P. dactylifera*) mean $\pm$ SE, $n = 3$. No significant difference among all treatments was found.

freeze-dried Barhi dates, with citric acid dip being the most effective for moisture reduction and potential shelf-life extension. These results are in agreement with previous research on drying methods and pre-treatment effects in dates and other fruits, highlighting the importance of optimizing processing steps for quality preservation (Ahmed et al., 2021; Jomlaperatikul et al., 2023).

3.9 Effect of dipping treatments on glycemic index and glycemic load of freeze-dried Barhi date fruits

The GI and GL of freeze-dried Barhi date fruits were assessed across various dipping treatments (Figure 3). The results demonstrated minimal variation in GI, with values ranging from 39.72 to 39.80, indicating no significant differences among treatments (Figure 3). Similarly, GL values remained stable, fluctuating between 35.32 and 35.63, further supporting the consistency in glycemic response. These findings suggest that the dipping treatments did not substantially alter the carbohydrate metabolism or sugar bioavailability of Barhi dates. The stability in GI and GL aligns with previous studies on date fruits, which classify them as low to moderate glycemic foods (Alkaabi et al., 2011). The negligible effect of treatments may be attributed to the inherent composition of dates, including their high fiber and polyphenol content, which can modulate postprandial glucose responses. The results reinforce the potential of Barhi dates as a functional food for glycemic management, consistent with reports on other date varieties (Abdelkhalek et al., 2022).

4 Conclusion

This study demonstrates that freeze-drying, particularly when combined with ascorbic or citric acid pre-treatments, effectively

conserved perishable Barhi dates at the Khalal stage into stable, nutrient-rich products. The conducted assays on these extracts, such as DPPH, ABTS, TPC, TE, and HPLC profiling, confirmed that pre-treatment and extraction procedures yield higher recoveries of key phenolic acids and flavonoids, resulting in improved *in vitro* antioxidant capacity. While a_w remained consistently low across all treatments, indicating extended shelf life and microbial safety, glycemic index determinations performed on fruit extracts showed low to medium values, especially for samples pre-treated with organic acids, making them suitable as healthy snack options despite their natural sugar content. These extract-based findings underscore the importance of treatment selection and extraction conditions in optimizing the recovery of potential antioxidant compounds rather than asserting their *in vivo* activity or the intact fruit's nutritional functionality. Future work should assess these compounds' long-term stability and bioavailability under physiological conditions, refine extraction protocols, and analyze economic feasibility. Integrating these freeze-drying and pre-treatment strategies can help reduce post-harvest losses, diversify date-based products, and support a more sustainable and resilient food supply chain, particularly for delicate varieties like Barhi dates.

Data availability statement

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

Author contributions

HB: Conceptualization, Formal analysis, Methodology, Supervision, Writing – original draft, Writing – review & editing. MA: Data curation, Formal analysis, Investigation, Methodology,

Writing – original draft. TA: Formal analysis, Investigation, Methodology, Software, Validation, Writing – original draft.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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