



Green Extraction of Bioactive Compounds from Sweet Potato (*Ipomoea batatas* L.) Peels and Comparative In Vitro and Biological Model Antioxidant Evaluation

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Abstract

This study evaluated the antioxidant potential of orange sweet potato (*Ipomoea batatas* L.) peel extracts obtained through green extraction technologies—pulsed electric fields (PEFs) and pressurized liquid extraction (PLE)—using *Saccharomyces cerevisiae* BY4741 as a yeast-based biological model for oxidative stress. Conventional maceration was used as a control, and in vitro antioxidant capacity was determined by ABTS, ORAC, FRAP, and DPPH assays. The composition of the extracts was analyzed by spectrophotometry and LC–MS/MS. Compared with maceration, both technologies significantly enhanced antioxidant recovery. PEF–water extracts reached 1.79 μM Trolox equivalents/g in the FRAP assay versus 0.54 $\mu\text{M/g}$ for maceration, while PLE–ethanol achieved 6.30 $\mu\text{M/g}$ (ABTS) and 16,782.8 $\mu\text{M/g}$ (ORAC), showing the highest antioxidant capacity. A consistent relationship was observed between in vitro results and the biological yeast model, confirming that chemical and cellular assays followed a parallel trend in antioxidant response. Under oxidative stress (0.5 and 4 mM H_2O_2), PLE–5 μL of the preculture was inoculated into each flask to achieve an initial OD_{600} of 0.005 ± 0.001 , followed by incubation at 28 °C with shaking at 190 rpm for 18 h. After incubation, the cultures were centrifuged at 3000 rpm and 20 °C for 10 min, washed with phosphate-buffered saline (PBS, pH 7.4), and adjusted to a final OD_{600} of 0.1. Ethanol extracts were effective at 1 and 10 mg GAE/mL, respectively, whereas PEF–water extracts required 10 and 20 mg GAE/mL to achieve comparable protection. These findings demonstrate that orange sweet potato peels are a valuable source of phenolic antioxidants and that PEF and PLE represent eco-efficient alternatives to conventional extraction, offering reduced solvent use and energy demand. The observed agreement between in vitro and biological model assays highlights their potential for identifying predictive in vitro methods and supports the functional application of these extracts in sustainable food and pharmaceutical formulations.

Keywords Sweet potato peel · Green extraction technologies · Pulsed electric fields (PEF) · Pressurized liquid extraction (PLE) · Yeast model

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Abbreviations

ABTS	2,2'-Azino-bis(3-ethylbenzothiazoline-6-sulfonic acid)
ADME	Absorption, distribution, metabolism, and excretion
DPPH	2,2-Diphenyl-1-picrylhydrazyl
FRAP	Ferric reducing antioxidant power
GAE	Gallic acid equivalents
OD	Optical density
ORAC	Oxygen radical absorbance capacity
PBS	Phosphate-buffered saline
PEF	Pulsed electric fields
PLE	Pressurized liquid extraction
TAC	Total antioxidant capacity

TPC Total phenolic content
 H₂O₂ Hydrogen peroxide

Introduction

The food industry, particularly in the processing of fruits and vegetables, generates large amounts of side streams such as peels. When not treated properly, these by-products are often disposed of in landfills, releasing polluting gases such as methane (Abu Qdais et al., 2019). However, fruit and vegetable peels are known to contain high concentrations of bioactive compounds—such as tannins, polyphenols, and other phytochemicals—that frequently exceed those found in the edible portions of the produce, highlighting their potential as value-added materials rather than waste (Francisco et al., 2024).

Due to their bioactive richness, these side streams have attracted growing interest for applications in the food, cosmetic, and pharmaceutical sectors. Their reuse has been proposed in various forms, including functional ingredients in food products like pasta to meet the increasing consumer demand for sustainable products without altering traditional eating habits. They can also serve as substrates for microbial cultivation to produce polyunsaturated fatty acids or as precursors for biopolymers used in biodegradable packaging materials—both contributing to a more circular agri-food economy (Gulzar et al., 2023; Li et al., 2022; Rafiq et al., 2023).

Sweet potato (*Ipomoea batatas* L.) is a crop of major relevance, ranking fifth in global food consumption after rice, wheat, maize, and cassava. Its low production cost and resilience make it crucial for food security, especially in developing countries and under crisis conditions. Nevertheless, during agro-industrial processing, large volumes of sweet potato peels are discarded, representing a significant but underutilized resource (Alam, 2021; Zhu et al., 2023). In Spain, for example, approximately 90,000 tons of sweet potato are produced annually, generating an estimated 5400 tons of peel waste (MERCASA, 2023). This biomass represents a valuable opportunity for valorization due to its richness in phenolic compounds and minerals.

Conventional maceration methods used for extracting antioxidant compounds are limited by the use of large solvent volumes, long processing times, and the degradation of thermolabile compounds (Alara et al., 2018). To address these challenges, green extraction technologies such as pulsed electric field-assisted extraction (PEF) and pressurized liquid extraction (PLE) have emerged as efficient and environmentally sustainable alternatives. PEF promotes electroporation of cell membranes, enhancing mass transfer

while preserving bioactive compound integrity (Kumar et al., 2023). Meanwhile, PLE operates under controlled temperature and pressure conditions below the solvent's critical point, optimizing solvent penetration and recovery of target compounds (Alvarez-Rivera et al., 2020; Oliveira et al., 2024). Although both techniques have been applied to other fruit and tuber matrices (e.g., potato, carrot, and apple peels), their comparative performance on sweet potato peels remains scarcely explored. This represents a relevant knowledge gap considering the distinct phenolic profiles and structural characteristics of this matrix.

Among the bioactive molecules present in sweet potato peels, phenolic compounds stand out for their strong antioxidant and anti-inflammatory properties, which are essential in preventing oxidative stress-related diseases (Laveriano-Santos et al., 2022). Nevertheless, while chemical in vitro assays are commonly employed to evaluate antioxidant capacity, they do not always accurately reflect cellular responses in living systems (Cano-Lou et al., 2025). The yeast *Saccharomyces cerevisiae*, due to its well-characterized metabolic and genetic pathways, serves as a robust eukaryotic biological model for investigating oxidative stress mechanisms (Peláez-Soto et al., 2020).

In this context, the present study provides a novel contribution by integrating both in vitro and yeast-based model antioxidant evaluations within a single comparative framework. This dual approach enables a more realistic assessment of the bioactivity of sweet potato peel extracts obtained by green extraction techniques. Specifically, this work advances prior research by directly comparing two eco-sustainable extraction technologies (PEF and PLE) applied to sweet potato peels, a matrix that remains underexplored compared with other vegetable by-products. The combined analysis of extraction efficiency, phenolic profile, and biological antioxidant response establishes a comprehensive model for evaluating the potential of food industry residues as sources of functional compounds.

Materials and Methods

Plant Material

Sweet potatoes (*Ipomoea batatas*) variety Beauregard (OSP) were obtained in October 2023 at the Central Market of the City of Valencia (Spain). The tubers were washed with tap water and then peeled manually. Only the peel with the first layer of flesh was cut into small pieces of 4–5 mm² and then stored in glass jars at 4 °C until later use. Figure 1 schematically represents the methods of obtaining the extract used in the study.

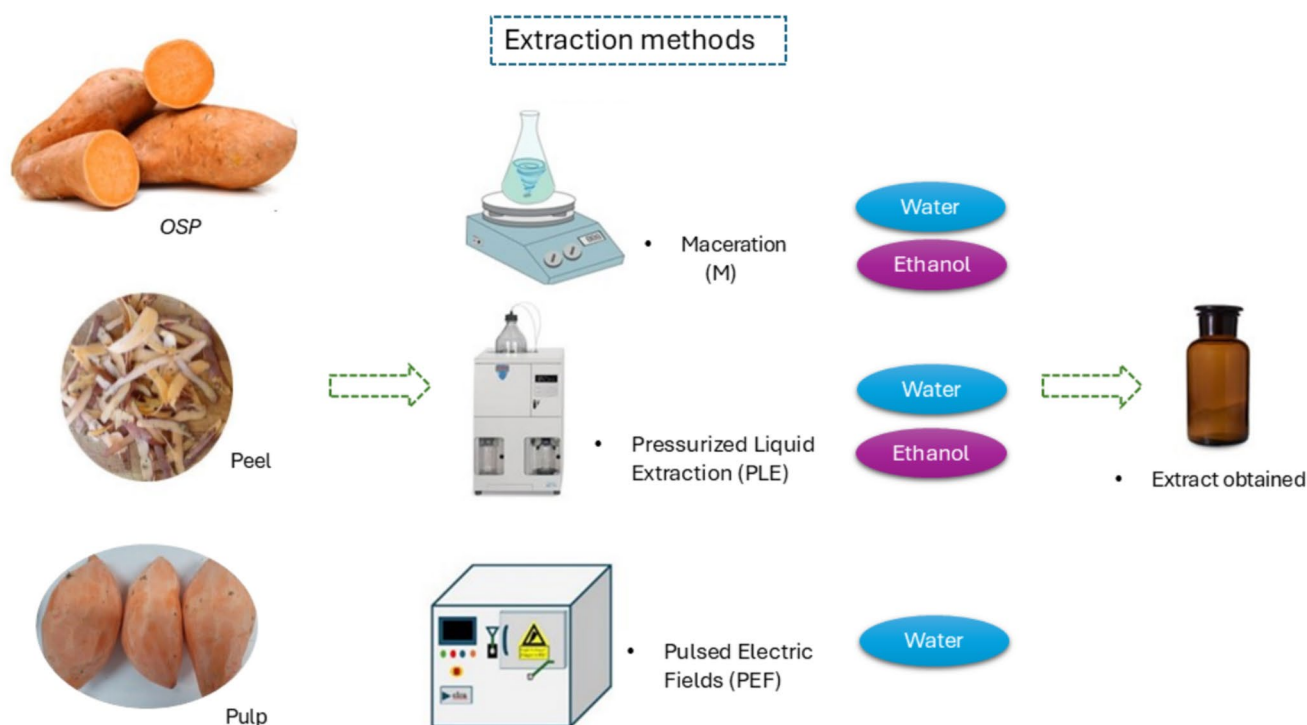


Fig. 1 Diagram of the extraction processes applied to the orange sweet potato peel using different non-thermal technologies

Extraction Methods

Maceration Method (M)

From the material obtained in step 1, a maceration extraction was performed to obtain bioactive compounds. To do this, a suspension was prepared in an amber Erlenmeyer flask by weighing 15 g of sweet potato peel and adding 100 mL of distilled water. The suspension was then shaken on an orbital shaker at 400 rpm for 3 h at room temperature (24 °C). Then, the solids were separated through Whatman No. 4 filter paper. The same process was done with absolute ethanol as the solvent. The ethanol extract was subsequently evaporated to dryness at 45 °C under a stream of N₂ using a TurboVap-LV (Zymark, Allschwil, Switzerland) and then redissolved in 6 mL of water by stirring (15 s). The extracts were stored in amber-colored bottles at –20 °C for later use. Each extract was prepared in duplicate.

Pulsed Electric Field–Assisted Extraction (PEF)

To obtain the extracts by pulsed electric fields (PEF), the PEF-Cellcrack III equipment (German Institute of Food Technology (DIL)) (ELEA, Germany) located at the ALISOST lab at the Faculty of Pharmacy and Food Sciences of the Universitat de València (Burjassot, Valencia, Spain) was used. The treatment conditions applied—3 kV/cm, 56

pulses, and the specific energy input (700 kJ/kg)—were calculated from the monitored electrical parameters (voltage, current, pulse width, and pulse number) according to Bernabeu et al. (2024). Thirty grams of the plant material was placed in the extraction chamber, and 200 mL of distilled water was added. The conductivity and the initial and final temperatures were measured using a portable conductivity meter ProfiLine Cond 3310 (WTW, Xylem Analytics, Weilheim in Oberbayern, Germany).

Water was selected as the extraction solvent because the PEF technique requires a conductive medium to promote efficient electroporation and ensure energy transfer. Aqueous systems provide optimal dielectric stability and prevent electric discharge, whereas organic solvents such as ethanol may decrease conductivity and compromise pulse homogeneity. Moreover, when applied to water-based systems, PEF has been reported to operate at lower temperatures, with reduced solvent consumption and higher extraction efficiency of phenolic compounds (Athanasiadis et al., 2023). After applying the PEF pretreatment, the water and the peels were transferred to an amber flask and processed following the same procedure as in maceration extraction.

Pressurized Liquid–Assisted Extraction (PLE)

For the extract obtained by PLE, a Dionex™ ASE™ 150 system (Thermo Scientific) was used under the working

conditions previously optimized by the ALISOST research group (Zhou et al., 2022). Briefly, 5 g of plant tissue was mixed with diatomaceous earth in a 1:2 (w/w) ratio using a mortar to ensure uniform dispersion. The mixture was then packed into 34-mL stainless steel extraction cells equipped with a cellulose filter at the bottom. The solid-to-liquid ratio was approximately 1:6.8 (w/v), considering 5 g of peel and 34 mL of solvent per cell.

Absolute ethanol was used as the extraction solvent under the following operating conditions: 1 min of pre-heating, 5 min of static extraction, 60% flush volume, and 100 s of nitrogen purge at 80 °C and 103.4 bar. The extraction was performed in two cycles, yielding a total volume of approximately 50 mL per run. The same procedure was subsequently repeated using distilled water as solvent.

The ethanolic extracts were evaporated to dryness at 45 °C under a gentle nitrogen stream using a TurboVap-LV (Zymark, Allschwil, Switzerland) and reconstituted in 6 mL of water by stirring for 15 s. All extracts were stored in amber bottles at −20 °C until further analysis.

These parameters were selected based on previous optimization studies demonstrating maximum phenolic recovery and extract stability for similar plant matrices (Zhou et al., 2022).

Chemical Analyses

Determination of Polyphenols

Following the protocol previously established by the ALISOST research group (Salgado-Ramos et al., 2022), the content of soluble phenols in the extracts was determined using the Folin–Ciocalteu method originally described by Singleton and Rossi (1965). The Folin–Ciocalteu method was employed as a standardized and widely accepted assay to estimate the total phenolic content (TPC), providing a global indicator of the phenolic fraction contributing to the antioxidant capacity of the extracts. This method was selected as it allows direct comparison among extraction techniques under identical analytical conditions, without focusing on the quantification of individual phenolic subclasses. One hundred microliters of each of the extracts obtained in Sect. "Phenolic Profile of the Extracts" was mixed with 100 µL of the 50% (v/v) Folin–Ciocalteu reagent; after incubating for 5 min, 3 mL of a 4% sodium carbonate solution was added. The sample was then shaken and left to incubate at room temperature in the dark for one hour, and finally, the absorbance at 765 nm was measured in a UV–visible spectrophotometer (Perkin-Elmer UV/Vis Lambda 2) (Perkin-Elmer, Rodgau-Jügesheim, Germany). Each sample was prepared in triplicate, and the quantitative determination was carried out by interpolation of the values on the previously calculated calibration line. The total

phenolic content was expressed as milligrams of gallic acid equivalents (GAE) per gram of dry material.

The phenolic profile was performed by Triple TOF–LC–MS–MS according to the method described in the work published by Roselló-Soto et al. (2019). The separation of the different polyphenols was carried out using a 1.7 µm Waters C18 column (2.1 × 50 mm) Acquity UPLC BEH.C18 (Waters, Cerdanyola del Vallès, Spain) implemented in an Agilent 1260 Infinity chromatography instrument (Agilent, Waldbronn, Germany). The identification of the compounds was carried out on a Triple TOF™ 5600 LC/MS/MS system (AB SCIEX, Foster City, CA, USA). For HPLC separation, a mobile phase composed of two solvents was used: A (0.1% formic acid, water) and B (0.1% formic acid, methanol), with a flow rate of 0.4 mL/min and a sample injection volume of 5 µL. MS data were obtained in the range of 80 to 1200 m/z in negative mode, and the acquisition method was carried out by topographic scanning type (TOF–MS). PeakView 1.1 software (AB SCIEX, Foster City, CA, USA) was used for data acquisition and analysis.

In Vitro Determination of Total Antioxidant Power

The TEAC assay was carried out following the methodology proposed by Re et al. (1999) which is based on the reduction of the ABTS•+ complex (2,2'-azinobis-(3-ethylbenzothiazoline-6-sulfonic acid)) (Sigma–Aldrich Co., USA) previously formed. For this test, the stock solution was prepared containing 25 mL of 7 mM ABTS and 440 µL of K₂S₂O₈ (Sigma–Aldrich Co., USA). The working solution was obtained by diluting the stock solution with ethanol to an absorbance of 0.70 ± 0.02 at 30 °C. Trolox® (Sigma–Aldrich Co., USA) was used as an antioxidant standard. To perform the analysis, 100 µL of the sample was added to a cuvette followed by 2.5 mL of the working solution. After 10 min of incubation avoiding contact with light, the absorbance of each of the cuvettes was determined and the result was expressed as mM Trolox equivalents (TE).

The ORAC (oxygen radical absorbance capacity) assay was performed using the methodology validated by Al Khawli et al. (2021) in 96-well flat-bottom microplates, incubated at 37 °C, the optimal temperature to induce thermal decomposition of the radical-generating compound AAPH (2,2'-azobis(2-amidinopropane) dihydrochloride) in phosphate buffer solution (PBS), according to the sensitivity of fluorescein (FL) to pH variations. Working solutions were prepared daily and included fluorescein (0.015 mg/mL), Trolox (100 µM) as an antioxidant standard, and AAPH (221 mM), all dissolved in PBS (75 mM, pH 7.0). Considering the high sensitivity of the method, the samples were diluted 1:250 (v/v) in PBS before analysis. For each assay, 50 µL of fluorescein and 50 µL of sample, standard, or blank (PBS) were added

to the corresponding wells. Then, 25 μL of the AAPH solution was incorporated to initiate the reaction, and the fluorescence was recorded every 5 min for 60 min, until the relative fluorescence intensity decreased below 5% of the initial value. The antioxidant capacity was expressed as Trolox equivalents (μM), calculated by integrating the area under the curve (AUC) of fluorescence decay, applying the following formula:

$$\text{ORAC}(\mu\text{MTroloxEquivalent}) = \frac{C_{\text{Trolox}} \cdot (AUC_{\text{Sample}} - AUC_{\text{Blank}}) \cdot k}{(AUC_{\text{Trolox}} - AUC_{\text{Blank}})}$$

where C_{Trolox} is the Trolox concentration, k is the dilution factor, and AUC is the area under the fluorescence droplet curve of the sample, blank, and Trolox, respectively.

FRAP assay was also performed on each of the OSP peel extracts obtained from different non-thermal technologies. To prepare the FRAP solution, 10 mL of acetate buffer (300 mM, pH 3.6) was mixed with 1 mL of FeCl_3 (20 mM) (dissolved in water) and 1 mL of 2,4,6-tris(2-pyridyl)-s-triazine (10 mM) dissolved in 40 mM HCl. Then, 10 μL of sample was mixed with 190 μL of FRAP solution. Results were obtained by linear regression from a calibration graph obtained with Trolox (0–1 mM). The assay was performed in triplicate, and results are reported as the mean $\pm$ SD expressed as mg of Trolox equivalent (TE) per gram of dry extract.

Finally, for the DPPH assay, 50 μL of the different extracts obtained was mixed with 5 mL of methanolic DPPH solution (0.004%) and, after 30 min of storage at room temperature in a dark place, the absorbance of the samples was read at a wavelength of 517 nm.

Biological Model Determination of Antioxidant Capacity Using *S. cerevisiae*

Yeast Strains

For this assay, the strain *Saccharomyces cerevisiae* BY4741 (MATa; his3 Δ 1; leu2 Δ 0; met15 Δ 0; ura3 Δ 0) was used, obtained from the European *Saccharomyces cerevisiae* Archive for Functional Analysis (EUROSCARF). The strain was maintained and cultured in YPD medium (2% glucose (w/v), 1% yeast extract (w/v), 2% peptone (w/v)) with 2% (w/v) plate agar (all ingredients were from Condalab, Madrid, Spain). The strain was activated from a frozen glycerol stock in fresh liquid YPD medium and incubated at 28 °C overnight with shaking. To obtain single colonies, the strain was plated on YPD plates that were incubated at 28 °C for 72 h.

Determination of Biological Model Antioxidant Activity in *S. cerevisiae* BY4741 After Exposure to Extracts

The assay was performed following the method described by (Peláez-Soto et al., 2017). A single colony of *Saccharomyces cerevisiae* was inoculated into 5 mL of YPD medium and incubated at 28 °C with shaking at 190 rpm until reaching an optical density (OD) of approximately 0.6. Subsequently, several 3-mL Erlenmeyer flasks were prepared under different experimental conditions. One flask containing YPD medium only was used as a negative control. A second flask containing YPD medium supplemented with 5 mM ascorbic acid (Sigma–Aldrich Co., Ukraine) served as a positive control. The working concentration was obtained by diluting a 23 mM stock solution (0.016 g in 4 mL sterile water, filtered) and adding 650 μL to 3 mL of culture. Four additional flasks were prepared with different concentrations of the extract (0.1, 1, 10, and 20 mg GAE/mL). Five microliters of preculture, adjusted to an initial OD₆₀₀ of 0.005 ± 0.001 , was added to each flask, which were then incubated at 28 °C with shaking at 190 rpm for 18 h.

After incubation, cultures were transferred to centrifuge tubes and spun at 3000 rpm at 20 °C for 10 min in a M-Universal centrifuge (18,000 rpm, MPW Med. Instruments, Warsaw, Poland). The resulting pellets were washed with 3-mL phosphate-buffered saline (PBS, Sigma–Aldrich Co., USA) at pH 7.4 and diluted to a final OD of 0.1. Sublethal oxidative stress was induced under two conditions: 0.5 mM and 4 mM H_2O_2 (17 μL and 136 μL , respectively) (Sigma–Aldrich Co., Ukraine), incubated for 60 min at 28 °C, without shaking and protected from light. Afterwards, the supernatants were separated by centrifugation at 3000 rpm for 10 min at 20 °C, and the pellets were resuspended in YPD medium. Finally, each sample was plated in triplicate in a 96-well microplate at 250 μL /well. Yeast growth was monitored in a plate reader (FLUOstar Omega, BMG Labtech, Ortenberg, Germany) by measuring OD at 600 nm every 30 min for 15 h at 28 °C. (Note: The specific volume of extract added to each flask varied depending on its total phenolic content (TPC) to reach the target final concentrations mentioned above.)

Calculation of Antioxidant Activity

To evaluate the antioxidant capacity of the extracts and reduce the variability between assays, the growth rate curves of the yeast grown under different conditions were determined. The growth rate curves (Eq. 1) were obtained by dividing the curves corresponding to the stress conditions by

those of the non-stress conditions, for each ingredient. These growth rate curves were then normalized against controls without ingredients subjected to different levels of oxidative stress, thus allowing the construction of the effect curves (OD_{600} ratio) (Eq. 2):

$$\left(\frac{\text{Stress}(XmM)}{\text{Withoutstress}(0mM)} \right)_{\text{Withingredient}} \quad (1)$$

$$\frac{\left(\frac{\text{Stress}(XmM)}{\text{Withoutstress}(0mM)} \right)_{\text{Withingredient}}}{\left(\frac{\text{Stress}(XmM)}{\text{Withoutstress}(0mM)} \right)_{\text{Withoutingredient}}} \quad (2)$$

The sample size ($n=3$) for dose–response analyses was determined based on previous studies employing *S. cerevisiae* as a biological model, which reported comparable variability and sufficient statistical power to detect significant differences under similar experimental conditions. Dose–response curves were subsequently constructed to represent the maximal statistically significant effect observed for each treatment, considering the concentrations used in the assays (Peláez-Soto et al., 2017).

Statistical Analysis

All in vitro assays were performed in triplicate, corresponding to three analytical replicates per extract. Experiments involving biological models using *Saccharomyces cerevisiae* were conducted with three independent biological replicates, and each biological replicate was plated in triplicate. Statistical analyses were performed using GraphPad Prism 10. Error bars represent the standard deviation. Data were analyzed by one-way analysis of variance (ANOVA), followed by Tukey's post hoc test to identify statistically significant differences among samples ($p < 0.05$). Dose–response curves were analyzed using Student's *t*-test ($p < 0.05$).

Results and Discussion

Evaluation of Polyphenols

Sweet potato peels (*Ipomoea batatas* L.) constitute a rich source of polyphenols with a wide range of polarities, necessitating a constant optimization in solvent and technique selection for their efficient and selective recovery. Figure 2 illustrates the total phenolic content (TPC) obtained from sweet potato peel extracts using different extraction techniques and solvents. A clear influence of both extraction method and solvent polarity on phenolic recovery was observed. Pressurized liquid extraction (PLE) using ethanol achieved the highest phenolic

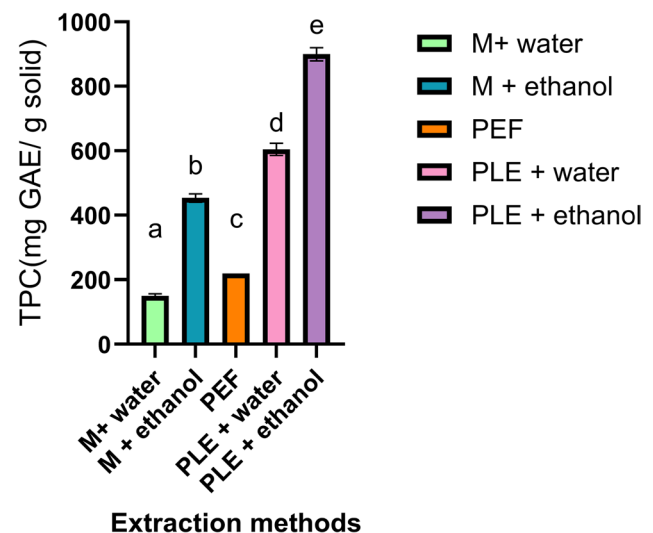


Fig. 2 Recovery of total polyphenol compounds (TPCs) by different extraction techniques: maceration (M), pulsed electric fields (PEFs), and pressurized liquid–assisted extraction (PLE), and different solvents from orange sweet potato peel. Data represent mean $\pm$ standard deviation (SD) of three independent replicates ($n=3$). Error bars correspond to standard deviation values. Letters above each bar represent significant differences between extractions obtained ($p < 0.05$)

yield (900.00 mg GAE/g solid), followed by aqueous PLE (604.96 mg GAE/g solid). These values were significantly higher ($p < 0.05$) than those obtained from conventional maceration (M), confirming the superior efficiency of PLE under elevated temperature and pressure conditions. Under these conditions, ethanol behaves as a subcritical fluid, enhancing solute diffusivity and solvent penetration within the plant matrix, which facilitates the release of bound phenolic compounds. In contrast, PEF-assisted extraction (PEF + water) yielded intermediate TPC values, approximately 45% higher than maceration in water, which is consistent with its electroporation mechanism that transiently disrupts cell membranes and promotes solvent diffusion.

Overall, the extraction efficiency followed the trend PLE + ethanol > PLE + water > PEF + water > M + ethanol > M + water, indicating a synergistic effect between solvent type and extraction intensity. These results are consistent with previous reports in other plant by-products such as apple, lemon, and potato peels, where the application of PLE and PEF significantly enhanced phenolic recovery compared with conventional techniques (Frontuto et al., 2019; Peiró et al., 2019; Pollini et al., 2021).

To facilitate a direct comparison between the present findings and published literature, Table 1 summarizes the TPC values obtained for the sweet potato peel under the different extraction approaches alongside representative data from other studies. The combined analysis reinforces that PLE, particularly when coupled with ethanol,

Table 1 Effect of extraction technique and solvent system on total phenolic content (TPC) of sweet potato peel and comparison with literature data

Extraction method	Solvent/matrix	TPC (mg GAE/g)	% increase vs. maceration	Reference
Maceration	Water	150.54	–	This study
	Ethanol	453.43	–	This study
PEF	Water	218.44	45	This study
PLE	Water	604.96	302	This study
	Ethanol	900.00	98.5	This study
PEF	Lemon peels	–	142–292	Peiró et al. (2019)
PEF	Potato peels (50% EtOH/H ₂ O)	–	10	Frontuto et al. (2019)
PEF	Tomato (water)	56.16 mg GAE/kg	100	Andreou et al. (2020)

constitutes the most effective green technology for maximizing polyphenol recovery from this agro-industrial by-product while maintaining process sustainability.

From an analytical perspective, these results confirm that PLE is markedly superior to maceration and PEF in extracting phenolics from sweet potato peels. The strong dependence on solvent polarity also reinforces the importance of matching solvent systems to the target phenolic profile, a pattern consistent with previous findings in other agro-industrial by-products (Alara et al., 2018; Alvarez-Rivera et al., 2020).

Phenolic Profile of the Extracts

Polyphenols in orange sweet potato peels include a wide diversity of flavonoid and non-flavonoid compounds, whose relative abundance depends strongly on solvent polarity and

extraction conditions. Figure 3 shows that ethanolic extracts obtained by pressurized liquid extraction (PLE) contained the highest concentrations of total flavonoids, followed by aqueous PLE and pulsed electric fields (PEF) extracts. This trend reflects the higher affinity of flavonoids for ethanol due to their intermediate polarity and hydrogen-bonding capacity (Zheng et al., 2016).

The LC–MS/MS analysis (Table 2) confirmed the presence of flavonols (quercetin, kaempferol), phenolic acids (chlorogenic acid), and lignans (pinosresinol, matairesinol) as dominant constituents. The predominance of quercetin glycosides in ethanolic PLE extracts is consistent with previous findings for sweet potato matrices (Andres et al., 2018; Kim et al., 2021). The low concentration of quercetin in aqueous systems is explained by its limited stability in water and tendency to oxidize (Luca et al., 2020).

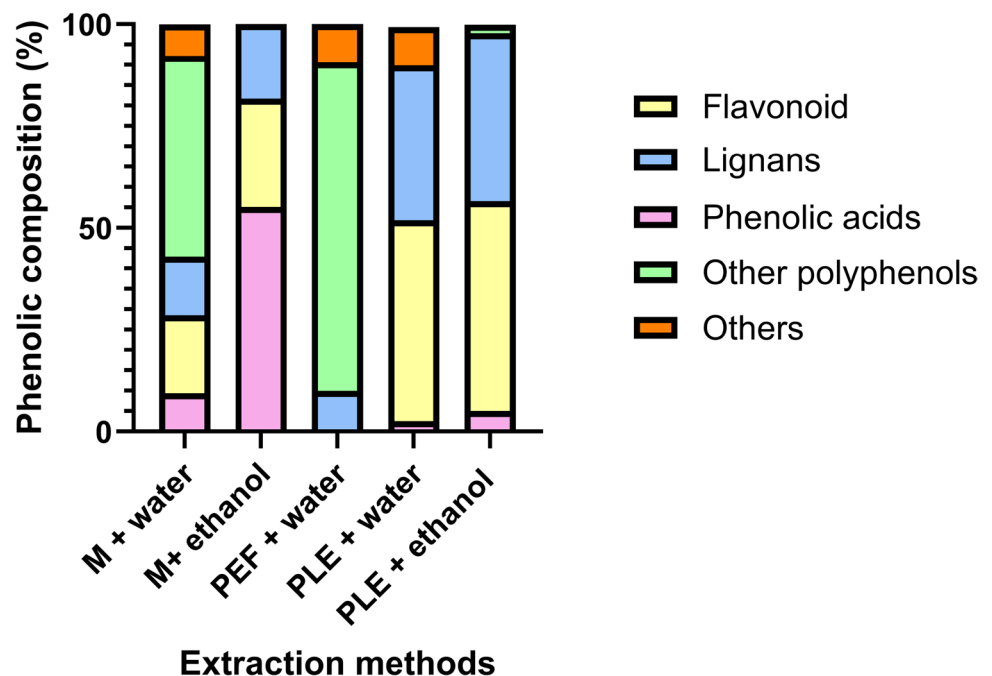
Fig. 3 Antioxidant capacity determined by ABTS assay for sweet potato peel extracts obtained by PEF and PLE using water and ethanol as solvents

Table 2 Phenolic composition of the extracts obtained by different methods from orange sweet potato peels, being the compounds classified according to their nature. Relative abundance values were calculated as the peak area percentage of each compound with respect to the total chromatogram signal at 280 nm

Compound type	Compound	Compound name	Molecular formula	T _r (min)	Relative abundance (% ± DS)				
					M + water	M + ethanol	PEF	PLE + water	PLE + ethanol
Phenolic acids	1	Chlorogenic acid	C ₁₆ H ₁₈ O ₉	6.3	-	14.79	-	-	-
	2	3-Caffeoylquinic acid	C ₁₆ H ₁₈ O ₉	6.3	-	14.79	-	-	-
	3	Trans-3-caffeoylquinic acid	C ₁₆ H ₁₈ O ₉	6.3	-	14.79	-	-	-
	4	Cis-3-caffeoylquinic acid	C ₁₆ H ₁₈ O ₉	6.3	-	14.79	-	-	-
	5	Myricetin3-O-rutinoside	C ₂₇ H ₃₀ O ₁₇	5.7	-	-	-	-	3.63
	6	3-Feruloylquinic acid	C ₁₇ H ₂₀ O ₉	5.2	-	-	-	-	2.20
	7	2-Hydroxybenzoic acid	C ₇ H ₆ O ₃	2.04	5.94	-	-	-	-
	8	3,4-Dimethoxybenzoic acid	C ₉ H ₁₀ O ₄	3.87	3.47	-	-	-	-
Flavonoids	9	Kaempferide	C ₁₆ H ₁₂ O ₆	6.13	-	6.64	-	11.38	-
	10	Chrysoeriol	C ₁₆ H ₁₂ O ₆	6.13	-	6.64	-	11.38	-
	11	Diosmetin	C ₁₆ H ₁₂ O ₆	6.13	-	6.64	-	11.38	-
	12	Hispidulin	C ₁₆ H ₁₂ O ₆	6.13	-	6.64	-	8.84	-
	13	Kaempferol3-O-sophoroside	C ₂₇ H ₃₀ O ₁₆	6.18	9.58	-	-	-	11.04
	14	Quercetin3-O-rutinoside	C ₂₇ H ₃₀ O ₁₆	6.17	-	-	-	2.12	11.04
	15	Quercetin3-O-sophoroside	C ₂₇ H ₃₀ O ₁₇	5.7	-	-	-	2.12	3.63
	16	6-O-Malonylglycitin	C ₂₅ H ₂₄ O ₁₃	6.25	-	-	-	-	11.09
	17	Quercetin3,4-O-diglucoside	C ₂₇ H ₃₀ O ₁₂	8.09	-	-	-	2.12	3.63
	18	Kaempferol3,7-O-diglucoside	C ₂₇ H ₃₀ O ₁₆	6.18	9.58	-	-	-	11.04
Lignans	19	Matairesinol	C ₂₀ H ₂₂ O ₆	6.49	-	6.49	4.98	5.44	-
	20	Pinoresinol	C ₂₀ H ₂₂ O ₆	6.49	-	6.49	4.98	30.50	44.30
	21	Sesamol	C ₇ H ₆ O ₃	2.04	5.94	-	-	-	-
	22	Conidendrin	C ₂₀ H ₂₀ O ₆	9.89	2.58	-	-	-	-
	23	Sesaminol2-O-b-D-glucoside	C ₂₆ H ₂₈ O ₁₂	7.46	5.82	-	-	6.63	-

Table 2 (continued)

Compound type	Compound	Compound name	Molecular formula	T _r (min)	Relative abundance (% ± DS)				
					M + water	M + ethanol	PEF	PLE + water	PLE + ethanol
Other polyphenols	24	Mellein	C ₁₀ H ₁₀ O ₃	9.18	-	-	4.94	-	-
	25	Carvacrol	C ₁₀ H ₁₄ O	12.14	-	-	7.08	-	-
	26	Thymol	C ₁₀ H ₁₄ O	12.14	-	-	7.08	-	-
	27	[6]-Gingerol	C ₁₇ H ₂₆ O ₄	10	-	-	7.84	-	-
	28	4-Hydroxycoumarin	C ₉ H ₆ O ₃	5.09	42.46	-	12.19	-	4.84
	29	Umbelliferone	C ₉ H ₆ O ₃	5.1	-	-	12.19	-	-
	30	Hydroquinone	C ₆ H ₆ O ₂	1.35	-	-	14.68	-	-
	31	Catechol	C ₆ H ₆ O ₂	1.35	-	-	14.68	-	-
	32	Demethoxycurcumin	C ₂₀ H ₁₈ O ₅	6.98	-	-	-	-	2.47
	33	Esculin	C ₁₅ H ₁₆ O ₉	1.66	3.39	-	-	-	-
Other	34	Syringaldehyde	C ₉ H ₁₀ O ₄	3.87	3.47	-	-	-	-
	35	4-Vinylphenol	C ₈ H ₈ O	5.13	-	-	3.54	-	-
	36	Protocatechuicaldehyde	C ₇ H ₆ O ₃	1.16	-	-	5.82	-	-
	37	Sinapoylglucose	C ₁₇ H ₂₂ O ₁₀	5.38	7.79	-	-	9.10	-

Under the subcritical conditions of PLE, enhanced solvent diffusivity and reduced viscosity facilitate desorption of bound phenolics from the lignocellulosic matrix, yielding a broader and more diverse phenolic spectrum (Francisco et al., 2024). In contrast, PEF-assisted extraction favored the recovery of hydrophilic phenolics, including catechol, resorcinol, and hydroquinone derivatives, as well as phenolic terpenes (thymol, carvacrol)—compounds with recognized

antioxidant and antimicrobial properties (Chauhan et al., 2023). These differences highlight how extraction mechanism and solvent polarity determine compound selectivity and biological functionality.

A concise summary of the main compounds identified, grouped by extraction method and associated bioactivity, is presented in Table 3. This functional mapping is crucial for industrial application, as it provides a clear rationale

Table 3 Main phenolic compounds identified in orange sweet potato peel extracts obtained by green extraction technologies

Compound/class	Extraction method	Solvent	Functional relevance	Key reference
Quercetin (glycosides)	PLE	Ethanol	Major antioxidant; modulates MDA and GSH; high radical scavenging	Kim et al. (2021); Andres et al. (2018)
Kaempferol	PLE	Ethanol	Antioxidant; possible metabolite from quercetin	Rodríguez et al. (2024)
Chlorogenic acid (and isomers)	M	Ethanol	Regulates mitochondrial metabolism; hepatoprotective	Wilson et al. (2017)
Pinoresinol	PLE/PEF	Water, ethanol	Lignan with antioxidant and antiviral properties	Miklasínska-Majdanik et al. (2018)
Matairesinol	PLE	Both	Precursor of estrogenic metabolites; cardioprotective	Nikolić et al. (2017)
Catechol, hydroquinone, resorcinol	PEF	Water	Strong antioxidants; nitrite scavengers	Lu et al. (2016); Chauhan et al. (2023)
Thymol, carvacrol (phenolic terpenes)	PEF	Water	Synergistic antioxidant and antimicrobial effects	Ozogul et al. (2024)
Other minor flavones (hispidulin, diosmetin, chrysoeriol)	M	Ethanol	Contribute to total antioxidant pool	This study

for selecting the optimal extraction technology (PLE, PEF, or maceration) based on the target bioactive compound and the desired health-promoting outcome.

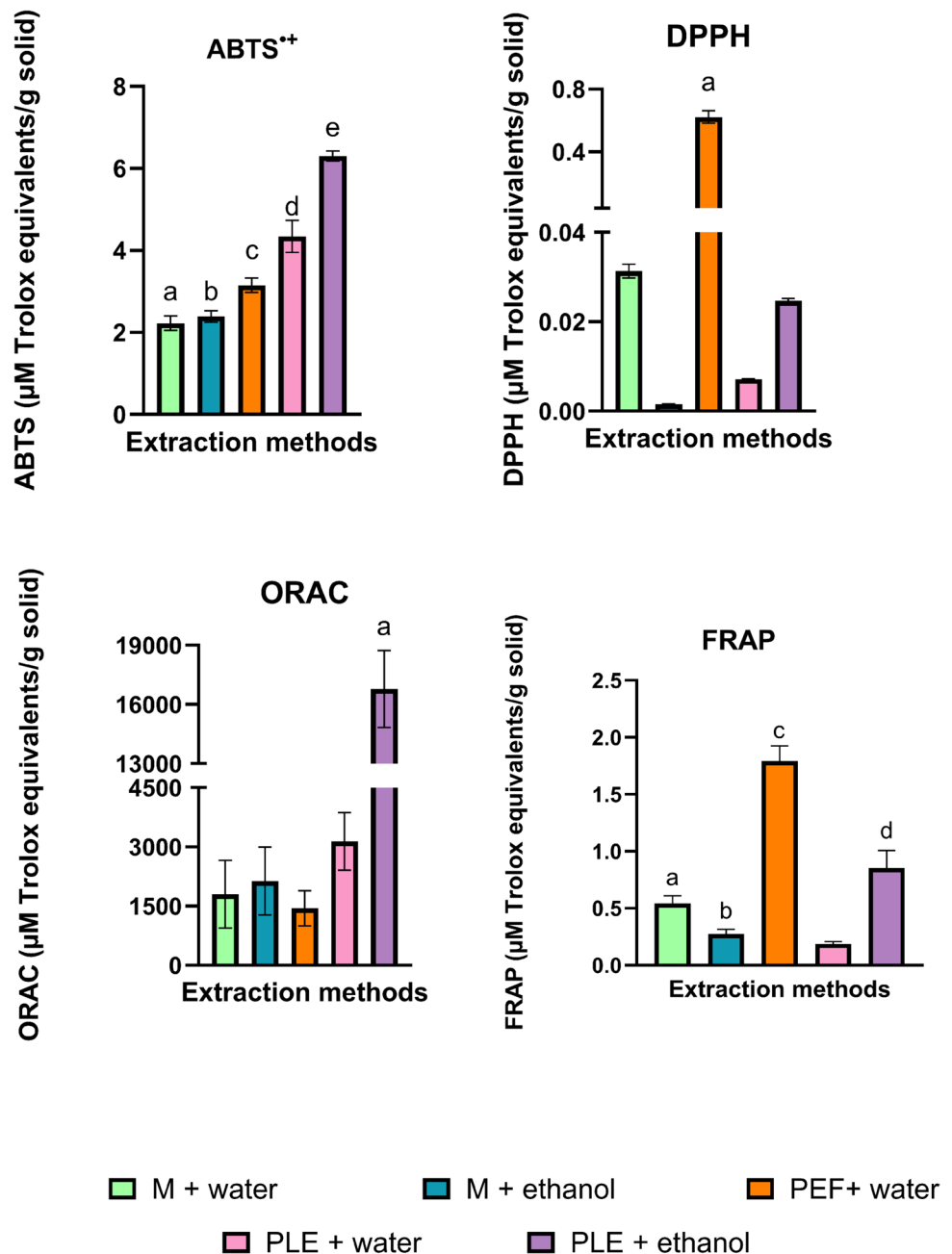
Determination of the In Vitro Antioxidant Activity of the Extracts

Free radical or oxidant scavenging assays have been the most used to evaluate the antioxidant activity of phenolic compounds from vegetable and fruit residues. The two most common radical scavenging assays used non-biological oxidizing species: ABTS•+ (2,2'-azino-bis

(3-ethylbenzothiazoline-6-sulfonic acid)) and DPPH (2,2-diphenyl-1-picrylhydrazyl) radicals (Olivares-Galván et al., 2020).

Regarding the antioxidant capacity of the extracts determined with the ABTS•+ technique (Sect. "Phenolic Profile of the Extracts"), the PLE technique with ethanol allowed obtaining extracts with a higher radical reduction capacity (6.30 $\mu\text{M/g}$ solid) compared to the use of water (4.34 $\mu\text{M/g}$ solid) and M with ethanol (2.39 $\mu\text{M/g}$ solid) and with water (2.23 $\mu\text{M/g}$ solid) (Fig. 4). These results agree with the findings of Li et al. (2019) in grape peel extracts and He et al. (2018) in goji berry residues, where PLE was shown to be

Fig. 4 Determination of in vitro antioxidant activity by different techniques (ABTS•+ radical reduction, DPPH, ORAC, and FRAP) of extracts obtained using different extraction techniques and solvents from orange sweet potato peels (OSP). Data represent mean $\pm$ SD ($n=3$). Different letters indicate significant differences between treatments according to Tukey's test ($p < 0.05$). Results are expressed as μM Trolox equivalents per gram of solid ($\mu\text{M TE/g}$). Error bars correspond to standard deviation values. Letters above each bar represent significant differences between extractions obtained ($p < 0.05$)



superior to M in terms of antioxidant activity. This increase in the result can be attributed to the combination of pressure and temperature. In addition, the PLE + ethanol method has better reproducibility than M due to automation. Therefore, the PLE method seems to be a more promising technique for obtaining compounds with high antioxidant activity content from grape peel with a shorter time and a higher yield (Li et al., 2019).

For the ABTS measurements, when the solvent used was water, it is possible to observe how PEF method enhanced the antioxidant capacity ($3.15 \mu\text{M/g}$ solid) compared to the M ($2.23 \mu\text{M/g}$ solid), which could also be observed for the case of plant extracts of carrot and apple peel (Wiktor et al., 2015) and as in orange peel (Luengo et al., 2013).

In the determination of antioxidant activity by the DPPH assay (Fig. 4), the aqueous extract obtained by pulsed electric field (PEF) showed a significantly higher capacity ($0.6217 \mu\text{M/g}$ of solid) compared to the aqueous extracts obtained by conventional M ($0.0313 \mu\text{M/g}$ of solid) and pressurized liquid extraction (PLE) ($0.0072 \mu\text{M/g}$ of solid). These results agree with previous studies carried out on plant matrices, where an increase in the scavenging capacity of the DPPH radical has been reported after treatment with PEF. Representative examples include onion peel (Liu et al., 2018), grape peel (Delso et al., 2022), quince peel (Athanasiadis et al., 2023), and red prickly pear peel, where a 40% to 50% increase in antioxidant capacity was observed (Surano et al., 2022), as well as asparagus treated under similar conditions (Symes et al., 2023).

Regarding ethanolic extracts, the PLE technique demonstrated higher efficiency ($0.0247 \mu\text{M/g}$ of solid) compared to conventional maceration ($0.0016 \mu\text{M/g}$ of solid) (Fig. 4). This behavior is consistent with that reported by Montenegro-Landívar et al. (2021), who showed that PLE extraction significantly improves the antioxidant capacity of plant extracts from spinach, kale, and beet, as well as fruit matrices such as grapes, which exhibited significantly higher DPPH values.

Similarly, Santos et al. (2021) conducted a comparative evaluation of ethanolic and aqueous extracts obtained using the M and PLE methods from *Acca sellowiana* (O. Berg) Burret (feijoa) leaves. They concluded that the extracts generated using PLE exhibited a greater neutralization capacity for DPPH-type free radicals (Fig. 4), thus corroborating the effectiveness of this extraction technique in obtaining bioactive compounds with high antioxidant capacity.

The metal ion chelation capacity represents a relevant parameter for evaluating the antioxidant potential of compounds under different oxidative conditions. In this context, ferric reducing power (FRAP) is one of the most appropriate methodologies for such evaluation. As shown in Fig. 4, aqueous extracts obtained by pulsed electric field (PEF) showed a significantly higher FRAP activity ($1.79 \mu\text{M/g}$

of solids) compared to those obtained by conventional M ($0.54 \mu\text{M/g}$ of solids) and pressurized liquid extraction (PLE) ($0.18 \mu\text{M/g}$ of solids). These results are consistent with those reported in previous studies evaluating polyphenolic extracts obtained from defatted apricot kernel biomass using PEF, where a significant increase in reducing activity (FRAP) was observed (Makrygiannis et al., 2023). Similar findings were described by Athanasiadis et al. (2023) in quince peel extracts treated with PEF, as well as in research conducted on red prickly pear peel (Surano et al., 2022) and asparagus (Symes et al., 2023), where comparable increases in antioxidant capacity were recorded.

In the case of ethanolic extracts, a similar trend was observed: Extracts obtained using the PLE technique presented higher antioxidant activity ($0.85 \mu\text{M/g}$ of solid) compared to those obtained by maceration ($0.27 \mu\text{M/g}$ of solid) (Fig. 4). These results are consistent with previous research, such as that conducted by Grisales-Mejía et al. (2022), who reported higher antioxidant activity in extracts of the endocarp and seed coat of avocado obtained using PLE. Likewise, Viganó et al. (2022) demonstrated that within the same extraction system (PLE), the increase in the concentration of ethanol as a solvent favors the recovery of phenolic compounds with greater antioxidant capacity, evaluated by the FRAP and ORAC assays. This phenomenon is consistent with what was observed in the present study, where, as represented in Fig. 4, the antioxidant capacity of the extracts obtained by PLE increases when using ethanol as a solvent, with the PLE ethanolic extract presenting the highest capacity in ORAC with $16,782.8 \mu\text{M/g}$ of solid.

The presence of phenolic compounds with significant antioxidant potential indicated that these extracts can be used as excellent natural antioxidant agents for industrial applications.

Determination of the Biological Model Antioxidant Capacity of the Extracts

Evaluation of the Effect Based on the Extraction Technique and Solvent Used

In this study, the capacity of different concentrations of OSP peel extracts, obtained by means of various extraction techniques and solvents, to induce antioxidant response in living microorganism (*S. cerevisiae*) was evaluated by obtaining effect curves. When the effect curves are above 1, they suggest a protective capacity of the extract, while curves below 1 indicate a pro-oxidant effect. Figure 5 shows the results obtained from the extracts acquired using different extraction techniques with water as solvent. In the presence of $0.5 \text{ mM H}_2\text{O}_2$, a statistically significant ($p < 0.05$) capacity to induce antioxidant response in yeast was observed after 6 h

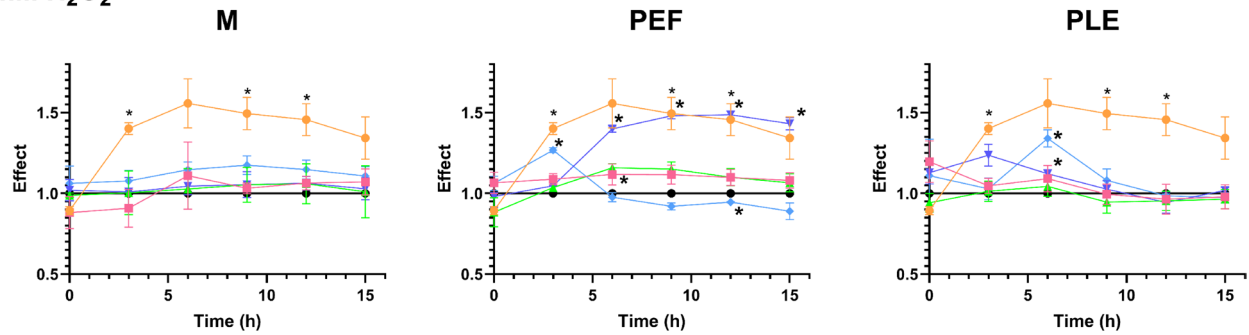
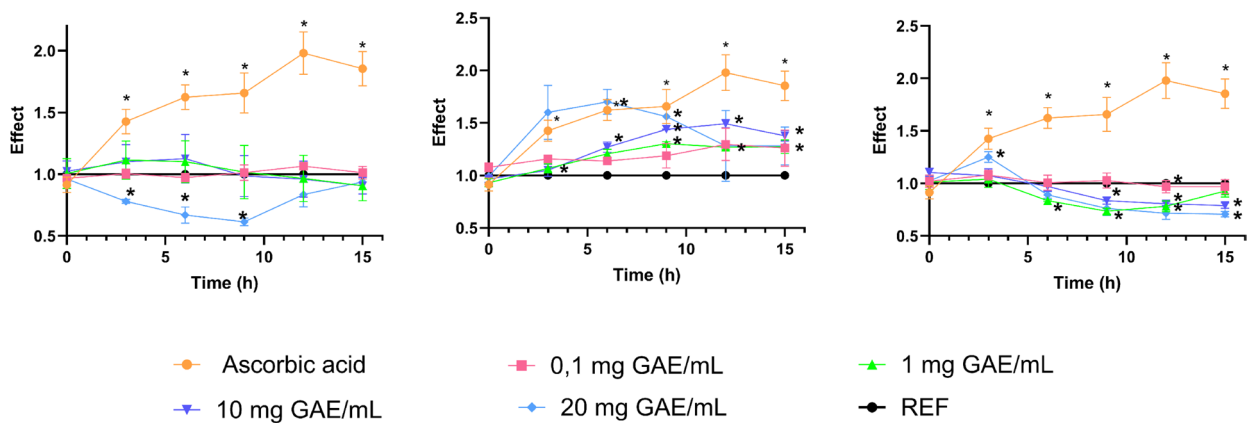
0,5 mM H₂O₂4 mM H₂O₂

Fig. 5 Effect curves of the extracts obtained using water as extraction solvent. Tests exposed *S. cerevisiae* BY4741 cells to 0.5 and 4 mM of oxidative stress with H₂O₂ with different concentrations of the extracts. Results are expressed as effect (OD₆₀₀ ratio) relative to the untreated control. Mean values $\pm$ standard deviation between three

independent tests are represented. The asterisks accompanying the points indicate statistically significant differences with respect to the control without ingredient by ANOVA with $p < 0.05$. M: maceration. PEF: pulsed electric field. PLE: pressurized liquid extraction. GAE: gallic acid equivalent

with concentrations of 10 and 20 mg GAE/mL of the extract obtained by PLE (Fig. 5). On the other hand, the extract obtained by PEF showed a statistically significant protective effect with 10 mg GAE/mL, even surpassing ascorbic acid in the last hours (Fig. 5). We can also observe how in the first hours at a concentration of 20 mg GAE/mL of the extract used, it presents a significantly greater antioxidant capacity.

Under more extreme conditions (4 mM H₂O₂), the extract obtained by M showed a significant pro-oxidant effect with 20 mg GAE/mL (Fig. 6), while the extracts obtained by PLE demonstrated a dual behavior, initially antioxidant and then pro-oxidant (Fig. 6). In contrast, the extracts obtained by PEF maintained a consistent antioxidant effect, especially with 20 mg GAE/mL, surpassing the effectiveness of ascorbic acid in the first hours of the test. In addition, it is also possible to observe how concentrations of 1 and 10 mg GAE/mL presented a statistically significant antioxidant effect in the last hours of the assays (Fig. 5). With all this information exposed it is possible to affirm that when the solvent used in

the extracts is water, the extract that presented the greatest antioxidant capacity was the one obtained by PEF.

Dose–response curves were constructed, evaluating the maximum statistically significant effect obtained for each tested concentration of each extract (Fig. 6). The results show that, when water was the solvent used, under conditions of oxidative stress induced by 0.5 and 4 mM H₂O₂, the PEF-obtained extracts exhibited the highest protective effect. At 0.5 mM H₂O₂, the optimal protection concentration was 10 mg GAE/mL. By increasing the stressor to 4 mM, the maximum protective effect was observed with 20 mg GAE/mL of PEF extracts, followed by the same extract at 10 and 1 mg GAE/mL.

The antioxidant capacity of the extracts obtained with ethanol as extraction solvent was then evaluated. It can be observed that under an oxidative stress of 0.5 mM H₂O₂, the extracts obtained by M (Fig. 7) showed minimal antioxidant protection, even exerting a pro-oxidant effect at 20 mg GAE/mL. In contrast, the PLE extracts (Fig. 7)

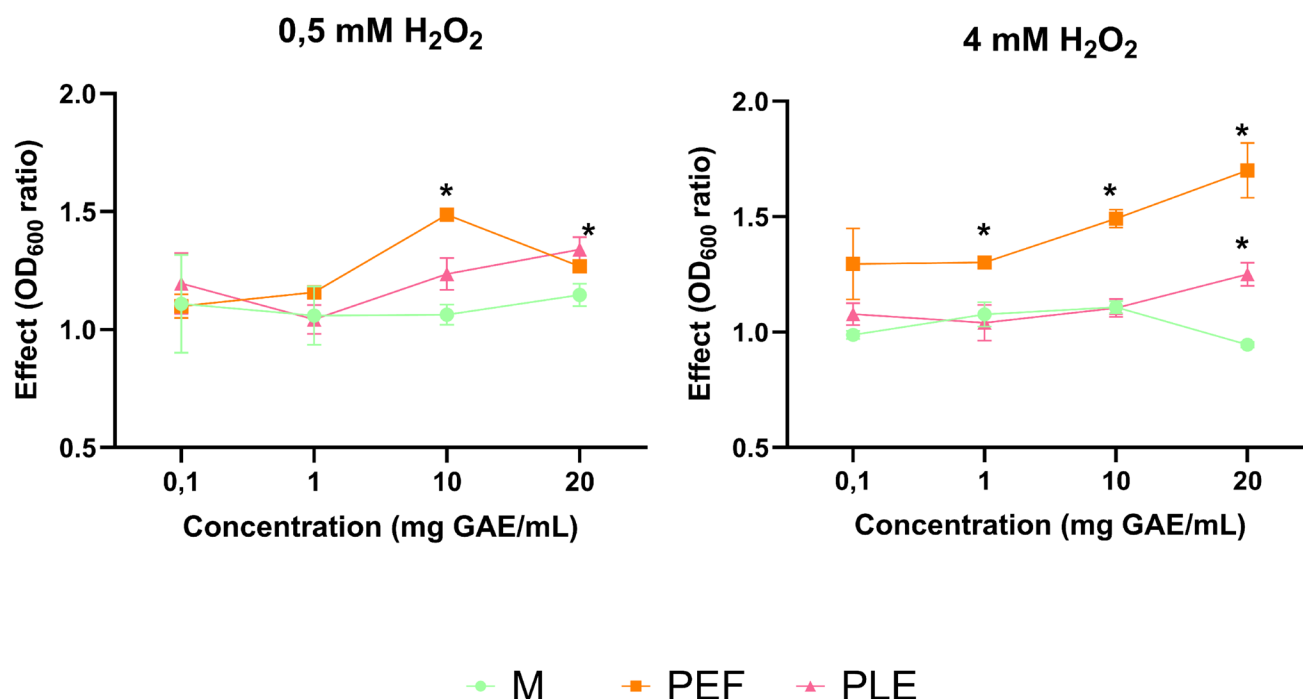


Fig. 6 Dose–response curves of the extracts obtained by different techniques using water as the extraction solvent. The curves were constructed by representing the highest effect value detected in the effect curves for each concentration of the tested extracts. Assays were made at two sublethal concentrations of H₂O₂. Results are

expressed as effect (OD₆₀₀ ratio) relative to the untreated control. Mean values $\pm$ standard deviation between three independent tests are represented. Asterisks indicate significant differences compared to M according to ANOVA ($p < 0.05$). M: maceration. PEF: pulsed electric field. PLE: pressurized liquid extraction. GAE: gallic acid equivalent

demonstrated a significantly higher antioxidant response, especially at 1 mg GAE/mL, with no toxic effects over time. Under an oxidative stress of 4 mM H₂O₂, the M extract at 1 mg GAE/mL showed significant protection up to 6 h, and it can also be seen that at a concentration of 10 and 20 mg GAE/mL it presents a significant pro-oxidant effect (Fig. 7). PLE extracts at 10 mg GAE/mL provided significantly superior and sustained protection over time (Fig. 7). Dose–response curves were generated for the extracts obtained by the M and PLE methods (Fig. 8). From these graphs we can confirm that, when ethanol is used as extraction solvent, at a stress concentration of 0.5 mM H₂O₂, the best antioxidant protection was observed at 1 mg GAE/mL of the PLE extract, and for a concentration of 4 mM H₂O₂, the greatest protection was observed when a concentration of 1 mg GAE/mL of the M extract and a concentration of 10 mg GAE/mL of the PLE extract were used. Regarding the influence of the solvents on the antioxidant effect achieved by the extracts, we see that for the M extraction method, ethanol significantly improves the antioxidant effect achieved by the extract at a concentration of 1 mg GAE/mL, when 4 mM H₂O₂ is used. In the case of the extracts obtained by PLE, ethanol statistically significantly improves the antioxidant effect achieved at the two concentrations of H₂O₂ tested.

This effect is observed at 1 mg GAE/mL of the extract for 0.5 mM H₂O₂ and at a concentration of 10 mg/mL of the extract for 4 mM H₂O₂.

The effectiveness of ethanol and other organic solvents compared to water is due to their superior capacity to break down cell walls and other plant structures, thus facilitating the release of bioactive compounds (Alvarez-Rivera et al., 2020).

When water was used as the extraction solvent, PEF technology produced extracts with superior antioxidant performance, consistent across DPPH, FRAP, and the *Saccharomyces cerevisiae* oxidative stress assays. This enhancement is attributed to the electroporation phenomenon induced by PEF, which increases cell membrane permeability, improving mass transfer of hydrophilic compounds while minimizing thermal degradation (Kumar et al., 2023). The mild extraction conditions also favor the preservation of redox-active structures and facilitate cellular uptake of low-molecular-weight phenolics, explaining their higher antioxidant efficiency in the yeast model.

In contrast, PLE combined with ethanol produced extracts with the highest total phenolic content (TPC) and antioxidant activity, both in vitro and in biological models. This can be explained by the subcritical conditions used (high temperature and pressure), which enhance solvent

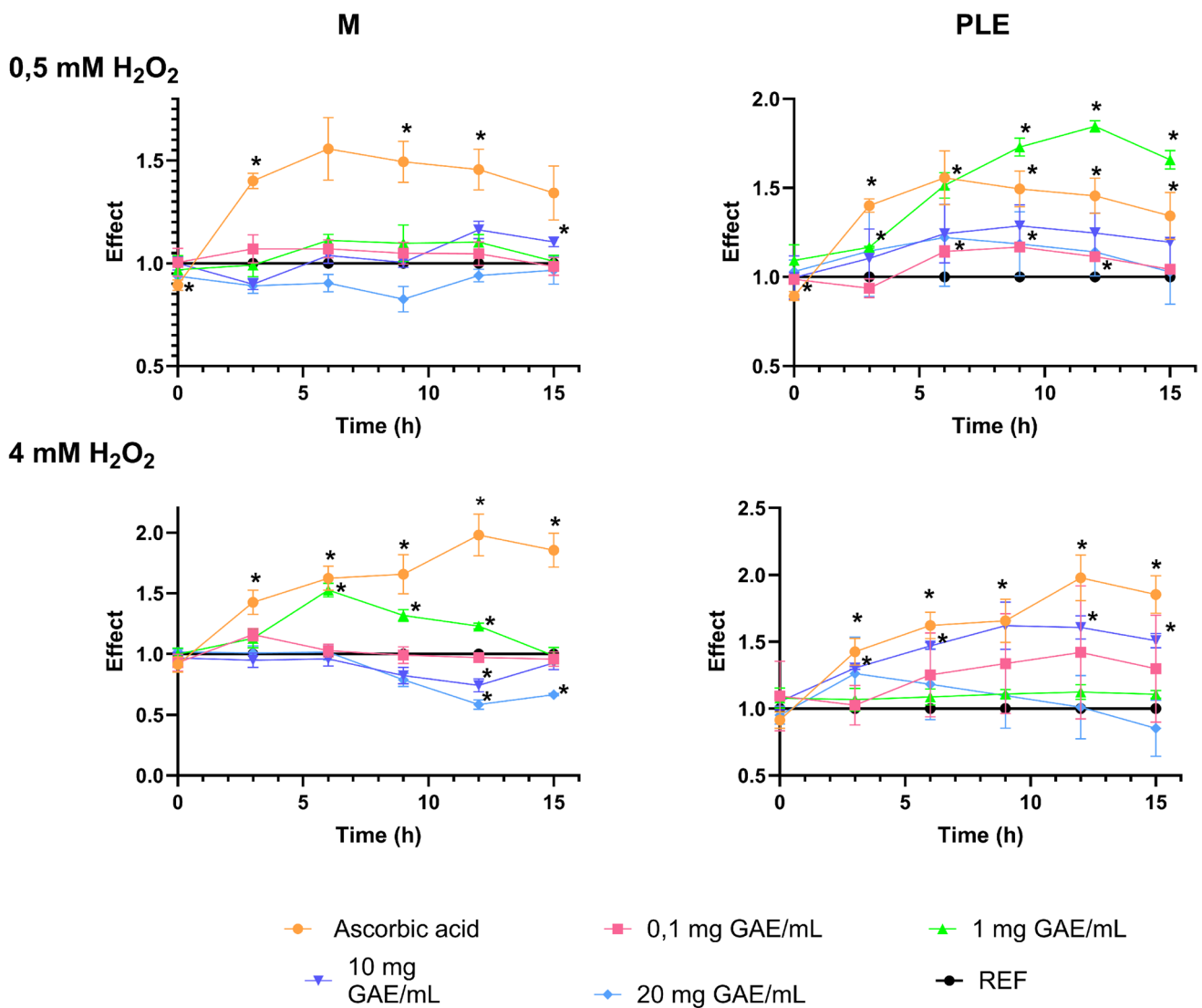


Fig. 7 Effect curves of the extracts obtained using ethanol as extraction solvent. Tests exposed *S. cerevisiae* BY4741 cells to 0.5 mM and 4 mM of oxidative stress with H₂O₂ with different concentrations of the extracts. Results are expressed as effect (OD₆₀₀ ratio) relative to

the untreated control. Mean values $\pm$ standard deviation between three independent tests are represented. The asterisks accompanying the points indicate statistically significant differences with respect to the control without ingredient by ANOVA with $p < 0.05$

diffusivity and desorption of bound phenolics (Alvarez-Rivera et al., 2020). The positive correlation observed between TPC, DPPH, and cellular antioxidant protection confirms the contribution of polyphenols to the biological response.

Previous studies by Bernabeu et al. (2024) and Frontuto et al. (2019) reported similar improvements in TPC and antioxidant activity in sweet potato and potato peels extracted by PEF, while Salgado-Ramos et al. (2023) found that PEF-extracted almond hulls displayed enhanced antioxidant activity versus conventional maceration. Such improvements are associated with the synergistic interaction of multiple phenolic subclasses within the extracts (Karabegović et al., 2014).

The qualitative LC–MS/MS analysis confirmed the presence of several bioactive compounds, including hydroxycoumarin, gingerol, and phenolic terpenes such as thymol and carvacrol, which are known for their combined antioxidant and antimicrobial activity (Ozogul et al., 2024). Additionally, PLE + ethanol extracts exhibited higher concentrations of flavonols (quercetin, kaempferol), consistent with their polarity and stability in ethanol. According to the study by Alugoju et al. (2020), quercetin protects *S. cerevisiae* against oxidative stress by inducing trehalose biosynthesis and activating the cell wall integrity pathway. Its catechol moiety confers greater radical-scavenging ability compared to kaempferol's resorcinol group, which may explain the

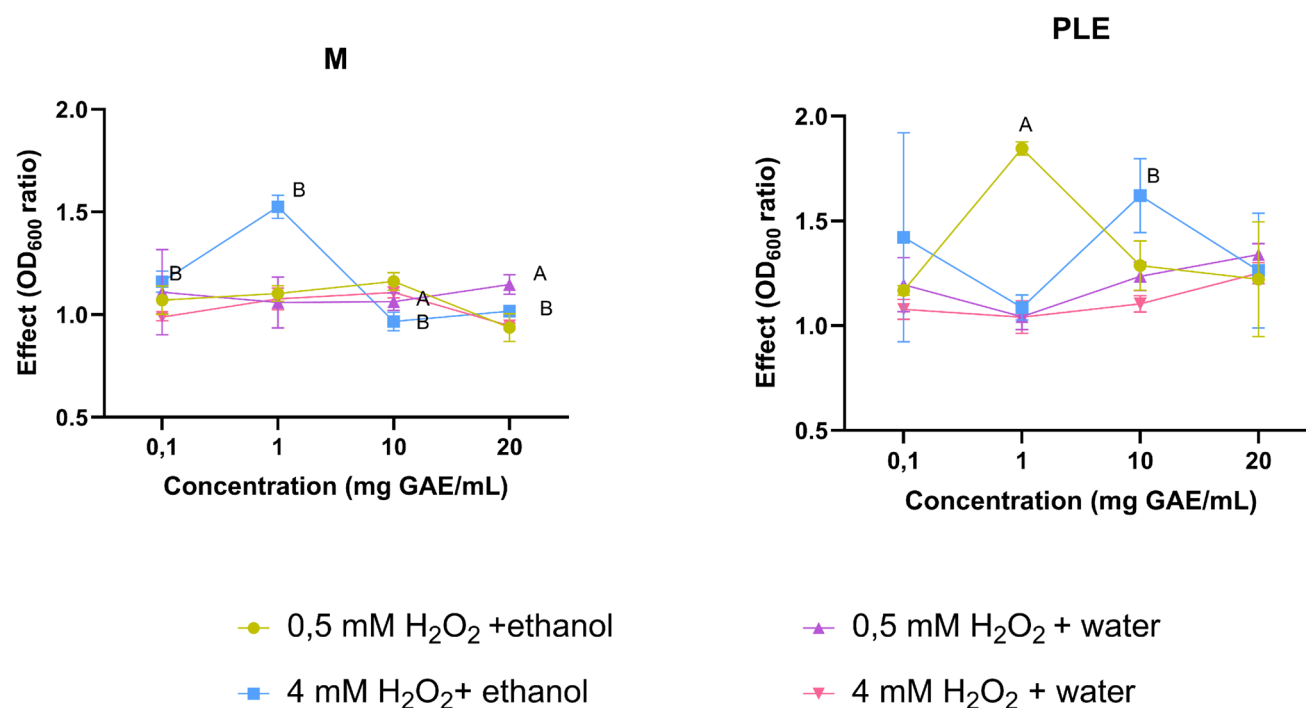


Fig. 8 Dose–response curves for M (maceration) and PLE (presurized liquid extraction) comparing the influence of the solvent on extraction. The curves were constructed by representing the highest effect value detected in the effect curves for each concentration of the tested extracts. Two sublethal concentrations of the stressor were used (0.5 and 4 mM H₂O₂), for the two types of solvent. Results are expressed as effect (OD₆₀₀ ratio) relative to the untreated control.

Mean values $\pm$ standard deviation between three independent tests are represented. Letters A and B indicate statistically significant differences ($p < 0.05$) between the effects of the extracts transported in water and ethanol, evaluated at the same concentration of H₂O₂ (0.5 mM or 4 mM, respectively) using the unpaired Student's *t*-test. Comparisons were made point by point depending on the extract concentration (0.1–20 mg GAE/mL)

superior antioxidant response of PLE + ethanol extracts (Figs. 4, 7, and 8).

A good correlation was observed between TPC values and antioxidant response, especially for PLE + ethanol extracts, suggesting increased bioactivity and redox efficiency under oxidative stress (Bittencourt et al., 2015). It should be noted that the Folin–Ciocalteu assay provides a global estimation of phenolics without distinguishing subclasses; hence, future studies incorporating targeted spectrophotometric or chromatographic quantification of specific groups (flavonoids, anthocyanins, proanthocyanidins) could yield a more comprehensive understanding of their individual contributions.

Finally, regarding dose–response behavior, the effective concentrations determined in the yeast model were 1 mg GAE/mL (0.5 mM H₂O₂) and 10 mg GAE/mL (4 mM H₂O₂) for PLE + ethanol and 10 mg GAE/mL (0.5 mM H₂O₂) and 20 mg GAE/mL (4 mM H₂O₂) for PEF + water extracts. While phenolics are known for their antioxidant benefits, excessive doses can exert pro-oxidant effects (Quetglas-Llabrés et al., 2023); therefore, controlled evaluation of bioactivity and safety remains essential.

To further explore the findings obtained in the biological model with *S. cerevisiae*, the correspondence between

the magnitude of cellular protection and the in vitro chemical assays was analyzed. The PLE–ethanol extracts, which exhibited the highest TPC and ABTS/ORAC values, also showed the most consistent protection in the dose–response curves (Figs. 7 and 8), suggesting that semipolar compounds—such as flavonols and lignans—are likely responsible for the observed intracellular activity. In contrast, the PEF–water extracts, rich in hydrophilic phenolics, displayed better performance in some assays (FRAP, DPPH) and a dose- and time-dependent protection pattern (Fig. 6), indicating differences in bioavailability and/or mechanisms of action among fractions. These results highlight two key factors that modulate the response of the biological model: (i) the affinity of phenolic compounds for membranes and subcellular compartments, which facilitates their interaction with mitochondrial pathways (Peláez-Soto et al., 2017; Quetglas-Llabrés et al., 2023), and (ii) the dose, since higher concentrations may trigger pro-oxidant effects (Mu et al., 2023). Collectively, these findings emphasize the importance of defining optimal concentration windows for each extract to ensure a balance between antioxidant efficacy and cellular safety.

Correlation Between In Vitro and Biological Model Antioxidant Assays

To deepen the interpretation of the biological model findings, we analyzed the correspondence between the magnitude of cellular protection in *Saccharomyces cerevisiae* and the chemical antioxidant assays. ABTS and FRAP showed the strongest correlation with the cellular protection index for PLE–ethanol and PEF–water extracts, respectively, whereas ORAC did not exhibit a consistent relationship across treatments. These differences reflect the mechanistic diversity of the assays: ABTS and DPPH evaluate direct radical-scavenging capacity, FRAP measures reducing and chelating power, and ORAC assesses peroxy radical inhibition. Therefore, the cellular antioxidant response in yeast represents not only radical scavenging but also the compounds' interaction with enzymatic redox systems and their intracellular permeability.

Accordingly, we recommend that future studies aiming to predict cellular antioxidant protection include at least one assay based on reducing capacity (FRAP) and one on radical-scavenging (ABTS or DPPH), together with a peroxy radical indicator (ORAC), to improve biological predictability.

Overall, the distinct physicochemical mechanisms of PEF and PLE explain the compositional and functional differences observed. PEF primarily enhances diffusion-driven extraction via cell membrane electroporation, favoring recovery of hydrophilic and thermolabile phenolics. In contrast, PLE operates through solvent property modulation under controlled temperature and pressure, facilitating solubilization of both polar and semi-polar compounds while minimizing oxidative degradation (Alvarez-Rivera et al., 2020; Kumar et al., 2023). These complementary mechanisms account for the differentiated phenolic profiles and the consistent antioxidant protection observed in the yeast-based biological model for PEF–water and PLE–ethanol extracts.

As shown in Figs. 4, 5, 6, 7, and 8, a strong agreement was found between DPPH and FRAP values and the total antioxidant capacity (TAC) measured through the yeast model. Extracts obtained by PEF–water and PLE–ethanol exhibited the highest TAC, mirroring their superior protection against oxidative stress compared to other extraction techniques. This result is particularly relevant given that multiple in vitro assays were used to mitigate methodological variability, as previously recommended. The consistent alignment between in vitro and biological responses suggests that specific chemical assays can serve as reliable predictors of biological antioxidant efficacy, streamlining screening efforts and improving comparability.

Among all treatments, the PLE–ethanol extract displayed the highest concordance between in vitro and biological results, consistent with its elevated content of quercetin and

related derivatives. The ortho-dihydroxyl group and the hydroxyl substituent at position 3 of quercetin confer strong electron-donating capacity, explaining its high antioxidant performance, whereas glycosylation generally reduces activity (Villaño et al., 2005). Pinoresinol was also identified as a major phenolic in both PLE–ethanol and PEF–water extracts. For PLE, the clear correspondence between in vitro and yeast-model TAC aligns with recent studies demonstrating antioxidant effects of pinoresinol through ROS attenuation and mitochondrial protection in mammalian cells (Hasanein et al., 2024). Conversely, the lower concordance in PEF extracts may stem from differences in compound polarity and intracellular bioavailability, which can influence the capacity to modulate redox signaling.

Although a strong correlation between DPPH and ABTS has been reported for matrices such as garlic and onion (Číž et al., 2010), grape (Göktürk Baydar et al., 2007) and vegetables like broccoli and spinach (Montenegro-Landívar et al., 2021), this trend was not uniformly observed in orange sweet potato peel extracts. Such divergence likely reflects matrix-specific compositional variability and synergistic or antagonistic effects among phenolic subclasses.

From a sustainability standpoint, both PEF and PLE represent eco-efficient alternatives to conventional extraction. PEF requires low temperature and short treatment time, minimizing degradation and energy input, while PLE enables solvent recycling under moderate pressure and temperature, reducing solvent consumption and waste. Despite higher equipment costs, both technologies offer reduced operational time, energy demand, and environmental footprint, reinforcing their alignment with green extraction principles. Future studies should quantify energy efficiency and life cycle impacts to further validate the eco-innovation potential of these extraction systems (Kumar et al., 2023).

Limitations of the Yeast Model

Although *Saccharomyces cerevisiae* is a widely used eukaryotic model for investigating cellular responses to oxidative stress, certain considerations should be taken into account when extrapolating these findings to human biological systems. Comparative analyses of pathway conservation between yeast and human tissues indicate that this model is particularly suitable for the study of fundamental and evolutionarily conserved cellular processes, whereas highly tissue-specific mechanisms are only partially represented (Mohammadi et al., 2015).

From a structural and physiological perspective, yeast differs from mammalian cells in aspects such as the presence of a rigid cell wall and variations in plasma membrane lipid composition, which may modulate membrane permeability and intracellular availability of phenolic compounds. These

characteristics should be considered when interpreting the magnitude of the observed antioxidant responses (Lu et al., 2022).

In this context, yeast-based assays can be regarded as a robust first-tier biological screening tool, especially suitable for assessing intracellular antioxidant capacity in a well-controlled eukaryotic system. Nevertheless, the extrapolation of the observed effects to more complex physiological settings requires subsequent validation in mammalian cell lines or other relevant biological models, particularly when potential implications for human biology or therapeutic applications are considered (Lu et al., 2022; Peláez-Soto et al., 2020; Silveira Coelho et al., 2019).

Conclusions

This study demonstrated that green extraction technologies, namely, pulsed electric fields (PEFs) and pressurized liquid extraction (PLE), are effective eco-sustainable approaches for recovering polyphenolic compounds with antioxidant activity from orange sweet potato (*Ipomoea batatas* L.) peels. The antioxidant capacity of the extracts was assessed through both in vitro assays and a *Saccharomyces cerevisiae* biological model, revealing consistent and complementary results.

Ethanol was identified as the most efficient solvent, yielding phenolic-rich extracts with superior antioxidant activity, particularly when combined with PLE. A strong correlation was observed between in vitro assays (ABTS, ORAC, FRAP, and DPPH) and the biological model responses, especially for PLE–ethanol extracts, highlighting their enhanced bioactivity under oxidative stress conditions. Similarly, PEF–water extracts exhibited notable antioxidant protection, confirming the effectiveness of PEF for recovering hydrophilic phenolics.

These results confirm that both PEF and PLE enable efficient valorization of sweet potato peel by-products into high-value antioxidant extracts. The phenolic profile, characterized by compounds such as quercetin, kaempferol, and pinoresinol, likely underlies the observed antioxidant potential. From a sustainability standpoint, these technologies support circular bioeconomy strategies by minimizing solvent use and energy demand while converting agricultural waste into functional ingredients for food, nutraceutical, or cosmetic applications.

Future work should extend these findings to mammalian cell models and in vivo systems to validate the bioavailability and physiological effects of these extracts in more complex biological contexts.

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Data Availability The data that support the findings of this study are available on request from the corresponding author.

Declarations

Conflict of Interest The authors declare no competing interests.

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