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Valorization of commercial carrot discards through a dehydration and hydroalcoholic extraction process

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ABSTRACT

Carrot discards (*Daucus carota L.*)—rejected for visual flaws yet rich in carotenoids, phenolics, and fibre—offer a sustainable raw material. This study valorized non- commercial carrots via convective drying (50, 60, 70 °C) followed by hydroalcoholic extraction (50 %, 70 %, 100 % v/v ethanol; 40–60 °C; 1:10–1:30 w/v). A Box–Behnken design evaluated effects on carotenoid content, total phenolics, extraction yield, and productivity. Drying produced a fibre rich fraction (FF) and a carotenoid phenolic concentrate (CS) later freeze dried. Both products were analyzed for carotenoids, phenolics, antioxidant activity (DPPH, ABTS), sugars, dietary fibre (total, soluble, insoluble), and water/oil holding capacities.

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Ethanol concentration was the key driver: 100 % ethanol lowered carotenoid retention and yield in FF but improved carotenoid recovery in CS and overall yield. Optimal FF conditions (70 °C drying, 50 % ethanol, 50 °C extraction, 1:20 ratio) delivered 14.0 ± 4.7 mg carotenoids/100 g db and 12.0 ± 3.9% yield, plus high fibre, protein, and desirable hydration and fat binding properties. Best CS results (60 °C drying, 70 % ethanol, 40 °C extraction, 1:30 ratio) achieved 11.0 ± 0.2 mg carotenoids/100 g db and 649 ± 82 mg phenolics/100 g db, suitable for powdered functional extracts.

The process converts edible waste into two value added ingredients: a techno-functional fibre matrix and a bioactive rich powder, supporting circular economy goals and reducing food waste.

KEYWORDS

carrot discards, convective drying, hydroalcoholic extraction, bioactive compounds, circular economy

1. INTRODUCTION

Fruits and vegetables are essential for human nutrition as they represent significant sources of natural antioxidants, including vitamins, carotenoids, and phenolic compounds (Bochnak and Świeca, 2020). However, they are among the food categories with the highest post-harvest losses and waste (FAO, 2019). These losses may result from biotic factors, such as insects, fungi, or nematodes, as well as abiotic factors, including temperature, soil salinity, drought, or nutrient deficiencies, which negatively impact crop yield and quality, leading to economic losses (Paparella et al., 2024). Additionally, fruits and vegetables are often rejected for failing to meet market standards that prioritize aesthetic characteristics, despite maintaining their nutritional quality and safety (Ballesteros and Gómez, 2021; Pietrangeli and Cicatiello, 2024). Reducing such losses could increase the availability of essential nutrients, including carbohydrates, proteins, and phytochemicals, while also decreasing production costs and improving environmental sustainability (Capanoglu et al., 2022). Utilizing food discards to extract valuable nutrients or components and repurposing them for new products offers a promising approach to mitigating environmental impacts and generating economic benefits (Sindhu et al., 2019). Carrot cultivation has significantly increased worldwide over the past 50 years (Coe et al., 2023). Market standards often require farmers to discard carrots with shape imperfections, such as twisting, blemishes, or uneven coloration. These flaws hinder processing and contribute to substantial carrot waste during the harvest stage. It is estimated that 30–40% of carrots are discarded for such reasons, despite being edible and nutritious (Truong et al., 2019).

In the La Costa District of Santa Fe, Argentina, the cultivated area of carrots (*Daucus carota L.*) spans 1,634 ha (Terán, 2023). Typically, only 65–90% of harvested carrots are considered marketable, resulting in daily discards of 20–100 tons during the harvest season due to morphological defects that render them unsuitable for commercialization. Despite their rejection, these carrots often exhibit optimal maturity and freshness (Aimaretti et al., 2013). While some strategies have been explored to utilize these discards, a large proportion remains unprocessed. These are transported from local packaging facilities, responsible for washing, sorting, and packing carrots for sale, to nearby fields for animal feed. However, livestock consume only 15–20% of the discarded carrots, leaving the remainder to decompose in the fields, leading to

insect proliferation, decomposition byproducts, and unpleasant odors (Bakshi et al., 2016). Measures to reduce these discards are therefore urgently needed.

Unlike the discards of other vegetables such as broccoli or cauliflower, which primarily consist of leaves and stems, carrot discards have the advantage of being edible and nutrient-rich (Amin et al., 2023). They are a valuable source of bioactive compounds, non-nutritive food-derived substances with biological activity that can interact with living tissues and provide health benefits (Donda Zbinden et al., 2024). These bioactive compounds, also known as phytochemicals, include carotenoids, phenolic compounds, dietary fibre, vitamins (such as riboflavin, niacin, folic acid, vitamins C and E), and minerals (calcium, phosphorus, potassium, magnesium, manganese, iron, and sodium) (Mandrich et al., 2023; Jayesree et al., 2021). Additionally, carrots are notable for their simple sugars, including fructose, glucose, and sucrose, as well as minimal starch content (Mandrich et al., 2023).

Carotenoids, a family of tetraterpenes, are natural pigments responsible for the yellow, orange, and red colors of fruits, leaves, and flowers (Nagraj et al., 2020). In carrots, the major carotenoids are β-carotene (75%) and α-carotene (23%), followed by lutein (1.9%), and smaller amounts of β-cryptoxanthin, lycopene, and zeaxanthin (Mandrich et al., 2023). These compounds exhibit significant biological functions, including gene expression regulation, platelet activation, and monocyte adhesion inhibition. In particular, β-carotene has been associated with health benefits such as reduced risks of cardiovascular diseases, Alzheimer's disease, and certain cancers, as well as ocular health promotion through lutein and zeaxanthin (Mandrich et al., 2023). Furthermore, carotenoids can be used as natural colorants (Tiwari et al., 2022).

Phenolic compounds, a diverse group of substances with high antioxidant activity, contribute to human health by preventing oxidative stress, reducing inflammation, and lowering the risk of cancer and cardiovascular diseases (Dong et al., 2021; Vaz et al., 2022). In carrots, the predominant phenolic compound is chlorogenic acid, accounting for 42.2%–61.8% of total phenolics (Mandrich et al., 2023). These compounds can be present in free forms or bound to sugars, low-molecular-weight molecules, or structural cell wall components such as proteins, fibre, and lipids (Rocchetti et al., 2022).

Carrots are also a notable source of dietary fibre, consisting of approximately 74% total dietary fibre (Ramirez et al., 2023). This includes cellulose (35–48%), hemicelluloses, lignin, and pectin, the latter containing homogalacturonan and rhamnogalacturonan polysaccharides with immune-modulating and microbiota-balancing effects (Hotchkiss et al., 2023). The dietary fibre composition of carrots, with a soluble-to-insoluble ratio of 1:3, offers excellent functional and nutritional properties for use as a dietary supplement (Ramirez et al., 2023).

Carrots have a water content exceeding 86%, making them highly perishable and prone to quality deterioration due to storage conditions and microbial activity (Mina et al., 2022). Owing to their high moisture content and composition, optimal storage conditions are set at a temperature of 0–1 °C, a relative humidity of 98–100%, and an ethylene-free atmosphere, under which they can be stored for 6–8 months. Nevertheless, their quality gradually declines due to dehydration and desiccation, fungal and bacterial activity, as well as rooting and sprouting. Additionally, sweetness decreases while bitterness and harsh flavors increase (Edelenbos et al., 2020). This high water content also poses a significant challenge for the development of stable products derived from carrot nutrients and bioactive compounds (Capanoglu et al., 2022).

Therefore, dehydration technologies are essential for extending shelf life, with drying being the most widely used method due to its versatility (Nandhu Lal et al., 2022). Drying also reduces

packaging, storage, and transportation costs by decreasing the volume and weight of produce (Richards et al., 2024). Among drying methods, hot-air convective drying is the most common (Keskin et al., 2021).

Among the methods applied to valorize fruit and vegetable by-products, drying and solvent extraction are the most widely reported. Several approaches have been explored, including freeze-drying, spray-drying, vacuum drying, and hot-air drying, each differing in efficiency, cost, and scalability (Salim et al., 2017). Likewise, assisted extraction techniques such as ultrasound, microwave-assisted extraction, and supercritical fluids have been investigated for bioactive recovery (Taghian Dinani and van der Goot, 2023). However, convective hot-air drying and hydroalcoholic solvent extraction remain the most suitable methods for large-scale processing due to their relatively low cost, technical simplicity, and feasibility of industrial implementation (Dadan and Nowacka, 2021; Murugan et al., 2021; Pappou et al., 2022).

From the literature, it is observed that research specifically focused on the recovery of nutrients from carrot discards remains limited, particularly when considering processing technologies that may result in the simultaneous recovery of high value bioactive compounds through a circular economy strategy. In this context, the aim of this study was to propose a method for valorizing commercial carrot discards through a dehydration process followed by the extraction of bioactive compounds and other nutritionally relevant components. To achieve this, optimal dehydration conditions for carrot discards and hydroalcoholic extraction parameters were determined to maximize carotenoid (CAR) recovery. Additionally, the feasibility of producing a final powder enriched with carotenoids and other bioactive compounds through freeze-drying was evaluated, while total dietary fibre (TDF), and total sugars in the final products were quantified to evaluate nutrient recovery throughout the valorization process, aiming to minimize waste generation.

2. MATERIALS AND METHODS

2.1. Materials

Carrot discards (*D. carota L.*) were obtained from a producer in the town of Santa Rosa de Calchines, Santa Fe, Argentina. The discards were stored for no longer than 48 h at 4 ± 2 °C until use.

All reagents were used of analytical grade, including absolute ethyl alcohol, hexane, acetone, anhydrous monobasic sodium phosphate, potassium persulfate, hydrochloric acid (Ciccarelli, Argentina), Folin-Ciocalteu reagent (Biopack, Argentina), gallic acid, (±)-6-Hydroxy-2,5,7,8-tetramethylchromane-2-carboxylic acid (Trolox), 2,2-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), 2,2-diphenyl-1-picrylhydrazyl (DPPH), and sodium carbonate (Sigma-Aldrich, Argentina). For the extractions, food-grade triple-distilled 96° ethyl alcohol was used (Porta Hermanos, Argentina).

2.2. Processing steps

Each experimental run followed the processing steps outlined in Fig. 1. A Box-Behnken design with 27 experimental runs performed in duplicate was employed to evaluate the influence of drying and extraction variables on the retention and extraction yields of carotenoids and

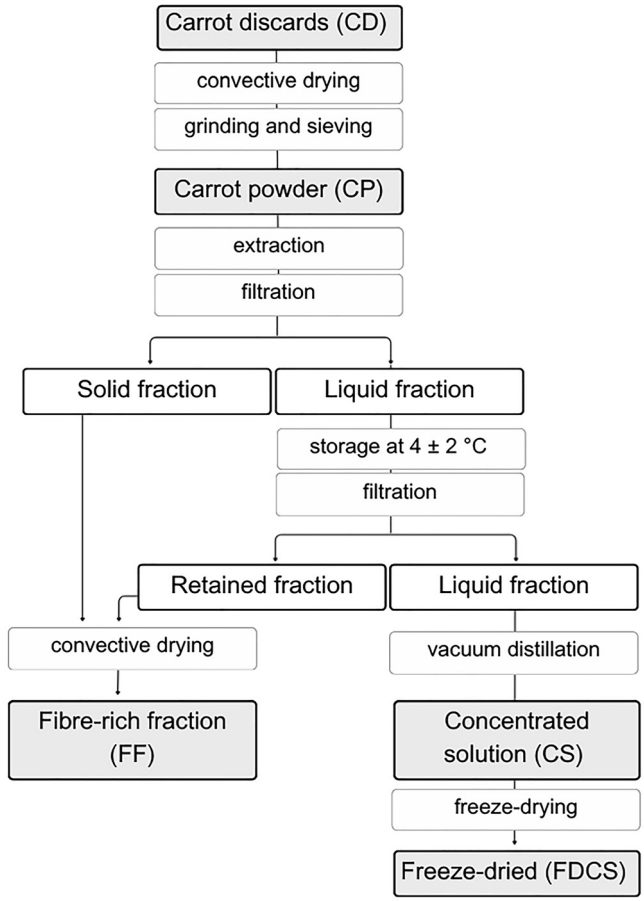


Fig. 1. Diagram of the processing steps for the valorization of the carrot discards (own source)

polyphenols. This design resulted from four variables in three levels: drying temperature (50, 60, and 70 °C), extraction temperature (40, 50, and 60 °C), solid: solvent ratio (1:10, 1:20, and 1:30 w/v) and ethanol concentration (50, 70, and 100% v/v).

The ranges of the selected variables for the drying and extraction stages were based on previous studies regarding the extraction of polyphenolic compounds and carotenoids from various vegetables. The selection of 70 °C as the maximum drying temperature studied was based on achieving greater preservation of the CAR present in carrots, as higher temperatures increase the degradation rate of CAR (Demiray and Tulek, 2017; Eim et al., 2013; Saleh et al., 2020). On the other end, drying temperatures lower than 50 °C would require excessively long times to reduce the moisture content below the 7% limit established by the Argentine Food Code (All Nutrition and Food Code of Argentina [CAA], 2025) for dehydrated vegetables, thus rendering them unsuitable from a technological perspective. The ethanol concentration range (% v/v) was selected based on the studies conducted by Balzarini et al. (2024) and Mohammed

et al. (2022), who extracted polyphenols from other plant matrices with relevant results. The extraction temperatures were chosen according to the findings of Fikselová et al. (2008), who recommended using values between 40 and 60 °C to enhance carotenoid extraction from fresh carrots. The solid-to-solvent ratios (w/v) were selected based on the study by Balzarini et al. (2024), which employed ratios of 1:20 and 1:30 to obtain hydroalcoholic extracts rich in polyphenols. The 1:10 ratio was adopted to evaluate the process performance with lower solvent consumption.

2.2.1. Convective drying. The washed carrot discards (CD) were sliced into approximately 1 mm-thick rounds using a slicing machine (Andi Goli-Inox slicing machine, Argentina). Drying was carried out in a convective dehydrator oven (Multiequip Byrd HDT-2, Argentina) operating with an air velocity of approximately 2 m s^{-1} and a capacity for 6 kg of sliced carrots distributed as a single layer in 10 of the 20 available trays, each measuring 90 × 70 cm.

A drying curve depicting moisture content (HS) variation over time was constructed for each tested temperature (50, 60, and 70 °C), with each experiment performed in duplicate. For this purpose, carrot samples were placed on two control trays located at the bottom and top positions of the dehydrator. Weight measurements were recorded every 5 min during the first 40 min and every 10 min thereafter, using a digital balance with an accuracy of ± 0.01 g. Relative humidity was kept by the drier in the range of 20–35% in all experimental runs. Drying continued until the equilibrium moisture content (HS_{eq}) was reached, defined as the point at which no significant weight change occurred between two consecutive measurements.

2.2.2. Grinding and sieving. The dehydrated carrots were ground using a blade mill (Tecno Dalvo TDMC, Argentina) for 30 s and sieved to achieve a particle size between 25 mesh (710 µm) and 100 mesh (150 µm). The grinding time and sample amount were kept constant throughout all experiments to ensure reproducibility and to prevent excessive temperature increase during milling, which could otherwise affect the characteristics of the dried material. The resulting product, referred to as carrot powder (CP), was stored at −20 °C until further use.

2.2.3. Extraction. The extraction process was carried out using a batch extractor with continuous agitation provided by a 6-blade impeller (Precylec, Argentina), placed within a thermostatic bath (Tecno Dalvo, Argentina). The temperature of the bath was set according to the specific conditions defined in the experimental design for each extraction, and the duration of the process was maintained at 90 min, previously determined as the time necessary to achieve equilibrium at the lowest extraction temperature (Balzarini et al., 2024; Lin et al., 2018). For each extraction run, the weight of dried carrot powder was determined as specified by the experimental design, and it was combined with 600 mL of the hydroalcoholic solvent at the corresponding ethanol concentration, also as defined by the experimental design.

2.2.4. Fractions separation and product recovery. After the extraction process, the sample was filtered using a filter press, yielding two fractions: a solid fraction (SF) and a liquid fraction. The liquid fraction was stored at 4 ± 2 °C to promote the precipitation of carotenoids due to reduced solubility at lower temperatures (Clementz et al., 2019), and then subjected to a second filtration with medium paper filters (N102, Paralwall, China), separating it into a retained fraction and a remaining liquid fraction. The latter was subjected to vacuum distillation at 37.5 °C and 660 mmHg, resulting in a concentrated solution (CS) by concentrating the filtered liquid and evaporating the ethanol content. The retained fraction was mixed with the SF and subjected

to convective drying at 50 °C for 24 h, resulting in a product referred to as the fibre-rich fraction (FF). The final products for the 27 experimental runs of the Box-Behnken design were the FF and CS, that were stored at 4 °C until further characterization.

2.2.5. Additional processing of concentrated solutions. The two most efficient runs for carotenoids recovery were selected and subjected to a freeze-drying process. For this purpose, the selected samples were stored at −18 °C for 24 h in a freezer (Rificor C200, Argentina). Freeze-drying was performed using a laboratory-scale freeze dryer (Rificor L-T4-A-B3, Argentina) operating at a product temperature of −15 °C and a condenser temperature of −40 °C for 48 h.

For the freeze-drying process, the ethanol concentration of the hydroalcoholic mixture was considered, as the ethanol content in the mixture must be taken into account. Using ethanol concentration of 100% as the extraction solvent is not feasible for freezing the product at −18 °C prior to freeze-drying.

2.3. Characterization of fractions

2.3.1. Proximate analysis. Moisture content was determined using AOAC method 925.10 (AOAC, 2012) and reported as % wb (i.e. on a wet basis). Protein content was measured using the Kjeldahl method through AOAC method 2001.11 (AOAC, 2005), where the total protein content was derived by multiplying the total nitrogen by 6.25 (Akter et al., 2024; Riaz et al., 2022; Sahni and Shere, 2017) and reported as % db (i.e. on a dry basis). The lipid content was measured following the method described by Bligh and Dyer (1959) and expressed as % db. The ash content was analyzed using the AOAC 942.05 method (AOAC, 2005) and reported as % db. Total dietary fibre (TDF), soluble dietary fibre (SDF) and insoluble dietary fibre (IDF) were quantified using the enzymatic-gravimetric AOAC method 985.29 (AOAC, 2012) and reported as % db. Total carbohydrates were calculated as the difference between the total mass of the sample and the total value of protein, lipid and ash and reported as % db. Total sugars were determined post-hydrolysis using the Fehling Causse Bonnans method through IRAM Standard 15934 (IRAM, 2018), with results expressed as % db.

2.3.1.1. Water activity (aw). Water activity in the carrot powders (CP) was determined using a water activity meter (AquaLab, USA) at 25 °C. The results were expressed as the mean and standard deviation of three determinations.

2.3.1.2. Color. The Lab* color space (CIELAB) was determined following the procedure reported by Pathare et al. (2013), by means of the ImageJ software (National Institutes of Health, Bethesda, MD, USA), for uniformly comminuted samples of the carrot discards (CD) and randomly selected samples of the carrot powders (CP) dried at the three selected temperatures. Prior to the color measurements, all samples were arranged as a uniform thin layer under controlled lighting conditions. The results were expressed as the mean and standard deviation of three determinations. ΔE was calculated to express the magnitude of the color difference between the CD and respective CP as reported Equation (1).

$$\Delta E = \sqrt{\left(L^*_{CP} - L^*_{CD}\right)^2 + \left(a^*_{CP} - a^*_{CD}\right)^2 + \left(b^*_{CP} - b^*_{CD}\right)^2} \quad (1)$$

where L^* is lightness/darkness, a^* is red/green (–a = green, +a = red), b^* is blue/yellow (–b = blue, +b = yellow) (Riaz et al., 2022).

2.3.1.3. Carotenoids content (CAR). The determination of CAR was performed according to the method described by Saleh et al. (2020) with slight modifications. For solid samples (CD, CP, FF, and FDCS), between 0.03 and 0.1 g of sample was placed in a test tube. For liquid samples (CS), 0.5 g of sample was placed in a test tube. Then, 10 mL of a solvent mixture composed of hexane, acetone, and absolute ethanol in a 2:1:1 ratio was added. The samples were centrifuged (Rolco, 2036, Argentina) for 20 min at 2,500 rpm. The test tubes were then stored at 4 °C and protected from light for 60 min. After this time, 5 mL of distilled water was added to allow phase separation. The upper hexane phase was separated from the aqueous phase, and the CAR absorbance (Abs) was measured using a spectrophotometer (Agilent Varian Cary 50, USA) at 450 nm. Hexane was used as the blank. The CAR content was calculated according to Equation (2) using the formula proposed by Rodríguez Amaya (1997), and reported as mg of carotenoids per 100 g of sample (db).

$$CAR\ (mg/100\ g\ db) = \frac{Abs\ .\ Volume\ of\ the\ upper\ phase\ (ml)\ x\ 10^3}{A^{1\%}_{1\ cm}\ .\ Sample\ weight\ (g\ db)} \tag{2}$$

where $A^{1\%}_{1\ cm}$ is the absorption coefficient of β-carotene in hexane, adopting a value of 2,592 (Finkel'shtein, 2016).

2.3.1.4. Total phenolic content (TPC). The total phenolic content (TPC) was determined in carrot discards (CD), carrot powders (CP), fibre-rich fractions (FF), freeze-dried concentrated solutions (FDCS), and concentrated solutions (CS). The TPC was measured using the Folin–Ciocalteu method described by (Mohammed et al., 2022), with slight modifications.

For solid samples, including CD, CP, and FF, a liquid extract was first obtained through hydroalcoholic extraction. 50 g of sample were extracted with 2,000 mL of a hydroalcoholic solution containing 50% ethanol (v/v), at a solid-to-liquid ratio of 1:40 (w/v), at 50 °C under continuous agitation (Precytec, Argentina) at 260 rpm for 10 h. The extract was separated by filtration, and the solid residue was re-extracted under the same temperature and agitation conditions for 4 h using enough hydroalcoholic solution to achieve a 1:10 w/v ratio. Both filtrates were combined, and the TPC of the resulting extract was determined.

For FDCS, 1 g of sample was dissolved in 40 mL of a hydroalcoholic solution containing 50% ethanol (v/v) in 50 mL test tubes wrapped with aluminium foil. The suspension was stirred manually to aid dissolution, allowed to stand for 1 h at room temperature, and then placed in a 60 °C water bath for 10 min with occasional stirring to ensure complete solubilization. The resulting solution was used for TPC determination.

For CS, no preliminary extraction step was needed, and the sample was directly subjected to the Folin–Ciocalteu assay.

In all cases, the following procedure was used to determine the TPC: 60 µL of the sample (liquid extract or CS) were mixed with 4.74 mL of distilled water and 300 µL of Folin–Ciocalteu reagent in a test tube protected from light. After vortexing for 30 s (Precytec, Argentina), 900 µL of 20% Na_2CO_3 saturated solution were added, and the mixture was vortexed again for 2 s. The reaction mixture was incubated in the dark for 120 min at room temperature. Absorbance was measured at 760 nm using a spectrophotometer (Agilent Varian Cary 50, USA).

The TPC was expressed as mg of gallic acid equivalent (GAE) per 100 g of dry sample (mg GAE/100 g db), based on a calibration curve prepared from a gallic acid stock solution (10 mg mL^{-1}, $R^2 = 0.9981$), according to Equation (3).

$$TPC\ (mg\ GAE/100\ db) = \frac{GAE\ concentracion\ (mg\ GAE/ml) \cdot Volume\ of\ solvent\ (ml)}{Sample\ weight\ (g\ db)} \cdot 100 \tag{3}$$

2.3.1.5. Antioxidant capacity: ABTS and DPPH. The antioxidant capacity was evaluated for the fibre-rich fractions (FF) and the freeze-dried products (FDCS). The antioxidant capacity was evaluated using the ABTS and DPPH assays. These assays measure the ability to neutralize the ABTS•+ and DPPH•+ antioxidant radicals, respectively, through single-electron reduction of these stable radicals (Galante et al., 2019). Both assays were performed following the method described by Lingiardi et al. (2025), with slight modifications.

For the DPPH assay, a mixture of 0.6 mL of sample extract and 3.6 mL of 0.1 mM DPPH solution was vortexed for 20 s. The mixture was then incubated in the dark at room temperature for 50 min, and its absorbance was measured at 517 nm using a spectrophotometer (Agilent Varian Cary 50, USA). A 2.4 mM Trolox solution was used as a standard. The control consisted of hydroalcoholic solution with an ethanol concentration of 50% a mixed with the DPPH solution, while the blank used a hydroalcoholic solution with an ethanol concentration of 50% and sample extract. The antioxidant activity (AA) was expressed as mg Trolox equivalents (TE) per 100 g sample (db) and calculated using Equation (4).

$$AA_{DPPH}\ (mg\ TE/100\ g\ db) = \frac{Abs_c}{\Delta Abs_{sb}} \tag{4}$$

where Abs_c is the absorbance of the control and ΔAbs_{sb} is the difference between the absorbance of the sample extract and the absorbance of the blank without DPPH.

For the ABTS assay, an ABTS solution (7 mM) was prepared in phosphate buffer (5 mM, pH 7). For the activation of the ABTS•+ radical, 5 mL of the ABTS solution was combined with 88 µl of $K_2S_2O_8$ and incubated in the dark at room temperature for 24 h prior to use. The resulting ABTS solution was diluted with phosphate buffer (5 mM, pH 7) to obtain an absorbance of 0.70 ± 0.02, measured at 734 nm using a spectrophotometer (Agilent Varian Cary 50, USA). To determine the antioxidant compound content in the sample, 990 µl of the diluted ABTS solution was transferred to a microcuvette, and its absorbance at 734 nm was recorded. Subsequently, 10 µl of the sample was added, and the absorbance at 734 nm was measured after 6 min. The same procedure was applied using a 2.4 mM Trolox solution. Results were expressed as mg of Trolox equivalents (TE) per 100 g sample (db). The antioxidant activity (AA) was calculated using Equation (5).

$$AA_{ABTS}\ (mg\ TE/100\ g\ db) = \frac{\Delta Abs_s\ x\ 2.4\ mM}{\Delta Abs_t} \tag{5}$$

where ΔAbs_s is the difference between the absorbance of the ABTS radical solution at time 0 (Abs_{s0}) and the absorbance of the ABTS radical measured 6 min after the addition of the sample, and ΔAbs_t is the difference between the absorbance of the ABTS radical solution at time 0 and the absorbance of the ABTS radical measured 6 min after the addition of the Trolox solution.

2.3.1.6. Water holding capacity and oil holding capacity. To evaluate the functionality of the fibre-rich fractions (FF), water holding capacity (WHC) and oil holding capacity (OHC) were evaluated as functional properties. Both properties were determined according to Wang et al. (2021) with slight modifications. A FF sample (1 g wb) was mixed in a 50 mL centrifuge tube with distilled water (25 mL) or high oleic sunflower oil (25 mL) in a vortex mixer for 30 s (Precytec, Argentina) and then left to rest for 24 h at room temperature. Then, each tube was centrifugated at 3,000×g for 20 min in a laboratory centrifuge (Rolco, Argentina). The supernatant was decanted, and the remaining sediment in the centrifuge tube was weighed. The water holding capacity (g/g wb) and oil holding capacity (g/g wb) were calculated as the amount of water or sunflower oil held per gram of the fibre-rich fraction, as outlined in Equations (6)–(7), respectively.

$$WHC = \frac{Mass\ of\ water\ retained\ (g)}{Mass\ of\ fibre\ rich\ fraction\ (g\ wb)} \tag{6}$$

$$OHC = \frac{Mass\ of\ sunflower\ oil\ retained\ (g)}{Mass\ of\ fibre\ rich\ fraction\ (g\ wb)} \tag{7}$$

2.3.2. Evaluation of carotenoid retention and recovery. Carotenoids retention reflects the ability of the drying process to preserve the carotenoid content initially present in the fresh carrot discards (CD), considering the applied drying temperature, allowing for an evaluation of how temperature impacts carotenoid preservation during processing. To evaluate the percentage of carotenoid retention in carrot powders (CP), Equation (8) was applied.

$$CR\ (\%) = \frac{CAR_{CP}}{CAR_{CD}}.100 \tag{8}$$

where CAR_{CP} is the concentration of carotenoids (mg/100 g db) in the carrot powder after drying at the corresponding temperature (50, 60 or 70 °C), and CAR_{CD} is the concentration of carotenoids (mg/100 g db) in the fresh carrot discards.

Carotenoids recovery quantifies the total amount of carotenoids extracted and retained across all final products obtained from the process, providing an overall assessment of the efficiency of both drying and extraction steps. Since the optimal extraction run is not solely determined by carotenoid concentration but also by the mass of each fraction relative to the mass of CP, the extraction yields for each fraction will be assessed individually before calculating the total recovery. Thus, the recovery from the extraction process ($Y_{EXT,FF}$ and $Y_{EXT,CS}$) is calculated using Equations (9)–(10), expressed as the quantity of carotenoids obtained from each individual fraction (CAR_{FF} and CAR_{CS}, respectively) per gram of carotenoids (db) in the CP produced at the corresponding drying temperature. Then, the total extraction yield ($Y_{EXT,T}$) is obtained as the sum of these individual yields, providing an overall evaluation of the carotenoid recovery across all extracted fractions, as reported Equation (11).

$$Y_{EXT,FF}\ (\%) = \frac{mass\ of\ carotenoids\ in\ FF\ (g\ db)}{mass\ of\ carotenoids\ in\ CP\ (g\ db)}.100 \tag{9}$$

$$Y_{EXT,CS}\ (\%) = \frac{mass\ of\ carotenoids\ in\ CS\ (g\ db)}{mass\ of\ carotenoids\ in\ CP\ (g\ db)}.100 \tag{10}$$

$$Y_{EXT,T}\ (\%) = Y_{EXT,FF} + Y_{EXT,CS} \tag{11}$$

The overall carotenoids recovery (Y_T) after both drying and extraction is determined using Equation (12) and is expressed as the quantity of carotenoids obtained from fractions FF and CS per gram of carotenoids (db) in CD.

$$Y_T\ (\%) = \frac{mass\ of\ carotenoids\ in\ FF + mass\ of\ carotenoids\ in\ CS\ (g\ db)}{mass\ of\ carotenoids\ in\ CD\ (g\ db)}.100 \tag{12}$$

2.3.3. Productivity. Productivity of the recovery process (kg products db/kg discard db) was computed as the sum of the quantity of the final products after the extraction process, i.e. the mass of the FF and CS fractions, per kilogram of carrot discards CD, as defined Equation (13).

$$P_T\ (kg\ products\ db/kg\ discard\ db) = \frac{mass\ of\ FF + mass\ of\ CS\ (kg\ db)}{mass\ of\ CD\ (kg\ db)} \tag{13}$$

2.4. Statistical analysis

The results were analyzed using one-way or multi-factor ANOVA, assuming a normal distribution with a 95% two-tailed confidence level. Each experimental measurement was performed in quadruplicate, and the results are presented as the mean value with the corresponding standard deviation. Significant differences ($P < 0.05$) between experimental values are indicated by different letters, as determined by Tukey's post-hoc tests. Statistical analyses were conducted using R software version 3.6.0.

3. RESULTS AND DISCUSSION

3.1. Obtention and characterization of carrot powders (CP) by convective drying

Figure 2 presents the experimental profiles of moisture content (HS) during the convective drying of carrot discards (CD) at 50, 60, and 70 °C. The results show that higher air temperatures lead to shorter drying times ($P < 0.05$) to reach the equilibrium moisture levels. Compared to drying at 70 °C, reaching equilibrium moisture levels requires an additional 70 min at 50 °C and 30 min at 60 °C. The observed trend is similar to the findings of Sarpong et al. (2019), who reported that the time required to achieve complete drying of carrot slices at 60, 70 and 80 °C, is reduced by approximately 45–60 min. The observed results are consistent with those reported by other authors (Demiray and Tulek, 2017; Doymaz, 2016; Filipovic et al., 2022; Saleh et al., 2020; Raut et al., 2021) for the drying of carrot, showing that lower drying temperatures require significantly longer times to reach the equilibrium moistures.

The physicochemical characteristics of the carrot powders (CP) obtained by convective drying at the three temperatures are shown in Table 1.

It is observed that CPs dried at 60 and 70 °C exhibited significantly lower moisture contents ($P < 0.05$) compared to those dried at 50 °C. Additionally, CP dried at 60 °C showed significantly lower a_w ($P < 0.05$) than CP dried at 50 °C. However, the water activity of CP dried at 70 °C did not differ significantly ($P > 0.05$) from that of the powders obtained at the other two drying

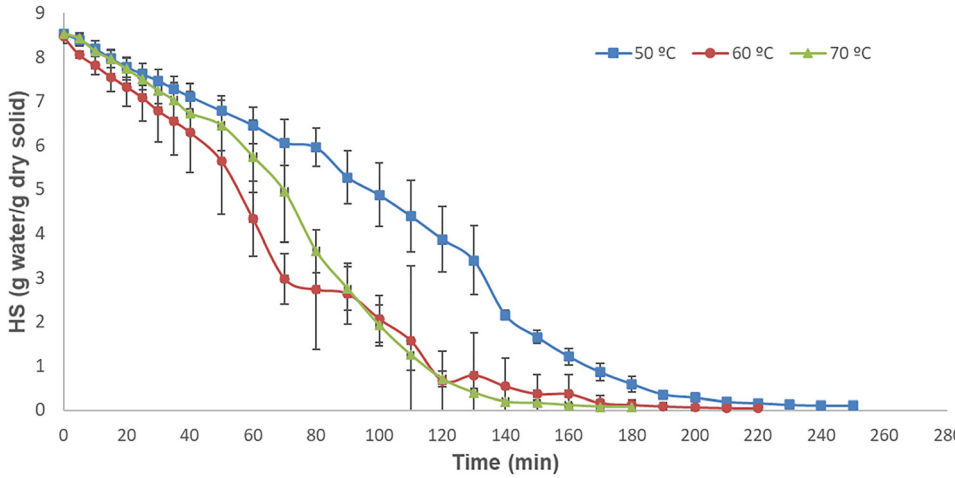


Fig. 2. Moisture content profile during convective drying of carrot discards at different temperatures (own source)

Table 1. Physicochemical characteristics of carrot discards CD and carrot powders CP

	CD	CP 50 °C	CP 60 °C	CP 70 °C
Moisture (%, wb)	89.4 ± 0.27 a	6.85 ± 0.92 b	3.88 ± 0.19 c	4.75 ± 1.06 c
Water activity, a_w		0.39 ± 0.02 a	0.30 ± 0.02 b	0.33 ± 0.03 ab
CAR (mg/100 g db)	124.14 ± 1.19 a	42.91 ± 2.26 c	54.84 ± 1.23 b	40.29 ± 3.39 c
CR (%)		35.00 ± 1.84 b	44.78 ± 1.00 a	32.86 ± 2.77 b
TPC (mg GAE/100 g db)	146.82 ± 21.98 c	329.30 ± 24.50 b	399.70 ± 25.60 a	353.60 ± 34.80 ab
AA_{DPPH} (mg TE/100 g db)	5555.24 ± 28.05 a	1540.60 ± 44.43 b	1666.37 ± 127.25 b	2050.56 ± 274.74 b
AA_{ABTS} (mg TE/100 g db)	979.18 ± 0.00 a	337.97 ± 46.88 b	430.57 ± 18.15 b	404.72 ± 17.31 b

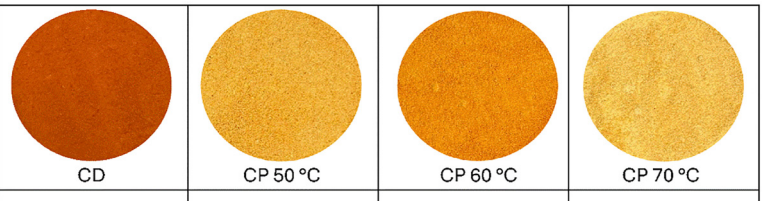
One-way ANOVA for each variable, where different letters within the same row indicate significant differences between the samples analyzed, according to Tukey's test.

temperatures. Despite these differences, all the moisture values obtained are well below the maximum limit of 7% established by the Argentine Food Code for dehydrated vegetables (All Nutrition and Food Code of Argentina [CAA], 2025). Additionally, a_w values of the three CP were below 0.6, a level considered microbiologically safe as it inhibits biological processes, particularly the growth and multiplication of microorganisms (Akter et al., 2024; Dadan and Nowacka, 2021). These results align with those reported by Saleh et al. (2020) and Raut et al. (2021), who also evaluated the drying of carrots at 50, 60, and 70 °C. Saleh et al. (2020) dried carrots until reaching a final moisture content of 0.14 ± 0.02 g water/g dry matter and found that the final products obtained at all three temperatures had a_w values ranging from 0.34 to 0.36, similar to those observed in this study. Raut et al. (2021) reported that carrots dried at 60 °C exhibited the lowest a_w, followed by those dried at 70 and 50 °C. Dadan and Nowacka (2021) dried carrot slices at 70 °C and obtained a final product with an a_w of 0.27, also in the range of

the values reported here. Similarly, Alam et al. (2013) evaluated different drying methods for carrot pulp, including convective drying at 55 and 65 °C, and found no significant differences in a_w, with values of approximately 0.35–0.36. Water activity is influenced by various factors, including matrix porosity, chemical composition, physicochemical state, drying temperature, and surface tension. As a result, the same moisture content achieved at a given drying temperature may lead to different a_w values due to variations in chemical composition, either within the same variety or among different varieties (Saleh et al., 2020). In addition, low a_w levels, particularly those below 0.40, help prevent carotenoid degradation and sample deterioration caused by enzymatic and non-enzymatic browning reactions, as well as microbial activity (Raut et al., 2021). Furthermore, understanding the interactions of moisture content and a_w is essential to avoid undesirable phenomena such as clumping, agglomeration, and stickiness of powders during handling and storage (Kapoor and Feng, 2022).

Figure 3 presents the color parameters of the carrot powders (CPs) obtained at the three drying temperatures. Compared to the fresh carrot discards (CDs), some CPs produced at different drying temperatures showed significant differences ($P < 0.05$) in the L^*, a^*, and b^* color parameters. An increase in the L^* parameter ($P < 0.05$) was observed as a result of the drying process, with a more pronounced increase for the CPs obtained at 50 and 70 °C. This increase could be attributed to the isomerization of carotenoids from trans to cis configuration, leading to lighter-colored derivatives with reduced biological activity (Sarpong et al., 2019).

A decrease in the a^* parameter ($P < 0.05$) was observed in carrots dried at 50 and 70 °C, with a more pronounced decrease at the higher drying temperature. An increase in the b^* parameter ($P < 0.05$) was noted for CPs obtained at 50 and 60 °C, with the largest increase occurring in CPs dried at 60 °C. The changes in a^* and b^* resulting from drying at different temperatures can be associated with factors such as carotenoid loss, oxidation reactions, and enzymatic and non-enzymatic browning (Wang et al., 2018). The color difference between the CPs and the fresh carrot discards (ΔE) can be classified as very distinct, as the ΔE exceeded the threshold value of 3 as proposed by Adekunte et al. (2010). ΔE was significantly higher ($P < 0.05$) for the CPs obtained through drying at 50 and 70 °C. Saleh et al. (2020) also reported higher ΔE values for drying at 50 and 70 °C compared to 60 °C. According to these authors, such variations are explained by the longer drying times at lower temperatures, which increase the exposure of



	CD	CP 50 °C	CP 60 °C	CP 70 °C
L*	57.45 ± 1.46 c	75.76 ± 0.78 a	67.21 ± 2.59 b	80.27 ± 0.38 a
a*	28.59 ± 0.22 a	12.82 ± 0.20 b	28.57 ± 0.91 a	6.66 ± 0.39 c
b*	55.96 ± 0.30 c	65.35 ± 0.62 b	70.77 ± 2.73 a	60.02 ± 0.85 c
ΔE		25.93 ± 0.45 a	17.76 ± 3.70 b	31.92 ± 0.44 a

Fig. 3. Effect of drying temperature on the color parameters of carrot discards (CD) and carrot powders (CP) obtained at different drying temperatures (own source)

the sample to heat; or by the heightened carotenoid degradation due to higher drying temperatures with shorted drying times, resulting in a lighter sample color. In addition, prolonged exposure of the sample to hot air may also intensify non-enzymatic browning reactions, such as the Maillard reaction (Filipovic et al., 2022). Raut et al. (2021) also observed greater color degradation at 70 °C compared to 50 and 60 °C during the drying of carrot slices.

The carotenoid content (CAR) of fresh carrot discards was consistent with values reported by other authors for the same variety, with Ghosh et al. (2019) reporting 96.31 mg/100 g db and Santos et al. (2021) reporting 120 mg/100 g db. During drying, carotenoids undergo thermal degradation, which is also reflected in color loss (Saleh et al., 2020; Raut et al., 2021). Table 1 shows this trend, with significant differences ($P < 0.05$) in carotenoid content between fresh carrot discards and carrot powders ($P < 0.05$). After drying, the highest CAR and corresponding carotenoid retention (CR) were observed in samples dried at 60 °C, consistent with the findings of Saleh et al. (2020) and Raut et al. (2021). Lower values, with no significant differences ($P > 0.05$), were found for prolonged drying at a lower temperature (50 °C) and for shorter drying times at a higher temperature (70 °C). This agrees with several authors who have reported that carotenoid degradation is directly proportional to increases in temperature or prolonged heat exposure (Zhao et al., 2021; Demiray and Tulek, 2017; Eim et al., 2013). Kamel et al. (2023) proposed a drying pretreatment involving steam blanching for 3 min to enhance the bioavailability of β-carotene through thermal treatment and to inactivate enzymes such as pectinase and peroxidase. This process resulted in higher CAR concentrations after drying at 55 °C for 12 h, although the initial CAR content in fresh carrots was not reported, making it impossible to estimate and compare carotenoid retention (CR).

Drying temperatures above 60 °C are not recommended due to several factors contributing to carotenoid degradation and color loss, since the activation of the lipoxygenase enzyme catalyzes oxidation reactions under aerobic conditions (Akter et al., 2024; Alam et al., 2013). Additionally, high drying temperatures accelerate water loss at the surface of carrot slices, increasing the exposure of carotenoids to hot air, which can lead to degradation through lipid peroxidation and both enzymatic and non-enzymatic browning reactions (Saleh et al., 2020; Raut et al., 2021). The β-carotene molecule, with its highly unsaturated structure, is particularly susceptible to isomerization and oxidation at high temperatures. Non-enzymatic browning, such as the Maillard reaction, occurs through interactions between amines and carbonyl groups of reducing sugars, producing brown pigments or colored polymers like melanoidins, as well as browning associated with ascorbic acid degradation (Sarpong et al., 2019; Saleh et al., 2020).

Total phenolic contents (TPC) for carrot discards and carrot powders are also reported in Table 1. Higher TPCs ($P < 0.05$) were observed for dried samples respect to fresh discards. The TPC content in fresh carrots was similar to the values reported by Yusuf et al. (2021) and Ignaczak et al. (2023), who found concentrations of 224.4 mg/100 g (db) and 127.1 mg/100 g (db), respectively. The increase in TPC concentration in the carrot powders (CPs) could be explained by the cutting stress to which the fresh carrots were subjected prior to drying. Post-harvest abiotic stress, such as wounding, infection, atmospheric changes, radiation, and storage, leads to an accumulation of phenols in carrots by promoting the activation of phenylalanine ammonia-lyase (PAL), which involves ATP and reactive oxygen species (ROS) as signalling molecules, while high drying and storage temperatures further enhance this accumulation by inducing ROS generation (Mandrich et al., 2023; Paparella et al., 2024).

Phenolic compounds are naturally present in plant cells, bound to other molecules such as proteins, carbohydrates, fibres, and lipids. These interactions, through covalent bonds (with carbohydrates, lipids, and proteins) and non-covalent bonds (with proteins), reduce the bioaccessibility of phenolic compounds. However, bioaccessibility increases as a result of various food transformations, which promote the breakdown of bonds between phenolic compounds and other molecules (Bochnak and Świeca, 2020; Vaz et al., 2022). Previous results reported by other authors regarding TPC during drying showed considerable variability. Santana-Gálvez et al. (2016) reported no significant differences in TPC before and after drying carrot slices in an oven at 60 °C for 30 h. Balzarini et al. (2024) found higher TPC values in samples of chicory roots dried in a convective oven at 60 °C compared to 80 °C. Matys et al. (2023) tested the drying of apple slices at 55, 70, and 85 °C, obtaining the highest TPC at 70 °C. Zhao et al. (2021) dried persimmon slices at 50, 60, and 70 °C and observed a higher concentration of TPC in slices dried at 50 °C.

The antioxidant activity (AA), measured using the ABTS and DPPH assays, significantly decreased ($P < 0.05$) between CD and the CPs obtained at three drying temperatures (Table 1). Carotenoids (CAR) have the ability to neutralize free radicals, which explains their AA (Kamel et al., 2023). Therefore, the reduction in AA in the CPs could be related to the significant decrease in CAR during the dehydration process. Additionally, thermal drying leads to the loss of other endogenous water-soluble compounds with antioxidant activity present in fresh carrots, such as amino acids, phenols (Saleh et al., 2020), and ascorbic acid (Akter et al., 2024).

AA did not follow the same trend as the one previously discussed for TPC, showing a behavior similar to that reported by Balzarini et al. (2018). The influence of drying on the AA of carrots has been reported by several authors. Eim et al. (2013) stated that the AA of carrot samples decreased during drying, with a greater reduction as the drying air temperature increased. Nguyen and Le (2018) dried carrot peels at 50 and 100 °C, obtaining a DPPH value of 1,799 ± 426 mg TE/100 g (db) for peels dried at 50 °C, which was higher than the value obtained in this study for the same drying temperature; while for carrot peels dried at 100 °C, the authors reported a total loss of AA. Marić et al. (2019) evaluated the effect of different drying methods including convective drying at 50 and 70 °C on the antioxidant content of carrots, as measured by the DPPH assay. These authors found that drying significantly reduced the AA in respect to the fresh carrots, with the greatest AA loss observed in carrots dried at 70 °C.

3.2. Evaluation of carotenoid recovery and total phenolic content after hydroalcoholic extractions

Table 2 presents the complete Box-Behnken design and the concentration of carotenoids (CAR) in the two recovery fractions FF and CS, the carotenoid recovery yields from the carrot powders in both aforementioned fractions ($Y_{EXT,FF}$ and $Y_{EXT,CS}$, calculated using Equations (9)–(10)), and the total extraction yield ($Y_{EXT,T}$, according to Equation (11)) as well as the overall carotenoid recovery (Y_T, calculated using Equation (12)). Additionally, Table 2 provides the total phenolic content of CS and the productivity of the recovery process (P_T, calculated using Equation (13)). For each response some significant differences ($P < 0.05$, four-way ANOVA) were found with respect to drying temperature, ethanol concentration, extraction temperature and solid:solvent ratio.

Table 2. Box-Behnken design and results obtained from the recovery process of carrot discards

Run	Drying temperature (°C)	Ethanol concentration (% v/v)	Extraction temperature (°C)	Solid: solvent ratio (w/v)	CAR_{FF} (mg/100 g db)	CAR_{CS} (mg/100 g db)	$Y_{EXT,FF}$	$Y_{EXT,CS}$	$Y_{EXT,T}$	Y_T	TPC_{CS} (mg/100 g db)	P_T (kg products db/kg discard db)
1	50	50	50	1:20	8.24 ± 0.40 bcd	6.05 ± 4.31 d	7.20 ± 1.69 bcde	6.53 ± 4.15 ef	13.73 ± 5.83 fg	4.75 ± 2.02 de	368.27 ± 34.90 def	0.85 ± 0.02 abcde
2	70	50	50	1:20	14.01 ± 4.72 a	3.81 ± 0.96 d	11.99 ± 3.87 a	3.98 ± 0.86 ef	15.97 ± 3.01 defg	5.18 ± 0.98 de	437.50 ± 20.22 bcdef	0.77 ± 0.01 bcde
3	50	100	50	1:20	6.28 ± 0.75 bcd	39.65 ± 13.24 ab	6.21 ± 0.19 bcde	29.17 ± 10.11 b	35.38 ± 9.92 ab	12.23 ± 3.43 b	358.12 ± 53.47 def	0.74 ± 0.04 de
4	70	100	50	1:20	10.38 ± 0.16 ab	22.01 ± 2.38 c	12.33 ± 1.25 a	13.46 ± 0.56 cde	25.78 ± 1.81 bcdef	8.37 ± 0.59 bcd	404.20 ± 38.72 cdef	0.73 ± 0.02 e
5	60	70	40	1:10	7.66 ± 0.47 bcd	4.86 ± 0.27 d	5.71 ± 0.01 bcde	3.85 ± 0.40 ef	9.56 ± 0.39 g	4.21 ± 0.17 de	456.51 ± 70.36 bcdef	0.84 ± 0.00 abcde
6	60	70	60	1:10	9.98 ± 1.16 abc	3.92 ± 1.03 d	7.28 ± 10.82 bcd	3.32 ± 1.06 ef	10.60 ± 0.24 g	4.67 ± 0.11 de	448.79 ± 6.87 bcdef	0.86 ± 0.03 abcd
7	60	70	40	1:30	8.55 ± 1.75 bcd	11.03 ± 0.22 cd	5.37 ± 1.01 bcde	11.08 ± 0.88 def	16.45 ± 1.89 cdefg	7.24 ± 0.83 cde	648.78 ± 81.64 abcd	0.89 ± 0.05 ab
8	60	70	60	1:30	7.67 ± 1.31 bcd	8.03 ± 2.41 d	4.63 ± 0.67 cde	7.79 ± 1.73 ef	12.43 ± 2.40 g	5.47 ± 1.06 de	588.04 ± 57.10 abcde	0.87 ± 0.05 abcd
9	50	70	50	1:10	10.26 ± 1.05 ab	5.89 ± 2.81 d	9.51 ± 0.47 ab	5.50 ± 2.69 ef	15.00 ± 2.22 efg	5.19 ± 0.77 de	436.85 ± 22.22 bcdef	0.80 ± 0.03 abcde
10	70	70	50	1:10	6.88 ± 0.08 bcd	1.09 ± 0.31 d	6.69 ± 0.23 bcde	1.01 ± 0.15 f	7.70 ± 0.08 g	2.50 ± 0.03 e	672.40 ± 55.08 abc	0.77 ± 0.06 abcde
11	50	70	50	1:30	9.98 ± 0.63 abc	6.46 ± 0.15 d	7.64 ± 0.15 bc	7.20 ± 0.06 ef	14.84 ± 0.10 efg	5.13 ± 0.03 de	563.68 ± 67.13 abcde	0.81 ± 0.03 abcde
12	70	70	50	1:30	6.89 ± 1.44 bcd	4.11 ± 0.29 d	5.41 ± 1.16 bcde	5.19 ± 0.36 ef	10.59 ± 1.52 g	3.44 ± 0.49 e	749.94 ± 197.92 a	0.82 ± 0.00 abcde
13	60	50	40	1:20	10.17 ± 2.17 ab	4.93 ± 1.72 d	6.97 ± 1.86 bcde	4.47 ± 1.35 ef	11.44 ± 0.51 g	5.04 ± 0.22 de	564.16 ± 84.92 abcde	0.87 ± 0.05 abcd
14	60	100	40	1:20	4.79 ± 0.18 cd	37.28 ± 1.45 b	4.11 ± 0.30 cde	24.01 ± 0.55 bc	28.12 ± 0.85 bcd	12.38 ± 0.37 b	323.95 ± 20.57 ef	0.82 ± 0.01 abcde
15	60	50	60	1:20	8.82 ± 0.31 abcd	4.00 ± 0.03 d	6.03 ± 0.01 bcde	3.72 ± 0.11 ef	9.75 ± 0.11 g	4.29 ± 0.05 de	540.83 ± 22.01 abcdef	0.88 ± 0.03 abc
16	60	100	60	1:20	3.52 ± 0.12 d	44.55 ± 1.18 ab	2.90 ± 0.01 e	25.91 ± 1.12 b	28.81 ± 1.12 bc	12.69 ± 0.49 b	368.09 ± 20.80 def	0.77 ± 0.01 abcde
17	50	70	40	1:20	7.85 ± 0.51 bcd	2.35 ± 0.69 d	6.73 ± 0.40 bcde	2.57 ± 0.69 ef	9.31 ± 0.28 g	3.22 ± 0.10 e	568.41 ± 14.38 abcde	0.84 ± 0.01 abcde
18	70	70	40	1:20	5.38 ± 0.01 bcd	8.58 ± 0.95 cd	4.47 ± 0.02 cde	9.53 ± 0.56 ef	14.00 ± 0.58 fg	4.54 ± 0.19 de	726.86 ± 60.13 ab	0.78 ± 0.02 abcde
19	50	70	60	1:20	9.36 ± 1.77 abc	2.63 ± 1.25 d	8.17 ± 0.93 abc	2.95 ± 1.45 ef	11.12 ± 2.39 g	3.84 ± 0.82 de	672.36 ± 33.54 abc	0.86 ± 0.02 abcde
20	70	70	60	1:20	3.77 ± 0.31 d	6.19 ± 1.34 d	3.04 ± 0.27 de	6.74 ± 1.90 ef	9.79 ± 2.17 g	3.18 ± 0.71 e	748.38 ± 159.88 a	0.76 ± 0.03 cde
21	60	50	50	1:10	8.37 ± 0.10 bcd	4.07 ± 1.84 d	5.95 ± 0.10 bcde	3.13 ± 1.64 ef	9.08 ± 1.74 g	4.00 ± 0.76 de	409.58 ± 57.67 cdef	0.80 ± 0.01 abcde
22	60	100	50	1:10	5.19 ± 1.14 bcd	43.87 ± 3.85 ab	5.29 ± 1.28 bcde	21.96 ± 0.38 bcd	27.25 ± 0.90 bcde	12.00 ± 0.40 bc	253.57 ± 22.06 f	0.83 ± 0.03 abcde
23	60	50	50	1:30	8.35 ± 0.43 bcd	7.09 ± 1.61 d	5.33 ± 0.39 bcde	5.81 ± 1.29 ef	11.15 ± 1.67 g	4.91 ± 0.74 de	444.98 ± 74.54 bcdef	0.80 ± 0.00 abcde
24	60	100	50	1:30	3.85 ± 0.96 d	52.60 ± 7.38 a	3.09 ± 0.57 de	44.18 ± 7.75 a	47.27 ± 8.32 a	20.82 ± 3.66 a	353.66 ± 30.96 ef	0.90 ± 0.01 a
25	60	70	50	1:20	8.23 ± 0.37 bcd	5.62 ± 0.70 d	5.31 ± 0.07 bcde	5.18 ± 0.30 ef	10.49 ± 0.37 g	4.62 ± 0.16 de	535.29 ± 40.45 abcdef	0.86 ± 0.01 abcd
26	60	70	50	1:20	9.61 ± 1.00 abc	6.03 ± 0.38 d	6.25 ± 0.44 bcde	5.69 ± 1.12 ef	11.94 ± 0.67 g	5.26 ± 0.30 de	580.69 ± 33.07 abcde	0.87 ± 0.08 abcd
27	60	70	50	1:20	8.07 ± 0.46 bcd	3.36 ± 0.50 d	5.25 ± 0.22 bcde	3.06 ± 0.45 ef	8.31 ± 0.66 g	3.66 ± 0.29 de	568.47 ± 127.15 abcde	0.85 ± 0.01 abcde

Multi-factor ANOVA for each variable, where different letters within a column represent significant differences between experimental results according to post-hoc Tukey tests.

The carotenoid recovery across both fractions exhibited varied patterns, influenced by fraction weight and carotenoid concentration. In the solid fraction, the highest CAR_{FF} concentration was obtained in Run 2 ($P < 0.05$, four-way ANOVA) for a CP dried at 70 °C, using a 50% ethanol concentration, a temperature of 50 °C, and a solid-to-solvent ratio of 1:20 in the extraction. Additionally, Run 2 also showed the highest extraction recovery yield for FF ($Y_{EXT,FF}$).

For the liquid phase, the highest CAR_{cs} concentration and recovery yield $Y_{EXT,\ SC}$, were obtained in Run 24 ($P < 0.05$, four-way ANOVA) for a CP dried at 70 °C, using an extraction with 100% ethanol concentration at 50 °C and a solid-to-solvent ratio of 1:20. These results highlight the inherent trade-off in extraction behavior, as it is not possible to achieve the highest recovery yields in both phases under the same conditions. When the system favors higher carotenoid extraction into the liquid phase, resulting in increased concentration and recovery in SC, the solid phase FF retains a lower carotenoid concentration.

Analyzing the one-way ANOVA tests for each independent variable, it was observed that only ethanol concentration significantly influenced CAR_{FF} ($P < 0.05$). For CAR_{FF}, ethanol concentrations of 50% and 70% statistically favored higher carotenoid concentrations compared to a concentration of 100%. On the other hand, an ethanol concentration of 100% led to a significant increase in CAR_{cs}, as well as in the extraction yield $Y_{EXT,\ SC}$. However, for $Y_{EXT,\ FF}$, the only significant factor was drying temperature, with 50 and 70 °C promoting higher extraction yields.

The highest $Y_{EXT,T}$ and Y_T were achieved also for Run 24, for a CP dried at 60 °C, with an ethanol concentration of 100%, a solid:liquid ratio of 1:30, and an extraction temperature of 50 °C. These results indicate that the total extraction yield is more influenced by the mass and carotenoid concentration in SC than in FF, highlighting the greater contribution of the liquid phase to overall carotenoid recovery. One-way ANOVA tests for Y_{EXT} and Y_T indicated that ethanol concentration had a significant effect ($P < 0.05$) on both responses, obtaining higher yields with a 100% ethanol concentration. Furthermore, the analysis conducted thus far reveals that drying temperature, extraction temperature, and the solid-to-liquid ratio do not significantly impact the extraction and recovery of carotenoids. Since carotenoids were quantified in all fractions, it was possible to identify that the main losses occurred during the convective drying for obtaining the carrot powders (CP) (an average value of 60% loss with respect to CD), and the convective drying for obtaining the fibre-rich fraction (FF) (an average value of 87% with respect to the solid fraction obtained from the hydroalcoholic extraction of CP), both due to thermal degradation, while minor losses also occurs during the vacuum distillation.

For total phenolic content, higher TPC_{CS} values were observed in specific runs ($P < 0.05$, one-way ANOVA), such as Run 12 (749.94 ± 197.92 mg/100 g db) and Run 20 (748.38 ± 159.88 mg/100 g db). Both runs share a drying temperature of 70 °C and an ethanol concentration of 70%, indicating that an ethanol concentration of 70% played a key role in enhancing the solubility of phenolic compounds. On the other hand, extraction temperature and the solid-to-liquid ratio did not exert a significant influence, according to the respective one-way ANOVA.

The highest productivity values P_T were observed also in Run 24, with a value of 0.90 ± 0.01 kg products db/kg discard db. As confirmed by one-way ANOVA, only the drying temperature exhibited significant effect on the productivity, with higher values for CP dried at 50 and 60 °C; while extraction temperature, ethanol concentration and solid:liquid ratio did not significantly influence productivity. Again, this finding is advantageous from an energy optimization and

sustainability perspective, as it suggests that operational conditions can be adjusted to minimize solvent consumption and reduce energy demands during both extraction and drying.

Sharma et al. (2020) evaluated the effect of different operating conditions on the extraction of β-carotene from pumpkin pulp dehydrated at 55 °C. The variables considered included extraction temperature (room temperature, 30, 40, and 50 °C), extraction time (60, 120, 180, and 240 min), and extraction solvents (acetone, hexane, and ethanol). From the solvent screening, ethanol resulted in the lowest β-carotene concentrations, with an average value of 54.3 mg/100 g. Although ethanol is not the most efficient solvent for carotenoid extraction, it remains widely used due to its lower toxicity and regulatory acceptance in the food industry. Additionally, emerging extraction technologies are being explored to improve carotenoid recovery and extraction efficiency (Kumari et al., 2018).

The results obtained so far indicate that extraction temperature did not have a significant effect on carotenoid recovery. This can be explained by previous findings showing that, at temperatures above ambient, β-carotene extraction efficiency increases until reaching an optimal point around 40 °C, with no significant improvements at higher temperatures (Sharma et al., 2020). This is because moderate temperatures promote the release of carotenoid pigments by disrupting the structure of plant tissues, facilitating their dissolution in the solvent (Dunford et al., 2010); while higher temperatures may lead to thermal degradation of carotenoids, which could explain the lack of significant differences observed when increasing the extraction temperature beyond 40 °C (Sharma et al., 2020).

Clementz et al. (2019) evaluated the efficiency of carotenoid extraction from fresh carrot discards using alternative processes. One of the methods was similar to the one analyzed in this study, involving extractions over four successive 15-min cycles using a Soxhlet extractor with ethanol as the solvent at 60 °C and a 1:1 (w/v) ratio. This approach resulted in a carotenoid recovery yield of 64.7%, slightly higher than the values obtained in the present study for runs under comparable conditions, like Run 24, which may be attributed to the prior drying step and different extraction strategy here implemented. On the other hand, Umair et al. (2021) achieved higher carotenoid recovery yields of approximately 28–30% from carrot pomace, using ethanol concentration of 50% in a batch vessel assisted by ultrasonication at 40 °C. In their study, ethanol concentrations were tested up to 75%, along with other solvents such as methanol, acetone, acetonitrile, and n-hexane. When testing freshly harvested, frozen, and refrigerated carrot samples, Sharmin et al. (2016) obtained β-carotene concentrations of 4.28 mg/100 g at 60 °C after 2–4 h of extraction using an extraction solvent with an ethanol concentration of 100% at a solid-to-liquid ratio of 1:4 (w/v), which Haga clic o pulse aquí para escribir texto.are considered intermediate concentration levels with respect to the experimental design carried out in this study.

Considering the total phenolic content (TPC) in the concentrated solution (CS), previous studies have demonstrated that aqueous ethanol solutions enhance phenolic compound extraction compared to absolute ethanol, as water facilitates particle hydration, improves solvent penetration into the matrix, and enhances mass transfer by diffusion (Janarny et al., 2022). This is consistent with the findings of Wojeicchowski et al. (2021), who reported significantly higher TPC extraction yields from dried rosemary leaves when using an ethanol concentration of 70% compared to 100%. Similarly, Ferreira-Santos et al. (2021) observed significantly higher TPC extraction yields from dried eggplants when ethanol concentrations of 30%, 50%, and 70% were used, compared to 90%. However, Balzarini et al. (2024) evaluated the effect of different

drying and extraction conditions on the recovery of TPC from chicory roots, and observed a significant influence of the solid-to-liquid ratio, ethanol concentration, and agitation speed, as well as, unlike in our study, the extraction temperature. They reported higher TPC concentrations when using lower ethanol concentrations, a lower solid-to-liquid ratio, and higher extraction temperatures. Kaptso et al. (2022) analyzed the TPC and AA content in Rambutan (*Nephelium lappaceum*) extracts obtained at different temperatures and extraction times while maintaining a solid-to-liquid ratio of 1:40 and using an ethanol concentration of 50%; and observed a significant impact of extraction temperature on TPC and AA concentrations, reporting higher yields at higher temperatures (45 °C, compared to 25 and 35 °C).

In addition, Ferreira-Santos et al. (2021) investigated the effect of different solvents on the extraction of TPC from dehydrated eggplants and evaluated the antioxidant activity using the DPPH and ABTS assays, and found that extracts obtained using ethanol concentration of 50% and 70% contained significantly higher amounts of TPC and AA compared to those obtained with a 90% ethanol concentration. According to Janarny et al. (2022), the use of aqueous ethanol instead of absolute ethanol promotes particle hydration, facilitating the penetration of the organic solvent into the matrix and thus enhancing mass transfer by diffusion. Therefore, it must be considered that hydroalcoholic solvents are not selective for carotenoids and phenolics but also solubilize other components such as sugars and organic acids, whose solubility varies depending on the ethanol-to-water ratio. The co-extraction of these non-target compounds not only affects the overall composition of the extracts but may also influence mass transport phenomena during extraction. This explains the presence of sugars detected in the freeze-dried concentrated solutions, highlighting that the final products contain a combination of bioactive and nutritional compounds.

3.3. Selection of optimal extraction runs

Among the experimental configurations tested, Run 24 was identified as the most effective for carotenoid recovery. Characterized by a drying temperature of 60 °C, ethanol concentration of 100%, an extraction temperature of 50 °C, and a solid-to-solvent ratio of 1:30, this run exhibited the highest carotenoid concentration in the concentrated solution (CAR_{CS} of 52.60 ± 7.38 mg/100 g db) and the highest total extraction yield ($Y_{EXT,T}$ of 47.27 ± 8.32%). This condition is particularly suitable for applications where alcoholic extracts can be directly incorporated into food formulations.

However, in scenarios where the extract needs to be used in solid form, Runs 2 and 7 were selected as the more promising alternatives. Involving a drying temperature of 70 °C, ethanol concentration of 50%, an extraction temperature of 50 °C, and a solid-to-solvent ratio of 1:20, Run 2 showed the highest carotenoid concentration in the fibre-rich fraction (CAR_{FF} of 14.01 ± 4.72 mg/100 g db) and a high extraction yield ($Y_{EXT,FF}$ of 11.99 ± 3.87%). On the other hand, performed at 60 °C drying temperature, ethanol concentration of 70%, extraction at 40 °C, and a solid-to-solvent ratio of 1:30, Run 7 provided a more balanced carotenoid recovery across fractions, with a carotenoid concentration in CS (CAR_{CS} of 11.03 ± 0.22 mg/100 g db) and a high total phenolic content (TPC_{CS} of 648.78 ± 81.64 mg/100 g db), indicating its viability for further processing into powdered extracts.

An evaluation of the physicochemical composition of the fibre-rich fraction (FF) and the freeze-dried concentrated solution (FDCS) from Runs 2 and 7 was conducted, as presented in

Table 3, which compares physicochemical properties and functional properties (water and oil holding capacities) of the obtained products.

Regarding the FF from both runs, no significant differences were observed in moisture, protein, ash and total carbohydrates content. The total dietary fibre TDF content was higher ($P < 0.05$) in the FF from Run 2, due to an increase in soluble dietary fibre SDF. The lipid content was also significantly higher in the FF obtained in Run 2, which could be associated with the higher CAR content in this fraction, as these compounds are terpenoids, which are classified as lipid-macromolecules (Zhang et al., 2024).

The total carbohydrates include those that are digestible in the human gastrointestinal tract, and those that are not digestible, which are referred to as dietary fibre (McCleary and McLoughlin, 2021). Both FF products had a carbohydrates content close to 77% (db), similar to the value reported by Oncică et al. (2024) for freeze-dried carrot pomace. However, Run 2 exhibited a lower content of available carbohydrates due to the higher percentage of dietary fibre, which accounted for approximately 83% of the total carbohydrates present in the FF. In carrot pomace dried at 60 °C for 24 h, Luca et al. (2022) reported an average available carbohydrate content of 55%. Cozma et al. (2024) reported a similar value of approximately 51% available carbohydrates in carrot pomace obtained under the same dehydration conditions. These values are considerably higher than that found in both FFs obtained in the present study, which were approximately 17% for Run 2 and 18% for Run 7.

Bhatia et al. (2023) evaluated TDF, SDF, and IDF in fibre concentrate powders obtained from carrot pomace -a juice production byproduct- processed under different water immersion conditions and drying. Despite compositional differences due to raw material and processing, their TDF, IDF, and SDF values aligned with those found in the FF fractions here obtained, except for the lower SDF in Run 7 (~12%). IDF to SDF ratios (1.9–3.47) reported by Bhatia et al. (2023) were also comparable to the ones reported in the present work. Then, the FF from Run 2 would be more suitable for formulating functional foods, as an IDF/SDF ratio closer to 2 is considered optimal for its use as a functional ingredient in food formulation (Bhatia et al., 2023; Richards et al., 2024).

The IDF:SDF ratio influences not only dietary and functional properties but also structural and sensory characteristics (Clementz et al., 2019). In fibre-fortified food products, the SDF content should represent between 30% and 50% of the TDF (Bhatia et al., 2023). In the FF product from Run 2, SDF accounted for 24% of the total dietary fibre (TDF), whereas in the FF product from Run 7, this value was 19.36%. The higher SDF content in the FF from Run 2 may be associated with the treatment applied to the sample. As highlighted by Richards et al. (2024), the drying method significantly influences SDF content. The FF from Run 2, which showed the highest SDF percentage, was obtained using a higher drying temperature and higher extraction temperature compared to Run 7. Elevated temperatures can promote the cleavage of glycosidic bonds in polysaccharides, leading to the formation of oligosaccharides and, consequently, increasing the SDF content (Richards et al., 2024). Similarly for carrot pomace dried at 60 °C and milled, Sharoba et al. (2013) reported TDF, IDF, and SDF values of 69.85%, 45.12 ± 1.08%, and 24.73 ± 1.22% (db), respectively, with an IDF/SDF ratio of 1.82. In turn, Clementz et al. (2019) evaluated three processing methods for discarded carrots and, for the most efficient one, obtained TDF, SDF, and IDF values of 74.00 ± 0.22%, 54.30 ± 0.50%, and 19.60 ± 1.20% (db), respectively. Although these values were higher than those in the present study, the IDF/SDF ratio (2.77) was comparable to that of the FF from Run 2.

The protein content in the powders obtained in this study ranged from 13.28 ± 0.00% to 13.37 ± 0.70% (db), exceeding the values reported in most previous studies using carrot pomace derived from juice extraction processes. Sahni and Shere (2017) reported a value of 6.12 ± 0.03%, while Cozma et al. (2024) and Luca et al. (2022) reported values of 6.32 ± 0.49 to 7.34 ± 0.80%, and 8.64%, respectively. Similarly for dehydrated pomace, Vaz et al. (2022) and Salari et al. (2024) observed protein contents of 6.73 ± 0.23% and 6.40% (db), respectively. In carrot pomace, Sharoba et al. (2013) and Oncică et al. (2024) reported slightly higher values of 10.06 ± 0.18% and 9.86 ± 0.03% (db), respectively, the latter in freeze-dried samples. These discrepancies may be explained by differences in raw material origin, since most studies analyzed pomace resulting from juice extraction, while the present study focused on the recovery of bioactive compounds from non-commercial carrots.

Regarding lipid content, values of 4.12 ± 0.10% and 2.51 ± 0.01% (db) were observed, which are in line with or slightly above those previously reported for dehydrated carrot pomace. Sahni and Shere (2017) reported values of 3.48 ± 0.03%, while Cozma et al. (2024) and Vaz et al. (2022) reported lipid contents ranging from 0.88 ± 0.12% to 1.36 ± 0.16%, and 1.73 ± 0.18% (db), respectively.

The ash content was consistent with values reported for dehydrated carrot pomace, for which Sahni and Shere (2017) and Vaz et al. (2022) found values of 6.38 ± 0.03% and 5.03 ± 0.12% (db), respectively. Likewise, Cozma et al. (2024) and Luca et al. (2022) reported values of approximately 6.71% and 5.66%, respectively; while Salari et al. (2024) found values ranging from 5.8% to 6% (db).

The antioxidant activity (AA) measured by the DPPH assay was significantly higher in the solid fraction FF from Run 2, which may be attributed to its higher carotenoid content CAR. Since carotenoids are lipophilic compounds (Zhang et al., 2024) known for their antioxidant capacity, and the DPPH reagent is soluble only in organic media (Bibi Sadeer et al., 2020), this assay primarily evaluates the antioxidant capacity of low-polarity compounds, such as carotenoids. In contrast, the AA measured by the ABTS assay showed no significant differences between the products.

The water holding capacity WHC can be defined as the amount of water that remains bound to hydrated fibre after the application of an external force (Bhatia et al., 2023). Industrially, a product with a good WHC will be able to prevent dehydration and shrinkage, thus extending its shelf life (Pramana et al., 2024), and it would allow for modifications in the viscosity and texture of formulated foods (Clementz et al., 2019). In the present study, the WHC was higher ($P < 0.05$) in the FF fraction from Run 2, which could be explained by the higher SDF content, since SDF exhibits higher water retention than IDF (Bhatia et al., 2023; Sharoba et al., 2013). The WHC values obtained from for both FF fractions is in line with values reported by other authors for carrot pomace (Bhatia et al., 2023), and also higher than the WHC of other plant fibres, such as those from apple and citrus fruits for which (Figuerola et al., 2005) reported values of 1.76 g/g and 1.92 g/g, respectively. The lower WHC of the mentioned fruits could be attributed to the lower soluble fibre content.

Oil holding capacity (OHC) refers to a product's ability to bind and retain oils, which is influenced by the chemical structure of plant polysaccharides, the source of dietary fibre, and the content of insoluble dietary fibre (IDF) (Bhatia et al., 2023). The addition of fibres with a good OHC to food formulations may contribute to obtaining products with a desirable texture, flavor, and stability (Pramana et al., 2024). In samples with a similar IDF content, OHC is expected to

be comparable, as reported in this study with no significant differences between the products ($P > 0.05$). Bhatia et al. (2023) reported OHC values in carrot pomace powders ranging from 1.41 to 2.46 g/g. On the other hand, Clementz et al. (2019) reported values of 5 g/g in carrot fibre. In the present study, the values obtained were higher than those reported by Bhatia et al. (2023) and lower than those of Clementz et al. (2019), though all the results are consistent in showing that the WHC was higher than the OHC.

Finally, Table 3 also reported the results for the freeze-dried concentrated solutions (FDCS). The total sugar content in the FDCS product from Run 7 was lower than that of the product from Run 2 ($P < 0.05$). This was expected as a greater proportion of available carbohydrates was retained in the solid fraction (FF) of Run 7 during the extraction process. The differences in total sugar content between the products from both runs could be explained by the influence of the process variables of the extraction process, since a lower ethanol concentration resulted in a FDCS with higher total sugar content. Nunes Silva et al. (2021) also reported higher carbohydrate content in extracts obtained using a greater proportion of distilled water (compared to 70% ethanol) as the extraction solvent from various aromatic herbs.

During freeze-drying, the water present in the food is removed through sublimation (Richards et al., 2024), and may lead to the loss of certain bioactive compounds (Fikselová et al., 2008), as demonstrated in the present study for phenolic compounds. The TPC in the

Table 3. Physicochemical properties of the fibre-rich fraction FF and freeze-dried concentrated solution FDCS for selected experimental runs

	Run 2	Run 7
FF		
Moisture (%, wb)	5.00 ± 0.35 a	4.92 ± 0.14 a
Protein (% db)	13.37 ± 0.70 a	13.28 ± 0.00 a
Lipid (% db)	4.12 ± 0.10 a	2.51 ± 0.01 b
Ash (% db)	5.52 ± 0.44 a	6.85 ± 0.47 a
Total carbohydrates (% db)	76.99 ± 0.16 a	77.36 ± 0.47 a
TDF (% db)	63.60 ± 0.52 a	59.85 ± 0.22 b
SDF (% db)	15.26 ± 0.22 a	11.59 ± 0.37 b
IDF (% db)	48.34 ± 0.30 a	48.26 ± 0.60 a
IDF/SDF ratio	3.17	4.16
AA_{DPPH} (mg TE/100 g db)	1843.41 ± 62.17 a	1635.32 ± 17.26 b
AA_{ABTS} (mg TE/100 g db)	136.17 ± 8.65 a	135.38 ± 7.09 a
WHC (g/g wb)	13.25 ± 0.21 a	10.50 ± 0.71 b
OHC (g/g wb)	4.31 ± 0.27 a	3.20 ± 0.71 a
FDCS		
Moisture (%, wb)	18.75 ± 0.56 a	18.14 ± 0.62 a
Total sugars (% db)	199.66 ± 3.98 a	33.44 ± 0.00 b
CAR (mg/100 g db)	2.77 ± 0.03 a	2.88 ± 0.57 a
TPC (mg GAE/100 g db)	454.93 ± 55.36 a	376.75 ± 28.36 a
AA_{DPPH} (mg TE/100 g db)	1013.14 ± 10.23 a	807.74 ± 2.24 b
AA_{ABTS} (mg TE/100 g db)	422.59 ± 29.61 a	495.46 ± 54.14 a

One-way ANOVA for each variable, where different letters within the same row indicate significant differences between the samples analyzed, according to Tukey's test.

FDCS significantly decreased in Runs 2 and 7 with respect to the values of TPC in the CSs. However, the CAR content was not affected by the freeze-drying process ($P > 0.05$).

For the FDCS, the highest antioxidant activity (AA) measured by the DPPH method was observed in Run 2, where the solvent with the highest water content (ethanol concentration of 50%) was used. These results contrast with the findings of (Jayaprakasha et al., 2019), who reported lower AA in aqueous extracts of carrot powder. Despite these differences, both FDCS samples analyzed in this study showed similar total phenolic content (TPC), suggesting that compounds other than phenolics, such as ascorbic acid, may contribute to AA (Akter et al., 2024). A similar observation was made by (Azman et al., 2019) in citrus peel extracts, where no correlation between TPC and DPPH scavenging activity was found, likely due to the presence of ascorbic acid.

4. CONCLUSIONS

This study proposed a method for valorizing commercial carrot discards through a combination of convective drying and hydroalcoholic extraction of bioactive compounds and other nutritionally and functionally relevant components, followed by freeze-drying. Using a Box-Behnken experimental design, optimal conditions were determined to maximize carotenoid recovery while preserving phenolic compounds. The process resulted in two distinct products: a fibre-rich powder fraction and a freeze-dried product obtained from the hydroalcoholic extract. The fibre-rich fraction exhibited notable levels of carotenoids, phenolic compounds, antioxidant activity, ash, and dietary fibre, with a favorable insoluble/soluble dietary fibre ratio and good water-holding capacity. The freeze-dried product, in addition to containing carotenoids and phenolic compounds, showed a high sugar content.

When the drying process was evaluated independently, the lower and higher temperatures assessed (50 and 70 °C) led to greater carotenoid loss, either due to prolonged heat exposure for the former or thermal degradation for the latter. However, when analyzed in combination with the other variables involved in the hydroalcoholic extraction process, drying temperature no longer had a significant influence on bioactive compound retention. Ethanol concentration emerged as a key factor in modulating the recovery and distribution of compounds between the two final fractions. Lower ethanol concentrations favored higher carotenoid content in the fibre-rich solid fraction.

The resulting products, rich in one or more of the extracted compounds, could be incorporated into various food matrices to enhance their nutritional profile, color, stability, and antioxidant capacity, as is the case with bakery and pastry products, healthy snacks such as cereal bars and confectionery, breakfast cereals such as granolas, and meals intended for mountaineering and emergency relief situations. This valorization strategy could be considered not only for carrot discards generated through agricultural losses but also for those produced during industrial processing. In future works, the techno-economic prefeasibility of process scalability will be assessed through a detailed life cycle analysis to thus evaluate its potential for industrial application.

Conflicts of interest: The authors declare no conflicts of interest.

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