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FRACCIONES DE TOMATE DE ÁRBOL *(SOLANUM BETACEUM)* CON POTENCIAL FUNCIONAL OBTENIDAS POR ULTRAFILTRACIÓN*

Fractions from Tree Tomato (Solanum betaceum) *with Functional Potential Obtained by Ultrafiltration*

Frações de tomate de árvore (Solanum betaceum) *com potencial funcional obtidas por ultrafiltração*

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ABSTRACT
The tree tomato *(Solanum betaceum)* contains important bioactive compounds, including phenolic compounds, carotenoids, vitamins, and minerals, which possess beneficial effects on human health. This research aimed to evaluate the potential of ceramic membranes with different pore sizes / Molecular Weight Cut-Off (MWCO) for obtaining phenolic enriched fractions from tree tomato (50 nm to 1 kDa). The juice had two pretreatments, enzymatic maceration and centrifugation. Subsequently, the supernatant was microfiltered and the resulting fractions were obtained by an ultrafiltration process using a benchtop crossflow pilot unit (Membralox®, model XLAB 5, Pall Corporation, France). Their physicochemical characteristics were then analyzed. The UF-10 allowed concentrating the total phenolic compounds (CF=1.5) with acceptable characteristics of color (L*=52.4±3.46, C*=20.6±2.89, hº=86.0±2.30), total soluble solids (10.4±0.28 ºBx), total insoluble solids (0.49±0.26%) and titratable acidity (1.55±0.04%). Therefore, this fraction could be used as a functional ingredient in

KEYWORDS
Tamarillo, phenolics, Molecular Weight Cut-Off (MWCO).

RESUMEN
El tomate de árbol *(Solanum betaceum)* contiene importantes compuestos bioactivos, tales como compuestos fenólicos, carotenoides, vitaminas y minerales, los cuales presentan efectos benéficos en la salud humana. El propósito de esta investigación fue evaluar el potencial de membranas cerámicas con diferente tamaño de poro o tamaño de corte de peso molecular (MWCO, por sus siglas en inglés) (50 nm a 1 kDa) en la obtención de fracciones enriquecidas en compuestos fenólicos del tomate de árbol. Inicialmente, el jugo de tomate de árbol se sometió a dos pretratamientos, maceración enzimática y centrifugación. Posteriormente, el supernadante fue sometido a un proceso de clarificación por microfiltración, se obtuvieron las diferentes fracciones por ultrafiltración usando una unidad piloto de filtración de flujo tangencial (Membralox®, modelo XLAB 5, Pall Corporation, France) y se analizaron las características fisicoquímicas de estas. La fracción UF-10 permitió concentrar los compuestos fenólicos (FC=1,5) con características de color (L*=52,4±3,46, C*=20,6±2,89, hº=86,0±2,30), sólidos solubles totales (10,4±0,28 ºBx), sólidos insolubles totales (0,49±0,26%) y acidez titulable (1,55±0,04%) aceptables. Por lo cual, esta fracción podría usarse como un ingrediente funcional en la industria alimentaria y nutracéutica.

PALABRAS CLAVE
Tamarillo, compuestos fenólicos, tamaño de corte de peso molecular (MWCO).

RESUMO
O tomate de árvore *(Solanum betaceum)* contém importantes compostos bioativos, como compostos fenólicos, carotenoides, vitaminas e minerais; que apresentam efeitos benéficos para a saúde humana. O objetivo desta pesquisa foi avaliar o potencial de membranas cerâmicas com diferentes tamanhos de poro ou tamanho de corte de peso molecular (MWCO, na sigla em inglês) (50 nm a 1 kDa) na obtenção de frações enriquecidas em compostos fenólicos do tomate de árvore. Inicialmente, o suco de tomate de árvore foi submetido a dois pré-tratamentos, maceração enzimática e centrifugação. Posteriormente, o sobrenadante foi submetido a um processo de clarificação por microfiltração e as diferentes frações foram obtidas por um processo de ultrafiltração usando uma unidade piloto de filtração de fluxo tangencial (Membralox®, modelo XLAB 5, Pall Corporation, França) e as características físico-químicas destas foram analisadas. A fração UF-10 permitiu concentrar os compostos fenólicos (FC=1,5) com características de cor (L*=52,4±3,46, C*=20,6±2,89, hº=86,0±2,30), sólidos solúveis totais (10,4±0,28 ºBx), sólidos insolúveis totais (0.49±0.26%) e acidez titulável (1,55±0,04%) aceitáveis. Esta fração poderia ser usada como um ingrediente funcional na indústria alimentícia e nutracêutica.

PALAVRAS-CHAVE
Tamarilho, compostos fenólicos, tamanho de corte de peso molecular (MWCO).

Introduction

Colombia has a variety of tropical and exotic fruits such as the tree tomato (*Solanum betaceum*), also known as tamarillo. It is native to the Andean region, Colombia, Ecuador, Perú, and Bolivia (Chen et al., 2021; Rito et al., 2023; Viera et al., 2022). In Colombia, it also is a crop with high economic value in the departments of Cundinamarca, Antioquia, Tolima, and Boyacá. According to Agronet (2022), its yield reported from year 2018 to 2022 was about 18.1 t/ha, and the highest yield was obtained in 2021 (20.2 t/ha) with annual national production of 199236 t. The tree tomato fruit is used mainly in juice, salads, sauces, chutney, pickles, desserts, jams and compotes, among others (Hu et al., 2023; Kumar et al., 2024).

The tree tomato is also a fruit with excellent nutritional and nutraceutical quality due to its high bioactive content (Phenolic compounds, carotenoids, vitamins A, B_6, C, and E, minerals principally potassium, and alkaloids) (Viera et al., 2022; Espín et al., 2016). Bioactive compounds have shown to have anti-hypertensive, anti-oxidation, anti-inflammatory, antinociceptive and anti-cholinergic inhibitory activities (Diep et al., 2022; Sarkar et al., 2022; Bailon-Moscoso et al., 2020; Wang and Zhu, 2020). These compounds also have shown to decrease the total cholesterol, LDL cholesterol, glucose levels and contribute to weight loss (Bailon-Moscoso et al., 2020; Salazar-Lugo et al., 2016).

Besides, fractions of tree tomato enriched in phenolic compounds may be used as functional ingredients with benefits for our health in different food and, cosmetic and pharmaceutical products (Diep et al., 2022; Sarkar et al., 2022; Wang and Zhu, 2020). In the food industry, these compounds improve the sensory quality of added-value products (García et al., 2016) and they can be used as emulsifiers, stabilizers, and food preservatives (Wang and Zhu, 2020). Martínez-Girón (2022) showed the functional potential from tree tomato juice in the elaboration of a margarine with antioxidant activity and Figueroa-Flórez et al. (2016) showed its potential in tree tomato beverages. Thus, tree tomato ingredients are promising source of healthy and nutraceutical products (Salazar-Lugo et al., 2016; Wang and Zhu, 2020).

Pressure-driven membrane technology has emerged as an efficient process for obtaining fractions with high content of bioactive compounds as they operate at low-temperature and moderate pressure, require low energetic consumption and less manpower, and reduce operating cost (Koop et al., 2021). These technologies are based on the differences in the compound sizes and have been effectively applied to the clarification, separation, concentration, and purification of bioactive compounds in aqueous solutions (dos Santos et al., 2020; Le et al., 2021).

Technologies such as ultrafiltration (UF) and nanofiltration (NF) have been used to concentrate and fractionate phenolic compounds from clarified blood orange juice, dragon fruit juice (Le et al., 2021), yerba mate extracts (dos Santos et al., 2020), and wine sediments (Arboleda-Mejia et al., 2022), all of them with good antioxidant activity. While membrane technologies have been widely studied, there are not enough studies reported in the clarification and the fractionation from tree tomato phenolic compounds. The aim of this research was to evaluate the potential of ceramic membranes with different pore sizes / Molecular Weight Cut-Off (MWCO) for obtaining phenolic enriched fractions from tree tomato.

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Materials and methods

Tree tomato characterization

Tree tomato fruits (cv. Rojo común) were obtained from a farm near Tibaná - Boyacá, Colombia, village Suta Abajo (2400 m.a.s.l.). Fruits were selected in an edible maturity stage (red color with orange tones or 100 % orange) according to specifications of the Colombian Technical Standard NTC 4105: "Tree tomato. Specifications" (ICONTEC, 1997). They were washed with potable water, disinfected with 200 mg/l sodium hypochlorite, washed again, and dried with paper towels. Six fruits were randomly chosen for determining their physical-chemical characteristics such as the total soluble solids (TSS), total insoluble solids (TIS), titratable acidity (TA), maturity index (MI) and moisture according to methods from the Association International of Official Analytical Chemists (AOAC, 1990 and 2000). It also determined color parameters (L, a* and b*), total polyphenol content (TPC) and yield of pulp.

Sample preparation and pretreatments

Fruits were stored at 4 °C until the juice obtention. The tree tomato fruits were peeled manually and cut into approximately 2 cm^2 pieces and squeezed strongly over a nylon filter for recovering the juice. After that, the juice was depectinized with Pectinex® Ultra SP-L enzyme (1 ml/kg) at 30 °C for 30 min under constant agitation. Finally, due to high concentration of suspend solids the juice was centrifuged at 3400 g for 10 min in a Hettich Rotina 46S centrifuge (Andreas Hettich GmbH & Co.KG, Tuttlingen, Germany, 2001) and the supernatant was microfiltered immediately for removing the initial microbial charge.

Microfiltration (MF) and ultrafiltration (UF) membranes

The supernatant from tree tomato juice was clarified (Control) using a membrane with pore diameter of 0.1 µm. The clarified juice was separated employing membranes with pore diameter ranging from to 50 nm to 1 kDa. Table 1 provides the specifications of the membranes used according to the manufacturers.

Tabla 1. Especificaciones de membranas
Table 1. Membrane specifications

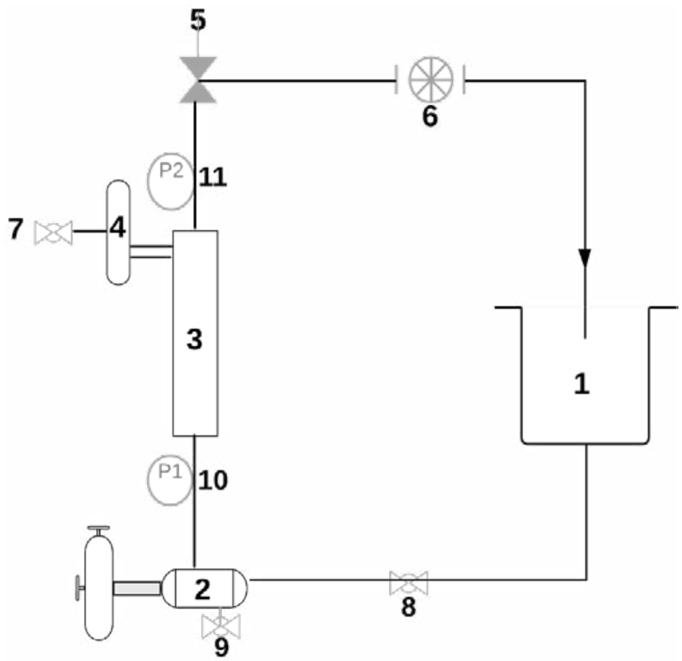
Membrane	Pore size MWCO	Length (mm)	Filtration area (cm2)	Diameter (mm)	Manufacture
MF	0.1 µm	250	50	7	Membralox®
UF-50	50 nm	250	50	7	Membralox®
UF-10	10 nm	250	50	7	Membralox®
UF-8	8 kDa	254	47	6	Tami Industries®
UF-1	1 kDa	254	47	6	Tami Industries®

Where MWCO, molecular weight cut-off; MF, microfiltration membrane; UF-50, UF-10, UF-8, UF-1, ultrafiltration membranes with pore sizes of 50 nm, 10 nm, 8 kDa, 1 kDa, respectively. Source: own elaboration. Donde MWCO, corte de peso molecular; MF, membrana de microfiltración; UF-50, UF-10, UF-8, UF-1, membranas de ultrafiltración con tamaño de poros de 50 nm, 10 nm, 8 kDa, 1 kDa, respectivamente. Fuente: elaboración propia.

Clarification and fractionation processes

The clarification and fractionation processes were carried out using a benchtop crossflow pilot unit (Membralox®, model XLAB 5, Pall Corporation, France) located at Universidad Pedagógica y Tecnológica de Tunja. The equipment and its components are shown in Figure 1.

Figure 1. Schematic diagram of the benchtop crossflow pilot unit
Figura 1. Diagrama esquemático de la unidad piloto de flujo tangencial



Where 1. Double jacket feed tank, 2. Volumetric circulation pump, 3. Filtration module T1-70, 4. Back pulse, 5. Relief valve, 6. Membrane pressure valve, 7. Permeate valve, 8. Feed tank drain valve, 9. Pump drain valve, and 10 and 11. Manometers. Source: own elaboration. Donde 1. Tanque de alimentación de doble camisa, 2. Bomba de circulación volumétrica, 3. Módulo de filtración T1-70, 4. Pulso de retorno, 5. Válvula de alivio, 6. Válvula de presión de membrana, 7. Válvula de permeado, 8. Válvula de descarga del tanque de alimentación, 9. Válvula de descarga de la bomba, y 10 y 11. Manómetros. Fuente: elaboración propia.

The membranes were rinsed with distilled water before the treatments. After the rinse, the supernatant or clarified sample was poured into the feed tank (3L) and pumped through the different membranes. When the transmembrane pressure and tangential velocity were constant, the permeate valve was opened and the permeate was collected continually without taking out the retentate (Batch concentration mode) until a Volumetric Reduction Factor (VRF = total feed volume / resultant retentate volume) of 2. The transmembrane pressure (TMP) was 2 bar for MF and 3 bar for UF at a temperature less than 30 °C until it reaches a constant flux. Once the process finished, the permeate (Control) was recovered, poured into sterilized containers, and stored immediately at 4 °C until the fractionation by UF.

Efficiency of the Process

The clarified (feed UF), the permeate, and the retentate samples from the UF were stored in centrifuge tubes of 50 ml at -80 °C for the following analysis, except for determining the permeate flux:

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Permeate flux. It was calculated with the permeate volume measured in a graduated cylinder per filtration area per unit of time. It was determined with equation following (Arboleda-Mejia et al., 2022):

where J is the permeate flux (L/m2*h), V_p is the permeate volume (L) collected during the

$$J = \frac{V_p}{A * t}$$

time interval *t* (h) and A is the filtration area (m_2).

Concentration factor. The concentration factor (CF) of total phenolic compounds (TPC) was determined from the following equation (Koop et al., 2021):

where *C* is the concentration of evaluated parameters in retentate and feed, respectively.

$$CF\ (\%) = \left(\frac{C_{retentate}}{C_{feed}}\right) * 100$$

Analytical evaluations

pH. The pH value was measured using a pH meter (pH 211 microprocessor pH Meter, HANNA instruments), which was calibrated with buffers at 4.0 and 7.0.

Total soluble solids. Total soluble solids (TSS) were determined by refractometer (BOECO Hand Refractometer) with a range of 0-32 ºBx by placing two drops of sample on the prism. The refractometer was calibrated with distilled water (0 °Bx) and the prism was washed with distilled water and dried before each measurement.

Rheological parameters. The rheological parameters of fresh and depectinized juice, supernatant, permeate and retentate samples were determined at 30 °C using a Brookfield DV-III Ultra viscosimeter® and two spindles (S0 and S21). The shear rate varied from 1.25 – 25.0 s^{-1}. The progress of apparent viscosity (μ_a) as a function of the shear rate ɣ was plotted. Since fresh and depectinized juice had shear thinning with yield stress behavior, the following equation was used to determine the consistency index (k) and the flow behavior index (n):

where *T* is the shear stress, T_o is shear stress with yield stress, k is consistency index and n is behavior index.

$$\tau = \tau_0 + k\dot{\gamma}^n$$

Total insoluble solids (TIS). 20 g of each permeate and retentate fraction were centrifuged at 6000 rpm for 10 min. The precipitate was weighted and the TIS was determined with the following equation:

$$TIS\ (\%) = \frac{\text{Precipitate weight (g)}}{\text{Sample weight (g)}} * 1($$

Titratable acidity. Titratable acidity (TA) was determined according to the official method AOAC 942.15: Acidity (Titratable) of fruit products (AOAC, 2000). Two milliliters of sample were transferred to 20.0 ml distilled water in an erlenmeyer flask, and it was titrated with a standardized 0.1 N sodium hydroxide to the endpoint with phenolphthalein (pH = 8.1 ± 0.1). The results were expressed as percentage of citric acid.

Color. The color measures were determined using a colorimeter (Colourflex EZ HunterLab 45/0, Rango spectral 400-780 nm) previously calibrated with black and white porcelain plates. The color was determined using the parameter luminosity (L*), a* = blue-green/red-purple and b* = yellow-blue, applying the reference D65 (standard daylight). It was determined the Saturation or Chroma (C*) and tone or hue angle (h°) (Jha, 2010).

$$\Delta E = \sqrt{\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2}}$$

Color change. Color change was determined using the following equation:

Total Polyphenol Content. Total polyphenol content (TPC) was determined using the microscale protocol named Folin-Ciocalteu colorimetry. A 20 µl volume of blank, standard or extract was placed into an assay tube to which was added 1580 µl distilled water and 100 µl Folin-Ciocalteu reagent. The mixture was allowed to stand for 6 min in darkness at room temperature. After this time, 300 µl of 20% sodium carbonate solution was added and the mixture was swirled and incubated for 120 min at room temperature. Finally, the absorbance was measured at 760 nm using a Spectronic Genesys TM8 spectrophotometer (Thermo Electron Scientific Instruments, Madison, Wisconsin, USA). Soluble total polyphenols content was calculated using a standard curve of gallic acid. The results were expressed as gallic acid equivalents (GAE) in mg per 100 g of fresh weight (mg GAE/100 g FW) (Zambrano-Moreno et al., 2015).

Fouling models

Four Hermia's models were used for determining the fouling nature during crossflow filtration (Satyannarayana and Kumar, 2023):

Cake filtration. The fraction particles' size is larger than the membrane pore size, which permits the formation of a cake layer over the membrane, and its thickness increases with time.

$$J^{-2} = {J_0}^{-2} + k_c t$$

Intermediate pore blocking. The fraction particles' size is similar to the membrane pore size. Some fraction particles limit the openings of the pores, and other particles can accumulate over the membrane.

$$J^{-1} = {J_0}^{-1} + k_i t$$

Standard pore blockage. The fraction particles' size is smaller than the membrane pore size.

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The particles cross through the membrane and accumulate on the sides of the walls, reducing the membrane pore size.

$$J^{-0.5} = {J_0}^{-0.5} + k_s t$$

Complete pore blocking. Complete pore blocking. The fraction particles' size is slightly larger than the membrane pore size. The particles accumulate on the surface of the membrane and block its pores.

$$LnJ^{-1} = Ln{J_0}^{-1} + k_b t$$

Statistical analysis

The characterization of the fruits was analyzed using summary statistics (media and standard deviation). The effect of the sample preparation on physicochemical properties was analyzed following a complete randomized scheme with two treatments (Fresh, Pectinex® and centrifugation) and three replications. Data from the tree tomato fractions were analyzed as a completely randomized design where the treatments were the membrane pore size / MWCO with three replications. The normality assumption and homogeneity of variance were verified. It was used an analysis of variance (ANOVA) using the statistical software R, version 1.4.17©, with a significance level of 5% (α = 0.05). For the medias comparison was used the Tukey test.

Results and discussion

Tree tomato characterization

According to Colombian Technical Standard "NTC 4105: Tree tomato. Specifications", the tree tomato was classified as Category I due to its diameter (B) (6.01±0.84 cm), pulp content (72.0±6.20 %), TSS (10.1±0.6 °Bx), and tone orange (°h*) (38.6±12.7), corresponding to colors five and six from the standard values (ICONTEC, 1997) (Figure 2).

Figure 2. Tree tomato fruit – Category I (NTC 4105, 1997)
Figura 2. Fruta de tomate de árbol – Categoría I (NTC 4105, 1997)

Source: own elaboration. Fuente: elaboración propia

The variables weight (117±16.4 g) and TSS (10.1±0.60 °Bx) had similar results to those reported by Vasco et al. (2009) of 107±6.0 g and 11.0±1.10 °Bx, respectively. The pH (4.28±0.20) was close to that reported by Nor et al. (2018) (4.12±0.11) and TA (1.43±0.08 %) to that reported by Figueroa-Flórez (2016) (1.66±0.08 %). L* (41.9±3.80) and the MI (7.10±0.20) were comparable with values reported by Pinchao et al. (2016) of 41.2±1.94 and 6.76, respectively. These parameters showed the relationship between the color and MI and the grade of orange and red, which are characteristic colors of these fruits (Table 2).

Table 2. Physicochemical characteristics from tree tomato fruit
Tabla 2. Características fisicoquímicas de la fruta de tomate de árbol

Characteristic	
Weight (g)	117±16.4
Caliber (cm)	6.01±0.84
pH	4.28±0.20
TSS (°Bx)	10.1±0.60
TA (%)	1.43±0.08
Maturity index (MI)	7.10±0.20
Moisture (%)	85.2±0.46
Pulp content (%)	72.0±6.20
L*	41.9±3.80
C*	25.9±2.80
°h	38.6±12.7

Results expressed as the mean ± standard deviation. Source: own elaboration. Resultados expresados como media ± de desviación estándar. Fuente: elaboración propia.

Pretreatments of tree tomato juice

The use of enzymes allowed the enzymatic hydrolysis of pectin from fruit cellular wall. The centrifugation improved the separation from suspended solids, which improves the flux and yield in a subsequent filtration process (Montero-Barrantes, 2008). Table 3 reports the characteristics of fresh juice subjected to different pretreatments (enzymatic maceration and centrifugation process). The pretreatments were not significantly different ($p > 0.05$) in terms of TSS, TA, pH, Moisture, ΔE, and n. But the TIS decreased significantly ($p < 0.05$) by 55.9% with enzymatic maceration and 98.2 % with centrifugation.

L*, C*, and ºh* showed significant differences ($p < 0.05$) between the pretreatment applied. The fresh juice presented the lowest value of L* (33.5±1.05), which was close to that reported by Pinchao et al. (2016) of 35.12±2.27. L* increased by 23.3% with enzymatic maceration and 33.7 % with centrifugation, C* decreased by 43.8% with enzymatic maceration and 34.5 % with centrifugation and, hº increased by 32.1% with enzymatic maceration and 25.5% with centrifugation. Both pretreatments showed a visible ΔE (20.5±1.00) from dark orange to a lighter orange-yellow color, which accorded with Wojdyło et al. (2021) who affirm that the samples present tones yellow in their composition after a maceration process. The fruit extracts have a variety of pigments, which are responsible for color changes in the products (Sant'Anna et al., 2013). The orange color from carotenoids in the fresh juice decreased with the enzymatic maceration due to the liberation of phenolic compounds from the cellular

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wall during the hydrolysis and the separation of carotenoids as suspended particles during the centrifugation. The obtained samples had more translucent and lighter colors (de Farias et al., 2020; Wojdyło et al., 2021).

The TPC in fresh juice (57.9±4.37 mg GAE/100 g FW) was higher than that reported by Cuesta et al. (2013) (45 – 55 mg GAE/100 g FW) but lower than those reported by Vasco et al. (2009) (78±2 mg GAE/100 g FW) and Martínez-Girón (2022) (83.6±6.78 mg GAE/100 g FW). The TPC increased significantly ($p < 0.05$) with the enzymatic maceration (21.6%) but decreased significantly ($p < 0.05$) with the centrifugation process. Although some of these compounds are hydrosoluble and remain in the aqueous phase of the fractions. Other compounds are not-soluble and are removed with the suspended solids in the centrifugation process (Montero-Barrantes, 2008).

Table 3. Physicochemical characteristics of fresh, depectinized and centrifugated juice
Tabla 3. Características fisicoquímicas de jugo fresco, depectinizado y centrifugado

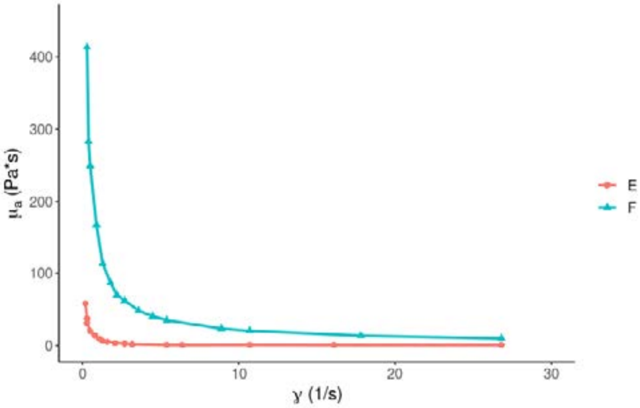
Parameter	Fresh	Pectinex®	Centrifugate
TSS (°Bx)	10.1±0.60^{b}	13.4±0.40^{a}	11.3±0.40^{b}
TIS (%)	66.9±1.20^{a}	36.7±1.20^{b}	2.00±1.20^{c}
TA (%)	1.43±0.08^{b}	1.73±0.06^{ab}	1.85±0.06^{a}
pH	3.88±0.05^{a}	3.64±0.05^{a}	3.56±0.05^{a}
Moisture (%)	85.2±0.99^{b}	86.3±0.99^{b}	91.6±0.99^{a}
L*	42.0±0.90^{a}	42.8±0.90^{a}	45.1±0.90^{a}
C*	56.8±1.30^{a}	44.9±1.30^{b}	40.6±1.30^{b}
°h*	57.7±0.7^{0}c	76.2±0.70^{a}	72.4±0.70^{b}
ΔE	---	20.4±1.00^{a}	20.6±1.00^{a}
TPC (mg GAE/100 g FW)	57.9±4.37^{ab}	70.4±4.37^{a}	43.3±4.37^{b}
k (Pa*s^{2})	24.6±1.00^{a}	4.60±0.4^{0}b	1.30±0.30^{a}
n	0.24±0.30^{a}	0.40±0.43^{a}	---

Results expressed as the mean ± standard deviation. Means followed by the same letter are not significantly different ($p > 0.05$). Source: own elaboration. Resultados expresados como la media ± de desviación estándar. Medias seguidas de una letra común no son significativamente diferentes ($p > 0.05$). Fuente: elaboración propia.

Rheological parameters

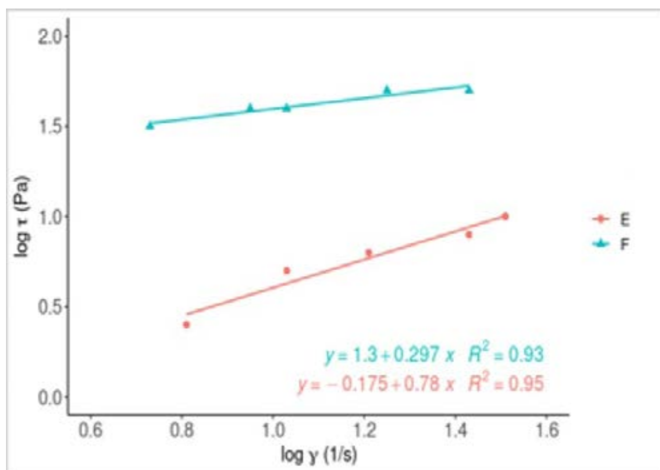
Figure 3 presents the progress of the μ_a as a function of the ɣ for fresh and depectinized juice, the μ_a in both samples decreases as the ɣ increases (shear thinning behavior). The μa in fresh juice decreased at a higher rate than the depectinized juice due to the enzyme hydrolysis on the pectin from the cellular wall. To model shear thinning behavior, the data of and ɣ were linearized by $\log(T - T_0) = n.\log ɣ + \log k$ and the data were fixed to Herschel-Bulkley model with a correlation coefficient higher to 0.93 and behavior index smaller to 1 ($0 < n < 1.0$) (Figure 4). The fresh juice presented larger k (24.6±1.00 Pa*s^{2}) in contrast to depectinized juice (4.60±0.40 Pa*s^{2}), due to enzyme activity. This is typical behavior from several fruit and vegetables juices, where the pectin promotes the behavior of No-Newtonian fluid (Muñoz-Puntes et al., 2012; Ricci et al., 2021). On the other hand, the centrifuged juice and, the permeate and retentate samples presented behavior of Newtonian fluid (1.3±0.3 mPa*s) due to separation from suspended particles from the fresh juice due to enzymatic activity on the macromolecule, principally pectin (Montero-Barrantes, 2008).

Figure 3. Apparent viscosity from fresh and depectinized tree tomato
Figura 3. Viscosidad aparente de tomate de árbol fresco y macerado enzimáticamente



Source: own elaboration. Fuente: elaboración propia.

Figure 4. Rheological parameters from fresh and depectinized tree tomato
Figura 4. Parámetros reológicos de tomate de árbol fresco y macerado enzimáticamente



Source: own elaboration. Fuente: elaboración propia.

MF and UF process conditions

Permeate flux. The permeate flux determined the productivity of the MF and UF processes during the filtration. Figure 5 depicts the behavior of the permeate flux with the processing time of the MF at 2.0 bar (a.) and UF at 3.0 bar (b.), respectively. A high flux was evidenced at the beginning of the process, but then the flux decreased with time. This decrease is caused by the fouling effect due to the accumulation of suspended particles in the pores and the concentration polarization and gel formation on the membrane surface (Destani et al., 2013) (Destani et al., 2013). Moreover, the permeate flux is directly proportional to the pore size or MWCO and inversely proportional to the operation time (Figure 5).

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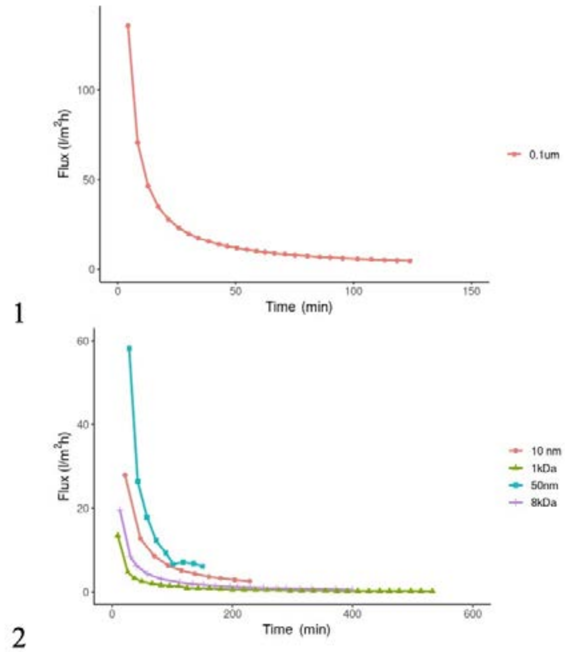
Figure 5. Permeate flux and operation time from tree tomato fractions: **1.** Membrane 0.1 µm; **2.** Membranes 50 nm, 10 nm, 8 kDa and 1 kDa

Figura 5. Flux de permeado y tiempo de operación de fracciones de tomate de árbol: **1.** *Membrana 0.1 µm;* **2.** *Membranas 50 nm, 10 nm, 8 kDa y 1 kDa*



Source: own elaboration. Fuente: elaboración propia.

Fouling models

The reduction in the flux depends on the different membrane fouling mechanisms due to the particle size present in the fractions. These mechanisms can be explained by the Hermia's models, whose parameters are shown in Table 4. In four of five membranes (0.1 um, 10 nm, 8 kDa and 1 kDa) the dominant mechanism is the intermediate pore blocking model (R^2 = 1.00). Satyannarayana and Kumar (2023) in clarified juice of lime after an enzymatic pretreatment at 2.0 bar reported a good fit to the same model (R^2 = 0.99). This shows that the juice fractions have suspended particles of similar size to the membrane size and this mechanism allows a more straightforward cleaning process than the other fouling mechanisms. Besides to the small values of the fouling coefficient K_i (1.67 – 7.91 $*10^{-3}$) the juice fractions presented a low content of pectin, due to its hydrolysis during the enzymatic pretreatment and its separation during the centrifugation and clarification. On the other hand, the membrane of 50 nm presented a less fit to the fouling model complete pore blocking (R^2 = 0.86) and a larger fouling parameter K_b ($0.58*10^{-2}$) due to the variability in the size of suspended particles in this fraction or particles with similar size to the size of the membrane.

Table 4. Hermia's model parameters from permeate streams

Tabla 4. Parametros del modelo de Hermia de las corrientes de permeado

Membrane/model	Parameter	0.1 um	50 nm	10 nm	8 kDa	1 kDa
Cake filtration	R^2	0.942	0.399	0.947	0.930	0.935
	K_c*10^{-4}	5.32	2.16	6.95	60.7	329
	J_0^{-2}	0.017	-0.025	-0.032	-0.395	-2.86
Intermediate pore blocking	R^2	1.00	0.669	1.00	1.00	0.998
	K_i*10^{-3}	1.67	0.63	1.67	3.92	7.91
	J_0^{-1}	0.00	-0.024	1.37*10^{-16}	7.73*10^{-16}	-0.037
Standard pore blocking	R^2	0.967	0.824	0.977	0.966	0.968
	K_s*10^{-3}	2.33	0.90	1.99	2.51	3.10
	$J_0^{-0.5}$	0.155	0.116	0.189	0.334	0.521
Complete pore blocking	R^2	0.830	0.865	0.898	0.843	0.830
	K_b*10^{-2}	1.47	0.58	1.02	0.73	0.56
	LnJ_0^{-1}	-3.51	-3.77	-3.04	-1.98	-1.08

Source: own elaboration. Fuente: elaboración propia.

Quality of tree tomato fractions

Table 5 shows the effect of the UF process on the physicochemical characteristics obtained with membranes of different pore sizes / MWCO compared to the control (MF). The TSS, pH, and moisture content did not differ significantly ($p > 0.05$) between treatments, which is comparable in magnitude to that reported by Beltrán et al. (2016) in purple tree tomato and by dos Santos et al. (2020) in yerba mate extract. The UF-50 membrane concentrated the soluble solids from 1.61±0.05 to 1.81±0.04 ºBx (CF = 1.12), which was similar to that reported by Ghosh et al. (2018) from 16.07±0.34 to 19.36±0.32 ºBx (CF = 1.20) and Koop et al. (2021) from 1.65±0.07 to 1.65±0.07 (CF = 1.06) in Indian blackberry using UF and NF membranes, respectively. The TSS and TA are similar in all the fractions because sugars and organic acids have a particle size smaller than the membrane pore size and are well separated by nanofiltration and reverse osmosis (Beltrán et al., 2016). The TIS presented a significant difference respect to the control (P 0.1 µm), where all membranes decreased the suspended particles and allowed to obtain homogenized fractions.

Table 5. Physicochemical characteristics of the control, permeate and retentate from tree tomato fractions

Tabla 5. Características fisicoquímicas del control, permeado y retenido de las fracciones de tomate de árbol

Fraction	TSS (ºBx)	TIS (%)	TA (%)	pH	µa (mPa*s)	Moisture (%)
Control	10.3±0.35	4.69±0.47[a]	1.61±0.05[abc]	3.59±0.01	1.33±0.09[a]	92.7±2.74
UF50-P	9.31±0.28	0.11±0.26[b]	1.64±0.05[ab]	3.54±0.01	1.22±0.05[abc]	91.6±2.74
UF50-R	10.3±0.28	0.24±0.26[b]	1.81±0.04[a]	3.55±0.01	1.10±0.05[abc]	91.1±2.74
UF10-P	9.91±0.28	1.03±0.26[b]	1.43±0.04[bcd]	3.58±0.01	1.04±0.05[bc]	90.3±2.16
UF10-R	10.4±0.28	0.49±0.26[b]	1.55±0.04[bcd]	3.61±0.01	1.11±0.05[abc]	89.2±2.74
UF8-P	9.73±0.28	0.63±0.33[b]	1.38±0.05[d]	3.69±0.01	1.02±0.06[c]	90.5±2.74
UF8-R	9.63±0.28	0.44±0.26[b]	1.53±0.04[bcd]	3.65±0.01	1.28±0.05[ab]	89.8±2.74
UF1-P	9.49±0.28	0.01±0.26[b]	1.42±0.04[cd]	3.63±0.01	1.19±0.05[abc]	90.3±2.74
UF1-R	10.2±0.28	0.01±0.26[b]	1.45±0.04[bcd]	3.63±0.01	1.18±0.05[abc]	89.1±2.74

Results expressed as the mean ± standard deviation. Means followed by the same letter are not significantly different ($p > 0.05$). Source: own elaboration. Resultados expresados como la media ± de desviación estándar. Medias seguidas por una letra común no son significativamente diferentes ($p > 0.05$). Fuente: elaboración propia.

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The color parameters of the fractions obtained by UF membranes presented higher lightness (L*) in the permeates (52.4±3.46 – 57.6±3.46) than in the retentates (28.9±3.46 – 48.3±2.68); higher values in C* in the retentates (43.0±2.89 – 66.3±2.89) than in the permeates (20.6±2.89 – 37.04±2.89). These changes are explained because the retentate retains a higher content of phenolic compounds and the permeate generates translucent fractions due to the higher content of water (Table 6). These results were similar to those reported by Koop et al. (2021) in Indian blackberry. The change in the tone (°h*) values, from 79.9±1.78 for MF to 81.6±2.30 – 97.7±1.78 for the fractions represents the transition color between red-orange and orange–brown (Table 6) due to greater retention of phenolic compounds and high molecular weight molecules that form larger particles, which cause darker colors such as brown in the retentate (dos Santos et al., 2020).

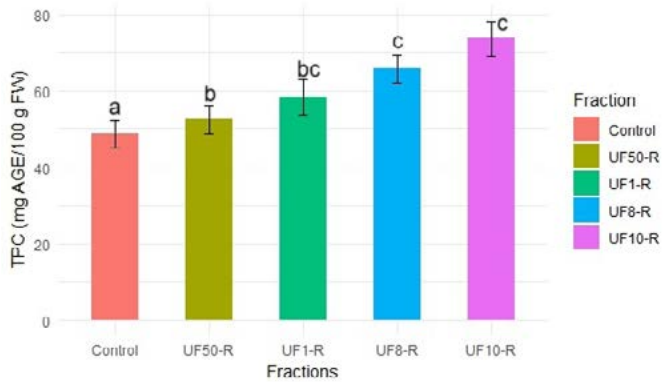
Table 6. Color parameters of the control, permeate and retentate from tree tomato fractions.
Tabla 6. Parámetros de color del control, permeado y retenido de las fracciones de tomate de árbol

Membrane	Fraction	L*	C*	°h*	ΔE*
MF	Control	48.2±2.68[ab]	23.2±2.24[f]	79.9±1.78[de]	---
UF-50	Permeate	57.6±3.46[a]	25.8±2.89[ef]	81.6±2.30[d]	8.80±2.75[ef]
	Retentate	36.2±2.68[bc]	45.8±2.24[bc]	97.7±1.78[a]	27.8±2.13[bc]
UF-10	Permeate	55.0±3.46[a]	37.04±2.89[cde]	92.2±2.30[abc]	24.4±2.75[bcd]
	Retentate	48.3±2.68[ab]	50.4±2.24[b]	93.3±1.78[ab]	33.1±2.13[ab]
UF-8	Permeate	52.4±3.46[a]	20.6±2.89[f]	86.0±2.30[bcd]	7.19±2.75[f]
	Retentate	28.9±3.46[c]	66.3±2.89[a]	89.1±2.30[abcd]	19.7±2.75[cde]
UF-1	Permeate	56.8±3.46[a]	31.4±2.89[def]	82.9±2.30[cd]	13.2±2.75[def]
	Retentate	44.0±3.46[ab]	43.0±2.89[bcd]	71.03±2.30[e]	25.0±2.75[bc]

Results expressed as the mean ± standard deviation. Means followed by the same letter are not significantly different ($p > 0.05$). Source: own elaboration. Resultados expresados como media ± de desviación estándar. Medias seguidas por una letra común no son significativamente diferentes ($p > 0.05$). Fuente: elaboración propia.

With respect to TPC, there were not significant differences ($p > 0.05$) among the retentates of UF-10, UF-8, and UF-1, but they were significantly different from the Control ($p < 0.05$). In terms of magnitude, the UF-10, UF-8, and UF-1 membranes had a higher content of TPC of 73.6±4.59 mg GAE/100 g FW (CF equal to 1.5), 65.7±3.65 mg GAE/100 g FW (CF equal to 1.4), 58.3±4.56 mg GAE/100 g FW (CF equal to 1.2), respectively. Such retentions are due to the higher fraction particle size and the membrane fouling effect, where these compounds are deposited on the membrane surface or entrapped inside the cake layer (Onsekizoglu, 2013); this behavior. The membrane of 1 kDa did not retain a high content of TPC (58.3±4.59) as expected, which may be due to the pressure caused by higher solute amounts pushed through the membrane to the permeate (Le et al., 2021). TPC in the Control (48.7±3.65 mg AGE/100 g FW) was similar to results reported by Orqueda et al. (2021) on orange variety from two locations in Argentina (45.5±1.09 mg GAE/100 g FW). Orqueda et al. (2020) reported that the content of phenolic compounds makes them important candidates for functional foods or ingredients (Kumar et al., 2024) due to the potential benefit of its consumption on human health and the ultrafiltration permitted to obtain more concentrated fractions in these compounds.

Figure 6. TPC of the control and retentates from tree tomato fractions
Figura 6. CPT del control y retenidos de las fracciones de tomate de árbol



Results expressed as the mean ± standard deviation. Means followed by the same letter are not significantly different ($p > 0.05$). Source: own elaboration. Resultados expresados como media ± de desviación estándar. Medias seguidas por una letra común no son significativamente diferentes ($p > 0.05$). Fuente: elaboración propia.

Conclusion

Pretreatments such as the maceration with Pectinex® and a centrifugation step are essential in the clarification and fractionation processes for obtaining fractions of high functional quality. The maceration with Pectinex® permitted the pectin hydrolysis from the cellular wall of the fruit, which decreased the macromolecules in the initial sample, and the centrifugation allowed the separation of suspended particles. These pretreatments improved the filtration yield due to the decrease of the fouling effect and the obtention of higher fluxes in less time, favoring the filtration processes.

The Hermia's models predicted with high correlation coefficients the fouling mechanism of the membranes due to the compounds presented in the tree tomato juice fractions, indicating that the membranes have a fabrication process of similar size and, by their nature are widely used in the fractionation processes of compounds with different MWCO.

On the other hand, the UF-10 membrane slightly concentrated the TPC with an acceptable color, permeate flux, and operation time compared to other membranes. To evaluate the content of phenolic compounds and the processing time is important for choosing the best membrane in the obtention of a high functional quality. This study showed that the tree tomato fractions can be used in the food and nutraceutical industry as a functional ingredient in the elaboration of beverages enriched with phenolic compounds.

Finally, it is recommended to include a fraction concentration process such as reverse osmosis or osmotic evaporation, which will allow obtaining fractions with higher content of bioactive compounds. In the fractionation processes with membranes of different MWCO is important to evaluate all the aspects that affect the quality of the obtained fractions; if the content of bioactive compounds is high but the process is prolonged, it is important to decide whether to continue or not the process. It also is important to evaluate the process with transmembrane pressure higher at 3.0 bar since the use of higher values, in some of them higher at 10 bar, have been reported.

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