



Valorization of dehydrated broccoli agroindustrial residues

Valorización de residuos agroindustriales de brócoli deshidratado

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Abstract

Mexico is a country that produces, processes, and exports vegetables, generating large amounts of losses and waste with nutritional qualities that can be used to create new foods. Broccoli is prized for its nutritional quality and is mainly exported frozen. In industrial processing, large quantities of the stem, rich in phytochemicals, are generated. In this project, the dehydration of broccoli stem cubes in a tray dryer with hot air was studied. Dehydrated stem cubes must achieve high rehydration percentages and retain their integrity when used in the preparation of soups and other foods. It was found that slow-freezing broccoli pieces at -18°C before dehydration favors their capacity and speed of rehydration in hot water. It was found that broccoli stem cubes dehydrated at 70°C retain a high content of phenolic compounds and their antioxidant capacity. The dehydration of pieces of floret was also studied comparatively, observing similar behaviors and results.

Keywords: Broccoli, stems broccoli, dehydration, food loss and waste, rehydration.

Resumen

México es un país productor, procesador y exportador de hortalizas, lo que genera grandes pérdidas y desperdicios con cualidades nutricionales que pueden aprovecharse para crear nuevos alimentos. El brócoli es apreciado por su calidad nutricional y se exporta principalmente congelado. En el procesamiento industrial, se generan grandes cantidades del tallo, rico en fitoquímicos. En este proyecto, se estudió la deshidratación de cubos de tallo de brócoli en un secador de bandejas con aire caliente. Los cubos de tallo deshidratados deben alcanzar altos porcentajes de rehidratación y conservar su integridad al utilizarse en la preparación de sopas y otros alimentos. Se descubrió que la congelación lenta de los trozos de brócoli a -18 °C antes de la deshidratación favorece su capacidad y velocidad de rehidratación en agua caliente. Se observó que los cubos de tallo de brócoli deshidratados a 70 °C conservan un alto contenido de compuestos fenólicos y su capacidad antioxidante. También se estudió comparativamente la deshidratación de trozos de florete, observándose comportamientos y resultados similares.

Palabras clave: Brócoli, tallo de brócoli, deshidratación, pérdida y residuo de alimento, rehidratación.

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1 Introduction

The goal set by the United Nations in 2015 to reduce food loss and waste (FLW) to 50% by 2030 has encouraged great efforts by activists, researchers, and authorities, however, it has been difficult to measure and evaluate progress at different stages of the supply and consumption chains (Malefors *et al.*, 2022, Salmoran *et al.*, 2025). Do *et al.*, (2021) in a review of articles on FLW topics found that scientific publications have been mainly oriented toward environmental impact assessment, biorefineries, and nutrient recycling with emphasis on anaerobic digestion applications. Only 7.5% of the publications report on the valorization and utilization of by-products for human consumption. In an analysis conducted in the United States in 2016 on alternatives to reduce FLW, alternative solutions with the potential to avoid or take advantage of FLW were identified: Waste prevention amounts to 2,624 kt/yr, focusing on campaigns to raise consumer awareness. On the other hand, food recovery amounts to 1,098 kt/yr, highlighted by Donation Tax Incentives, while composting and aerobic digestion practices amount to 9,478 kt/yr. FLW processing to obtain value-added food products such as soups and pasta only identified a potential of 102 kt/yr (ReFED-2016). FLW of plant origin under proper handling and processing retain valuable nutritional and nutraceutical attributes.

It is recommended worldwide to consume fruits and vegetables to maintain good health because they provide macronutrients, micronutrients, fiber and compounds with antioxidant capacity (Arias *et al.*, 2022). The prevention of certain diseases such as cancer, cardiovascular disorders and diabetes are associated with the consumption of vegetables, due to the presence of non-nutritional antioxidant compounds such as phenolic compounds (Lin & Chang, 2005). Residues, by-products and non-consumable portions of fruits and vegetables contain significant amounts of antioxidant compounds and nutrients. Some pigments such as anthocyanins, betalains, beta-carotenes, among others, with important antioxidant activity are mainly found in fruit and vegetable peels (Sharma *et al.*, 2021).

Calvo *et al.*, (2017) highlight the importance of innovating in the creation of new products from fruit and vegetable waste, such as juices, soups and smoothies, without worrying about the aesthetic standards of raw materials. (Winkworth *et al.*, 2015) emphasize that, by recovering and avoiding fruit and vegetable waste, the loss of essential micronutrients that are necessary to combat the deficiency known as "Hidden hunger" is prevented.

Globally, approximately 1,257 million tonnes (Mt) of vegetables are harvested each year, of which around

110 Mt are lost at various stages of the supply and consumption chain, according to FAO data (2019). Mexico, in particular, is a major vegetable producer, with an annual output of 11.44 Mt, 51% of which is destined for export. However, an estimated 0.915 Mt of vegetables are also lost along the production and distribution processes (FAO, 2019). It is noteworthy that a significant portion of these losses occurs during the industrial processing of vegetables (Baysal & Ülkü, 2021). The waste generated during the processing of vegetables is usually clean, abundant, and available in considerable quantities, which gives them a high potential to be transformed into food products intended for human consumption.

Mexico stands out as the sixth largest producer of broccoli worldwide. In particular, the state of Guanajuato stands out for its agricultural production, with approximately 1.2 million hectares destined for agriculture, of which around 430,000 hectares (equivalent to 36%) are cultivated under irrigation conditions (Melesio *et al.*, 2011). Guanajuato is the main producer of broccoli nationwide, generating approximately 567,000 t, according to SIAP data in 2019 (SIAP -2019). In addition, various agroindustries operate in Guanajuato specializing in the processing and freezing of vegetables, mainly for export to the United States and Canada markets (Ríos-Fuentes *et al.*, 2022).

Ares *et al.*, (2013) carried out a review related to the extraction and quantification of bioactive compounds present in broccoli. These compounds stand out for their healthy properties, which include antioxidant, anticancer, and antibacterial activities, among others. Some of these bioactive compounds found in broccoli include lipids, phenols, vitamins, glucosinolates, and essential elements such as selenium. One of the compounds of particular interest due to its potential anticancer effect is sulforaphane.

Given the established link between broccoli consumption and consumer health benefits, according to Conzatti *et al.*, (2015), the demand for this vegetable has increased significantly. The most common way to find broccoli in the market is in the presentation of frozen florets. However, the industrial production of frozen broccoli generates a considerable amount of by-products and waste, mainly broccoli stems, as noted by Ríos-Fuentes *et al.*, (2022).

Gudiño *et al.*, (2022) carried out a study to examine the presence of bioactive compounds in both broccoli florets and their agricultural by-products, that is, the stems and leaves. These bioactive compounds were extracted using a solution composed of 80% ethanol and water, and subsequently subjected to analysis using various analytical methods. The results showed concentrations of total phenolic compounds of 939 mg GAE (Gallic acid equivalents)/100 g of dry extract in the stems, 2435 mg GAE/100 g of dry

extract in the leaves, and 1074 mg GAE/100 g of dry extract in the florets. Furthermore, it was observed that glucosinolates were more abundant in the florets, while their presence in the stems and leaves was very low. Higher antibacterial activity was also identified in the stem extracts.

The intake of bioactive compounds can be done as concentrated extracts added to food supplements or pharmaceutical products or in the consumption of fresh and processed products. In the case of FLW, even though they are a source of bioactive compounds and nutrients, due to their origin and aesthetic characteristics, “ugly fruits” are preferred to be consumed in processed foods to have greater approval by consumers Calvo *et al.*, (2017). In the thermal processing of vegetables, there is a risk of changing their organoleptic and nutritional properties; however, the bioaccessibility of bioactive compounds can also be improved (Izzo *et al.*, 2022). Glucosinolates in fresh broccoli increase by between 37 and 39% when stem-cooked; in frozen broccoli, under the same processing they decrease by 11% (Fabbri & Crosby, 2016).

In this project, the production of dehydrated cubes from broccoli stems was proposed as an alternative for the valorization of this underutilized agro-industrial waste by transforming them into functional dehydrated cubes to promote their utilization and reduce food waste. To this end, the effect of temperature and drying time on nutritional and functional properties was evaluated.

Dehydration parameters and slow freezing pretreatments at -18°C affect the structure, porosity, and rehydration capacity of broccoli stems, which impact the retention and availability of bioactive compounds.

2 Materials and methods

2.1 Broccoli waste and sample preparation

The fresh broccoli heads were provided by a local company, were sanitized with a 4% sodium hypochlorite solution and drained to remove excess water. The broccoli was separated into florets and stems. The florets were cut into florets between 4 and 6 grams. The stem was cut into cubes of approximately 1cm on each side. A part of the broccoli was frozen in a domestic freezer at -18°C for 18h (Frozen). The remaining material was kept at 4°C and classified into Raw Floret (RF No Frozen) and Raw Stem (RS No Frozen) samples.

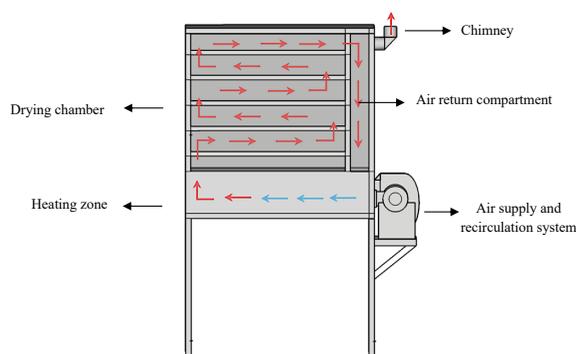


Figure 1. Tray dryer prototype.

2.2 Proximate composition

The proximal composition of the floret and stem samples was determined. Humidity was measured gravimetrically by weight loss in an oven at 105°C until reaching its constant weight (humidity: %H, NMX-F-083-1986). Subsequently, the samples were calcined at 600°C for 3 hours in a muffle to determine their ash content due to weight loss (%Ash, NMX-F-066-S1978). The crude fiber content was determined as the amount of undigested matter of a sample after being subjected to sequentially applied acid and alkaline digestions (%CF, NMX-F-090-S-1978). The ethereal extract was determined by extracting the fat using hexane in a Soxhlet extractor (%EE, NMX-F-089-S-1978). The percentage of protein was determined using the Kjeldahl method (%P, NMX-F-068-S-1980); carbohydrates were calculated as the percentage complementary to 100% (%NFE: carbohydrates, nitrogen free extract).

2.3 Drying

Broccoli stems and florets: frozen and not frozen, were dehydrated in a prototype tray dryer equipped with a system for air intake and recirculation. The air temperature was automatically controlled with 1800W finned electric resistances. One kilogram of cut broccoli was placed and distributed evenly on an aluminum tray 50cm wide and 70cm long. Broccoli dehydration was carried out at 60, 70, and 80°C . Tray's weight was monitored hourly to estimate weight loss.

In figure 1, the sketch of the dryer is shown from a side view, the parts of the dryer can be seen and the blue lines simulate the flow of cold air inlet, in the heating zone through the resistors the air is heated to continue the flow through the red arrows, 50% of the air is recirculated and the other 50% is released through the chimney.

2.4 Color

Color values of the samples were determined using a colorimeter (CR-400, Minolta, Konica Ramsey, NJ, USA). The color scale was used for measuring color

values: L^* , the lightness variable; a^* , from green to blue; and b^* , from yellow to red. The total color difference (ΔE) was calculated using Eq. (1 and 2):

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

where

$$\Delta L = L_{standard}^* - L_{sample}^*, \Delta a = a_{standard}^* - a_{sample}^*, \quad (2)$$

$$\Delta b = b_{standard}^* - b_{sample}^*$$

The standard plate (calibration plate $L^*=94.90$, $a^*=-0.45$, $b^*=3.93$) was used as a standard. Three measurements were collected on each sample.

2.5 Phenolic compounds

The phenolic content of the broccoli floret and stem samples was determined using the Folin – Ciocalteu colorimetric method as described by Gulcin, (2020). The absorbance was measured at 750nm using a spectrophotometer (UNICO S-2150). The total phenolic content of the extract was calculated from the gallic acid standard curve and expressed as mg gallic acid equivalents (GAE) on a dry weight basis (mg GAE/100g).

2.6 Antioxidant activity

To measure the antioxidant activity, DPPH (2,2-diphenyl-1-picrylhydrazyl) radical scavenging assay was used; the absorbance was measured in a spectrophotometer (UNICO, model) at 517nm and the results were expressed as mmol equivalent of Trolox (TE)/100g of dry sample, following the technique of Molyneux, (2004).

2.7 Rehydration

Rehydration was carried out following the methodology of García *et al.*, (2011). 5g of sample were immersed in 1L of water at 50 and 60°C for different times (5, 10, 15, 20, 25, and 30min) and the weights were recorded. Rehydration was evaluated using the rehydration coefficient (RC grams of retained water/grams of dry sample).

$$RC = \frac{W_r - W_{fd}}{W_{fd}} \quad (3)$$

Where W_r is the weight of the sample during rehydration and W_{fd} is the weight of the dry sample.

2.8 Mechanical properties

Mechanical properties of the broccoli were determined by a texture analyzer (TA-XT plus, Stable Micro Systems LTD, Surrey, UK), using a modified ASTM

D882-00 procedure, with a cylinder probe (TA4/1000 38.1 mm diameter) used for compression test. The speed of approach of the probe was 1 mm/s at 0.1N load cell was used.

2.9 Statistical analysis

Data were averaged from the replicates and mean values \pm standard deviations were reported. An analysis of variance (ANOVA) was performed to evaluate the effects of total polyphenol content, antioxidant activity, rehydration, and texture. The means were compared using the Tukey test $p < 0.05$. Statgraphics Centurion XVI.I software was used.

3 Results and discussion

3.1 Drying curves

The average drying curves for broccoli floret and stem are presented in Figure 2, for the different temperatures of 60, 70, and 80°C. The initial humidity of the broccoli floret and stem samples were 93.73 and 89.11%, equivalent to 14.97 and 8.19 kilograms of moisture per kilogram of dry matter, respectively. The drying time of the samples to reach their equilibrium humidity was between 5 and 7 hours. The increase in temperature also increases the drying rate leading to a reduction in drying time. During the first 3 hours, the greatest decrease in humidity was observed. The freezing phenomenon of the samples did not have a significant effect on the drying curves at 60 and 80°C. At 70°C, the drying curves of the previously frozen samples show higher dehydration speeds, reaching equilibrium humidity in less time compared to non-frozen samples.

During the slow freezing process, large water crystals form in the extra and intracellular spaces of the stem and floret. During the formation and growth of ice crystals, the breakdown of cell walls occurs, increasing porosity. Non-diffusive dehydration mechanisms can be favored by the increase in porosity mainly at the end of the drying curve. Vallespir *et al.*, (2019) reported the drying of slices of beet, apple, and eggplant, the first product with low porosity (0.043), showed longer drying times compared to apple (0.210) and eggplant (0.641) as they had medium and high porosity. Souza *et al.*, (2017) reported that broccoli has a high porosity of 0.78. Boukouvalas *et al.*, (2006) mention that many factors affect the drying process, in the case of vegetables, moisture is lost mainly through the areas subjected to cutting, however, the release of exudates with high sugar content causes the formation of an enteric coating on the exposed surface that becomes an important resistance to the evaporation of

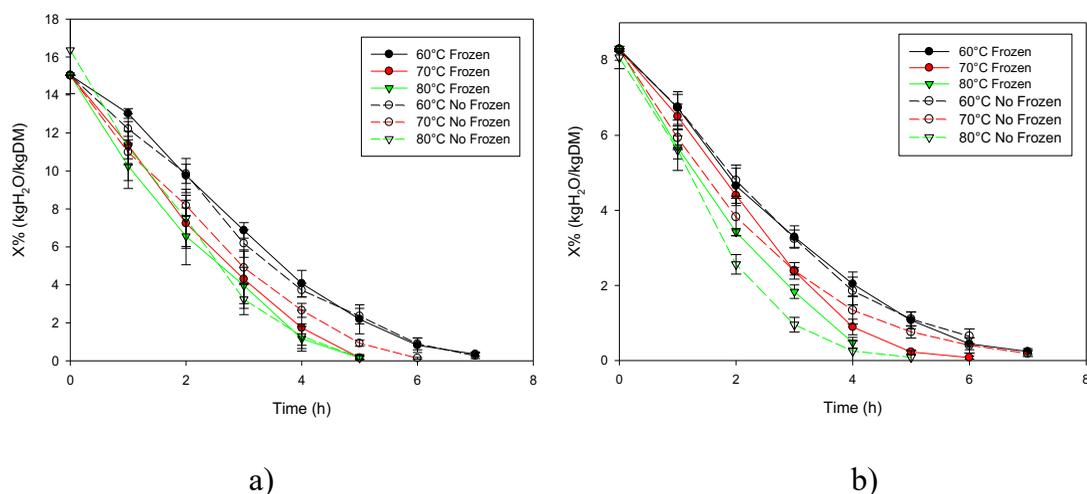


Figure 2. Broccoli drying curves at three different temperatures of (a) stem and (b) floret.

Table 1. Chemical composition of broccoli stem and floret

	Stem (%bs)	Floret (%bs)	Stem and leaves mix (%bs) (Guan <i>et al.</i> , 2020)	Floret (%bs) (Campas-baypoli <i>et al.</i> , 2009)	Floret and stem mix (%bs) (Mustafa & Baurhoo, 2016)	Floret (Dos Reis <i>et al.</i> , 2014)
Humidity	93.76 ± 0.61	89.24 ± 0.49	9.6	-	-	86.76 ± 0.50
Ash	7.97 ± 0.009	7.32 ± 0.96	7.11	7.87	9.7	9.19 ± 0.31
Protein	22.32 ± 0.90	26.05 ± 0.99	25	22.41	32.5	21.79 ± 0.31
Crude Fiber	15.33 ± 1.37	17.93 ± 1.31	13.26	11.65	-	46.93 ± 1.35
Raw Fat	5.45 ± 0.33	1.90 ± 0.49	4.24	4.59	2.9	2.56 ± 0.04
Carbohydrates	48.928	46.788	-	65.13	-	19.53 ± 0.00

water; this phenomenon occurs mainly at low drying temperatures.

The freezing pretreatment improved the drying kinetics only at 70 °C. This behavior can be attributed to the interaction between the porous structure generated during freezing and the energy level applied during dehydration. At 60 °C, the low drying temperature limits the vapor pressure gradient and promotes the formation of a sugar-rich surface layer, which increases resistance to moisture transfer (Boukouvalas *et al.*, 2006). At 70 °C, however, the temperature is sufficient to promote efficient water evaporation without causing surface hardening or pore collapse, allowing the porous network created by freezing to facilitate internal moisture diffusion. At 80 °C, the rapid formation of a hardened surface layer and structural collapse counteracts the advantages of the freezing-induced porosity, resulting in similar drying behavior to that of the non-frozen samples.

3.2 Chemical composition of broccoli stem and floret

Dehydrated broccoli stems and florets were analyzed. Table 1 presents the results obtained in this study, as well as those reported by other authors. The results are comparable with previous studies; it is worth noting that the differences in nutritional groups between stems and florets are not significant. In

this comparative table, the stems contain a similar nutritional value to the floret; however, currently, the floret is mainly consumed out of habit, without considering its bioactive content, which is directly associated with the prevention of various diseases.

3.3 Total phenolic content

A wide variety of edible vegetables belong to the *Brassica* genus, where broccoli stands out for its high content and variety of phenolic compounds. The high antioxidant potential of broccoli is associated with its high content of phenolic compounds derived from flavonol and hydroxycinnamoyl (Cartea *et al.*, 2011). Podsedek, (2007) reports that the content of phenolic compounds in broccoli varies from 34.5 to 337 mg GAE per 100g of edible portion (Approximately 345-3370 mg GAE per 100 g of dry matter considering 90% humidity).

Table 2 shows the levels of phenolic compounds present in the broccoli portions, both before and after the dehydration process. It is observed that, when using a drying temperature of 60°C for 7 hours, there is a notable decrease in phenolic compounds compared to the fresh stem (RS) and floret (FR) fractions, which serve as reference points. On the other hand, it has been noted that freezing broccoli fractions before dehydration leads to a significant increase in the concentration of phenolic compounds.

Table 2. Total phenolic contents in different broccoli samples (mg GAE/g dry matter).

	Drying temperature (°C)	Steam	Floret
Fresh	-	2.44±0.72	2.67±0.37
	60	1.15±0.47	0.68±1
No Frozen	70	1.22±0.40	0.48±0.48
	80	1.38±0.15	0.60±0.48
	60	1.76±0.56	2.10±0.81
Frozen	70	4.72±2.33	3.59±0.23
	80	3.77±0.10	4.13±1.27

Furthermore, increasing the drying temperature to 70°C and 80°C, and reducing the drying time, favors a substantial increase in the content of phenolic compounds in the broccoli portions compared to the reference materials.

Yilmaz & Bagci, (2018) studied the content of phenolic compounds in combined samples of broccoli floret and stem dehydrated by hot air and a combination of hot air and microwaves. The content of phenolic compounds in samples: fresh, dehydrated in hot air (60°C, 5h), and a combination of hot air and microwave at powers of 18, 36, and 54W were 892.4, 740.6, 507.1, 606.9 and 709.8 mg GAE per 100g of dry matter respectively, in particular, flavonoids and phenolic acids compounds may experience an increase or decrease in their concentration during thermal treatments. Quercetin and isorhamnetin decrease concerning fresh material, while trans-ferulic, p-Coumaric, and Chlorogenic acids increase with the combination of hot air and microwaves. These authors associate this phenomenon with the increase in the availability of these compounds in dehydrated materials; since during heat treatment, it causes mechanical damage to cell structures.

At high temperatures, plant tissue cell walls and membranes are more easily ruptured, facilitating the release of phenolic compounds and allowing solvent access during extraction (Thongsook & Barrett, 2005). Furthermore, oxidative enzymes, such as polyphenoloxidase and peroxidase, which degrade compounds, are inactivated, increasing the concentration of compounds at high temperatures (Goyeneche *et al.*, 2013). Freezing pretreatment also causes mechanical disruption of cell structures, favoring the release of phenolic compounds.

3.4 Antioxidant capacity

The antioxidant capacity observed in broccoli florets and stems (Figure 3) shows a decreasing trend in dehydrated materials compared to fresh broccoli. This behavior is mainly associated with the thermal and oxidative degradation of bioactive compounds, such as phenols and vitamin C, which are highly sensitive to heat and oxygen (Fogliano *et al.*, 2008). During dehydration at 60°C, the most pronounced reduction in antioxidant capacity can be attributed to the

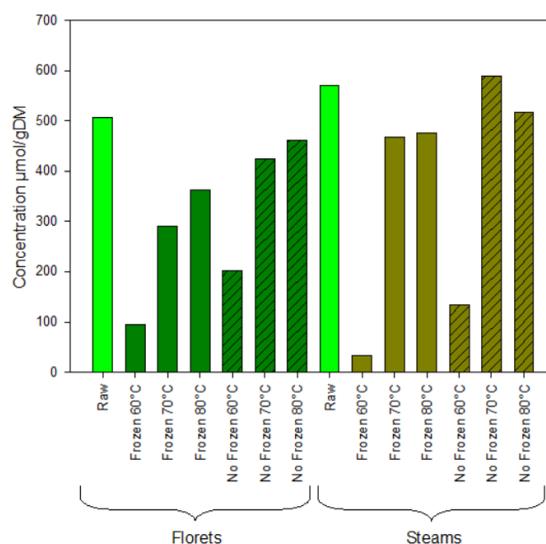


Figure 3. Effect of temperature on the antioxidant activity of broccoli.

loss of these thermosensitive compounds, as well as to the possible residual action of oxidative enzymes, such as polyphenol oxidase and peroxidase, which are not completely inactivated at this temperature. Thuy *et al.*, 2024 obtained similar results by subjecting potatoes to a thermal effect obtuvieron resultados similares al someter papas a un efecto térmico.

On the other hand, samples dehydrated at higher temperatures (70°C and 80°C) showed a smaller decrease in antioxidant activity. This behavior could be due to the inactivation of the aforementioned oxidative enzymes and the release of antioxidant compounds previously bound to cell wall structures, which increases their availability and ability to react with the DPPH radical (Porter, 2012). Likewise, it has been reported that certain heat treatments can promote the release of carotenoids by denaturing carotenoid-protein complexes, contributing to a relative increase in total antioxidant capacity (Fogliano *et al.*, 2008).

Regarding the effect of pre-freezing, no positive impact on the preservation of antioxidant capacity was observed. This result can be explained by the structural damage caused by the formation of ice crystals, which causes the rupture of cell membranes and facilitates the oxidation of phenolic compounds during thawing, as well as possible losses due to leaching.

Table 3. Stem and floret color parameters of dehydrated broccoli.

		L	a*	b*	ΔE
No Frozen	Raw Stem (RF)	69.86±9.15 ^a	-22.73±0.57 ^a	33.13±3.27 ^a	-
	Stem 60	33.4±1.64 ^b	8.12±1.25 ^{b,c}	23.77±4.12 ^{a,b}	48.81±0.47
	Stem 70	30.75±8.05 ^b	9.76±2.66 ^b	32.44±8.14 ^a	51.5±6.01
	Stem 80	23.58±6.64 ^b	5.51±1.76 ^d	18.91±12.81 ^{a,b}	57.02±6.96
Frozen	Stem 60	14.69±3.89 ^{b,c}	6.34±1.57 ^{c,d}	30.15±19.33 ^a	64.43±3.27
	Stem 70	17.67±5.49 ^c	3.6±3.03 ^d	29.53±8.78 ^a	59.08±5.11
	Stem 80	17.7±1.34 ^c	6.81±0.51 ^{b,c,d}	10.19±0.94 ^b	64.20±1.03
	Raw Floret (RF)	46.46±10.48 ^a	-16.87±6.45 ^a	19.73±3.86 ^a	-
No Frozen	Floret 60	22.55±8.41 ^{c,d}	2.31±1.81 ^{b,c}	10.44±5.23 ^b	32.69±6.04
	Floret 70	32.42±1.42 ^b	1.51±0.61 ^b	39.01±3.07 ^c	30.18±2.3
	Floret 80	31.71±1.25 ^{b,c}	1.23±0.71 ^b	34.57±8.17 ^c	28.27±4.3
	Floret 60	16.45±1.91 ^{d,e}	7.64±5.05 ^c	10.39±1.04 ^b	39.98±3.93
Frozen	Floret 70	9.31±1.21 ^e	0.41±0.2 ^b	4.98±0.4 ^b	43.55±1.09
	Floret 80	11.66±5.38 ^e	1.57±0.16 ^b	8.23±2 ^b	41.09±4.99

a-e Superscript letters in the same column indicate significant differences according to Tukey's multiple comparison test ($p < 0.05$).

Table 4. Color and texture parameters of stem and floret of broccoli rehydrated at 60°C.

		Hardness (N)	Elasticity	L	a*	b*	ΔE
Non Frozen Stem	RS	822.12±23.06	1.58±0.48	79.41±5.69	-26.95±3.72	47.84±8.49	-
	60°C	2.74±0.16 ^a	1.11±0.04 ^a	44.46±2.2 ^a	6.92±1.25 ^a	25.08±1.56 ^{abc}	50.06±1.99 ^a
	70°C	4.01±0.31 ^a	1.41±0.38 ^a	36.35±7.16 ^b	3.52±1.53 ^b	20.41±6.07 ^{bc}	41.09±2.81 ^{cd}
	80°C	1.86±0.08 ^a	1.13±0.06 ^a	42.67±1.27 ^{ab}	3.79±0.12 ^b	13.27±1.15 ^d	43.53±1.53 ^{bc}
Frozen Stem	60°C	6.86±0.03 ^b	1.21±0.04 ^b	23.69±5.19 ^c	2.77±1.04 ^b	29.93±4.62 ^a	37.26±0.04 ^c
	70°C	1.37±0.09 ^b	2.21±0.94 ^c	28.02±3.63 ^c	1.32±0.98 ^b	27.09±4.56 ^{ab}	37.85±1.75 ^{de}
	80°C	0.13±0.08 ^b	1.38±0.46 ^c	43.15±4.53 ^{ab}	4.05±3.39 ^{a,b}	19.21±2.85 ^{cd}	46.25±2.89 ^b
	RF	578.69±23.04	1.39±0.59	15.23±8.37	-4.22±5.83	7.32±12.44	-
Non Frozen Florets	60°C	0.58±0.01 ^a	1.56±0.12 ^a	35.11±1.96 ^a	5.33±0.38 ^a	21.33±1.94 ^{bc}	39.96±2.63 ^{bc}
	70°C	0.39±0.04 ^a	1.45±0.05 ^a	29.37±4.48 ^b	2.94±1.44 ^{ab}	47.80±3.55 ^a	54.97±1.19 ^d
	80°C	0.58±0.02 ^a	1.47±0.05 ^a	34.42±0.58 ^a	3.55±0.82 ^{ab}	34.04±6.44 ^{ab}	47.25±4.04 ^{cd}
	60°C	0.39±0.01 ^b	1.50±0.05 ^b	15.13±3.01 ^c	2.54±0.15 ^b	21.58±20.58 ^{bc}	27.24±16.05 ^b
Frozen Stem	70°C	0.39±0.01 ^b	1.42±0.04 ^b	9.49±1.79 ^d	2.07±0.21 ^b	7.55±1.97 ^c	10.79±2.62 ^a
	80°C	0.49±0.01 ^b	1.50±0.06 ^b	33.40±0.96 ^{ab}	3.24±2.88 ^{ab}	38.43±4.69 ^a	49.64±4.28 ^{cd}

^{a-c} Superscript letters in the same column indicate statistical significance ($p < 0.05$).

Finally, the differences observed between florets and stems may be related to the natural distribution of antioxidant compounds in the plant tissue, with the florets having a higher concentration of phenolic compounds and vitamin C, while the stems, although initially less active, show a more effective release of antioxidant compounds after heat treatment.

3.5 Color

Table 3 shows the color descriptors on the L, a, b, scale, for pieces of stem and floret of fresh and dehydrated broccoli. Stem and floret colors are described as combinations of green (-a) and yellow (+b); The stem pieces show a greater luminosity (L) than the florets. In all dehydration experiments, the green color intensity and luminosity of the vegetables decreased, while the yellow tones increased. This phenomenon is mainly due to the degradation of

chlorophyll and some darkening reactions due to some sugars that are released during drying (Ebrahimi & Lante, 2022). On the other hand, the increase in yellow color may be due to the release of carotenoids, associated with the destruction of carotenoid-protein complexes. At 80°C the loss of color concerning fresh vegetables (ΔE) is greater.

3.6 Rehydration

Table 4 presents the hardness, elasticity, and color parameters of fresh and rehydrated broccoli stem and floret samples after drying under the previously described conditions. The rehydrated broccoli pieces exhibited a marked reduction in hardness compared to the fresh samples. The initial firmness of fresh vegetables is primarily attributed to the integrity of their cellular structure and the turgidity of plant cells.

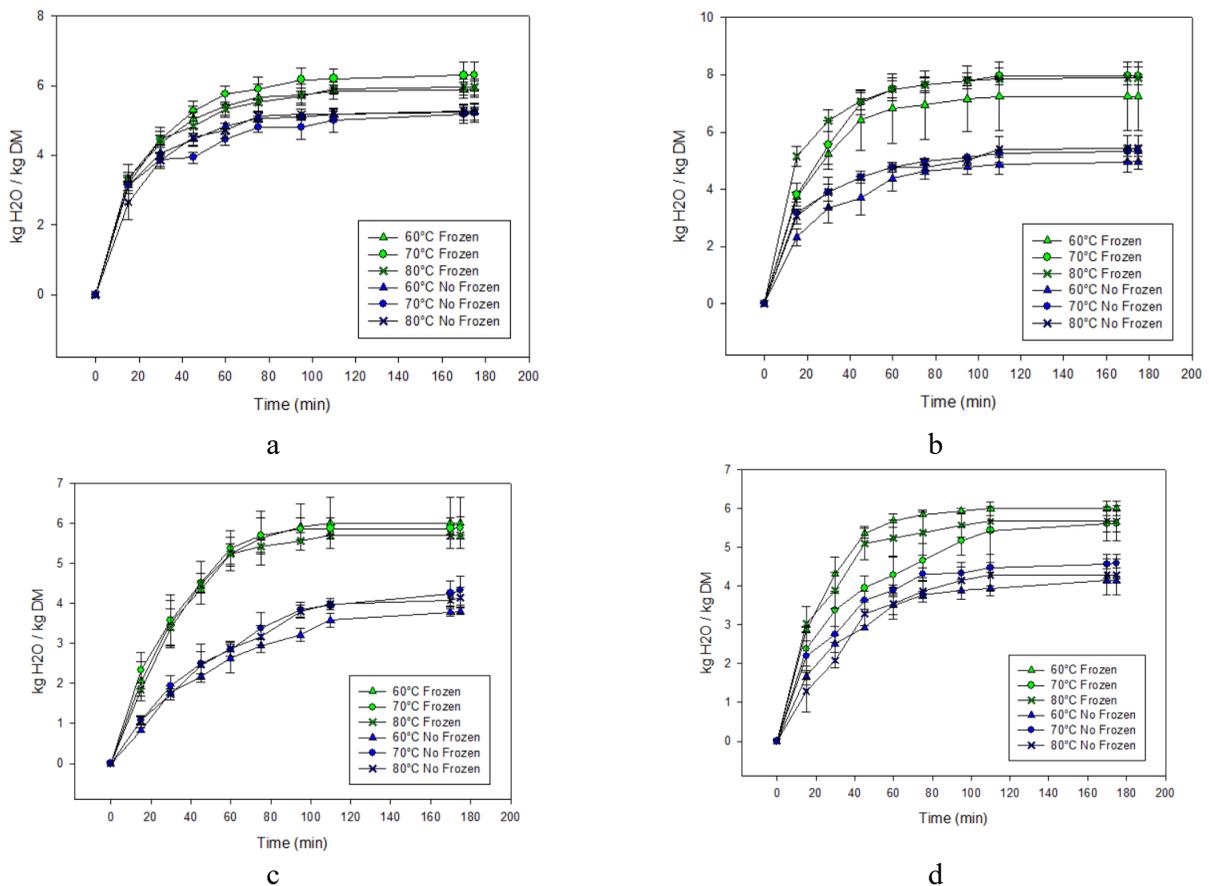


Figure 4. Rehydration of stalks and florets of broccoli dry. a) Stem 50°C b) Stem 60°C c) Floret 50°C d) Floret 60°C.

After drying and subsequent rehydration, the samples became softer yet maintained their elasticity. This residual elasticity is likely associated with the preservation of fibrous structural elements within the newly formed porous matrix generated during the freezing and dehydration processes.

Regarding color characteristics, the rehydrated samples showed an increase in luminosity compared to the dried solids (Table 4), along with a noticeable shift toward yellow hues.

Figure 4 illustrates the rehydration kinetics of dried stem and floret pieces at 50 and 60 °C. The results indicate that the freezing pretreatment prior to drying enhanced both the rehydration rate and the overall water absorption capacity. During slow freezing, the formation of large ice crystals disrupts the cellular structure, creating a new intraparticle porous network. Throughout the drying process, the loss of cellular turgor and moisture leads to shrinkage and hardening of the plant tissue, because of the collapse and compaction of cell walls. Upon rehydration, water does not completely refill the original intracellular spaces present in fresh vegetables; instead, it occupies the newly developed porous structure formed during the freezing and drying stages.

Conclusions

In the broccoli processing industry, stem pieces are generated as a by-product, whose nutritional composition is similar to the main floret product. The antioxidant activity and the content of phenolic compounds in pieces of broccoli stem and floret subjected to freezing and dehydrated with hot air do not decrease significantly, even at 70°C the content of phenolic compounds increases. Freezing pretreatment of broccoli pieces before dehydrating significantly increases the capacity and speed of rehydration of dried broccoli pieces. The rehydration capacity is essential in the production of dehydrated vegetables because they are normally used in the preparation of soups. The dehydrated broccoli stem pieces have nutritional value and antioxidant capacity and after dehydration, they are soft and whole. The processing described in this article transforms broccoli waste into value-added foods.

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