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Gabriel Emiliano Motta

UFSC: Universidade Federal de Santa Catarina

Amanda Tavares Germano

UFSC: Universidade Federal de Santa Catarina

Luciano Vitali

UFSC: Universidade Federal de Santa Catarina

Germán Ayala Valencia

UFSC: Universidade Federal de Santa Catarina

Sandra R.S. Ferreira

s.ferreira@ufsc.br

UFSC: Universidade Federal de Santa Catarina <https://orcid.org/0000-0003-3393-0995>

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**Recovery of bioactive compounds from *Musa acuminata* Cavendish bracts:
sustainable valorization of waste from Brazil's sweetest banana**

Gabriel Emiliano Motta^a, Amanda Tavares Germano^b, Luciano Vitali^b,
Germán Ayala Valencia^a, Sandra Regina Salvador Ferreira^{a,*}

^a Chemical and Food Engineering Department, Federal University of Santa Catarina,
Florianópolis, SC, CEP 88040-900, P.O. Box 476, Brazil.

^b Department of Chemistry, Federal University of Santa Catarina, Florianópolis, SC,
Brazil.

* Corresponding author. E-mail: s.ferreira@ufsc.br (Sandra R. S. Ferreira) Phone: +55 48
37212537.

ABSTRACT

This comprehensive study investigated the chemical composition and methods for recovering high-value compounds from the bracts of banana inflorescences. They were evaluated for the apolar fraction using CO₂ supercritical fluid extraction (SFE) and Soxhlet (hexane), and for the polar fraction using microwave-assisted extraction (MAE), pressurized liquid extraction (PLE), and conventional reflux extraction (CRE). SFE with CO₂ at 25 MPa achieved the greatest recovery of essential fatty acids (palmitic, oleic, and linoleic) and the highest carotenoid content (2.94 mg β -carotene equivalent/100 g DW), surpassing conventional Soxhlet extraction. For polar compounds, PLE (water 150 °C) yielded the highest extraction yield (53.09%), TPC (22.83 mg GAE/g DW), a good protein recovery (52.53%), and antioxidant capacities (ABTS: 489.36; DPPH: 170.35 μ mol TEAC/g DW). MAE demonstrated superior extraction efficiency of bioactive compounds. Notably, for the first time, these phytochemicals were identified: taxifolin, eriodictyol, rosmarinic acid, and abscisic acid. The evaluation confirmed the environmental superiority of SFE, MAE, and PLE against conventional methods, achieving an A status in the Eco-scale. Therefore, this approach highlights that banana inflorescence bracts are rich in high-value bioresources with considerable applications in the food, pharmaceutical, and other industries. The correct choice of solvent and extraction method can help achieve sustainable development.

KEYWORDS: Agro-industrial residues, *Musa acuminata* Cavendish bracts valorization, Techno-environmental evaluation, First-time phenolic identification

1. INTRODUCTION

Bananas are among the most produced and fresh consumed fruits in the world, with over 135 million tons produced annually [1, 2]. The most popular variety is *Musa acuminata* Cavendish, which accounts for over half of the world's production [3]. Brazil is the fourth largest worldwide producer of banana, where the region of Corupá (26°27'2"S 49°17'6"W), located in the north of the state of Santa Catarina, stands as the largest national banana exporter. Due to factors such as production methods, terroir, and altitude, the region holds the designation of origin for the sweetest banana in Brazil [4–6].

The banana production is widespread in tropical regions, and the plant generally produces only one bunch, with harvest leaving huge amounts of agricultural waste in the fields, such as pseudostems, leaves, and inflorescences [7, 8]. According to [7], 160 kg of inflorescences are generated and discarded for every ton of banana produced. These residues, as pointed out by several authors [7, 9, 10], can have high added value and wide application in food, health, medicine, and materials due to their antioxidant, antiviral, antimicrobial, anti-inflammatory, antidiabetic, and nutritional properties.

Evaluating and exploring alternative ways to obtain bioactive compounds can be a strategy to promote human well-being, especially when the raw materials are highly productive and easily accessible in many countries. Furthermore, the valorization of agro-industrial waste is an alternative to promoting a sustainable cycle of use of natural resources by the concepts of Sustainable Development of Nations United; this valorization comes through research and development, mainly SDG 12 (Responsible consumption and production) and SDG 9 (Industry, innovation, and infrastructure) [11]. This study compares different methodologies for fractionating the polar and non-polar fractions from banana inflorescences and evaluates the recovery of various bioactive compounds. The recovery of proteins and antioxidant components was investigated for the polar fraction, while the recovery of fatty acids and carotenoids was assessed for the non-polar fraction. The extraction methods included Microwave-Assisted Extraction (MAE), Pressurized Liquid Extraction (PLE), and Supercritical Fluid Extraction (SFE), compared with Conventional Reflux Extraction (CRE) performed using a Soxhlet apparatus with different solvents. The effects of process variables and solvents were evaluated.

2. MATERIAL AND METHODS

2.1 Material

Reagents: Carbon dioxide (CO₂) (99.9%) and Helium (99.999%) (White Martins Ltda., Joinville-SC, Brazil), Hexane (Synth, São Paulo, Brazil), 99.5% Ethanol, 99.5% Acetone, 98% Ethyl Ether, sodium carbonate (Lafan, São Paulo, Brazil), sodium hydroxide and hydrochloric acid (37%) from (A.C.S., Synth, São Paulo, Brazil), FeCl₃.6H₂O (A.C.S., Neon, São Paulo, Brazil). Trolox (97% pure) (6-hydroxy-2,5,7,8-tetramethylchroma 2-carboxylic Acid), TPTZ (2,4,6-tri(2pyridyl)-s-triazine), ABTS (2,2'-azino-bis(3-ethylbenzothiazoline-6-sulfonic Acid), DNS (3,5-dinitro salicylic Acid), Methanol High-Performance Liquid Chromatography (HPLC) grade (99.9%), DPPH (2,2-Diphenyl-1-picrylhydrazyl), Galic acid (98% pure), sulfuric acid (97%), Folin-Ciocateau, β -Carotene, Supelco F.A.M.E. MIX C4-C24 were acquired from Sigma Aldrich (Sigma Aldrich, St. Louis, MO, USA / Darmstadt, Germany).

Raw material: Bracts from the banana inflorescence were collected in Corupá (26°27'2"S 49°17'6"W), State of Santa Catarina, and cataloged at Herbarium Flor (FLOR0071264), from the Federal University of Santa Catarina [12]. The samples were manually separated (flowers and other structures), cleaned with distillate water, and dried using an oven with air circulation at 40 °C for 48h (Lucadema - 82/27, SP, Brazil). Then, the samples were ground in a knife mill (Marconi - MA340, SP, Brazil), sieved in mesh 40, and stored at -18 °C until use.

2.2 Proximal composition

The experiments were carried out following the methodologies: protein by Kjeldahl method with nitrogen (N = 6.25), 990.03 [13]; lipids content by Soxhlet method 920.39 [14]; moisture content by method 2.2.2.5 [15]; crude fibers by method 978.10 [16]; ashes by 942.05 [17]; total sugar by difference and by DNS [18].

2.3 Non-polar fraction

Non-polar fractions from banana inflorescence were obtained by Soxhlet with hexane (SOX-hex), according to AOAC (920.39), and by SFE with CO₂. The SFE was performed using equipment adapted by Mazzutti et al. (2018). SFE was conducted at 40 °C and pressures of 15, 20 and 25 MPa, with extraction time determined by the kinetics curve. The SFE conditions were defined based on Torres et al. (2022) [20], and data from *Musa paradisiaca* varieties Correa et al. (2016) [21]. The kinetics was conducted based on

Weinhold et al. (2008) [22] at 20 MPa, 40 °C, and 1.2 L CO₂/h. The volume of the cylindrical reactor used is approximately 107.7 mL (length of 329 mm and internal diameter of 20.42 mm). 15 g of dry and ground samples were filled into a stainless-steel extraction vessel, complementing the remaining volume with 3 mm glass spheres. The kinetics curve was obtained with samples recovered at 5-min intervals up to 60 min, followed by 10-min intervals up to 90 min, and 30-min intervals up to 270 min. After defining SFE time, by kinetics curve, the assays were conducted in duplicate at different conditions to obtain the supercritical non-polar fractions, to evaluate process yield, and quality of the samples (carotenoids content and fatty acids profile).

2.3.1 Total carotenoid content

Total carotenoids content (TCC) from the lipid fractions (SFE and SOX-hex samples) was determined by spectrophotometric analysis (multi-reader - Epoch, BioTek, São Paulo) at 450 nm, using a standard β -carotene curve, and following the methodology adapted from Kuhnen et al. (2009) [23]. The samples were diluted in a mixture of hexane, acetone, and ethanol (2:1:1) [23]. The assays were performed in triplicate, and the results expressed as β -carotene equivalents per gram of dry weight (DW) (mean $\pm$ standard deviation).

2.3.2 Fatty Acids profile of the non-polar fraction

The fatty acids profile of SFE and SOX-hex samples was evaluated by gas chromatography coupled with mass spectroscopy (GC-MS). The methodology followed O' Fallon et al. (2007) [24] with methylated samples. Then, 20 μ L of the sample was treated with 10 M KOH in methanol for 1.5 h at 55 °C, followed by adding 24 N H₂SO₄, and incubation for another 1.5 h at 55 °C. After vortexing and centrifuging with hexane, the bottom phase was collected for further analysis.

GC-MS analysis was conducted utilizing coupled detectors (Agilent GC 7890A and Agilent 5975C MS, Wilmington-DE, US) and an HP-5MS column (30 m $\times$ 250 μ m $\times$ 0.25 μ m) with a 5% phenyl-95% methylpolysiloxane coating. The mass spectrometer was set to operate with electron impact ionization at 70 eV and a quadrupole mass analyzer, scanning a mass range of 30 to 550 m/z. Helium was used as carrier gas at 1.2 mL/min. The split ratio injection was 1:50, and the transfer line was set at 300 °C. A 1.0 μ L sample was injected using Agilent GC Sampler 80 autosampler. The oven temperature program began at 60 °C for 3 minutes, increased to 270 °C at 4 °C/min, then to 300 °C at 30

°C/min, with total analysis time of 63.5 minutes. The fatty acids standard curves were assessed with Supelco C4-C24 mix, and the composition was determined as mg/100 g of DW.

2.4 Polar fraction

The polar extracts from banana inflorescence were obtained by MAE, PLE and CRE methods. The solvents were ethanol, ethanol/water 50%, and water, selected for their sustainability, abundance, low cost, low toxicity, and extraction power [25, 26]. The temperatures for MAE and PLE were 50, 100, and 150 °C. The PLE extraction was performed using equipment developed by Gonçalves Rodrigues et al. (2019) [25], in which the apparatus contains an extraction vessel of 90 mL (internal diameter of 25 mm and a height of 180 mm). The extraction occurred in a dynamic system, with a flow rate of 4 mL/min controlled by an HPLC pump (Waters, model 515, USA) under a pressure of 10 MPa. The bed was filled with 5 g of ground and dried sample and completed with 3 mm glass spheres. MAE, conducted in a microwave (Monowave 300, Anton Paar, GmbH Germany) at 1000 rpm, 850 W, 10 mL solvent, and 0.5 g sample in G30 glass flask. Extraction times were determined by kinetics curves. For PLE, the kinetics curve was obtained at 10 MPa, 100 °C, 4 mL/min, for the solvent water, ethanol and the equivolumetric mixture, and recovering samples at 5-min intervals up to 90 min. The MAE kinetics was obtained at 850 W, 100 °C, and 1000 rpm, for all solvents, and with samples recovered at 1, 2, 4, 8, 16, 24, and 30 min. The SOX method was conducted for 6 h (adapted from AOAC 920.39C). Solvents were removed by rotaevaporation (Fitason 802, São Paulo/SP - Brazil) for ethanolic samples; or by freeze drying (Liotop® L101, São Carlos, Brazil) for water samples. The dried extracts were stored at -18 °C in dark. The assays were conducted in duplicate to evaluate process yield, and protein recovery, antioxidant activity, total phenolics content, and phenolics profile of the samples.

2.4.1 Global extraction yield and protein recovery

Extraction yield was determined by the ratio between the amount of recovered solute and the sample before extraction multiplied by 100%. Protein content was determined by Kjeldahl method (section 2.2) for each extract sample. Results were expressed as mean value and standard deviation (expressed as percentage).

2.4.2 Phenolic compounds and antioxidant capacities

The phenolic and polyphenolic antioxidants were determined using the Folin-Ciocalteu reducing reagent (FCR), following the [27] method. The Folin reagent with sodium carbonate reacted for 2 hours with the extract, and the absorbance was read at 760 nm. The antioxidant potential was evaluated by the methods ABTS, FRAP and DPPH. The ABTS assay [28] assessed the antioxidant capacity of extracts by measuring the reduction of ABTS radical, prepared by reacting potassium persulfate with ABTS solution for 16 hours. After 30 minutes of reaction with diluted extracts in the dark, absorbance was measured at 734 nm. FRAP assay [29] evaluated iron reduction activity using FRAP reagent; absorbance was read at 593 nm after a 30 minute reaction in the dark. DPPH assay [30] tested antioxidant activity by adding diluted samples to DPPH solution, with absorbance measured at 517 nm after 30 minutes in the dark. Readings were taken with a multi-reader (Epoch, BioTek), and results were expressed as mean $\pm$ standard deviation of Trolox or Gallic acid equivalents per gram of dry sample, with all experiments conducted in triplicate.

2.4.3 Phenolics profile by LC-ESI-MS/MS

The extract samples that provided the highest phenolic content in Folin-Ciocalteu method were selected for the evaluation of the phenolics profile assessment by Liquid Chromatography - Electrospray Ionization - Mass Spectrometry (LC-ESI-MS/MS). Defatted extract samples were hydrolyzed with 5 mL of methanol and 5 mL of 6 M hydrochloric acid at 85 °C for 30 minutes, and the pH was adjusted to 2 with NaOH. The samples were then partitioned with 10 mL of diethyl ether, shaken, and centrifuged at 3400 rpm for 10 minutes, repeating the process three times before evaporating the diethyl ether. The residues were resuspended in 1 mL of HPLC-grade methanol, diluted tenfold with a methanol/water mixture (30/70 v/v), and analyzed using an LC-ESI-MS/MS system [31].

Phenolic compounds were identified and quantified using a liquid chromatography apparatus (Agilent Technologies 1200 Series) coupled with a Q Trap 3200 mass spectrometer (Applied Biosystems/MDS Sciex) in negative electrospray ionization mode. The MS/MS parameters included a capillary needle voltage of 4500 V, curtain gas at 10 psi, source temperature at 400 °C, and gas 1 and 2 at 45 psi. Separation was performed on a Synergi 4u Polar-RP column with a gradient elution: 10% methanol (A) for 0–5 minutes, increasing to 90% A from 5–7 minutes, 90% A from 7–10 minutes, and returning

to 10% A from 10–17 minutes at a flow rate of 250 μ L/min. The column was conditioned with the initial mobile phase proportion between analyses. Data were analyzed using the Analyst version 1.6.2 software. Forty-eight phenolic compounds were monitored, and quantification was based on calibration curves with standards. Compound identities were confirmed by matching two to three mass transitions for each analyte at specific chromatographic retention times, previously determined using individual standards in MS and chromatographic separations.

2.5 Analytical Eco-scale and Green Certificate modified Eco-scale

The Green Certificate method was applied to assess the sustainability of the extraction procedures. This approach calculates the overall sustainability score starting from a maximum of 100% environmental safety. From this, penalty points (PP_S) are subtracted based on three main criteria: the use of hazardous reagents and respective used volume (Penalty Points for Reagents – PP_R), the amount of energy consumed (Penalty Points for Energy – PP_E), and the generation of waste (Penalty Points for Waste – PP_W) [32, 33]. The lower the number of penalty points, the more sustainable the process.

2.6 Statistic analyses

The one-way ANOVA statistical analyses were realized in Statistica software (Statistica 10.0; Stat Soft Inc., Tulsa, OK, USA), followed by Tukey's test to identify significant differences among the means, with a significance level of p set at 0.05. Furthermore, the Spearman test was conducted at the same p level in RStudio (2025.05.0). Continuous variables (antioxidant capacities, total phenolics and temperature) were compared to categorical variables (polarity and method of extraction); for these, a positional classification was used (1, 2, and 3), where 1 was the highest and 3 the lowest polarity or extraction efficiency. To calculate the efficiency (equation 1), the desirability (individual: equation 2 and global: equation 3) was compared with the use of energy (in KWh values obtained by the equipment suppliers) and the solvent volume (mL) used during the extraction process.

$$Efficiency = \frac{D}{Energy (KWh). Solvent (mL)} \quad (1)$$

$$d_i(y_i) = \begin{cases} 0; & \text{if } (y_i \leq L_i) \\ \left(\frac{y_i - L_i}{T_i - L_i}\right)^{S_i}; & (L_i < y_i < T_i) \\ 1; & \text{if } (y_i \geq T_i) \end{cases} \quad (2)$$

240

241 y_i = observed value of response i ; L_i = lower tolerance limit (minimum acceptable value);
 242 T_i = target value for full desirability; S_i = shape factor (weighting exponent), which
 243 defines the curvature of the function; $d_i(y_i)$ = desirability of the i -th response.

244

$$D = \left(\prod_{i=1}^n d_i^{w_i}\right)^{1/\sum_{i=1}^n w_i} \quad (3)$$

246

247 D = global desirability index (overall score for optimization); d_i = individual desirability
 248 for the i -th response; w_i = weight assigned to response i ; n = number of response
 249 variables.

250

251 3. RESULTS AND DISCUSSION

252 3.1 The proximal composition of bracts of inflorescence

253 The proximal composition in dry weight (DW) of the bracts of inflorescence from the
 254 banana from Corupá region were: Protein: 10.12±0.39%; ashes: 12.65±0.29%; lipids:
 255 3.82±0.10%; moisture: 9.09±0.16%; crude fibers: 19.78±0.78%; sugar by difference
 256 44.53%; and sugar by DNS: 38.65±1.64. These results were compared to literature data
 257 for inflorescence samples from the same variety of banana (*Musa acuminata*) produced
 258 in different regions. The samples from Corupá bracts contained 1.4 times less lipid
 259 content than samples from Rio de Janeiro [34], and similar ash content to samples from
 260 Rio Grande do Sul [35]. Besides, the results had 20% less brute fibers and 20% more total
 261 carbohydrates compared to samples from Sri Lanka [36]. These variations are commonly
 262 due to natural factors such as cultivar difference, soil, harvest conditions, climate, among
 263 others. It is worth mentioning that, as already observed by Lau et al. (2020) [10], most
 264 papers reporting inflorescence characterization do not segregate them into its different
 265 parts (bract, flower, and other structures), making a direct data comparison very difficult.
 266 However, in general, bracts of the Corupá inflorescences contain more sugars, less crude
 267 fiber, less protein, and a similar amount of lipids as other inflorescence samples. The
 268 higher sugar content may be associated with the increased sweetness of the fruit (one of
 269 the reasons for the geographical indication), along with other factors. Even though it

presented lower values in the proximal composition compared to other regions, the raw material shows potential for food applications due to its compositional similarity to leaves of *Moringa oleifera*, *Pereskia aculeata* (ora-pro-nobis), and green *Artocarpus heterophyllus* (jackfruit) — plants that are currently under high scientific interest for food production and the development of plant-based ingredients [37–39].

3.2 Kinetics curves

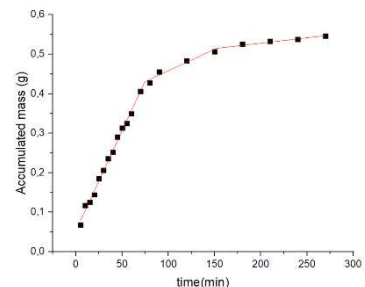
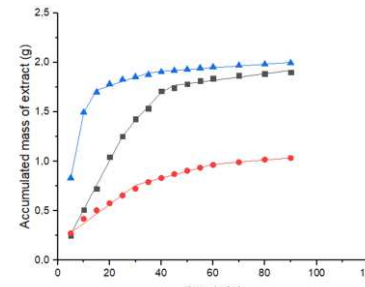
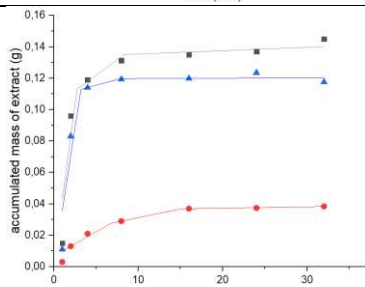
Kinetic extraction curves represent the gain in the concentration of extracted compounds over time. These graphs help identify distinct phases, such as the initial rapid release of compounds named constant extraction rate (CER), followed by a falling extraction rate (FER), and a slower extraction region where the extraction behavior is controlled by diffusion (DIF). The piecewise 3 function (eq. 4) was used to obtain kinetic parameters. Kinetic parameters for the SFE, PLE, and MAE techniques are presented in Table 1.

$$y = \begin{cases} b0 + b1 \cdot t; & (t < t_{cer}) \\ b0 + b1 \cdot t + b2 \cdot (t - t_{cer}); & (t_{cer} \leq t < t_{fer}) \\ b0 + b1 \cdot t + b2 \cdot (t - t_{cer}) + b3 \cdot (t - t_{fer}); & (t \geq t_{fer}) \end{cases} \quad (4)$$

Where: y: accumulated mass; t: time of the extraction; b0 = intercept, b1 = slope, t_{cer} = intersection at constant extraction rate time, b2 = slope, t_{fer} = intersection at falling extraction rate time, and b3 = slope.

Mathematical models are fundamental for observing extractive behavior through different mass transfer mechanisms. From the models, parameters can be obtained that enable standardization and consequently improve the time and economic viability of processes [40]. Through the piecewise model, different times and extraction parameters were possible to determine, in particular, the moment of entry into the diffusive stage of the process, where the extraction rate decreases due to solute exhaustion from the particle surface (usually, this is the extraction endpoint due to almost negligible extraction rate).

296 **Table 1** Kinetic parameters of all extractions using piecewise 3 as model

Method	Extraction Condition	Kinetic parameters						R^2_{adjust}	Curve fittings
		b0 (g)	b1 (g/min)	t_{cer} (min)	b2 (g/min)	t_{fer} (min)	b3 (g/min)		
SFE	CO ₂ 20 MPa – 40 °C	5.34 E-02	5.05 E-03	74.56	1.09 E-03	151.98	2.73 E-04	0.99	
PLE	Water 100 °C – 10 MPa	2.08 E-02	5.00 E-02	25.90	3.00 E-02	42.10	3.00 E-03	0.99	
	Ethanol 100 °C – 10 MPa	1.82 E-01	2.00 E-02	30.30	6.00 E-03	60.40	2.00 E-03	0.99	
	Ethanol/water [50:50] 100 °C – 10 MPa	1.67 E-01	1.30 E-01	11.50	8.00 E-02	36.20	2.00 E-03	0.99	
MAE	Water 100 °C – 850 W – 1000 rpm	2.31 E-03	3.60 E-02	2.74	5.75 E-03	8.36	3.68 E-05	0.88	
	Ethanol 100 °C – 850 W – 1000 rpm	3.87 E-03	4.08 E-03	5.51	1.07 E-03	15.25	9.69 E-05	0.93	
	Ethanol/water [50:50] 100 °C – 850 W – 1000 rpm	6.04 E-02	7.34 E-02	2.39	1.31 E-03	9.07	2.64 E-05	0.91	

297 Legend: ●, —: SFE – CO₂ extraction data; ▲, —: ethanol-water extraction data; ■, —: water extraction data; ●, —: ethanol extraction data, symbols
 298 are experimental data and lines are modeled data with piecewise 3 function model.

3.3 Non-polar fraction

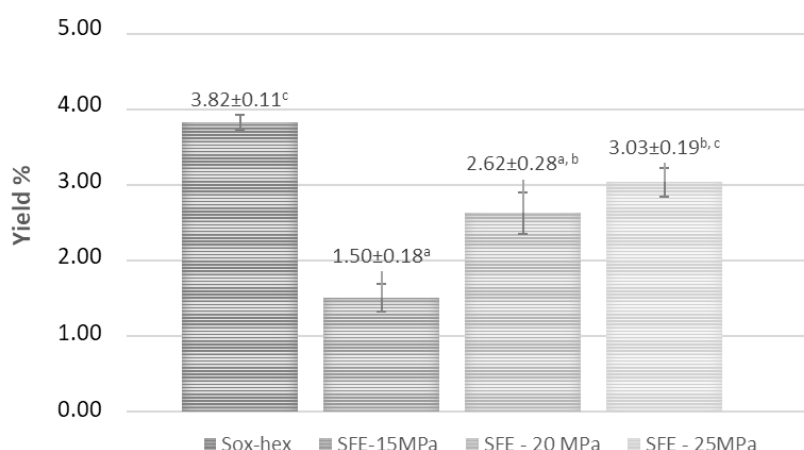
To our knowledge, this is the first study to apply supercritical fluid extraction (SFE) with carbon dioxide for the recovery of the non-polar fraction from the bracts *from M. acuminata* inflorescence. The efficacy of the SFE was compared with the Soxhlet extraction with hexane (SOX-hex, 6 hours) for fatty acids and total carotenoids (TCC) recovery.

3.3.1 Extraction Yield

The yield of non-polar fraction obtained by SFE at different pressure conditions are compared with the Soxhlet method with hexane at Figure 1. The pressure effect of the SFE can be observed with assays at 40 °C and pressures of from 15 MPa ($1.50 \pm 0.18\%$) and 20 MPa ($2.62 \pm 0.28\%$), with no significant difference. The increase in pressure up to 25 MPa increased yield ($3.03 \pm 0.19\%$) compared to 15 MPa due to the tuning of the solvent's density, which increases the solute solubility caused by the increase in the solvation power of the solvent, contributing to the recovery of the non-polar fraction [41, 42].

This behavior is consistent with presented by Correa et al. (2016) [21] for SFE from the entire inflorescence of *Musa paradisiaca*, which obtained yield up to 3.60% (SFE at 25 MPa and 40 °C). SFE-CO₂ is well recognized for recovering non-polar components due to CO₂ characteristics, and with the efficiency increasing with pressure [20, 43, 44]. The yield for SFE at 25 MPa at 40 °C was statistically similar to obtained by SOX-hex (3.82%). Besides, SFE with green solvent was 2.4 times faster than the Soxhlet, which also requires solvent (hexane) evaporation, adding time, energy, and cost to the process, and possible sample degradation. These results suggest that SFE is a good alternative to recover the non-polar fraction from the bract samples, offering similar yield in a more efficient process [45].

Fig. 1 Yield of non-polar extractions



Different letters represent significant difference in Tuckey test at $p < 0.05$

3.3.2 Total Carotenoids Content (TCC) and Essential fatty acids

Table 2 presents the characteristics of the oily fractions obtained by SFE and SOX-hex, considering TCC, related to the amount of β -carotene and fatty acid profile. Carotenoids are important bioactive compounds due to their antioxidant properties. They also play a crucial role in eye health and preventing chronic diseases like cancer and cardiovascular disease. Carotenoids are nonpolar compounds with high solubility in solvents such as hexane and supercritical CO_2 . Supercritical CO_2 is well established as a safer and environmentally friendly alternative in extraction processes, although hexane remains the most commonly used solvent. This occurs fundamentally due to the SFE's high costs and practical application complexity [46, 47].

The TCC results were up to 2.9 mg β -carotene equivalent/100 g DW detected from the extract recovered by SFE at 25 MPa. This value was statistically similar to the sample by SOX-hex (2.6 mg β -carotene equivalent/100 g DW). Also, an increase in TCC with pressure increase for SFE was observed, with statistical differences among values. From 15 MPa to 25 MPa, TCC increased 2.25 times due to increased CO_2 density, which, according to the Kumar-Johnston correlation as applied by Zúñiga-Moreno et al. (2019), also doubled the solubility of β -carotene at 40 °C when pressure increased from 15 to 25 MPa [48]. This behavior is well-established for samples that contain β -carotene; for instance, SFE from pitanga fruits with pressure from 15 to 25 MPa provides an increase in β -carotene yield from 802 to 1966 μg of β -carotene/g extract (5.8 to 15.94 mg/100 g

DW), and from tomato skin from 45 to 55 MPa (1.3 to 1.5 mg β -carotene /100 g DW) [46, 49].

Although various parts of the banana plant, including the fruit, peel, and whole inflorescence, have been reported to contain total carotenoid contents (TCC) ranging from 0.12 to 10.63 mg β -Carotene/100 g FW, [50, 51], although no specific information related to TCC from the bracts has been previously reported. Considering the biological importance of carotenoids for human health, the identification of the bracts from the inflorescence as a potential dietary source becomes relevant.

Table 2 Quality of the oily fractions obtained by SFE at different pressures and by SOX-hex: TCC expressed as mg β -carotene equivalent/100 g DW and the fatty acids in mg/100 g DW

Extraction method	TCC	Essential Fatty acids (mg/100 g DW)		
	(mg β -carotene equivalent/100 g DW)	C16:0 (palmitic acid)	C18:1 (oleic acid)	C18:2 (linoleic acid)
SOX – hex	2.68 $\pm$ 0.08 ^a	209.04 $\pm$ 4.48 ^{a,b}	62.11 $\pm$ 4.03 ^a	187.45 $\pm$ 12.36 ^a
SFE – CO ₂ (15 MPa)	1.30 $\pm$ 0.06 ^b	98.04 $\pm$ 1.79 ^b	34.35 $\pm$ 0.48 ^b	88.38 $\pm$ 4.32 ^b
SFE – CO ₂ (20 MPa)	2.01 $\pm$ 0.08 ^c	184.24 $\pm$ 24.09 ^{a,b}	60.61 $\pm$ 4.54 ^a	159.51 $\pm$ 8.59 ^a
SFE – CO ₂ (25 MPa)	2.94 $\pm$ 0.23 ^a	226.88 $\pm$ 3.80 ^a	74.92 $\pm$ 8.40 ^a	193.91 $\pm$ 5.21 ^a

Different letters on the column represent significant difference in Tukey test at p<0.05

From the whole inflorescence of *Musa acuminata* Cavendish from Las Palmas (Spain), Ramírez-Bolaños et al. (2021) reported the presence of several fatty acids, including linoleic (12.52%), palmitic (12.90%), and oleic (2.81%) acids [52]. Only these three compounds were quantified in the present study, as presented in Table 2. When expressed as relative proportions among them, the distribution found in SOH-Hex extract was (40.9% for linoleic, 45.6% for palmitic, and 13.5% for oleic acid), which was quite similar to that observed by Ramírez-Bolaños et al. (44.4%, 45.7%, and 10.0%, respectively). These results indicate that the lipid profile of banana bracts, particularly the proportions of linoleic, oleic, and palmitic acids, remains consistent with those found in other parts of the *Musa acuminata* inflorescence [52].

The Oleic and linoleic acids perform biological functions and, therefore, must be obtained via the diet, while palmitic acid has various applications in the food industry [53]. Highlighting the importance of efficient extraction strategies to obtain these compounds. Furthermore, the use of supercritical CO₂ demonstrated efficient recovery of essential fatty acids, especially at the higher pressure (25 MPa), where it exhibited higher concentrations of C16:0 (1.08x), C18:1 (1.21x), and C18:2 (1.03x) compared to the sample by SOX-hex. Moreover, as previously mentioned, the increase in pressure

contributes to SFE efficiency due to improvements in solvation power. According to Chrastil et al. (1982) [54], from 15 to 20 MPa, the solubility of C18:1 solubility increases by 1.72 times, while from 20 to 25 MPa increases by 3.29. Likewise, palmitic (C16:0) and linoleic (C18:2) acids presented similar behavior [53].

Therefore, supercritical CO₂ extraction effectively recovers bioactive compounds, including carotenoids and fatty acids, from banana inflorescence bracts. The recovery and utilization of these bioactive components, which promote human health and prevent chronic diseases, are related to SDG 3 (Good Health and Well-being) and SDGs 9 and 12 [11]. Nonetheless, economic feasibility studies need to be conducted to determine the cost-effectiveness of recovering these valuable compounds, as Canabarro et al. (2020) proposed for the recovery of compounds using supercritical CO₂ from *Eugenia uniflora* leaves [55].

3.4 Polar fractions recovery

3.4.1 Extraction Yield

The comparison of the process yields for the polar-fractions recovery using MAE and PLE with different solvents and temperatures and compared with Conventional Reflux Extraction (CRE) are presented at Table 3 for the different methods and solvents used.

The yield values obtained by all methods using water were higher than other solvents, and with performance increasing with solvent polarity (ethanol < ethanol50% < water), with significant differences among most values. Nevertheless, no significant differences were observed for yields obtained by ethanol/water with those by water, within the same extraction method. Regarding the extraction method the order of extraction efficiency was $PLE \geq CRE > MAE$, considering MAE and PLE at 100 °C to compare with CRE, which was conducted at similar temperature. Finally, the increase in temperature from 50 to 150 °C increased the water extraction in 1.35 times for MAE, and 1.82 times for PLE.

Table 3 Extraction yield (%) for the polar fraction from the bracts of banana inflorescence, comparing extraction methods (CRE, PLE, and MAE) and solvents (ethanol, ethanol: water 50%, and water).

Extraction Method	Solvent		
	ethanol	ethanol/water [50:50]	water
CRE	19.94±1.19 ^{b,c,d,e}	30.24±1.98 ^{f,g,h,i}	33.04±0.06 ^{i,j}
PLE 10MPa 50 °C	10.80±0.44 ^a	25.51±0.64 ^{d,e,f,g,h}	29.13±0.89 ^{f,g,h,i}
PLE 10MPa 100 °C	18.94±0.47 ^{b,c,d}	32.88±0.54 ^{i,j}	36.66±0.91 ^j
PLE 10MPa 150 °C	24.92±0.68 ^{d,e,f,g,h}	46.87±0.74 ^k	53.09±0.56 ^k
MAE 50 °C	10.77±0.15 ^a	27.05±0.15 ^{e,f,g,h,i}	22.28±0.07 ^{c, d, e, f}
MAE 100 °C	13.23±1.19 ^{a,b}	29.77±1.33 ^{g,h,i}	22.83±0.01 ^{c,d,e,f,g}
MAE 150 °C	16.77±0.18 ^{a,b,c}	34.18±0.12 ^{i,j}	30.34±0.19 ^{h,i}

Different letters represent significant difference in Tuckey test at p<0.05.

The increase in temperature and pressure with aqueous solvents enhances efficiency by reducing surface tension and increasing diffusivity, thereby benefiting the extraction of various compounds such as sugars, organic acids, bases, salts, and proteins present on the inflorescence [56, 57].

Similarly, the yield correlation with temperature for MAE and PLE from ora-pro-nobis leaves, considering the same solvents and temperature range, was also presented in the literature[38, 58]. PLE efficiency with water at 10 MPa was higher compared to ethanol for cashew nut testa shell, increasing 1.66 times with temperature from 80 to 160 °C [59].

3.4.2 Protein content at polar fractions

The protein recovery efficiency is compared at Table 4, with results showing the performance as PLE > CRE ≥ MAE. The results also show a positive direct influence of temperature and solvent polarity. For instance, PLE with water at 100 °C presented similar efficiency as CRE and 1.70 times superior to MAE. PLE at 150 °C was 1.30 times superior to CRE (100 °C) and 1.52 times superior to MAE (150 °C).

Table 4 Protein content (%) recovered from the bracts of banana inflorescence, comparing extraction methods (CRE, PLE, and MAE) and solvents (ethanol, ethanol/water 50%, and water).

Extraction Method	Protein content (%)		
	Solvent		
	ethanol	ethanol/water [50:50]	water
CRE	16.38±0.30 ^{b,c,d,e}	24.56±0.77 ^{f,g}	40.53±1.30 ^{i,j}
PLE 10MPa 50 °C	4.07±0.08 ^a	22.93±0.06 ^{e,f,g}	20.40±0.77 ^{d,e,f,g}
PLE 10MPa 100 °C	10.78±0.68 ^{a,b,c}	44.31±1.09 ^{j,k}	34.05±1.48 ^{h,i}
PLE 10MPa 150 °C	23.28±0.93 ^{e,f,g}	81.40±1.03 ^l	52.53±2.31 ^k
MAE 50 °C	7.74±0.31 ^{a,b}	18.84±0.18 ^{c,d,e,f,g}	18.57±0.66 ^{c,d,e,f}
MAE 100 °C	9.63±0.22 ^{a,b}	20.06±0.84 ^{d,e,f,g}	19.98±0.60 ^{d,e,f,g}
MAE 150 °C	14.15±0.11 ^{b,c,d}	27.24±1.03 ^{g,h}	34.52±0.74 ^{h,i}

Different letters represent significant difference in Tuckey test at p<0.05.

Pressure and temperature play a crucial role in PLE performance, altering the Kamlet-Taft solvatochromic parameters (π^* , α , and β), which describe the properties of solvents, such as polarity and their ability to form and accept hydrogen bonds [60]. For water as solvent, the increase in temperature reduces π^* and α , decreasing polarity and hydrogen donation capacity, while β increases, rising hydrogen bond acceptance capacity. Ethanol exhibits a similar trend for π^* and α , but β decreases with increasing temperature, a less efficient behavior for compounds that require hydrogen donation compared to water. The ethanol 50% recovers a wide range of compounds [60], and also from Table 4 this mixture solvent provided the highest protein recovery (81.40%) at 150°C for PLE method. Temperature had similar effect on PLE with water for cashew nut testa shell (10MPa from 80 to 140 °C) and for ora-pro-nobis leaves (80 to 185 °C) [58, 59].

3.4.3 Total Phenolics content (TPC) from polar fractions

The total phenolics content (TPC) from the polar fractions recovered by different methods (CRE, PLE and MAE), solvents (ethanol, ethanol 50% and water) and temperatures for PLE and MAE (50, 100 and 150 °C) are compared at Table 5.

Water was the best solvent, for all methods and temperatures, to recover total phenolics. Also, increase in temperature contributes to higher TPC values for all solvents, where from 50 to 100 °C, TPC was 3.33 times higher using water, and 1.82 higher with ethanol 50%, and improved 2.92 times for ethanol. Similar behavior was observed for cashew testa shell for PLE from 80 °C to 100 °C [59]. Compared with the literature, extracts obtained with different solvents and extraction techniques showed that the Cavendish cultivar showed values between 6 and 30 mg GAE/g DW a range within the threshold observed in the current work [61].

A similar discussion could be held here regarding solvatochromic parameters; however, their functionality is insufficient to justify the greater recovery of phenolic compounds from the plant matrix, as ethanol would theoretically provide more effective solvation of these compounds [57]. However, when evaluating the fibrous complexity of the plant matrix, it is observed that other nuances are necessary, such as a higher solvent density that favors penetration into the plant matrix and a lower viscosity that allows a greater mass transfer through the matrix. Furthermore, water under high temperature and pressure exhibits strong interactions with glycosylated or sterified phenolics (as frequently occurs with gallic, vanillic, ferulic, among others, phenolic acids), aiding in their extraction [62]. Additionally, water undergoes autoionization, releasing H^+ and OH^- ions in the medium,

which hydrolyze ester and glycosidic bonds present in conjugated phenolics, thereby liberating free phenolics into the extract. [63, 64].

Table 5 TPC (mg_{GAE}/g DW) by Folin-Ciocalteu method for the polar fractions from the bracts of banana inflorescence obtained by different extraction methods (CRE, PLE, and MAE) and solvents (ethanol, ethanol/water 50%, and water).

Extraction Methods	TPC (mg_{GAE}/g DW)		
	Solvent		
	ethanol	ethanol/water [50:50]	water
CRE	0.20±0.01 ^a	0.46±0.01 ^a	4.13±0.09 ^{e, f, g}
PLE 10MPa 50 °C	0.29±0.01 ^a	0.96±0.01 ^{a, b, c}	2.56±0.41 ^d
PLE 10MPa 100 °C	0.86±0.01 ^{a, b}	1.75±0.04 ^{c, d}	8.54±0.22 ⁱ
PLE 10MPa 150 °C	3.84±0.03 ^{e, f}	7.27±0.08 ^h	22.83±0.44 ^k
MAE 50 °C	0.26±0.02 ^a	0.92±0.01 ^{a, b, c}	3.53±0.05 ^e
MAE 100 °C	0.54±0.04 ^a	1.44±0.03 ^{b, c}	4.59±0.12 ^{f, g}
MAE 150 °C	2.34±0.02 ^d	4.81±0.05 ^g	11.86±0.23 ^j

Different letters represent significant difference in Tuckey test at $p < 0.05$.

This behavior is confirmed by the experimental results, as the compounds from the bracts are more soluble in polar solvents, suggesting higher presence of polar components at the raw material evaluated. This behavior was also observed for different vegetal materials where the major components were sugars, proteins, and other substances such as organic acids, hydro soluble vitamins, glycosides, phenolics, which may present higher interaction with the Folin reagent [59, 65, 66].

3.4.4 Antioxidant potential of the polar fractions

To assess the antioxidant potential of the polar fraction extracts, three complementary methods ABTS, DPPH, and FRAP were evaluated. The results are presented in Table 6. Additionally, Spearman's correlations between antioxidant capacities, TPC, extraction method, temperature and solvent polarity are presented in Figure 2.

The results from Table 6 show that the sample obtained by PLE at 150 °C with water presented the highest antioxidant potential for all methods, with the exception of the sample by PLE, 150°C and ethanol 50% that provided better results by FRAP method.

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Table 6 Antioxidant activities (ABTS, DPPH, and FRAP) from the bracts of banana inflorescence, comparing extraction methods (CRE, PLE, and MAE) and solvents (ethanol, ethanol/water 50%, and water).

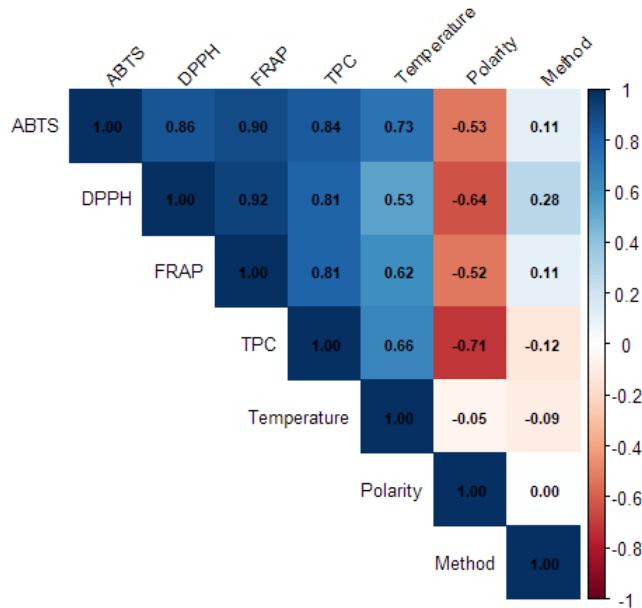
Extraction method	Solvent								
	ethanol	EtOH:H2O	water	ethanol	EtOH:H2O	water	ethanol	EtOH:H2O	water
	Antioxidant methodology								
	ABTS ($\mu\text{mol}_{TEAC}/\text{g DW}$)			DPPH ($\mu\text{mol}_{TEAC}/\text{g DW}$)			FRAP ($\mu\text{mol}_{TEAC}/\text{g DW}$)		
CRE	26.83±1.54 ^b	79.48±0.38 ^{e,f}	209.87±8.35 _h	11.44±0.68 ^{b,c}	26.83±1.54 ^{f,g}	57.23±0.06 ⁱ	13.68±0.35 ^{a,b}	56.11±0.35 ^{d,e}	72.42±1.39 ^f
PLE 10MPa 50 °C	3.60±0.17 ^a	73.23±0.85 ^e	14.37±1.35 ^{a,b}	3.68±0.10 ^a	22.81±0.71 ^e	34.60±0.90 ^g	14.89±0.15 ^{a,b}	40.56±0.30 ^c	66.02±0.99 ^{e,f}
PLE 10MPa 100 °C	70.12±5.45 ^{d,e}	218.96±5.82 _{h,i}	252.43±2.37 _j	20.53±0.19 ^{d,e}	32.76±0.18 ^g	75.82±0.94 ^j	34.14±0.48 ^c	83.72±0.80 ^g	107.86±1.02 ⁱ
PLE 10MPa 150 °C	228.09±2.84 ⁱ	416.31±1.54 ^l	489.36±2.34 _n	42.85±0.12 ^h	75.27±0.54 ^j	170.35±4.17 ^k	139.27±5.25 ^k	287.05±7.35 _m	235.90±0.61 ^l
MAE 50 °C	2.70±0.06 ^a	52.79±2.50 ^{c,d}	67.90±5.64 ^{d,e}	7.10±0.45 ^{a,b}	23.98±0.41 ^{e,f}	21.09±0.15 ^{d,e}	7.35±0.06 ^a	70.17±0.62 ^f	54.31±0.12 ^d
MAE 100 °C	4.34±0.15 ^a	93.33±5.73 ^f	119.13±1.99 _g	9.15±0.84 ^{a,b}	28.90±0.16 ^{f,g}	19.88±2.16 ^{d,e}	9.35±0.12 ^a	87.26±1.01 ^{g,h}	55.29±1.15 ^{d,e}
MAE 150 °C	48.81±1.27 ^c	299.67±0.71 _k	437.57±0.39 _m	15.66±0.30 ^{c,d}	53.88±0.12 ⁱ	43.97±0.65 ^h	21.77±0.18 ^b	121.23±1.25 _j	96.39±0.62 ^h

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Statistical analyzes, were conducted for each group of antioxidant methodology (ABTS, DPPH, and FRAP), and different letters represent significant difference in Tuckey test at p<0.05.

The antioxidant capacity results followed the same pattern observed for total phenolics, where subcritical water at 150 °C also presented the highest values. This reinforces the direct relationship between extracted phenolic content and antioxidant capacity, as confirmed by Spearman correlation ($r > 0.80$, $p < 0.05$). The extraction mechanisms discussed previously (section 3.4.3) - including higher density, lower viscosity, and water's autoionization capacity - not only favored the quantitative recovery of phenolics but also preserved/released compounds with greater antioxidant potential.

Fig. 2 Spearman's correlation for the variables ABTS, DPPH, FRAP, TPC, Solvent, Temperature, and method of extraction.



Legend: dark blue colors: positive correlations ($r > 0.7$), dark red color: negative correlations ($r < -0.7$), light blue: low and moderate positive correlations ($0.25 < r < 0.5$), light red: low and moderate negative correlations ($-0.5 < r < -0.25$); white: no correlation ($r = 0$)

The increase in temperature for PLE and MAE assays improved the antioxidant capacity by ABTS, DPPH and FRAP of the samples. This is observed by positive correlation ($r > 0.53$) in all tested methodologies. This behavior was detected for ora-pro-nobis extract samples obtained by MAE with water from 110 to 150 °C [67], and by PLE with water [58]. An increase in antioxidant potential for extract samples recovered from cashew nut testa shells by PLE with water from 100 to 120 °C was also observed by da Silva et al. (2024) [59]. This behavior is explained by the temperature influence on solvent properties and on the vegetal matrix, by affecting the structure of polysaccharides like lignin and cellulose, which contributed to the release of the antioxidant components to the solvent

phase, increasing the activity of the samples, or by the caramelization of simple sugar compounds above 110°C, also contributing to antioxidant potential [68, 69]. In PLE methods the temperature associated to the pressure can also, induce changes in protein conformation, which can increase the antioxidant activities [70, 71].

In contrast, the solvent correlations with TPC and antioxidant potential exhibited moderate negative correlations ($r < -0.52$), suggesting that decreasing the solvent polarity reduced the quantities of phenolic compounds and antioxidants that were quantified. The magnitude of the correlation is explained by the solvent's polarity ordination (water = 1; ethanol 50% = 2; ethanol = 3).

Although MAE was the most efficient method regarding time, solvent, and energy consumption, the positive Spearman correlations between extraction method (coded as MAE = 1, PLE = 2, CRE = 3) and antioxidant capacity presented a slight tendency for better antioxidant performance with methods other than MAE ($r = 0.11-0.28$).

In light of these findings, further analyses were conducted using HPLC to quantify and characterize the phytochemicals present in extracts obtained with water at 100 °C extracted by PLE, MAE, and CRE.

In light of these findings, further analyses were conducted using HPLC to quantify and characterize the phytochemicals present in extracts obtained with water at the same temperature using PLE, MAE, and CRE, in order to evaluate the effect of the extraction method on phytochemical recovery and the highest response method – water using PLE at 150 °C.

3.4.5 Phenolic components from the recovered extracts

The chemical profile of extracts of natural products defines their bioactivities (antioxidant, antimicrobial, and others), as well as the health benefits associated to its consume, such as cellular protection, improved cardiovascular health, reduced inflammation, and neuroprotective and anticancer effects [9, 10]. Therefore, the extraction method and solvent impacts in the efficiency of the bioactive compounds recovery, as they affect the extracts composition, stability, and biological activity, as well as the process yield [21].

Based on the correlation results (Figure 2) and quantitative data (Tables 5 and 6), water-based extracts obtained at 100 °C were selected for LC analysis due to similarities, and PLE at 150 °C, which showed the highest overall activity.

The most relevant compounds detected in the recovered extracts were phenolic acids, especially ferulic, p-cumaric, and protocatechuic acid. Vanillin was also detected in high amounts, among other minor compounds. The content of protocatechuic, ferulic, and p-cumaric acids, and vanillin of PLE samples increased with temperature from 100 °C to 150 °C. The thermal stability of these compounds has been demonstrated in different studies [72–74]. Coniferaldehyde, umbelliferone, and vanillic acid reduced concentration with increase in temperature [75]. Some phenolic acids and flavonols were detected only in the MAE sample, likely due to the low extraction temperature (100 °C) and short extraction time (7.59 min), which protected them from instability and degradation. Some of the components presented in Table 6 were also detected for the ethanolic extract of inflorescence from cultivar Palayankodan, with variation in concentration profile, such as (expressed in mg/100 g): gallic acid (0.82), protocatechuic acid (41.82), p-coumaric acid (1.32), vanillic acid (2.49), syringic acid 2.26 and ferulic acid 1.12 [76]. Also, cavendish cultivar presented 10 compounds as listed in Table 6, with differences in composition, as provided by [61]. These differences in composition or diversity are mainly due to the extraction method used, solvent, and region of origin of the plant, among others [77]. Some of the components from Table 6 were reported in the literature for banana inflorescences such as umbelliferone, vanillin, and rutin [10]. Although, others such as myricetin, taxifolin, chrysin, eriodictyol, sinapaldehyde, conifer aldehyde, abscisic acid, and rosmarinic acid were reported for the first time in banana inflorescences but have already been reported in peels and fruits [78, 79].

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Table 6 Phytochemicals detected by LC-ESI-MS/MS comparing different methods of extraction in mg of compound evaluated / 100 g DW.

Bioactive Phytochemicals		Extraction Methods with water as solvent			
Group	Compound	CRE (~ 100 °C) (mg/ 100 g DW)	MAE 100 °C (mg/ 100 g DW)	PLE 100 °C (mg/ 100 g DW)	PLE 150 °C (mg/ 100 g DW)
Phenolic Acids	Protocatechuic Acid	31.133±5.029 ^b	1.646±0.160 ^a	4.557±1.672 ^a	56.140±0.449 ^c
	<i>p</i> -Coumaric Acid	45.679±5.633 ^{ab}	7.215±1.681 ^a	29.093±8.662 ^a	83.446±13.947 ^b
	Vanillic Acid	n.d.	26.877±1.931 ^a	134.028±15.819 ^b	n.d.
	Gallic Acid	0.886±0.337 ^a	0.195±0.079 ^a	1.418±1.124 ^a	4.639±0.935 ^b
	Ferulic Acid	34.281±6.199 ^a	45.988±31.486 ^a	119.717±40.709 ^a	849.520±119.604 ^b
	Syringic Acid	n.d.	0.901±0.267	n.d.	n.d.
	Rosmarinic Acid	n.d.	0.036±0.015	n.d.	n.d.
	Abscisic Acid	n.d.	0.034±0.003	n.d.	n.d.
Aldehydes	Sinapaldehyde	n.d.	1.529±0.621 ^a	2.777±0.916 ^a	n.d.
Phenolics	Coniferyl aldehyde	n.d.	9.215±0.488 ^b	42.428±1.461 ^c	0.612±0.026 ^a
Flavonoids	Eriodictyol	n.d.	0.007±0.006	n.d.	n.d.
	Quercetin	0.270±0.225 ^a	0.531±0.012 ^a	0.300±0.250 ^a	1.491±0.278 ^a
	Myricetin	0.207±0.090 ^a	0.195±0.023 ^a	0.851±0.353 ^a	0.760±0.119 ^a
	Taxifolin	n.d.	0.144±0.016	n.d.	n.d.
	Rutin	n.d.	0.021±0.001	n.d.	n.d.
	Chrysin	n.d.	0.017±0.012	n.d.	n.d.
Other	Umbelliferone	0.236±0.095 ^a	0.284±0.142 ^a	1.044±0.047 ^a	n.d.
	Vanillin	36.282±6.849 ^{ab}	10.794±1.736 ^a	64.538±2.925 ^b	105.276±11.068 ^c

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Legend: n.d. not detected, values below the limit of detection. CRE: Conventional Reflux Extraction, MAE: microwave assisted extraction, and

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PLE: pressurized liquid extraction with water. Different letters on the line represent significant difference in Tuckey test at $p < 0.05$.

Considering the composition profile of the extracts and the process yield, we observe that PLE 150 °C provided the highest yield, and relevant amounts of thermostable compounds, such as protocatechuic, ferulic, and *p*-cumaric acids, and vanillin. In contrast, MAE 100 °C provided good efficiency to recover thermolabile compounds, such as eriodictyol, taxifolin, rutin, chrysin, syringic, rosmarinic, and abscisic acids. PLE 100 °C and CRE samples presented intermediate results in relation to the concentration of detected compounds and the presence of compounds not detected in PLE 150 °C. PLE 100 °C presented sinapaldehyde, vanillic acid, and umbelliferone, while CRE only presented umbelliferone.

These phytochemicals have high biological value for preventing and treating diseases due to their antimicrobial, anti-inflammatory, and anticancer action [10]. They can be applied to treating heart disease, hormonal disorders, and diabetes [9]. Consequently, they also hold significant commercial value. On the one hand, the recovery of compounds was quite high when applying the highest temperature in the PLE, with significant yields of acids such as ferulic and *p*-coumaric. However, these acids are widely abundant in nature, which can reduce the value of the compound [80]. On the other hand, the compounds uniquely recovered with MAE were lower in global concentrations but are less common, such as eriodictyol, taxifolin, rosmarinic acid, and abscisic acids. With that in mind, other conditions should be investigated to optimize the yield of these specific phenolic acid and flavonoid compounds.

3.5 Analytical Eco-scale and green certificate modified eco-scale

The green certificate assessment allows us to compare the environmental impact of extraction methods, highlighting the most sustainable processes. **Table 7** highlighting the extractions classification of each technique in terms of sustainability.

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Table 7 Analytical Eco-scale and Eco-scale and green certificate modified eco-scale for 15 g of dried sample under different extraction methods (or conditions) for non-polar and polar extracts.

Fraction	Extraction Method	Condition	Solvent	Solvent volume (mL)	PPR	PPE	PPW	Σ PPS	Total point (100 – Σ PPS)	Eco-Scale
Non-polar	SFE	(15 MPa/40 °C)	CO ₂	3896	0.00	2	1.46	9.67	90.33	A
		(20 MPa /40 °C)	CO ₂	3619	0.00	2	1.46	9.67	90.33	A
		(25 MPa /40 °C)	CO ₂	3456	0.00	2	1.47	9.68	90.32	A
	Soxhlet	BT	<i>n</i> -hexane	450	32.43	2	1.45	41.80	58.20	D
Polar	PLE	(10 MPa/50 °C)	Water	505.2	0.00	1	1.29	1.90	98.10	A
		(10 MPa/100 °C)	Water	505.2	0.00	1	1.23	1.84	98.16	A
		(10 MPa/150 °C)	Water	505.2	0.00	1	1.09	1.70	98.30	A
		(10 MPa/50 °C)	EtOH-water	434.4	8.02	1	1.31	9.86	90.14	A
		(10 MPa/100 °C)	EtOH-water	434.4	8.02	1	1.26	9.80	90.20	A
		(10 MPa/150 °C)	EtOH-water	434.4	8.02	1	1.15	9.69	90.31	A
		(10 MPa/50 °C)	EtOH	724.8	18.80	1	1.41	21.08	78.92	C
		(10 MPa/100 °C)	EtOH	724.8	18.80	1	1.36	21.03	78.97	C
		(10 MPa/150 °C)	EtOH	724.8	18.80	1	1.32	20.99	79.01	C
	MAE	(10 MPa/50 °C)	Water	150	0.00	0	1.34	1.39	98.61	A
		(10 MPa/100 °C)	Water	150	0.00	0	1.33	1.39	98.61	A
		(10 MPa/150 °C)	Water	150	0.00	0	1.28	1.34	98.66	A
		(10 MPa/50 °C)	EtOH-water	150	5.77	0	1.30	7.13	92.87	A
		(10 MPa/100 °C)	EtOH-water	150	5.77	0	1.28	7.11	92.89	A
		(10 MPa/150 °C)	EtOH-water	150	5.77	0	1.25	7.08	92.92	A
		(10 MPa/50 °C)	EtOH	150	11.53	1	1.41	13.05	86.95	B
		(10 MPa/100 °C)	EtOH	150	11.53	1	1.40	13.04	86.96	B
		(10 MPa/150 °C)	EtOH	150	11.53	1	1.37	13.01	86.99	B
	CRE	BT	Water	450	0.00	2	1.26	9.18	90.82	A
		BT	EtOH-water	450	8.11	2	1.28	17.31	82.69	B
		BT	EtOH	450	16.21	2	1.35	25.49	74.51	C

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Legend – SFE: Supercritical fluid extraction with CO₂, PLE: Pressurized Liquid extraction, MAE: microwave assisted extraction, CRE: Conventional reflux extraction, BT: Boiling temperature, PPR: Penalty Points for Reagents, PPE: Penalty Points for energy use, PPW: Penalty Points For waste generated, Σ PPS: Sum of penalty points, Green certificate: A (90–100), B (80–89), C (70–79), D (55–69), E(40–54), F (20–39), and G (0–19)

The methods using supercritical CO₂ demonstrated similar Eco-scale values (> 90.32), achieving an A rating in Eco-Scale, reinforcing once again how environmentally friendly and safe the technique is. In contrast, the conventional extraction using Soxhlet with hexane as the solvent presented an Eco-Scale value below 60, classified as D, which is far from ideal in terms of green chemistry. Literature reports an Eco-Scale score of 74.89 for Soxhlet extraction using methanol—a solvent already considered toxic—suggesting that hexane, being even more environmentally hazardous, results in an even lower score. As for supercritical CO₂, this analysis was not isolated in the literature; other studies calculated SFE with co-solvent, which changes the penalty related to the solvent points [33, 81].

For the polar fraction, differences in the Eco-scale are mainly due the solvent employed and volume used. Extractions with pure water applying the PLE, MAE, or CRE methods, achieved A score, reflecting the solvent's minimal environmental impact and efficiency. It is worth noting that the nominal power of the equipment was taken into consideration. On the other hand, the use of ethanol into the extractions, whether mixed with water or pure, resulted in progressive penalties [33]. The solvent mixture was classified as Class A and B, with scores between 82.69 and 92.92, still considered excellent, but with drawbacks regarding the solvent's hazardousness and environmental impact. Methods that used pure ethanol achieved scores between 74.51 and 86.99, being classified as Classes B and C, with emphasis on penalties related to environmental toxicity and operational risk. The excellent environmental evaluation for microwave-assisted extraction is consistent with the literature: cashew nut testa shells extracted with a mixture of ethanol and water presented an A score [82]; the same score is observed for PLE extracting jaboticaba bioactive phytochemicals [83].

Regarding the energy values, there are significant differences in energy consumption, which were intentionally overestimated here to avoid masking errors. In other words, variations associated with the type of solvent used were not explicitly stated, which would compensate for the higher energy consumption resulting from differences in density, specific heat, and latent heat of the fluids, as well as various heat losses throughout the system.

When comparing extraction methods, the MAE presented the lowest energy impact due to its short extraction time (~8 minutes with water) and enhanced energy utilization (heat generation through the dielectric effect). Next, the PLE, which presented a higher energy

impact, was attributed to the time of extraction (~42 minutes with water) and the robustness of the equipment. Finally, the CRE had the highest energy impact, as it operates under atmospheric pressure with a heating blanket, suffering the greatest heat losses to the environment and requiring energy to heat, evaporate, and condense the solvent, and also the longest time (6 hours).

Soxhlet extraction with hexane yields a higher total recovery; however, it is essential to consider the environmental implications of the economic rationale, particularly given the market value of some extracted compounds. Soxhlet extraction with hexane is a less expensive technique compared to supercritical CO₂. Still, the latter has proven more environmentally friendly and efficient for the recovery of certain compounds, which may justify its higher initial investment. In polar fraction evaluation, MAE's Eco-Scale rating proved more favorable for environmental efficiency compared to PLE, which, despite having higher overall yields, presented drawbacks due to its longer time and solvent volume requirements (compared with MAE). Once again, it is worth emphasizing the importance of accurately analyzing the operation costs and economic viability. Therefore, further analysis is required to validate these findings under industrial-scale conditions. These conclusions once again highlight that the technique and solvent choice are critical to achieving process sustainability and supporting SDGs 9, 12 and 13 (Climate Action) [11].

Conclusion

This study successfully demonstrated the biotechnological potential of banana inflorescence bracts as a valuable agricultural by-product, by applying environmentally sustainable extraction techniques. The implementation of supercritical fluid extraction (SFE), microwave-assisted extraction (MAE), and pressurized liquid extraction (PLE) enabled the efficient recovery of bioactive compounds, including essential fatty acids, carotenoids, phenolic compounds, and proteins, thereby transforming an underutilized agricultural waste into a high-value bioresource with environmental sustainability. The SFE with CO₂ achieved high recovery of non-polar compounds, particularly at 25 MPa, where palmitic, oleic, and linoleic acids were extracted in higher concentrations than conventional Soxhlet method, while simultaneously obtaining the highest total carotenoid content (2.94 mg β -carotene equivalent/100 g DW). The Eco-Scale evaluation confirmed the environmental superiority of SFE, achieving Class A ratings (> 90 points) compared to the Class D rating of hexane-based Soxhlet extraction.

Regarding the polar fraction, all extractions with water presented the highest yields compared with pure ethanol. The highest yield (53.09%), a good recovery of proteins (52.53%), total phenolic compounds (22.83 mg GAE/g DW), and antioxidant capacities (ABTS: 489.36 $\mu\text{molTEAC/g DW}$, DPPH: 170.35 $\mu\text{molTEAC/g DW}$) were observed in the PLE with water at 150 °C. On the other hand, in terms of efficiency, MAE was superior to PLE and CRE in terms of phenolic and antioxidant capacities, especially due to the short extraction time and low solvent usage.

A significant biotechnological contribution of this work was the identification of previously unreported bioactive compounds in banana bracts, including taxifolin, eriodictyol, rosmarinic acid, and abscisic acid, which were extracted using MAE at 100 °C. In contrast, PLE at 150 °C yielded the highest number of phytochemicals extracted (most thermostable phenolic acids such as ferulic, protocatechuic, *p*-coumaric, among others), probably due to the intense characteristics of the process.

These findings expand the phytochemical diversity of banana agricultural residues and enhance their potential for biotechnological applications in the development of functional foods, pharmaceuticals, and cosmetics.

Regarding the Eco-Scale extractions with pure water, regardless of the technique (PLE, MAE, or CRE), the highest scores were achieved (above 90%), reflecting not only the solvent's minimal environmental impact but also its high yield, while with ethanol the score decrease to around 74.51 with CRE and 86.99 with MAE at 150°C.

The integration of sustainable extraction processes with agricultural by-product valorization directly supports circular bioeconomy principles and aligns with UN Sustainable Development Goals 3, 9, 12, and 13. This biotechnological approach demonstrates how agricultural waste streams can be transformed into valuable bioproducts while minimizing environmental impact and promoting resource efficiency. Future research should focus on process scale-up, bioactivity validation of isolated compounds, and development of integrated biorefineries that maximize the biotechnological potential of banana agricultural residues. This work establishes a foundation for sustainable biotechnological valorization strategies that can be extended to other agricultural by-products.

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Data Availability: The dataset is publicly available on Zenodo: Emiliano Motta, G., Tavares Germano, A., Vitali, L., Ayala Valencia, G., & Ferreira, S. R. S. (2025). Dataset from the article Recovery of bioactive compounds from Cavendish bracts of *Musa acuminata*: sustainable valorization of residues from the sweetest banana in Brazil [Data set]. Zenodo. <https://doi.org/10.5281/zenodo.15875494>

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Reference

1. EPAGRI: Embrapa - Banana, <https://www.embrapa.br/mandioca-e-fruticultura/cultivos/banana#:~:text=A banana é a fruta,metade originária da agricultura familiar.>
2. FAO: FAOSTAT 2024, www.fao.org/faostat/en/#data/QC
3. FAO: Banana facts and figures, [https://www.fao.org/economic/est/est-commodities/oilcrops/bananas/bananafacts/en/#:~:text=According to some estimates%2C more,globally each year \(Bananalink\).](https://www.fao.org/economic/est/est-commodities/oilcrops/bananas/bananafacts/en/#:~:text=According to some estimates%2C more,globally each year (Bananalink).)
4. Lucion, J.M.R.: The identity building strategies around the geographical indication of “the sweetest banana of brazil” from corupá/sc region. Rev. INGI – INDICAÇÃO GEOGRÁFICA E INOVAÇÃO. 6, 1569–1585 (2022). <https://doi.org/10.51722/Ingi.v6.i1.187>
5. EPAGRI: Produção de banana se recupera em SC e deve ser 50% maior em comparação a 2021, <https://www.epagri.sc.gov.br/index.php/2022/05/26/producao-de-banana-se-recupera-em-sc-e-deve-ser-50-maior-em-comparacao-a-2021/>
6. Sebrae: Indicações geográficas brasileiras, <https://datasebrae.com.br/ig-regiao-de-corupa/>
7. Redondo-Gómez, C., Rodríguez Quesada, M., Vallejo Astúa, S., Murillo Zamora,

- 746 J.P., Lopretti, M., Vega-Baudrit, J.R.: Biorefinery of Biomass of Agro-Industrial
747 Banana Waste to Obtain High-Value Biopolymers. *Molecules*. 25, 3829 (2020).
748 <https://doi.org/10.3390/molecules25173829>
- 749 8. Borges, A.L., Silva, A.L. da, Batista, D. da C., Moreira, F.R.B., Flori, J.E.,
750 Oliveira, J.E. de M., Araújo, J.L.P., Pinto, J.M., Castro, J.M. da C. e, Moura,
751 M.S.B. de, Azoubel, P.M., Cunha, T.J.F., Silva, S. de O. e, Cordeiro, Z.J.M.:
752 Sistema de Produção da Bananeira Irrigada. Presented at the (2009)
- 753 9. Motta, G.E., Angonese, M., Ayala Valencia, G., Ferreira, S.R.S.: Beyond the
754 peel: Biorefinery approach of other banana residues as a springboard to achieve
755 the United Nations' sustainable development goals. *Sustain. Chem. Pharm.* 30,
756 100893 (2022). <https://doi.org/10.1016/j.scp.2022.100893>
- 757 10. Lau, B.F., Kong, K.W., Leong, K.H., Sun, J., He, X., Wang, Z., Mustafa, M.R.,
758 Ling, T.C., Ismail, A.: Banana inflorescence: Its bio-prospects as an ingredient
759 for functional foods. *Trends Food Sci. Technol.* 97, 14–28 (2020).
760 <https://doi.org/10.1016/j.tifs.2019.12.023>
- 761 11. ONU, U.N.: Transforming our world: the 2030 agenda for sustainable
762 development. the 2030 Agenda for Sustainable Development.,
763 <https://sustainabledevelopment.un.org/post2015/>
- 764 12. UFSC: Incorporação de amostras - Herbário Flor,
765 https://herbarioflor.ccb.ufsc.br/incorporar_amostras/
- 766 13. AOAC: Method 990.03, Protein (Crude) in Animal Feed, Combustion Method.
767 In: Official Methods of Analysis. pp. 30–31. AOAC INTERNATIONAL,
768 Gaithersburg, MD (2006)
- 769 14. AOAC: Method 920.39 Fat (Crude). In: Official Methods of Analysis. AOAC
770 INTERNATIONAL, Gaithersburg, MD (2000)
- 771 15. NAFTA: Method 2.2.2.5 Laboratory Dry Matter by Oven Drying for 3 hours at
772 105°C. (2001)
- 773 16. AOAC: Method 978.10, Fiber (Crude) in Animal Feed and Pet Food. In: Official
774 Methods of Analysis of AOAC International. pp. 46–47. AOAC International,
775 Gaithersburg, MD. (2005)
- 776 17. AOAC: Method 942.05, Ash of Animal Feed. In: Official Methods of Analysis of
777 AOAC International. p. 8. AOAC INTERNATIONAL, Gaithersburg, MD (2005)
- 778 18. Gonçalves, C., Rodriguez-Jasso, R.M., Gomes, N., Teixeira, J.A., Belo, I.:
779 Adaptation of dinitrosalicylic acid method to microtiter plates. *Anal. Methods*. 2,
780 2046 (2010). <https://doi.org/10.1039/c0ay00525h>
- 781 19. Mazzutti, S., Rodrigues, L.G.G., Mezzomo, N., Venturi, V., Ferreira, S.R.S.:
782 Integrated green-based processes using supercritical CO₂ and pressurized ethanol
783 applied to recover antioxidant compounds from cocoa (*Theobroma cacao*) bean
784 hulls. *J. Supercrit. Fluids*. 135, 52–59 (2018).
785 <https://doi.org/10.1016/j.supflu.2017.12.039>
- 786 20. Torres, T.M.S., Guedes, J.A.C., de Brito, E.S., Mazzutti, S., Ferreira, S.R.S.:
787 High-pressure biorefining of ora-pro-nobis (*Pereskia aculeata*). *J. Supercrit.*
788 *Fluids*. 181, 105514 (2022). <https://doi.org/10.1016/j.supflu.2021.105514>

- 789 21. Correa, M., Mesomo, M.C., Pianoski, K.E., Torres, Y.R., Corazza, M.L.:
790 Extraction of inflorescences of *Musa paradisiaca* L. using supercritical CO₂ and
791 compressed propane. *J. Supercrit. Fluids.* 113, 128–135 (2016).
792 <https://doi.org/10.1016/j.supflu.2016.03.016>
- 793 22. Weinhold, T. de S., Bresciani, L.F.V., Tridapalli, C.W., Yunes, R.A., Hense, H.,
794 Ferreira, S.R.S.: *Polygala cyparissias* oleoresin: Comparing CO₂ and classical
795 organic solvent extractions. *Chem. Eng. Process. Process Intensif.* 47, 109–117
796 (2008). <https://doi.org/10.1016/j.cep.2007.08.007>
- 797 23. Kuhnen, S., Lemos, P.M.M., Campestrini, L.H., Ogliari, J.B., Dias, P.F.,
798 Maraschin, M.: Antiangiogenic properties of carotenoids: A potential role of
799 maize as functional food. *J. Funct. Foods.* 1, 284–290 (2009).
800 <https://doi.org/10.1016/j.jff.2009.04.001>
- 801 24. O’Fallon, J. V., Busboom, J.R., Nelson, M.L., Gaskins, C.T.: A direct method for
802 fatty acid methyl ester synthesis: Application to wet meat tissues, oils, and
803 feedstuffs. *J. Anim. Sci.* 85, 1511–1521 (2007). [https://doi.org/10.2527/jas.2006-](https://doi.org/10.2527/jas.2006-491)
804 491
- 805 25. Gonçalves Rodrigues, L.G., Mazzutti, S., Vitali, L., Micke, G.A., Ferreira,
806 S.R.S.: Recovery of bioactive phenolic compounds from papaya seeds
807 agroindustrial residue using subcritical water extraction. *Biocatal. Agric.*
808 *Biotechnol.* 22, 101367 (2019). <https://doi.org/10.1016/j.bcab.2019.101367>
- 809 26. Plaskova, A., Mlcek, J.: New insights of the application of water or ethanol-water
810 plant extract rich in active compounds in food. *Front. Nutr.* 10, (2023).
811 <https://doi.org/10.3389/fnut.2023.1118761>
- 812 27. Singleton, V.L., Orthofer, R., Lamuela-Raventós, R.M.: [14] Analysis of total
813 phenols and other oxidation substrates and antioxidants by means of folin-
814 ciocalteu reagent. Presented at the (1999)
- 815 28. Re, R., Pellegrini, N., Proteggente, A., Pannala, A., Yang, M., Rice-Evans, C.:
816 Antioxidant activity applying an improved ABTS radical cation decolorization
817 assay. *Free Radic. Biol. Med.* 26, 1231–1237 (1999).
818 [https://doi.org/10.1016/S0891-5849\(98\)00315-3](https://doi.org/10.1016/S0891-5849(98)00315-3)
- 819 29. Benzie, I.F.F., Strain, J.J.: The Ferric Reducing Ability of Plasma (FRAP) as a
820 Measure of “Antioxidant Power”: The FRAP Assay. *Anal. Biochem.* 239, 70–76
821 (1996). <https://doi.org/10.1006/abio.1996.0292>
- 822 30. Mensor, L.L., Menezes, F.S., Leitão, G.G., Reis, A.S., Santos, T.C. dos, Coube,
823 C.S., Leitão, S.G.: Screening of Brazilian plant extracts for antioxidant activity
824 by the use of DPPH free radical method. *Phyther. Res.* 15, 127–130 (2001).
825 <https://doi.org/10.1002/ptr.687>
- 826 31. Schulz, M., Borges, G. da S.C., Gonzaga, L.V., Seraglio, S.K.T., Olivo, I.S.,
827 Azevedo, M.S., Nehring, P., de Gois, J.S., de Almeida, T.S., Vitali, L., Spudeit,
828 D.A., Micke, G.A., Borges, D.L.G., Fett, R.: Chemical composition, bioactive
829 compounds and antioxidant capacity of *juçara* fruit (*Euterpe edulis* Martius)
830 during ripening. *Food Res. Int.* 77, 125–131 (2015).
831 <https://doi.org/10.1016/j.foodres.2015.08.006>
- 832 32. Shi, M., Zheng, X., Zhang, N., Guo, Y., Liu, M., Yin, L.: Overview of sixteen

- green analytical chemistry metrics for evaluation of the greenness of analytical methods. *TrAC Trends Anal. Chem.* 166, 117211 (2023).
<https://doi.org/10.1016/j.trac.2023.117211>
33. Espino, M., Fernández, M. de los Á., Gomez, F.J.V., Boiteux, J., Silva, M.F.: Green analytical chemistry metrics: Towards a sustainable phenolics extraction from medicinal plants. *Microchem. J.* 141, 438–443 (2018).
<https://doi.org/10.1016/j.microc.2018.06.007>
34. Fingolo, C.E., Braga, J.M.A., Vieira, A.C.M., Moura, M.R.L., Kaplan, M.A.C.: The natural impact of banana inflorescences (*Musa acuminata*) on human nutrition. *An. Acad. Bras. Cienc.* 84, 891–898 (2012).
<https://doi.org/10.1590/S0001-37652012005000067>
35. Schmidt, M.M., Kubota, E.H., Prestes, R.C., Mello, R.O., Rosa, C.S., Scapin, G., Ferreira, S.: Development and evaluation of pork burger with added natural antioxidant based on extract of banana inflorescence (*Musa cavendishii*). *CyTA - J. Food.* 14, 280–288 (2016). <https://doi.org/10.1080/19476337.2015.1099118>
36. Liyanage, R., Gunasegaram, S., Visvanathan, R., Jayathilake, C., Weththasinghe, P., Jayawardana, B.C., Vidanarachchi, J.K.: Banana Blossom (*Musa acuminata* Colla) Incorporated Experimental Diets Modulate Serum Cholesterol and Serum Glucose Level in Wistar Rats Fed with Cholesterol. *Cholesterol.* 2016, 1–6 (2016). <https://doi.org/10.1155/2016/9747412>
37. Konsue, N., Bunyameen, N., Donlao, N.: Utilization of young jackfruit (*Artocarpus heterophyllus* Lam.) as a plant-based food ingredient: Influence of maturity on chemical attributes and changes during in vitro digestion. *LWT.* 180, 114721 (2023). <https://doi.org/10.1016/j.lwt.2023.114721>
38. Torres, T.M.S., Mazzutti, S., Castiani, M.A., Siddique, I., Vitali, L., Ferreira, S.R.S.: Phenolic compounds recovered from ora-pro-nobis leaves by microwave assisted extraction. *Biocatal. Agric. Biotechnol.* 39, 102238 (2022).
<https://doi.org/10.1016/j.bcab.2021.102238>
39. Dhakad, A.K., Singh, K., Oberoi, H.K., Kumar, V., Shah, J.N.: Proximate composition, mineral profiling and antioxidant potential in *Moringa oleifera* genotypes affected with leaf maturity stage. *South African J. Bot.* 168, 227–235 (2024). <https://doi.org/10.1016/j.sajb.2024.03.023>
40. Murugesh, C.S., Rastogi, N.K., Subramanian, R.: Athermal extraction of green tea: Optimisation and kinetics of extraction of polyphenolic compounds. *Innov. Food Sci. Emerg. Technol.* 50, 207–216 (2018).
<https://doi.org/10.1016/j.ifset.2018.06.005>
41. Cámara, M., de Cortes Sánchez-Mata, M., Fernández-Ruiz, V., Cámara, R.M., Manzoor, S., Caceres, J.O.: Lycopene. Presented at the (2013)
42. Rad, H.B., Sabet, J.K., Varaminian, F.: STUDY OF SOLUBILITY IN SUPERCRITICAL FLUIDS: THERMODYNAMIC CONCEPTS AND MEASUREMENT METHODS - A REVIEW. *Brazilian J. Chem. Eng.* 36, 1367–1392 (2019). <https://doi.org/10.1590/0104-6632.20190364s20170493>
43. Andrade, K.S., Gonçalves, R.T., Maraschin, M., Ribeiro-do-Valle, R.M., Martínez, J., Ferreira, S.R.S.: Supercritical fluid extraction from spent coffee

- 877 grounds and coffee husks: Antioxidant activity and effect of operational variables
878 on extract composition. *Talanta*. 88, 544–552 (2012).
879 <https://doi.org/10.1016/j.talanta.2011.11.031>
- 880 44. Teixeira, G.L., Maciel, L.G., Mazzutti, S., Gonçalves, C.B., Ferreira, S.R.S.,
881 Block, J.M.: Composition, thermal behavior and antioxidant activity of pracaxi
882 (*Pentaclethra macroloba*) seed oil obtained by supercritical CO₂. *Biocatal. Agric.*
883 *Biotechnol.* 24, 101521 (2020). <https://doi.org/10.1016/j.bcab.2020.101521>
- 884 45. Cravotto, C., Fabiano-Tixier, A.-S., Claux, O., Abert-Vian, M., Tabasso, S.,
885 Cravotto, G., Chemat, F.: Towards Substitution of Hexane as Extraction Solvent
886 of Food Products and Ingredients with No Regrets. *Foods*. 11, 3412 (2022).
887 <https://doi.org/10.3390/foods11213412>
- 888 46. Filho, G.L., De Rosso, V. V., Meireles, M.A.A., Rosa, P.T.V., Oliveira, A.L.,
889 Mercadante, A.Z., Cabral, F.A.: Supercritical CO₂ extraction of carotenoids from
890 pitanga fruits (*Eugenia uniflora* L.). *J. Supercrit. Fluids*. 46, 33–39 (2008).
891 <https://doi.org/10.1016/j.supflu.2008.02.014>
- 892 47. Yara-Varón, E., Fabiano-Tixier, A.S., Balcels, M., Canela-Garayoa, R., Bily, A.,
893 Chemat, F.: Is it possible to substitute hexane with green solvents for extraction
894 of carotenoids? A theoretical versus experimental solubility study. *RSC Adv.* 6,
895 27750–27759 (2016). <https://doi.org/10.1039/C6RA03016E>
- 896 48. Zúñiga-Moreno, A., Arenas-Quevedo, M.G., Elizalde-Solis, O.: Solubility of β -
897 carotene and co-solutes in supercritical carbon dioxide for ternary systems:
898 Experimental data and correlation. *J. Supercrit. Fluids*. 148, 66–73 (2019).
899 <https://doi.org/10.1016/j.supflu.2019.03.005>
- 900 49. PELLICANÒ, T.M., SICARI, V., LOIZZO, M.R., LEPORINI, M., FALCO, T.,
901 POIANA, M.: Optimizing the supercritical fluid extraction process of bioactive
902 compounds from processed tomato skin by-products. *Food Sci. Technol.* 40,
903 692–697 (2020). <https://doi.org/10.1590/fst.16619>
- 904 50. Ghag, S.B., Ganapathi, T.R.: Banana and Plantains: Improvement, Nutrition, and
905 Health. Presented at the (2019)
- 906 51. Ramu, R., Shirahatti, P.S., Anilakumar, K.R., Nayakavadi, S., Zameer, F.,
907 Dhananjaya, B., Nagendra Prasad, M.: Assessment of nutritional quality and
908 global antioxidant response of banana (*Musa* sp. CV. Nanjangud Rasa Bale)
909 pseudostem and flower. *Pharmacognosy Res.* 9, 74 (2017).
910 https://doi.org/10.4103/pr.pr_67_17
- 911 52. Ramírez-Bolaños, S., Pérez-Jiménez, J., Díaz, S., Robaina, L.: A potential of
912 banana flower and pseudo-stem as novel ingredients rich in phenolic compounds.
913 *Int. J. Food Sci. Technol.* 56, 5601–5608 (2021).
914 <https://doi.org/10.1111/ijfs.15072>
- 915 53. Jokić, S., Svilović, S., Zeković, Z., Vidović, S., Velić, D.: Solubility and kinetics
916 of soybean oil and fatty acids in supercritical CO₂. *Eur. J. Lipid Sci. Technol.*
917 113, 644–651 (2011). <https://doi.org/10.1002/ejlt.201000403>
- 918 54. Chrastil, J.: Solubility of solids and liquids in supercritical gases. *J. Phys. Chem.*
919 86, 3016–3021 (1982). <https://doi.org/10.1021/j100212a041>

- 920 55. Canabarro, N.I., Veggi, P.C., Vardanega, R., Mazutti, M.A., Ferreira, M. do C.:
921 Techno-economic evaluation and mathematical modeling of supercritical CO₂
922 extraction from *Eugenia uniflora* L. leaves. *J. Appl. Res. Med. Aromat. Plants*.
923 18, 100261 (2020). <https://doi.org/10.1016/j.jarmap.2020.100261>
- 924 56. Adeeyo, A.O., Oyetade, J.A., Alabi, M.A., Adeeyo, R.O., Samie, A., Makungo,
925 R.: Tuning water chemistry for the recovery of greener products: pragmatic and
926 sustainable approaches. *RSC Adv.* 13, 6808–6826 (2023).
927 <https://doi.org/10.1039/D2RA06596G>
- 928 57. Marcus, Y.: Extraction by Subcritical and Supercritical Water, Methanol, Ethanol
929 and Their Mixtures. *Separations*. 5, 4 (2018).
930 <https://doi.org/10.3390/separations5010004>
- 931 58. Torres, T.M.S., Mendiola, J.A., Álvarez-Rivera, G., Mazzutti, S., Ibáñez, E.,
932 Cifuentes, A., Ferreira, S.R.S.: Protein valorization from ora-pro-nobis leaves by
933 compressed fluids biorefinery extractions. *Innov. Food Sci. Emerg. Technol.* 76,
934 102926 (2022). <https://doi.org/10.1016/j.ifset.2022.102926>
- 935 59. da Silva, J., Torres, T.M.S., Ribeiro, P.R.V., de Brito, E.S., Ferreira, S.R.S.: An
936 Eco-Friendly High-Pressure Biorefinery Approach for the Recovery of Valuable
937 Compounds from Cashew Nut Testa Shell (*Anacardium occidentale* L.). *Food*
938 *Bioprocess Technol.* (2024). <https://doi.org/10.1007/s11947-024-03572-0>
- 939 60. Huaman-Castilla, N.L., Martínez-Cifuentes, M., Camilo, C., Pedreschi, F.,
940 Mariotti-Celis, M., Pérez-Correa, J.R.: The Impact of Temperature and Ethanol
941 Concentration on the Global Recovery of Specific Polyphenols in an Integrated
942 HPLE/RP Process on Carménère Pomace Extracts. *Molecules*. 24, 3145 (2019).
943 <https://doi.org/10.3390/molecules24173145>
- 944 61. Senevirathna, N., Hassanpour, M., O'Hara, I., Karim, A.: Investigation of the
945 Effects of Energy-Efficient Drying Techniques and Extraction Methods on the
946 Bioactive and Functional Activity of Banana Inflorescence. *Energies*. 17, 4119
947 (2024). <https://doi.org/10.3390/en17164119>
- 948 62. Alara, O.R., Abdurahman, N.H., Ukaegbu, C.I.: Extraction of phenolic
949 compounds: A review. *Curr. Res. Food Sci.* 4, 200–214 (2021).
950 <https://doi.org/10.1016/j.crfs.2021.03.011>
- 951 63. Madeira, P.P.: On the autodissociation of water. *J. Mol. Liq.* 426, 127329 (2025).
952 <https://doi.org/10.1016/j.molliq.2025.127329>
- 953 64. Brehm, B., Fuchs, V., Kobarle, P.: Autoionization and fragmentation processes in
954 methanol and ethanol. *Int. J. Mass Spectrom. Ion Phys.* 6, 279–289 (1971).
955 [https://doi.org/10.1016/0020-7381\(71\)80011-6](https://doi.org/10.1016/0020-7381(71)80011-6)
- 956 65. Ferro, D.M., Mazzutti, S., Vitali, L., Oliveira Müller, C.M., Ferreira, S.R.S.:
957 Integrated extraction approach to increase the recovery of antioxidant compounds
958 from *Sida rhombifolia* leaves. *J. Supercrit. Fluids*. 149, 10–19 (2019).
959 <https://doi.org/10.1016/j.supflu.2019.03.013>
- 960 66. Angonese, M., Motta, G.E., Silva de Farias, N., Molognoni, L., Daguer, H.,
961 Brugnertotto, P., de Oliveira Costa, A.C., Olivera Müller, C.M.: Organic dragon
962 fruits (*Hylocereus undatus* and *Hylocereus polyrhizus*) grown at the same
963 edaphoclimatic conditions: Comparison of phenolic and organic acids profiles

- and antioxidant activities. *LWT*. 149, 111924 (2021).
<https://doi.org/10.1016/j.lwt.2021.111924>
67. Torres, T.M.S., Álvarez-Rivera, G., Mazzutti, S., Sánchez-Martínez, J.D., Cifuentes, A., Ibáñez, E., Ferreira, S.R.S.: Neuroprotective potential of extracts from leaves of *ora-pro-nobis* (*Pereskia aculeata*) recovered by clean compressed fluids. *J. Supercrit. Fluids*. 179, 105390 (2022).
<https://doi.org/10.1016/j.supflu.2021.105390>
68. Moretton, C., Gouttefangeas, C., Dubois, C., Tessier, F.J., Fradin, C., Prost-Camus, E., Prost, M., Haumont, M., Nigay, H.: Investigation of the antioxidant capacity of caramels: Combination of laboratory assays and *C. elegans* model. *J. Funct. Foods*. 78, 104308 (2021). <https://doi.org/10.1016/j.jff.2020.104308>
69. Plaza, M., Turner, C.: Pressurized hot water extraction of bioactives. *TrAC Trends Anal. Chem.* 71, 39–54 (2015). <https://doi.org/10.1016/j.trac.2015.02.022>
70. Teixeira, R.F., Araujo, T.R., Oliveira, D. de, Zielinski, A.A.F.: Unveiling the potential of pressurized liquid extraction for recovering protein fractions from broken black beans: Insights into thermal and structural properties. *Food Hydrocoll.* 149, 109649 (2024). <https://doi.org/10.1016/j.foodhyd.2023.109649>
71. Medina-Navarro, R., Durán-Reyes, G., Díaz-Flores, M., Vilar-Rojas, C.: Protein Antioxidant Response to the Stress and the Relationship between Molecular Structure and Antioxidant Function. *PLoS One*. 5, e8971 (2010).
<https://doi.org/10.1371/journal.pone.0008971>
72. Cheng, Y., Xu, Q., Liu, J., Zhao, C., Xue, F., Zhao, Y.: Decomposition of Five Phenolic Compounds in High Temperature Water. *J. Braz. Chem. Soc.* (2014).
<https://doi.org/10.5935/0103-5053.20140201>
73. Villanueva, M.P., Gioia, C., Sisti, L., Martí, L., Llorens-Chiralt, R., Verstichel, S., Celli, A.: Valorization of Ferulic Acid from Agro-Industrial by-Products for Application in Agriculture. *Polymers (Basel)*. 14, 2874 (2022).
<https://doi.org/10.3390/polym14142874>
74. Doctor, N., Parker, G., Vang, K., Smith, M., Kayan, B., Yang, Y.: Stability and Extraction of Vanillin and Coumarin under Subcritical Water Conditions. *Molecules*. 25, 1061 (2020). <https://doi.org/10.3390/molecules25051061>
75. Dawidowicz, A.L., Bernacik, K., Typek, R.: Umbelliferone instability during an analysis involving its extraction process. *Monatshefte für Chemie - Chem. Mon.* 149, 1327–1340 (2018). <https://doi.org/10.1007/s00706-018-2188-9>
76. Gayathry, K.S., John, J.A.: Phenolic profile, antioxidant, and hypoglycaemic potential of pseudostem and inflorescence extracts of three banana cultivars. *Biomass Convers. Biorefinery*. (2023). <https://doi.org/10.1007/s13399-023-04970-8>
77. Tang, M., Zhou, X., Cai, J., Chen, G.: Chemical constituents from the fresh flower buds of *Musa nana* and their chemotaxonomic significance. *Biochem. Syst. Ecol.* 99, 104348 (2021). <https://doi.org/10.1016/j.bse.2021.104348>
78. Kritsi, E., Tsiaka, T., Sotiroidis, G., Mouka, E., Aouant, K., Ladika, G., Zoumpoulakis, P., Cavouras, D., Sinanoglou, V.J.: Potential Health Benefits of

1007 Banana Phenolic Content during Ripening by Implementing Analytical and In
1008 Silico Techniques. *Life*. 13, 332 (2023). <https://doi.org/10.3390/life13020332>

1009 79. Hikal, W.M., Said-Al Ahl, H.A.H., Bratovcic, A., Tkachenko, K.G., Sharifi-Rad,
1010 J., Kačániová, M., Elhourri, M., Atanassova, M.: Banana Peels: A Waste
1011 Treasure for Human Being. Evidence-Based Complement. *Altern. Med.* 2022, 1–
1012 9 (2022). <https://doi.org/10.1155/2022/7616452>

1013 80. Kumar, V., Sharma, A., Kohli, S.K., Bali, S., Sharma, M., Kumar, R., Bhardwaj,
1014 R., Thukral, A.K.: Differential distribution of polyphenols in plants using
1015 multivariate techniques. *Biotechnol. Res. Innov.* 3, 1–21 (2019).
1016 <https://doi.org/10.1016/j.biori.2019.03.001>

1017 81. Queffelec, J., Beraud, W., Ferron, S., Boustie, J., Rodríguez-González, I., Díaz-
1018 Reinoso, B., Torres, M.D., Domínguez, H.: Alternatives for the extraction of
1019 bioactives and biopolymers from *Evernia prunastri* for the formulation of
1020 antimicrobial bio-based films. *Green Chem.* 26, 10205–10224 (2024).
1021 <https://doi.org/10.1039/D4GC02741H>

1022 82. da Silva, J., Benvenuti, L., Ribeiro, P.R.V., de Brito, E.S., Ferreira, S.R.S.:
1023 Simultaneous optimization of microwave- and ultrasound-assisted extractions of
1024 bioactive compounds from cashew nut testa shell (*Anacardium occidentale* L.).
1025 *Biomass Convers. Biorefinery.* 15, 14017–14035 (2025).
1026 <https://doi.org/10.1007/s13399-024-06262-1>

1027 83. Benvenuti, L.: Selection and application of eutectic solvents for the valorization
1028 of jaboticaba processing byproduct using highpressure fluid technologies,
1029 <https://mobile.repositorio.ufsc.br/xmlui/handle/123456789/235322?show=full>,
1030 (2022)

1031

1032

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