

Article

Pulsed Electric Fields and Ultrasound-Assisted Extraction of Bioactive Compounds from Buriti (*Mauritia flexuosa* L.) Pulp: Antioxidant Potential, Microbial Effects and Cytocompatibility

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Abstract

Buriti (*Mauritia flexuosa* L.) is a native Brazilian fruit recognized for its high content of carotenoids and phenolic compounds, which confer considerable nutraceutical value. This study investigated the effects of pulsed electric field (PEF) and ultrasound (US), applied separately and in combination, on the recovery of bioactive compounds from freeze-dried buriti pulp. The resulting extracts were evaluated for colorimetric characteristics, total phenolic content (TPC), β -carotene, pro-vitamin A, and antioxidant activity by ABTS, DPPH, and FRAP assays, with β -carotene additionally quantified by UHPLC. Ultrasound at 100% intensity promoted the highest TPC recovery (301.28 mg GAE L⁻¹) and enhanced β -carotene extraction, reaching 13.2 mg g⁻¹ dry mass, compared with 9.9 mg g⁻¹ dry mass in the agitation control. FRAP values ranged from 7.7 to 10.1 μ mol Fe²⁺ E g⁻¹ dry mass, with PEF treatments generally showing lower antioxidant capacity, whereas ultrasound maintained values comparable to the control. In contrast, isolated and combined PEF treatments reduced β -carotene recovery (2.7–7.3 mg g⁻¹ dry mass), particularly at higher field intensity, suggesting degradation of carotenoids. Most treatments preserved the characteristic orange coloration of buriti extracts, with ΔE^* values below 5, indicating no visually perceptible color changes. The extracts did not inhibit probiotic or pathogenic bacteria at the tested concentration, although stimulation of *Lactobacillus acidophilus* growth was observed. Cytotoxicity assays demonstrated low toxicity toward HDFa cells, with viability values generally above 80%. The results indicate that high-intensity ultrasound is a promising strategy for recovering bioactive compounds from buriti pulp, while PEF application requires optimization to prevent degradation of sensitive phytochemicals.

Keywords: carotenoids; antioxidant capacity; probiotic bacteria; Cerrado fruits



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1. Introduction

Bioactive compounds are widely distributed in plants, algae, microorganisms, fruits, animals, and even insects. Among them, carotenoids constitute an important class of natural pigments that have attracted considerable attention because of their health-promoting properties [1] and their broad range of industrial applications, including cosmetics [2], natural food colorants [3], and nutraceuticals [4].

Chemically, carotenoids are tetraterpenoids formed by the condensation of isoprene units [5]. They are classified into two main groups: carotenes, which are hydrocarbon carotenoids (e.g., α -carotene, β -carotene, and lycopene), and xanthophylls, which are oxygenated carotenoids (e.g., lutein, zeaxanthin, and astaxanthin) [6]. Both groups are characterized by an extended system of conjugated double bonds, which is responsible for their antioxidant activity, photoprotective function, and characteristic coloration, ranging from yellow to orange and deep red due to light absorption between 400 and 500 nm [7,8]. In plants, carotenoids play an essential role in photosynthesis by harvesting light energy and protecting the photosynthetic apparatus against photo-oxidative damage [7].

Several native fruits from the Brazilian Cerrado biome, including cagaita (*Eugenia dysenterica*), pequi (*Caryocar brasiliense*), buriti (*Mauritia flexuosa*), and araticum (*Annona crassiflora*), are recognized for their high nutritional value and abundance of bioactive compounds, particularly carotenoids [9]. Among these species, buriti has received considerable attention because of its exceptionally high carotenoid content and associated functional properties. Previous studies have demonstrated that buriti bioactive compounds exhibit antioxidant, anti-inflammatory, anticarcinogenic, neuroprotective, and gut microbiota-modulating activities, highlighting their potential for food and pharmaceutical applications [10–12]. Nevertheless, despite its well-established chemical composition and antioxidant potential, studies focused on optimizing the extraction of bioactive compounds from buriti pulp remain limited [13].

Recent research has increasingly focused on combining emerging technologies to improve the extraction of bioactive compounds from different food matrices by increasing extraction efficiency while reducing processing time and energy consumption [14]. Among these technologies, ultrasound (US) has proven to be an effective technique for enhancing carotenoid recovery through cavitation-induced cell disruption, leading to shorter extraction times and higher extraction yields [15,16]. Moreover, ultrasound has been successfully combined with green solvents [12,17,18] or applied as a pretreatment prior to sequential extraction processes to further improve extraction efficiency [19].

Pulsed electric field (PEF) is another emerging non-thermal technology that has attracted considerable attention as a sustainable approach for the extraction of bioactive compounds from food materials [20]. The technique involves the application of short, high-intensity electric pulses that promote electroporation of cell membranes, thereby increasing membrane permeability and enhancing the release and mass transfer of intracellular constituents. Consequently, PEF can improve extraction efficiency while minimizing the degradation of heat-sensitive bioactive compounds [21].

Therefore, the aim of this study was to perform an exploratory evaluation of selected pulsed electric field (PEF) and ultrasound (US) processing conditions, applied individually and sequentially, to investigate their influence on the extraction of bioactive compounds from freeze-dried buriti pulp. Rather than optimizing the extraction process, this study sought to identify preliminary trends regarding the effects of these emerging technologies and to provide a basis for future optimization studies.

2. Materials and Methods

2.1. Chemicals and Cultures

ABTS (2,2'-azino-bis-(3-ethylbenzothiazoline-6-sulfonic acid) diammonium salt), DPPH (1,1-diphenyl-2-picrylhydrazyl radical), Trolox (6-hydroxy-2,5,7,8 tetramethylchroman-2-carboxylic acid), resazurin (7-hydroxy-3H-phenoxazine-3-one 10-oxide; catalog number: R7017) Folin–Ciocalteu reagent, pepsin, pancreatin, bile extract, kanamycin sulfate, and ampicillin sodium salt were obtained from Sigma-Aldrich Chemical, S.A. Ferrous sulfate (iron(II) sulfate, 99% purity; VETEC); 2,4,6-tris(2-pyridyl)-s-triazine (TPTZ, 99% purity; Sigma-Aldrich); ferric chloride (iron(III) chloride, 99.5% purity; Synth); sodium acetate (99% purity; Química Moderna); concentrated hydrochloric acid (HCl, 36.5–38% purity; Êxodo Científica); HPLC-grade methanol (MeOH, ACS grade); HPLC-grade methyl tert-butyl ether (MTBE; Sigma-Aldrich); YMC™ Carotenoid HPLC column (5.0 µm, 4.6 × 250 mm; Waters); and β-carotene standard (95% purity; Sigma-Aldrich). The other chemicals, solvents, and solids were of analytical grade. Aqueous solutions were prepared using ultrapure water (Millipore, São Paulo, Brazil). The culture mediums MRS (man rogosa and sharpe) agar, MRS (man rogosa and sharpe) broth, BHI (brain heart infusion) agar, and BHI (brain heart infusion) broth were obtained from Kasvi.

HDFa cells obtained from (Life Technologies, Inc.) were cultured in an incubator at 37 °C with an atmosphere containing 5% CO₂ in DMEM culture medium (Dulbecco's modified Eagles medium; Life Technologies, Inc.) supplemented with 5 mM sodium bicarbonate (Merck), 10% fetal bovine serum (FBS, Gibco), 100 units of penicillin g/mL, and 100 units of streptomycin g/mL (PS, Gibco).

2.2. Prepare of the Sample

The liquid buriti (*Mauritia flexuosa* L. f.) pulp was obtained from the municipal market Ver-o-Peso (Bélem-PA) with geographic coordinates (1°27'08.7" S 48°30'13.6" W). After that, it was frozen in an ultrafreezer (−80 °C) (ColdLab, CL580-86V) and was freeze-dried in a lyophilizer (TERRONI, LH 401 B) using a heating ramp of 15 °C for 1 h, followed by 35 °C for 4 h. The final lyophilized material presented 11.58% (±0.06) of dry mass.

2.3. Prepare of the Extracts with Coupled Applied Emergent Technologies

An extraction was conducted using agitation only, as a control, on a magnetic stirrer at room temperature, where the dry pulp was added with ethanol in a proportion of 1:10 (dry mass:solvent), then followed by agitation for 10 min. For the treatment of pulsed electric field, the dry pulp was added to a cuvette, then placed in the system using 6 kV and 8 kV and 6000 pulses, and the ethanol was added in a proportion of 1:10 (dry mass:solvent). The pulsed electric field (PEF) treatments were performed using a laboratory-scale system designed and assembled by our research group. For the treatment of probe ultrasound (Ultronique, Desruptor T5), the dry pulp was added to a beaker with ethanol in the proportion of 1:10 (dry mass:solvent), followed by ultrasound treatments of 30 and 100% potency (respectively, 255 and 850 W) at a fixed frequency (20 kHz), continuous pulse, and probed (13 mm) for 1 min.

For the combined treatments, pulsed electric field (PEF) was initially applied, followed by ultrasound-assisted extraction. Briefly, the dried buriti pulp was mixed with ethanol at a ratio of 1:10 (dry mass) and transferred to the treatment cuvette. The samples were then subjected to PEF treatment using 6 or 8 kV and 6000 pulses. After PEF application, the samples were immediately submitted to ultrasound treatment using a probe system at 30 or 100% power (255 and 850 W, respectively), a fixed frequency of 20 kHz, continuous pulse mode, and a 13 mm probe for 1 min.

All the samples were centrifuged at $3.194 \times g$ at 4 ± 1 °C, and the supernatant was collected and used for the following analysis. For colorimetric, total phenolic content, and antioxidant capacity (ABTS and DPPH methods) analysis, the final ethanolic extract was used. For pro-vitamin A and the effect of extracts in bacterial growth, the extracts were oven-dried at room temperature 25 ± 1 °C and suspended as described further in each method.

The processing conditions evaluated in this study were selected based on preliminary laboratory trials and the operational limits of the available equipment. Preliminary experiments indicated that ultrasound treatments at higher power levels promoted excessive degradation of the extracts and hindered solvent removal during post-processing. In addition, the PEF equipment allowed operation only between 6 and 8 kV, which defined the voltage range investigated. Therefore, the selected treatments should be interpreted as representative exploratory conditions rather than an optimized processing design.

2.4. Colorimetric Analysis

The colorimetric analysis was performed using a Hunterlab ColorQuest XE dual beam xenon flash spectrophotometer to determine the measures of L^* (black = 0; white = 100), a^* (red +; green −), and b^* (yellow +; blue −) parameters as described by Rigolon et al. (2020) [22], then calculate the chroma index (C^*) by Equation (1), the hue angle (h°) by Equation (2), and the color difference (ΔE^*) by comparing the color parameters of each treated extract with those of the agitation control extract, which was used as the reference sample, according to Equation (3):

$$\text{Chroma index } (C^*) \quad C^* = \sqrt{(a^*)^2 + (b^*)^2} \quad (1)$$

$$\text{Hue angle } (h^\circ) \quad h^\circ = \tan^{-1} \left(\frac{b^*}{a^*} \right) \quad (2)$$

$$\text{Color difference } (\Delta E^*) \quad \Delta E^* = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2} \quad (3)$$

For this analysis, the samples were read directly at 420 nm wavelength in a quartz cuvette ($45 \times 12.5 \times 12.5$ mm).

2.5. Pro-Vitamin a Content

The determination of pro-vitamin A was made according to the indirect method of Aremu and Nweze (2017) [23], with modifications. Briefly, a standard curve of β -carotene (100, 50, 45, 40, 35, 30, 25, 20, 15, 10 $\mu\text{g mL}^{-1}$) ($y = 0.2529x - 0.0043$) ($R^2 = 0.97$) in ethanolic hexane solution (80:20) was made, and the absorbances were recorded at 450 nm using a microplate reader (SpectraMax iD3, Molecular Devices). Then, 1 mL of the samples was oven-dried at room temperature (25 ± 1 °C) and suspended in 1 mL of ethanolic hexane solution (80:20). For this analysis, the ethanolic hexane solution (80:20) was used as a blanket. After the measurements, the value was applied to the standard curve of β -carotene, and the conversion of β -carotene to retinol was conducted using Equation (4) below:

$$12 \mu\text{g of betacarotene} = 1 \mu\text{g of retinol activity equivalent (RAE)} \quad (4)$$

2.6. Total Phenolic Content

The total phenolic content of the extracts was determined according to the Folin–Ciocalteu procedure described by Singleton and Rossi (1965) [24], with minor modifications. An aliquot of 100 μL of diluted ethanolic extract was mixed with 500 μL of 7.5% sodium carbonate solution. After 3 min, 400 μL of Folin–Ciocalteu reagent previously diluted (1:10, v/v) was added. The reaction mixture was protected from light and allowed to stand for

1 h before measuring the absorbance at 760 nm using a microplate reader (SpectraMax iD3, Molecular Devices). Gallic acid was used for calibration ($y = 107.74x + 2.1879$; $R^2 = 0.99$), and the results were expressed as mg gallic acid equivalents per liter of ethanolic extract (mg GAE L^{-1}).

2.7. Antioxidant Capacity

2.7.1. ABTS Assay

Antioxidant activity was determined using the ABTS radical cation assay following Re et al. (1999) [25], with slight modifications. The $\text{ABTS}^{\bullet+}$ solution was prepared by combining equal volumes of 7 mM ABTS and 2.45 mM potassium persulfate and allowing the mixture to react. Before analysis, the radical solution was diluted with 80% ethanol to an absorbance of 0.700 ± 0.005 at 734 nm. Subsequently, 500 μL of diluted sample was mixed with 3.5 mL of the $\text{ABTS}^{\bullet+}$ solution and incubated for 6 min. Absorbance was measured at 734 nm using a SpectraMax iD3 microplate reader (Molecular Devices). Antioxidant activity was expressed as μmol Trolox equivalents per milliliter of ethanolic extract ($\mu\text{mol TE mL}^{-1}$).

2.7.2. DPPH Assay

The DPPH radical scavenging activity was evaluated according to Kim et al. (2002) [26], with modifications. A 0.01 mM DPPH solution was prepared in 80% ethanol and sonicated for 10 min to ensure complete dissolution. The solution was then adjusted with 80% ethanol until reaching an absorbance of 0.700 ± 0.005 at 517 nm. Aliquots of 500 μL of diluted extract were mixed with 3.5 mL of the DPPH solution and kept in the dark for 1 h. Absorbance was subsequently recorded at 517 nm using a SpectraMax iD3 microplate reader (Molecular Devices). Trolox was used as the calibration standard, and the results were reported as μmol Trolox equivalents per milliliter of ethanolic extract ($\mu\text{mol TE mL}^{-1}$).

2.7.3. FRAP Assay

Ferric reducing antioxidant power (FRAP) was assessed according to Morais et al. (2013) [27], as adapted by Cândido et al. (2015) [28]. The FRAP working reagent was freshly prepared by mixing 0.3 M acetate buffer, 10 mM TPTZ, and 20 mM ferric chloride at a volumetric ratio of 10:1:1. For the assay, 8 μL of diluted sample, 24 μL of distilled water, and 240 μL of FRAP reagent were combined and incubated at 37 ± 1 °C for 30 min. Absorbance was measured at 595 nm using a Multiskan SkyHigh microplate reader (Thermo Fisher Scientific). Four sample dilutions were analyzed to generate the sample response curve, while ferrous sulfate served as the external calibration standard. The antioxidant capacity was expressed as $\mu\text{mol Fe}^{2+}$ equivalents per gram of dry mass ($\mu\text{mol Fe}^{2+} \text{g}^{-1}$).

2.8. Determination of β -Carotene by UHPLC

UHPLC analysis was performed according to the method described by Paes et al. (2019) [29], with minor modifications. Briefly, 1 mL of each extract was dried at room temperature (25 °C). The dried residue was then reconstituted in a mixture of methyl tert-butyl ether (MTBE) (MeOH) (80:20, v/v) to obtain a final extract concentration of 10 mg mL^{-1} . The solutions were filtered through a 0.22 μm PTFE membrane into amber UHPLC vials prior to analysis. A β -carotene calibration curve was prepared in MTBE (80:20, v/v) at concentrations ranging from 2.5 to 100 $\mu\text{g mL}^{-1}$ ($y = 894.62x - 1.7528$; $R^2 = 0.98$). A 20 μL aliquot of each sample was injected into a UHPLC system (Dionex Ulti-Mate 3000, Thermo Scientific, Chromeleon 7 software) equipped with a YMCTM Carotenoid column (5.0 μm , 4.6×250 mm; Waters), maintained at 30 °C. The mobile phase flow rate was 1.0 mL min^{-1} , using a binary solvent gradient consisting of solvent A (MeOH water, 95:5, v/v) and solvent B (MTBE) over a total run time of 50 min as follows: 0–5 min, 100%

A/0% B; 5–25 min, 45% A/55% B; 25–35 min, 10% A/90% B; 35–40 min, 10% A/90% B; 40–42 min, 100% A/0% B; and 42–50 min, 100% A/0% B. Detection was performed using a UV detector at 448 and 450 nm. β -Carotene was identified by comparison of its retention time with that of the external standard and quantified using the calibration curve. The results were expressed as mg of β -carotene g⁻¹ dry mass.

2.9. Effect of Extracts in Bacterial Growth

The effects of buriti extracts on bacterial growth were investigated according to the method described by Alcántara et al. (2020) [30], with minor modifications. Four probiotic bacterial strains from the LHMA culture collection were evaluated: *Lactococcus lactis*, *Lactiplantibacillus plantarum* ATCC 8014, *Lacticaseibacillus rhamnosus* ATCC 53103, and *Lactobacillus acidophilus* SACC0. In addition, four foodborne pathogenic strains were included, comprising two Gram-positive bacteria (*Staphylococcus aureus* ATCC 14458 and *Bacillus cereus* ATCC 10876) and two Gram-negative bacteria (*Escherichia coli* ATCC 20214 and *Pseudomonas fluorescens* ATCC 13525). Prior to the assays, probiotic cultures were activated on MRS agar under anaerobic conditions at 37 ± 1 °C for 24 h, transferred to MRS broth, and incubated again under the same conditions. The pathogenic strains were activated on brain heart infusion (BHI) agar at 37 ± 1 °C for 24 h, followed by cultivation in BHI broth for an additional 24 h at the same temperature.

To evaluate the effect of buriti extracts, 500 µL of the ethanolic extracts were oven-dried at room temperature 25 ± 1 °C, followed by suspension in distilled water to reach a concentration of 2 mg mL⁻¹, then the samples were pasteurized at 65 ± 1 °C for 30 min, and 100 µL was added to 100 µL of specific culture medium (MRS and BHI broths in double concentration).

The cell suspension was measured and diluted with 0.85% saline solution to range between 0.08 and 0.10 at 600 nm (corresponding to Mc Farland 0.5) in a UV–VIS spectrophotometer (BEL Photonics, UV-M51), then 10 µL of the cultures were added to the microplates, followed by incubation in the microplate reader at 37 ± 1 °C for 48 h (SpectraMax iD3, Molecular Devices).

2.10. Assessment of Cell Viability by Resazurin Assay

Cell viability was assessed using resazurin (7-hydroxy-3H-phenoxazin-3-one 10-oxide, catalog number R7017, Sigma-Aldrich), a blue weakly fluorescent dye that is reduced to resorufin, a pink fluorescent compound, by metabolically active cells. HDFa cells were seeded in 96-well plates at a density of 2 × 10⁴ cells/well with 0.1 mL of DMEM culture medium. After 24 h of stabilization, cells were treated with buriti extracts at a concentration of 500 µg/mL, calculated based on the dry mass of the extracts. Prior to cell exposure, extracts were solubilized in DMSO (catalog number D8418, Sigma-Aldrich). After 24 h of incubation at 37 °C and 5% CO₂, the culture medium was removed and replaced with a solution containing basal culture medium and resazurin (0.5 mg/mL), followed by incubation for 4 h under the same conditions. Optical density was measured at 570 nm using a Multiskan GO microplate reader (Thermo Scientific). To correct for possible interference from the extracts and culture medium in the resazurin assay, absorbance values obtained from wells without cells were used as blanks and subtracted from the corresponding readings. HDFa cells treated with 0.5% Triton X-100 (Sigma-Aldrich) were used as a positive control for cell death induction due to plasma membrane permeabilization [31].

2.11. Statistical Analysis

The extraction procedure was performed using two independent biological replicates. Each extract was subsequently analyzed in triplicate for all physicochemical, antioxidant, microbiological, and cytotoxicity assays. The results were subjected to analysis of variance

(ANOVA) and Tukey's test (with a significance level of $p < 0.05$), expressed as mean $\pm$ standard deviation (S.D.), using the Jamovi software (version 2.3.28 for Windows).

3. Results and Discussion

3.1. Colorimetric Analysis

Following the extraction process, all samples exhibited an intense orange coloration, which is characteristic of the high carotenoid content of buriti pulp. This coloration is mainly attributed to β -carotene, the predominant carotenoid and one of the major antioxidant compounds naturally present in buriti (*Mauritia flexuosa* L.) [32].

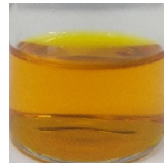
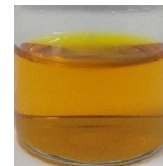
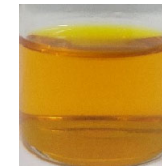
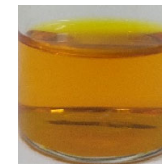
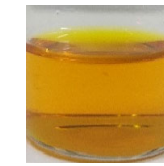
The colorimetric parameters are presented in Table 1. As expected for carotenoid-rich extracts, positive values of a^* and b^* were observed, corresponding to the red and yellow color coordinates, respectively. The a^* values ranged from 16.03 ± 0.18 in the control treatment (agitation only) to 17.09 ± 0.08 in the ultrasound treatment at 100% amplitude. Similarly, the b^* values varied from 35.52 ± 0.45 for the 8 kV PEF treatment to 37.18 ± 1.25 for ultrasound at 30% amplitude. The chroma (C^*), which reflects color saturation, ranged from 39.10 to 40.59, indicating highly saturated orange-colored extracts. Likewise, the hue angle (h°) ranged from 64.82° to 66.34° , corresponding to the yellow-orange region of the CIELAB color space, which is characteristic of carotenoid-rich matrices.

The color parameters obtained in this study are consistent with those reported for buriti-derived products. Marcelino et al. [32] reported L^* , a^* , b^* , C^* , and h° values of 43.87, 26.73, 22.16, 34.72, and 72.99° , respectively, for buriti oil, whereas De Souza Carvalho et al. [33] reported L^* values between 57 and 70, a^* values between 13 and 18, and b^* values between 34 and 40 for ultrasound-processed buriti juice. Although differences among these products are expected because of their distinct compositions and processing conditions, the color profiles observed in the present study remained within the characteristic range reported for buriti products.

The total color difference (ΔE^*) was lower than 5 for all treatments, indicating that the color changes were not perceptible to the human eye when compared with the control treatment (agitation only). In contrast, De Souza Carvalho et al. [33] reported ΔE^* values ranging from 10 to 15 in ultrasound-treated buriti juice, which was associated with the oxidation of bioactive compounds. The lower ΔE^* values observed in the present study suggest that pulsed electric field, ultrasound, and their combined application preserved the natural pigments of buriti extracts, minimizing color degradation during processing.

Overall, the color stability observed after the different extraction treatments indicates that the emerging technologies evaluated did not adversely affect the visual quality of the extracts. Since carotenoids are the main pigments responsible for the characteristic orange color of buriti, the preservation of color may also indicate limited degradation of these bioactive compounds during extraction. Nevertheless, complementary analyses of carotenoid composition are necessary to confirm the relationship between color preservation and carotenoid stability.

Table 1. Results of colorimetric analysis of ethanolic extracts of buriti pulp (*Mauritia flexuosa* L.).

PARAMETERS	TREATMENTS								
	Control	Uncoupled Technologies				Coupled Technologies			
	Agitation	Ultrasound (30%)	Ultrasound (100%)	PEF (6 kV)	PEF (8 kV)	PEF (6 kV) + Ultrasound (30%)	PEF (8 kV) + Ultrasound (30%)	PEF (6 kV) + Ultrasound (100%)	PEF (8 kV) + Ultrasound (100%)
L*	45.50 ± 0.01 ^a	45.58 ± 0.001 ^a	45.05 ± 0.29 ^a	45.98 ± 0.92 ^a	45.47 ± 0.01 ^a	45.12 ± 0.15 ^a	45.67 ± 0.09 ^a	45.59 ± 0.50 ^a	45.96 ± 0.22 ^a
a*	16.03 ± 0.21 ^b	16.58 ± 0.16 ^{ab}	16.35 ± 0.21 ^{ab}	16.27 ± 0.01 ^{ab}	17.09 ± 0.10 ^a	16.50 ± 0.57 ^{ab}	16.92 ± 0.13 ^a	17.02 ± 0.13 ^a	16.77 ± 0.49 ^{ab}
b*	36.35 ± 0.01 ^a	35.96 ± 1.29 ^a	35.52 ± 0.55 ^a	37.18 ± 1.53 ^a	36.96 ± 1.2 ^a	35.55 ± 0.39 ^a	36.46 ± 0.03 ^a	36.35 ± 0.59 ^a	36.91 ± 0.2 ^a
C*	39.72 ± 0.08 ^a	39.60 ± 1.24 ^a	39.10 ± 0.42 ^a	40.59 ± 1.4 ^a	40.16 ± 0.07 ^a	39.19 ± 0.59 ^a	40.19 ± 0.03 ^a	40.13 ± 0.68 ^a	40.54 ± 0.03 ^a
h°	66.21 ± 0.29 ^{ab}	65.23 ± 0.57 ^{ab}	65.28 ± 0.61 ^{ab}	66.34 ± 0.88 ^a	64.82 ± 0.1b ^b	65.12 ± 0.51 ^{ab}	65.11 ± 0.19 ^{ab}	64.91 ± 0.10 ^{ab}	65.57 ± 0.75 ^{ab}
ΔE*	—	1.57 ± 1.03 ^a	1.06 ± 0.12 ^a	1.28 ± 0.54 ^a	1.01 ± 0.57 ^a	1.22 ± 0.19 ^a	0.93 ± 0.31 ^a	1.17 ± 0.20 ^a	1.20 ± 0.28 ^a
Estimated color									
									

The averages are followed by standard deviation. Averages followed by the same letter, on the same line, do not show a significant difference at 5% using the Tukey test. (PEF = pulsed electric field).

3.2. Total Phenolic Content (TPC)

As shown in Figure 1a, the application of pulsed electric field (PEF) at 6 and 8 kV, either alone or combined with ultrasound (US), reduced the total phenolic content (TPC) of buriti extracts compared with the control treatment (agitation only). The 8 kV PEF treatment resulted in the lowest TPC values, both when applied individually (183.49 mg GAE mL⁻¹) and in combination with ultrasound (209.52 and 224.79 mg GAE mL⁻¹ for US at 30% and 100% amplitude, respectively), indicating that high-intensity electric fields negatively affected phenolic compound recovery under the evaluated conditions.

Among all treatments, US at 100% amplitude achieved the highest TPC (301.28 mg GAE mL⁻¹), demonstrating the positive effect of ultrasound on phenolic extraction. Ultrasound at 30% amplitude also promoted phenolic recovery (245.26 mg GAE mL⁻¹), although to a lesser extent. These results indicate that ultrasound was more effective than PEF for extracting phenolic compounds from freeze-dried buriti pulp under the processing conditions evaluated.

Similar findings have been reported in previous studies. Silva et al. [34] demonstrated that ultrasound effectively enhanced the extraction of phenolic compounds from buriti pulp, while Andrade et al. [35] reported increased phenolic recovery from araticum peel using ultrasound-assisted extraction. Likewise, several studies have shown that short ultrasound treatments performed at high acoustic power significantly improve the extraction of phenolic compounds, anthocyanins, chlorophylls, and carotenoids compared with conventional extraction methods [36–38]. These improvements are mainly attributed to acoustic cavitation, which disrupts plant tissues, enhances solvent penetration, and accelerates mass transfer.

Overall, the present results reinforce the potential of ultrasound as an efficient technology for recovering phenolic compounds from buriti pulp. However, they also demonstrate that extraction efficiency strongly depends on process parameters, particularly the interaction between ultrasound intensity, treatment time, and the intrinsic characteristics of the food matrix. Therefore, the optimization of processing conditions is essential to maximize the recovery of phenolic compounds while minimizing their degradation.

Similar findings have been reported in previous studies evaluating the individual and combined effects of pulsed electric field (PEF) and ultrasound (US) on the extraction of phenolic compounds. Nithya et al. (2025) [39] investigated PEF and ultrasound as pretreatments for red dragon fruit juice and observed that ultrasound resulted in a higher total phenolic content (55.85 mg 100 g⁻¹) than PEF (50.06 mg 100 g⁻¹). Nevertheless, both technologies improved phenolic recovery compared with the untreated control (46.88 mg 100 g⁻¹), demonstrating their potential to enhance extraction efficiency.

In contrast, Harish et al. (2025) [40] reported that the combination of PEF (40 kV cm⁻¹) and ultrasound (40 kHz, 120 W, 10 min) significantly reduced the concentrations of major phenolic compounds in cocoa when compared with the conventional non-alkalized process. The contents of catechin, caffeine, and theobromine decreased to 2555.71, 1504.41, and 6796.67 mg kg⁻¹, respectively, whereas the corresponding values in the non-alkalized samples were 3976.14, 1855.38, and 6942.33 mg kg⁻¹. The authors attributed these reductions to the high processing intensity, which may have promoted the oxidation and degradation of phenolic compounds.

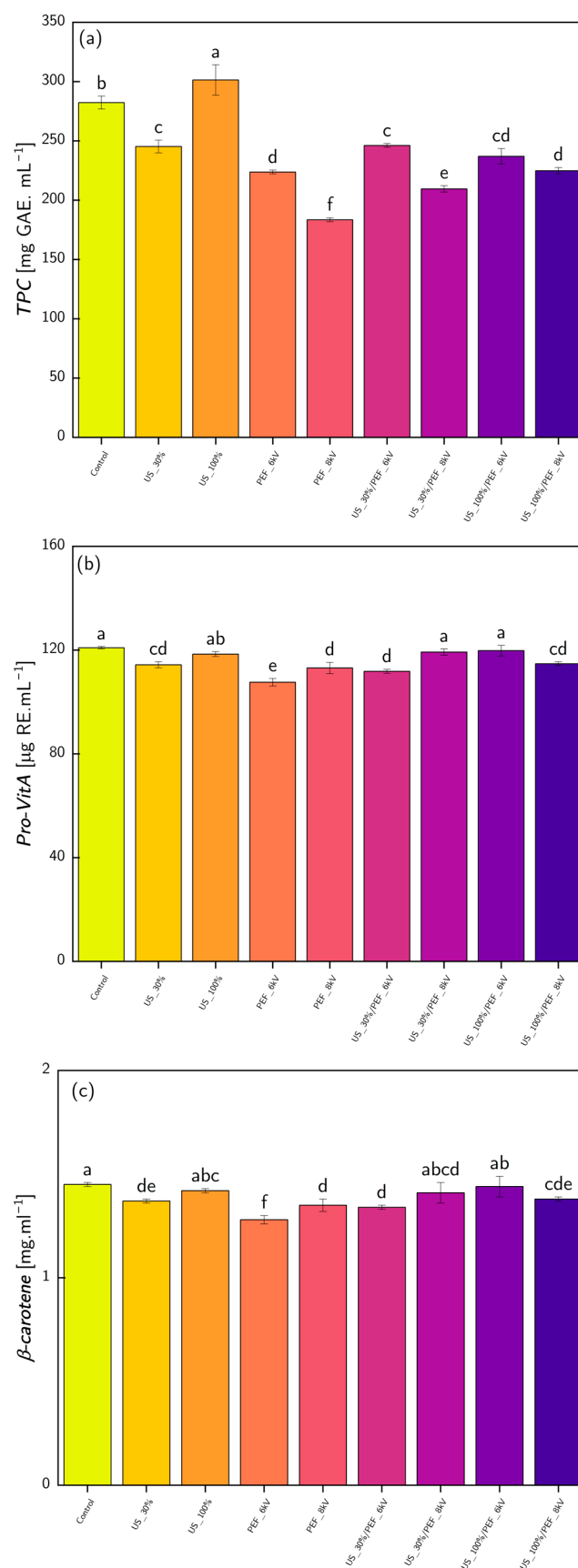


Figure 1. Results of total phenolic compounds (a), pro-vitamin A (b), and β -carotene contents (c). Means followed by the same letter are not significantly different according to Tukey's test at the 5% significance level ($p < 0.05$).

Overall, these findings indicate that the effect of combining PEF and ultrasound is highly dependent on both the processing conditions and the characteristics of the food matrix. Although PEF is well known for promoting electroporation and enhancing mass transfer, improved cell permeabilization does not necessarily result in higher extraction yields, since the final recovery reflects the balance between intracellular compound release and their chemical stability [41,42]. Under high electric field intensities, electrochemical reactions at the electrode–solution interface may promote the formation of reactive oxygen species capable of oxidizing phenolic compounds [15,43]. Likewise, high-intensity ultrasound generates acoustic cavitation and reactive radicals that may further accelerate the degradation of oxidation-sensitive phytochemicals when excessive power is applied [44,45]. Therefore, the reduced total phenolic content observed under the most intense combined treatments likely reflects the competition between enhanced mass transfer and the oxidative degradation of released compounds, emphasizing the need to carefully adjust extraction parameters according to the characteristics of the target food matrix.

3.3. Pro-Vitamin A Content

The β -carotene and pro-vitamin A contents exhibited similar trends, as pro-vitamin A activity is directly related to β -carotene concentration. As shown in Figure 1b,c, the highest β -carotene content was observed in the control treatment (1.45 mg mL^{-1} of ethanolic extract), whereas the lowest value was obtained after treatment with 6 kV PEF (1.28 mg mL^{-1}). Consequently, pro-vitamin A content ranged from 107.06 to $120.88 \text{ } \mu\text{g RE mL}^{-1}$, with the lowest and highest values corresponding to the 6 kV PEF and control treatments, respectively.

Although slight reductions were observed after some treatments, the overall differences among extraction conditions were relatively small, indicating that the application of PEF, ultrasound, and their combination did not substantially affect β -carotene stability under the evaluated conditions.

Considering the recommended dietary intake (RDI) of vitamin A, the obtained extracts represent an important source of pro-vitamin A. The World Health Organization (WHO) [46] and the Brazilian regulation (RDC No. 269/2005) [47] recommend a daily intake of $600 \text{ } \mu\text{g RE}$ for adults, whereas the U.S. National Institutes of Health (NIH) [48] recommends $900 \text{ } \mu\text{g RE day}^{-1}$ for men and $700 \text{ } \mu\text{g RE day}^{-1}$ for women. Similarly, the European Food Safety Authority recommends $750 \text{ } \mu\text{g RE day}^{-1}$ for men and $650 \text{ } \mu\text{g RE day}^{-1}$ for women [49]. Based on these recommendations, the extracts produced in the present study provide approximately 13–20% of the recommended daily intake of vitamin A, highlighting their potential as functional food ingredients or nutraceuticals.

The β -carotene contents obtained in this study are consistent with values previously reported for buriti. Nascimento-Silva et al. [50] reported total carotenoid contents ranging from 1.16 to 1.46 mg g^{-1} in buriti pulp collected from three Brazilian states (Goiás, Tocantins, and Pará), whereas Cândido et al. [28] found concentrations between 31.13 and $52.86 \text{ mg } 100 \text{ g}^{-1}$ in buriti fruits from the Cerrado and Amazon regions. In addition, Rudke et al. [51] reported β -carotene recoveries ranging from 23.38 to $1056.59 \text{ } \mu\text{g g}^{-1}$ in buriti peel. These variations are expected because carotenoid content depends on factors such as the plant tissue analyzed, extraction method, geographic origin, and fruit maturity.

Overall, the results indicate that the emerging technologies evaluated preserved β -carotene and pro-vitamin A during extraction, suggesting that the processing conditions were sufficiently mild to avoid significant degradation of these thermolabile compounds.

3.4. Antioxidant Capacity (ABTS Assay, DPPH Assay, and FRAP Assay)

The antioxidant capacity of buriti extracts was evaluated using the ABTS, DPPH, and FRAP assays, and the results are presented in Figure 2a–c, respectively. Overall, most

extraction treatments did not significantly affect the antioxidant capacity of the buriti extracts. The ABTS assay showed significant reductions only for the combined treatments 6 kV PEF + US 100% ($90.66 \mu\text{mol TE mL}^{-1}$) and 8 kV PEF + US 100% ($60.16 \mu\text{mol TE mL}^{-1}$). In contrast, the DPPH assay exhibited greater variability among treatments, with values ranging from $81.75 \mu\text{mol TE mL}^{-1}$ for the agitation control to $111.54 \mu\text{mol TE mL}^{-1}$ for the 8 kV PEF + US 30% treatment. The FRAP assay also revealed differences among the extraction treatments, with antioxidant capacity ranging from 7.7 to $10.1 \mu\text{mol Fe}^{2+}$ equivalents (Fe^{2+}E) g^{-1} dry mass. The PEF treatments, applied either individually or in combination with ultrasound, generally exhibited the lowest FRAP values ($7.7\text{--}8.2 \mu\text{mol Fe}^{2+}\text{E g}^{-1}$ dry mass). An exception was the 6 kV PEF treatment, which reached $9.6 \mu\text{mol Fe}^{2+}\text{E g}^{-1}$ dry mass, showing antioxidant capacity comparable to that of the agitation control and the ultrasound-only treatments.

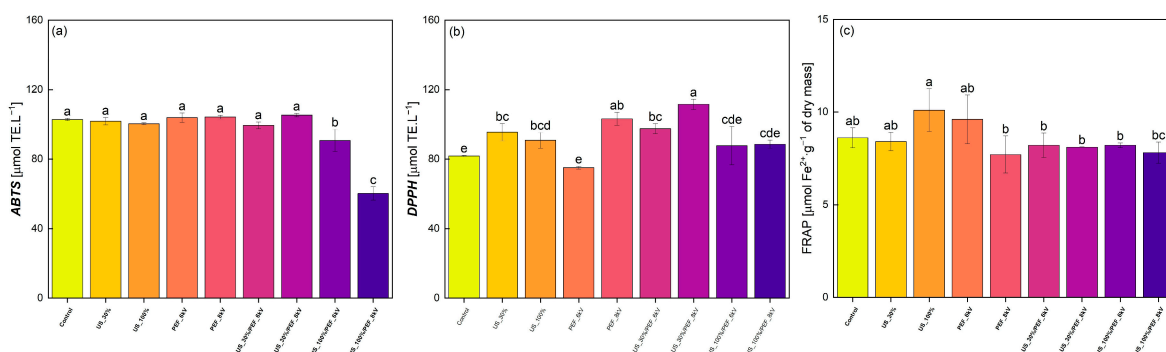


Figure 2. *In-vitro* antioxidant capacity of the buriti pulp extracts: ABTS (a), DPPH (b) and FRAP (c). Means followed by the same letter are not significantly different according to Tukey's test at the 5% significance level ($p < 0.05$).

The antioxidant capacities obtained are comparable with those previously reported for buriti products. Using the ABTS assay, Cândido et al. [28] reported values of 46.63 and $33.02 \mu\text{mol TE g}^{-1}$ for buriti pulp from the Cerrado and Amazon regions, respectively. Likewise, Nascimento-Silva et al. [50] found values ranging from 70.90 to $185.72 \mu\text{mol TE g}^{-1}$ in fruits collected from different Brazilian states. Leite et al. [52] also demonstrated the high antioxidant potential of buriti extracts obtained using octanoic acid-based supramolecular solvents.

Similar trends were observed for the DPPH assay. Cândido et al. [28] reported values of $123.28 \mu\text{mol TE g}^{-1}$, whereas Nascimento-Silva et al. [50] found antioxidant capacities between 167.76 and $561.73 \mu\text{mol TE g}^{-1}$, depending on the geographical origin of the fruits. These differences highlight the strong influence of environmental factors, including soil characteristics, climatic conditions, and harvest season, on the accumulation of antioxidant compounds in buriti fruits [52].

Studies evaluating different hydroethanolic buriti extracts have reported a wide variation in antioxidant capacity as determined by the FRAP assay [13,28,53,54]. This variability may be attributed to several factors, including differences in fruit maturity at the time of extraction, extraction solvent ratio, extraction time, and exposure to degrading conditions, such as light and oxygen. These factors can directly affect the stability and concentration of the major bioactive compounds found in buriti, particularly phenolic compounds, flavonoids, and carotenoids.

Among the evaluated treatments, 8 kV PEF, either applied alone or combined with 30% ultrasound, produced the highest antioxidant capacities in both assays. Since PEF increases cell membrane permeability through electroporation, facilitating the release of intracellular antioxidants [20,21], moderate ultrasound intensity may further enhance mass

transfer without causing significant degradation. Conversely, combining high-intensity PEF (8 kV) with 100% ultrasound amplitude likely promoted oxidative degradation of antioxidant compounds due to excessive cavitation and free radical formation, resulting in lower antioxidant capacities. These findings demonstrate that the balance between extraction efficiency and compound stability is highly dependent on the intensity of the combined technologies.

3.5. Effect of Pulsed Electric Field and Ultrasound Treatments on β -Carotene Content of Buriti Extracts

The results obtained highlight that, although the quantification based on the previously discussed standard curve did not show significant differences ($p < 0.05$), UHPLC analysis revealed variations in the actual β -carotene concentration among the extracts (Figure 3). These differences may be associated with the presence of other compounds in the extracts that absorb UV radiation at 450 nm or with overlapping absorption spectra of other carotenoids, resulting in interference during spectrophotometric quantification [55,56].

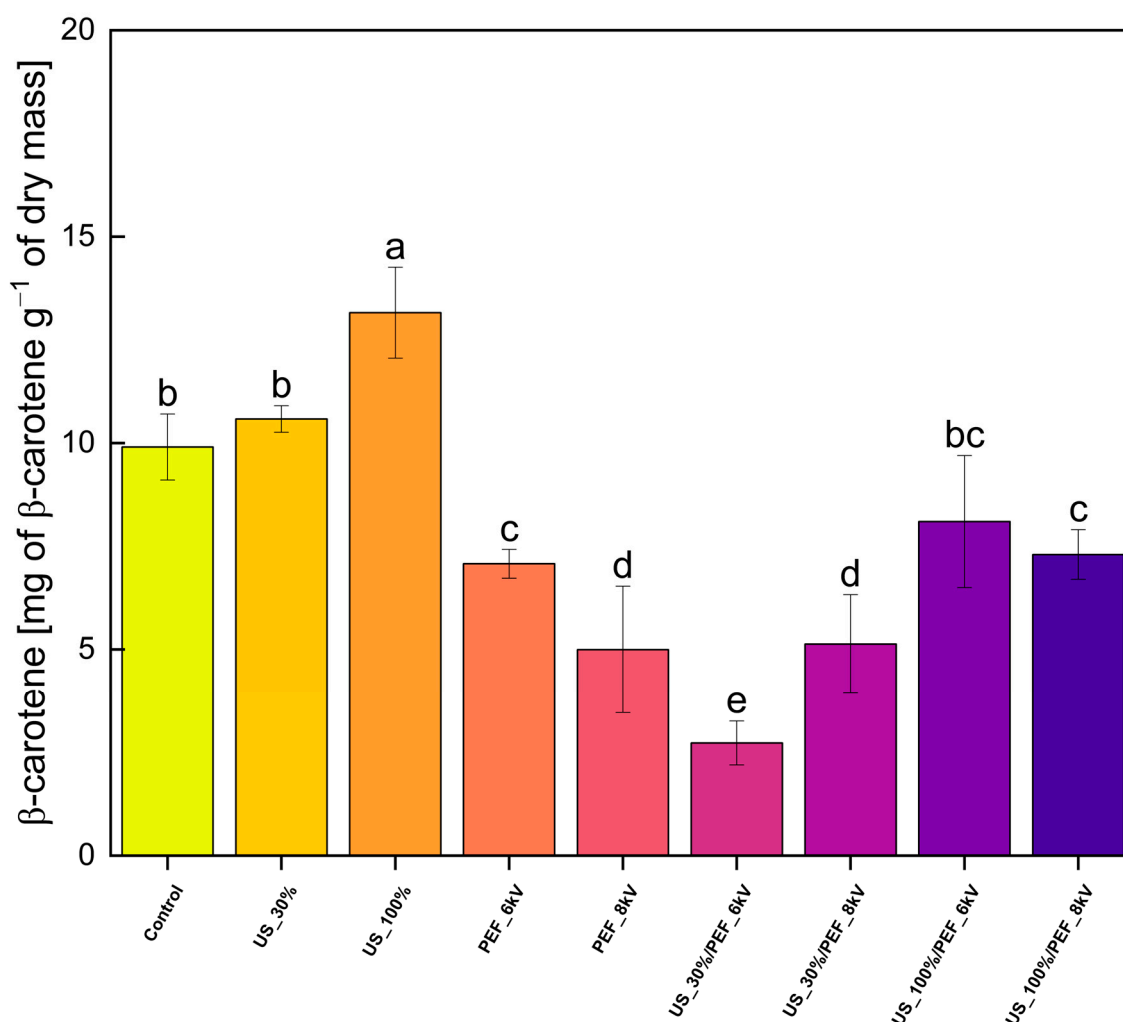


Figure 3. Effect of pulsed electric field and ultrasound treatments on β -carotene concentration in buriti pulp extracts determined by UHPLC. Means followed by the same letter are not significantly different according to Tukey's test at the 5% significance level ($p < 0.05$).

The pulsed electric field (PEF) treatments, applied alone or combined with ultrasound, resulted in a reduction in β -carotene content (2.7–7.3 mg g⁻¹ dry mass) compared with the agitation control (9.9 mg g⁻¹ dry mass). The combined treatment of PEF 6 kV + US 100%

(8.1 mg g⁻¹ dry mass) also showed a reduction, although to a lesser extent. In contrast, ultrasound treatment at 30% power resulted in a β -carotene content similar to that of the agitation control (10.6 mg g⁻¹ dry mass), whereas US 100% significantly increased the extracted β -carotene concentration (13.2 mg g⁻¹ dry mass). Overall, ultrasound application enhanced β -carotene extraction from the buriti matrix, while PEF treatments negatively affected the β -carotene content of the obtained extracts.

The reduction observed after PEF treatment may be related to the application of the electric field before extraction, which could have promoted degradation of carotenoids. Previous studies have reported that PEF application as a pre-treatment in plant matrices may either reduce carotenoid content or fail to improve carotenoid extraction efficiency [57,58]. In the present study, the buriti pulp was previously lyophilized, which may have caused structural damage to the cell walls and increased the exposure of bioactive compounds to degradation mechanisms during PEF application, rather than enhancing their release from the matrix.

In contrast, López-Gómez et al. (2021) evaluated the effect of PEF pre-treatment on fresh carrots and reported that PEF application did not significantly affect β -carotene content compared with untreated samples, although changes were observed in specific phenolic compounds [58]. This difference highlights the influence of matrix characteristics and processing history on the effectiveness of PEF-assisted extraction.

As previously reported, the optimization of ultrasound parameters, particularly the combination of treatment time and power intensity, can improve the extraction of target bioactive compounds from different plant matrices [36–38]. In this study, the enhanced β -carotene content observed after high-intensity ultrasound treatment may be associated with cavitation effects, which promote cell disruption and facilitate the release of intracellular compounds.

3.6. Effect of Extracts in Bacterial Growth

Figure 4 presents the growth curves of the lactic acid bacteria (LAB) *Lactiplantibacillus plantarum*, *Lactocaseibacillus rhamnosus*, *Lactococcus lactis*, and *Lactobacillus acidophilus* in the presence of buriti pulp extracts. Overall, the extracts, at a concentration of 1 mg mL⁻¹, did not inhibit the growth of any LAB strain, indicating good compatibility with these microorganisms. These results suggest that the extracts could potentially be incorporated into fermented foods without adversely affecting starter or probiotic cultures.

Among the evaluated strains, *L. acidophilus* exhibited the most pronounced response to the extracts. Compared with the control, cultures supplemented with buriti extracts showed a shorter adaptation phase and reached the stationary phase more rapidly, suggesting that components present in the extracts may stimulate bacterial growth. Similar results were reported by Graça et al. (2025) [59], who observed that buriti pulp enhanced the growth of *L. acidophilus* during the production of fermented milk and yogurt, increasing both the growth rate and cell multiplication. The authors also reported a reduction of approximately 3.75 h in the fermentation time, highlighting the prebiotic potential of buriti-derived compounds.

Overall, these findings indicate that buriti extracts do not exert antimicrobial activity against beneficial lactic acid bacteria and may even promote the growth of probiotic microorganisms, expanding their potential application as functional ingredients in fermented food products.

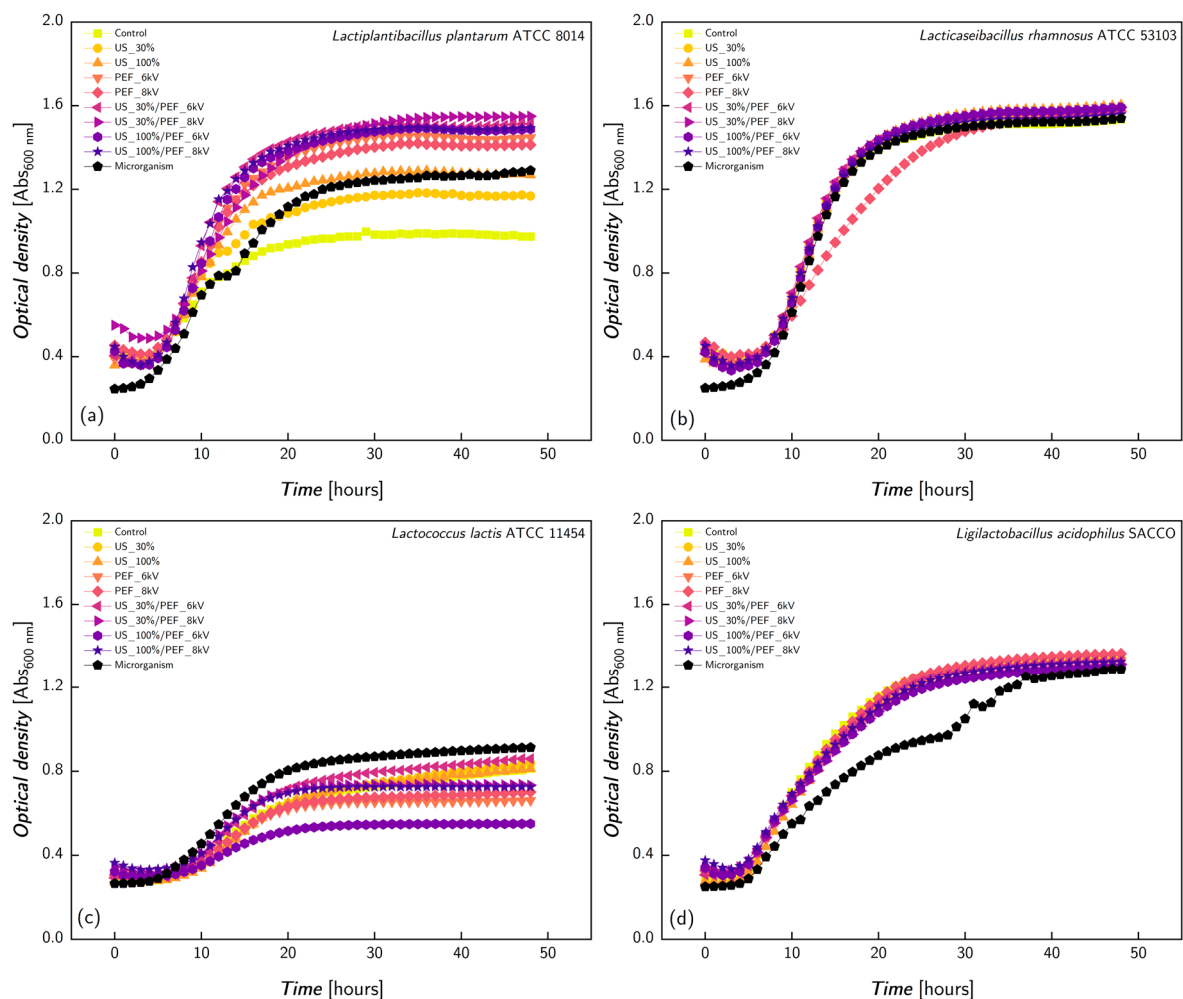


Figure 4. Effect of carotenoid extracts in probiotic strains of lactic acid bacteria: *Lactiplantibacillus plantarum* (a), *Lacticaseibacillus rhamnosus* (b), *Lactococcus lactis* (c) and *Ligilactobacillus acidophilus* (d).

The growth curves of the foodborne pathogens *Staphylococcus aureus*, *Bacillus cereus*, *Escherichia coli*, and *Pseudomonas fluorescens* are presented in Figure 5. Under the evaluated conditions, none of the buriti extracts inhibited bacterial growth, indicating that the extraction process did not generate antimicrobial concentrations of bioactive compounds against the tested microorganisms.

The growth of *B. cereus* and *E. coli* was not significantly affected by the extracts, exhibiting growth profiles comparable to the untreated controls. In contrast, *S. aureus* appeared to enter the exponential growth phase earlier in the presence of buriti extracts, suggesting a possible reduction in the adaptation period. Although the present study did not quantify bacterial growth kinetic parameters, such as lag phase duration or doubling time, this observation may be associated with the lipid-rich composition of buriti pulp. Buriti is naturally rich in triacylglycerols and unsaturated fatty acids [60], which have been reported as potential exogenous carbon and lipid sources for *S. aureus*. This microorganism possesses extracellular lipases capable of hydrolyzing lipids into free fatty acids, which may subsequently be incorporated into membrane phospholipids through the fatty acid kinase (FakA) pathway [61,62]. Because *S. aureus* lacks desaturase enzymes required for the synthesis of unsaturated fatty acids, the availability of exogenous fatty acids may facilitate membrane biosynthesis and cellular growth. Nevertheless, this mechanism remains hypothetical in the context of the present study and should be confirmed by future investigations combining bacterial growth kinetics with chemical characterization of the

extracts. Although no antimicrobial activity was observed, the stimulation of *S. aureus* growth deserves attention because this microorganism is capable of producing heat-stable staphylococcal enterotoxins, which remain active after thermal processing and represent a significant food safety concern [63].

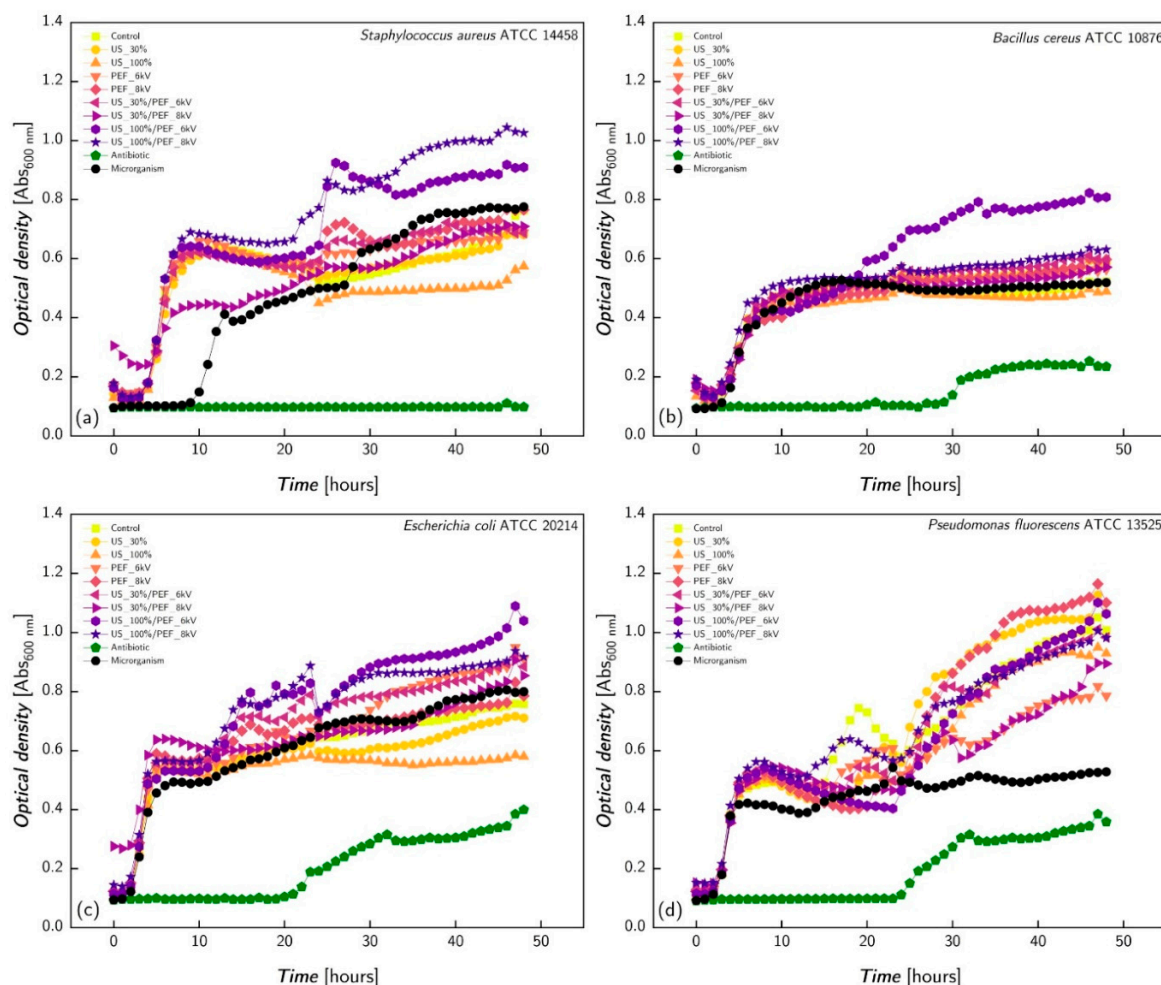


Figure 5. Effect of carotenoid extracts in foodborne pathogenic strains of bacteria: *Staphylococcus aureus* (a), *Bacillus cereus* (b), *Escherichia coli* (c) and *Pseudomonas fluorescens* (d).

From a food safety perspective, the apparent stimulation of *S. aureus* growth deserves particular attention. Although the extracts did not exhibit antimicrobial activity against this pathogen, any reduction in the adaptation period could potentially accelerate bacterial proliferation under inadequate storage conditions, increasing the risk of enterotoxin production. Since staphylococcal enterotoxins are highly heat stable, their formation cannot be eliminated by conventional thermal treatments. Therefore, the application of buriti extracts in food systems should be accompanied by appropriate preservation strategies, including adequate refrigeration, hygienic processing practices, and, when necessary, complementary antimicrobial hurdles.

A similar trend was observed for *P. fluorescens*, whose growth was also accelerated in the presence of buriti extracts. This finding is particularly relevant considering the potential application of these extracts in dairy products, since *Pseudomonas* spp. are among the predominant psychrotrophic spoilage microorganisms associated with refrigerated dairy matrices. The growth advantage observed in the presence of buriti extracts may be related to the chemical composition of the crude extract, particularly the presence of residual lipids derived from buriti pulp. As the extraction procedure did not include a purification

step, both carotenoids and lipid fractions were recovered, potentially providing additional carbon sources for bacterial metabolism.

P. fluorescens possesses a versatile enzymatic system, including extracellular lipases and proteases, which enables the degradation of milk components such as triglycerides and proteins, leading to the formation of off-flavors, bitterness, texture defects, and reduced shelf life of dairy products [64–66]. Therefore, although buriti extracts present promising bioactive properties, their direct incorporation into dairy formulations should be carefully evaluated. Further studies involving purified extracts, removal of residual lipid fractions, and assessment of microbial stability within the target food matrix are necessary to ensure their safe and effective application.

The absence of antimicrobial activity observed in the present study agrees partially with previous reports. Santos et al. (2018) [67] found that buriti oil did not inhibit the growth of *S. aureus*, *B. cereus*, *E. coli*, or *P. fluorescens*, although inhibitory activity was observed against *Salmonella typhimurium*. Likewise, Koolen et al. (2013) [68] reported that fruit extracts of buriti did not inhibit *E. coli* or *B. cereus*, whereas inhibitory effects against *S. aureus* and *Pseudomonas aeruginosa* were observed at lower extract concentrations. These discrepancies are likely associated with differences in plant material, extraction procedures, chemical composition, and the specific bioactive compounds recovered.

Overall, the present results indicate that crude ethanolic extracts of buriti pulp do not exhibit broad-spectrum antimicrobial activity against the foodborne pathogens evaluated. Considering the chemical complexity of buriti extracts, further studies should investigate purified or fractionated extracts to identify bioactive constituents with antimicrobial potential and to better understand possible synergistic or antagonistic interactions among the extracted compounds.

3.7. Evaluation of the In Vitro Cytotoxic Effect of the Extracts

Figure 6 presents the resazurin reduction assay results after 24 h of exposure of human dermal fibroblasts (HDFa) to buriti pulp extracts obtained by agitation, ultrasound (US), pulsed electric field (PEF), and the combination of both technologies. The assay was performed to evaluate the cytotoxic potential of the extracts under the different extraction conditions.

Overall, the extracts exhibited low cytotoxicity, as most treatments maintained cell viability above 80%, a threshold commonly considered indicative of good cytocompatibility for in vitro assays. As expected, the negative control showed high metabolic activity (approximately 145%), confirming normal cell proliferation, whereas the positive control exhibited low viability (approximately 15%), demonstrating the effectiveness of the cytotoxic treatment.

The extract obtained by conventional agitation maintained cell viability close to 100%, indicating that the conventional extraction process did not generate compounds capable of impairing cellular metabolism. Similarly, extracts obtained by isolated PEF (6 and 8 kV) showed viability values comparable to the control, suggesting that the application of moderate electric fields did not adversely affect the biological compatibility of the recovered compounds. Ultrasound-treated extracts exhibited a slight reduction in metabolic activity, particularly at 30% amplitude; however, cell viability remained above the cytotoxicity threshold, indicating that these treatments did not induce significant cellular damage.

Interestingly, the combined treatments PEF 6 kV + US 100% and PEF 8 kV + US 100% resulted in viability values slightly exceeding 100%, suggesting that the extracts did not interfere negatively with cell metabolism and may have preserved compounds capable of supporting cellular metabolic activity. Although this response cannot be interpreted as evidence of a proliferative effect, it may be associated with the presence of antioxi-

dant molecules, including carotenoids and phenolic compounds, which have been widely reported to protect mammalian cells against oxidative stress [69–71].

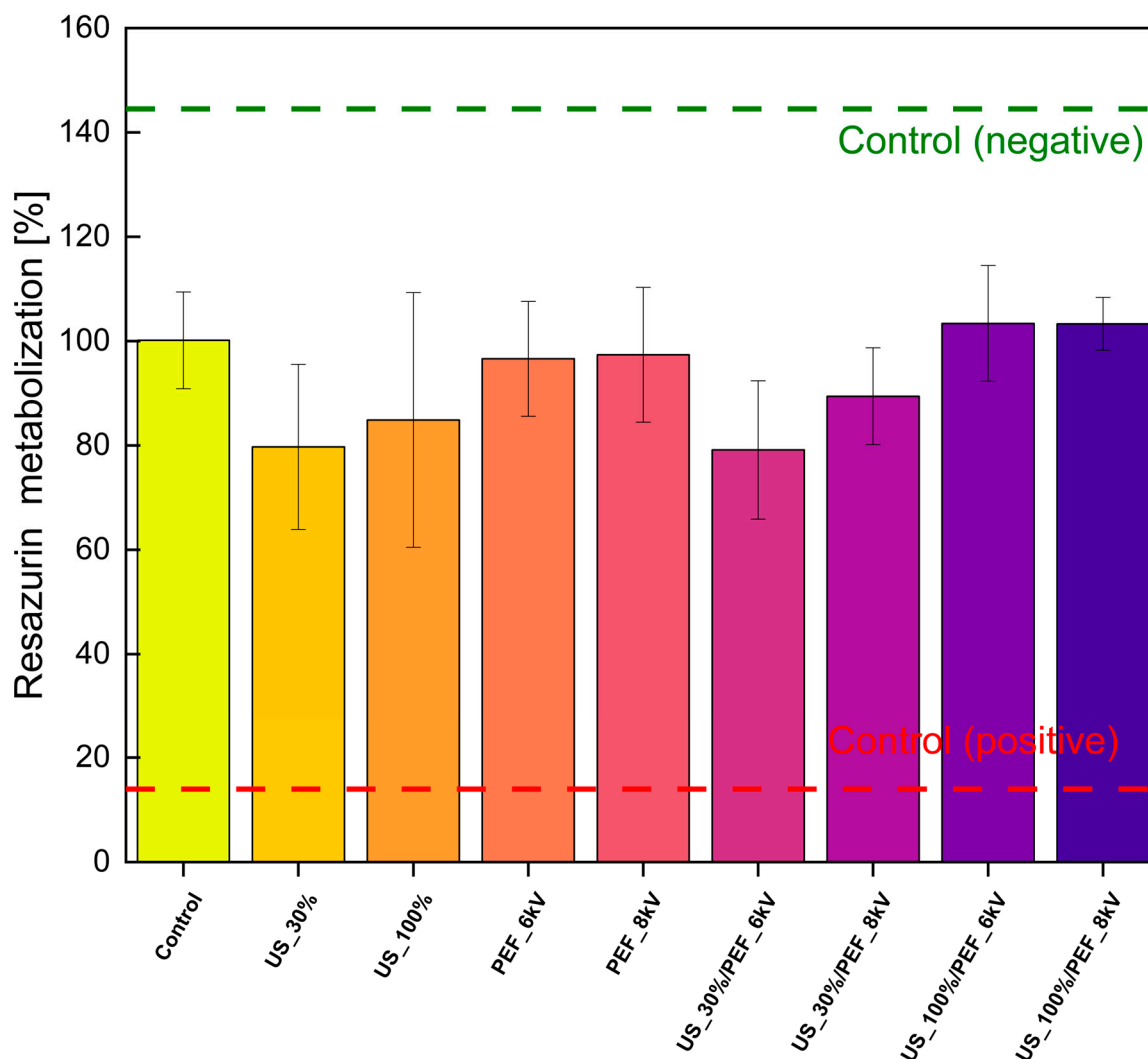


Figure 6. Metabolization of resazurin by HDFa cells exposed to different extracts over 24 h.

These findings are consistent with previous studies demonstrating the biocompatibility of buriti-derived products. Buriti oil has been reported to exhibit low cytotoxicity toward epithelial cells and fibroblasts while providing protection against oxidative damage through its high content of carotenoids, tocopherols, and phenolic compounds [69–71]. The preservation of cell viability observed in the present study therefore suggests that the emerging extraction technologies evaluated did not compromise the biological safety of the extracts.

Overall, the results indicate that buriti extracts obtained by ultrasound, PEF, and their combination possess favorable cytocompatibility, supporting their potential application as natural ingredients in food, cosmetic, and nutraceutical formulations. Nevertheless, additional studies involving different cell lines, longer exposure periods, and mechanistic analyses are required to confirm their biological activity and establish their safety profile for industrial applications.

4. Conclusions

The application of emerging technologies significantly influenced the extraction and stability of bioactive compounds from buriti pulp. Among the processing conditions

evaluated in this exploratory study, isolated ultrasound, particularly at 100% intensity, showed the most promising overall performance, promoting higher extraction of total phenolic compounds while maintaining elevated β -carotene content, pro-vitamin A activity, and antioxidant capacity. UHPLC analysis confirmed that ultrasound treatment improved the release of β -carotene from the buriti matrix, with the highest concentration observed after US 100% treatment. Conversely, PEF treatments, either alone or combined with high-intensity ultrasound, resulted in lower β -carotene concentrations, suggesting that the application of electric fields prior to extraction may promote the degradation of carotenoids or reduce their stability under the evaluated conditions.

The antioxidant potential of the extracts was confirmed by different complementary assays. Although ABTS, DPPH, and FRAP analyses showed different response patterns due to their distinct reaction mechanisms, the results demonstrated that the applied technologies influenced the antioxidant properties of buriti extracts. In general, ultrasound treatments maintained or enhanced antioxidant capacity, whereas more intense PEF-based treatments showed a reduction in antioxidant activity, particularly in combined processes involving high-intensity ultrasound.

Colorimetric analyses demonstrated that the extraction processes preserved the characteristic orange coloration associated with carotenoids, with no visually perceptible differences among treatments. The extracts also showed low cytotoxicity toward HDFa cells, indicating good biocompatibility and potential for food, cosmetic, and nutraceutical applications. Furthermore, no inhibitory effects against probiotic bacteria were observed, while *Lactobacillus acidophilus* growth was stimulated by the extracts.

Overall, these findings provide preliminary evidence of the potential of ultrasound-assisted extraction for obtaining bioactive-rich extracts from buriti pulp under the investigated conditions. However, because this study was designed as an exploratory evaluation rather than a process optimization study, the results should not be interpreted as defining optimal operating conditions. Future studies employing broader experimental designs and optimization strategies, such as response surface methodology, are required to establish the optimal combination of PEF and ultrasound parameters while minimizing the degradation of sensitive bioactive compounds.

A limitation of the present study is the use of two independent biological replicates for each extraction treatment. Although all analytical determinations were performed in triplicate to ensure measurement precision, future studies should include a larger number of biological replicates and broader experimental designs to improve statistical robustness and support process optimization.

Author Contributions: P.D.B.: writing—review and editing, writing—original draft, formal analysis, investigation, data curation, conceptualization, and methodology. B.d.S.C.: writing—review and editing, formal analysis, investigation, and data curation. D.W.: writing—review and editing, data curation, methodology, and supervision. T.C.B.R.: writing—review and editing, data curation, methodology, and supervision. D.A.G.: writing—review and editing, formal analysis, and data curation. E.E.d.S.F.: writing—review and editing, formal analysis, and data curation. V.M.d.S.: writing—review and editing, formal analysis, and data curation. M.A.R.: writing—review and editing, formal analysis, and data curation. E.M.: writing—review and editing, writing—original draft, data curation, conceptualization, and resources. P.C.S.: writing—review and editing, conceptualization, resources, project administration, and funding acquisition. P.H.C.: writing—review and editing, writing—original draft, data curation, conceptualization, supervision, resources, project administration, and funding acquisition. All authors have read and agreed to the published version of the manuscript.

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References

1. Bufka, J.; Vaňková, L.; Sýkora, J.; Křížková, V. Exploring Carotenoids: Metabolism, Antioxidants, and Impacts on Human Health. *J. Funct. Foods* **2024**, *118*, 106284. [\[CrossRef\]](#)
2. Baran, M.T.; Miziak, P.; Bonio, K. Characteristics of Carotenoids and Their Use in the Cosmetics Industry. *J. Educ. Health Sport* **2020**, *10*, 192–196. [\[CrossRef\]](#)
3. Generalić Mekinić, I.; Šimat, V.; Rathod, N.B.; Hamed, I.; Čagalj, M. Algal Carotenoids: Chemistry, Sources, and Application. *Foods* **2023**, *12*, 2768. [\[CrossRef\]](#) [\[PubMed\]](#)
4. Ashokkumar, V.; Flora, G.; Sevanan, M.; Sripriya, R.; Chen, W.H.; Park, J.-H.; Rajesh Banu, J.; Kumar, G. Technological Advances in the Production of Carotenoids and Their Applications—A Critical Review. *Bioresour. Technol.* **2023**, *367*, 128215. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Li, Y.; Li, T.; Yan, Z.; Bariami, W.; Wu, C.; Yan, S.; Fan, G.; Li, X.; Zhou, D.; Cong, K.; et al. Carotenoids in Berries: Composition, Benefits, Metabolic Processes and Influencing Factors—A Review. *Sci. Hortic.* **2024**, *329*, 112956. [\[CrossRef\]](#)
6. Devi, A.; George, N.; Khan, Z.A.; Dwibedi, V. (Eds.) *Exploring Herbal Synergies for Optimal Human Health*; CRC Press: Boca Raton, FL, USA, 2026.
7. Polyakov, N.E.; Focsan, A.L.; Gao, Y.; Kispert, L.D. The Endless World of Carotenoids—Structural, Chemical and Biological Aspects of Some Rare Carotenoids. *Int. J. Mol. Sci.* **2023**, *24*, 9885. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Meléndez-Martínez, A.J.; Esquivel, P.; Rodríguez-Amaya, D.B. Comprehensive Review on Carotenoid Composition: Transformations during Processing and Storage of Foods. *Food Res. Int.* **2023**, *169*, 112773. [\[CrossRef\]](#) [\[PubMed\]](#)
9. De Souza Costa, B.; Bieler, P.D.; Dehghani, S.; Wischral, D.; Rodrigues, R.C.; Rodrigues, S.; Martins, E.; Campelo, P.H.; Stringheta, P.C. Cerrado Fruits as Sources of Bioactive Extracts: Functional Food Applications and Emerging Technologies for Sustainable Extraction. *Sustain. Food Technol.* **2026**, *4*, 110–132. [\[CrossRef\]](#)
10. Metibemu, D.S.; Ogungbe, I.V. Carotenoids in Drug Discovery and Medicine: Pathways and Molecular Targets Implicated in Human Diseases. *Molecules* **2022**, *27*, 6005. [\[CrossRef\]](#) [\[PubMed\]](#)
11. Cholidis, P.; Kranas, D.; Chira, A.; Galouni, E.A.; Adamantidi, T.; Anastasiadou, C.; Tsoupras, A. Shrimp Lipid Bioactives with Anti-Inflammatory, Antithrombotic, and Antioxidant Health-Promoting Properties for Cardio-Protection. *Mar. Drugs* **2024**, *22*, 554. [\[CrossRef\]](#) [\[PubMed\]](#)
12. Panagiotakopoulos, I.; Nasopoulou, C. Extraction Methods, Encapsulation Techniques, and Health Benefits of Astaxanthin. *Sustainability* **2024**, *16*, 10859. [\[CrossRef\]](#)
13. Nogueira, G.M.; Cardoso, F.A.R.; Perdoncini, M.R.F.G.; Da Silva, M.V.; Rigobello, E.S. Evaluation of the Extraction of Antioxidant Compounds from Buriti Pulp (*Mauritia flexuosa* L.) by Response Surface Methodology. *Heliyon* **2025**, *11*, e41926. [\[CrossRef\]](#) [\[PubMed\]](#)
14. Wen, L.; Zhang, Z.; Sun, D.-W.; Sivagnanam, S.P.; Tiwari, B.K. Combination of Emerging Technologies for the Extraction of Bioactive Compounds. *Crit. Rev. Food Sci. Nutr.* **2020**, *60*, 1826–1841. [\[CrossRef\]](#) [\[PubMed\]](#)
15. Xue, L.; Wei, F.; Gao, G.; Yan, G.; Song, W.; Chen, B.; Xu, K.; Chen, H.; Wu, X. Development of an Ultrasound-Assisted Extraction Method for the Rapid Quantification of Seed Carotenoid Content in Oilseed Rape. *Crop Pasture Sci.* **2018**, *69*, 48–54. [\[CrossRef\]](#)
16. Bhimjiyani, V.H.; Borugadda, V.B.; Naik, S.; Dalai, A.K. Enrichment of Flaxseed (*Linum usitatissimum*) Oil with Carotenoids of Sea Buckthorn Pomace via Ultrasound-Assisted Extraction Technique. *Curr. Res. Food Sci.* **2021**, *4*, 478–488. [\[CrossRef\]](#) [\[PubMed\]](#)
17. Feizi, P.; Maghsoudlou, Y.; ShahiriTabarestani, H.; Jafari, S.M.; Bahri, A.-H. Green Astaxanthin Extraction Using Microwave and Ultrasound Pretreatments. *npj Sci. Food* **2025**, *9*, 147. [\[CrossRef\]](#) [\[PubMed\]](#)

18. Viñas-Ospino, A.; Rita Jesus, A.; Paiva, A.; Esteve, M.J.; Frígola, A.; Blesa, J.; López-Malo, D. Comparison of Green Solvents for the Revalorization of Orange By-Products: Carotenoid Extraction and in Vitro Antioxidant Activity. *Food Chem.* **2024**, *442*, 138530. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Saebi, A.; Mahmoudi, E.; Markom, M.; Minaei, S.; Mahdavian, A.; Ebadi, M.-T.; Siow, K.S. Tailoring Microalgal Extract Properties via Non-Thermal Pretreatments: Application-Specific Optimization in *Chlorella vulgaris*. *Eur. Food Res. Technol.* **2025**, *251*, 4469–4484. [\[CrossRef\]](#)
20. Chatzimitakos, T.; Athanasiadis, V.; Kalompatsios, D.; Mantiniotou, M.; Bozinou, E.; Lalas, S.I. Pulsed Electric Field Applications for the Extraction of Bioactive Compounds from Food Waste and By-Products: A Critical Review. *Biomass* **2023**, *3*, 367–401. [\[CrossRef\]](#)
21. Bocker, R.; Silva, E.K. Pulsed Electric Field Assisted Extraction of Natural Food Pigments and Colorings from Plant Matrices. *Food Chem. X* **2022**, *15*, 100398. [\[CrossRef\]](#) [\[PubMed\]](#)
22. Rigolon, T.C.B.; Barros, F.A.R.d.; Vieira, É.N.R.; Stringheta, P.C. Prediction of Total Phenolics, Anthocyanins and Antioxidant Capacity of Blackberry (*Rubus* sp.), Blueberry (*Vaccinium* sp.) and Jaboticaba (*Plinia cauliflora* (Mart.) Kausel) Skin Using Colorimetric Parameters. *Food Sci. Technol.* **2020**, *40*, 620–625. [\[CrossRef\]](#)
23. Aremu, S.; Nweze, C. Determination of Vitamin A Content from Selected Nigerian Fruits Using Spectrophotometric Method. *Bangladesh J. Sci. Ind. Res.* **2017**, *52*, 153–158. [\[CrossRef\]](#)
24. Singleton, V.L.; Rossi, J.A. Colorimetry of Total Phenolics with Phosphomolybdic-Phosphotungstic Acid Reagents. *Am. J. Enol. Vitic.* **1965**, *16*, 144–158. [\[CrossRef\]](#)
25. Re, R.; Pellegrini, N.; Proteggente, A.; Pannala, A.; Yang, M.; Rice-Evans, C. Antioxidant Activity Applying an Improved ABTS Radical Cation Decolorization Assay. *Free Radic. Biol. Med.* **1999**, *26*, 1231–1237. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Kim, D.-O.; Lee, K.W.; Lee, H.J.; Lee, C.Y. Vitamin C Equivalent Antioxidant Capacity (VCEAC) of Phenolic Phytochemicals. *J. Agric. Food Chem.* **2002**, *50*, 3713–3717. [\[CrossRef\]](#) [\[PubMed\]](#)
27. Moraes, M.L.; Silva, A.C.R.; Araújo, C.R.R.; Esteves, E.A.; Dessimoni-Pinto, N.A.V. Determinação do potencial antioxidante in vitro de frutos do Cerrado brasileiro. *Rev. Bras. Frutic.* **2013**, *35*, 355–360. [\[CrossRef\]](#)
28. Cândido, T.L.N.; Silva, M.R.; Agostini-Costa, T.S. Bioactive Compounds and Antioxidant Capacity of Buriti (*Mauritia flexuosa* L.f.) from the Cerrado and Amazon Biomes. *Food Chem.* **2015**, *177*, 313–319. [\[CrossRef\]](#) [\[PubMed\]](#)
29. Paes, M.C.D.; Okumura, F.; Guimarães, C.D.C. *Metodologia Científica: Determinação de Carotenoides em Milho por Cromatografia Líquida de Alta Eficiência*; Brazilian Agricultural Research Corporation (Embrapa): Brasília, Brazil, 2019.
30. Alcántara, C.; Žugčić, T.; Abdelkebir, R.; García-Pérez, J.V.; Jambrak, A.R.; Lorenzo, J.M.; Collado, M.C.; Granato, D.; Barba, F.J. Effects of Ultrasound-Assisted Extraction and Solvent on the Phenolic Profile, Bacterial Growth, and Anti-Inflammatory / Antioxidant Activities of Mediterranean Olive and Fig Leaves Extracts. *Molecules* **2020**, *25*, 1718. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Batista, J.M.; Gomes, D.A.; Armijos, M.J.G.; Rodrigues, M.A.; Menezes, H.C.; Cardeal, Z.L. A Biomarkers Study of Human Skin Fibroblasts Exposition to Glyphosate-Based Herbicide Using an Untargeted and Targeted Metabolomics Approach. *Chemosphere* **2025**, *370*, 143998. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Marcelino, G.; Hiane, P.A.; Pott, A.; de Oliveira Filiú, W.F.; Caires, A.R.L.; Michels, F.S.; Júnior, M.R.M.; Santos, N.M.S.; Nunes, Â.A.; Oliveira, L.C.S.; et al. Characterization of Buriti (*Mauritia flexuosa*) Pulp Oil and the Effect of Its Supplementation in an In Vivo Experimental Model. *Nutrients* **2022**, *14*, 2547. [\[CrossRef\]](#) [\[PubMed\]](#)
33. De Souza Carvalho, L.M.; Lemos, M.C.M.; Sanches, E.A.; Da Silva, L.S.; De Araújo Bezerra, J.; Aguiar, J.P.L.; Das Chagas Do Amaral Souza, F.; Alves Filho, E.G.; Campelo, P.H. Improvement of the Bioaccessibility of Bioactive Compounds from Amazon Fruits Treated Using High Energy Ultrasound. *Ultrason. Sonochem.* **2020**, *67*, 105148. [\[CrossRef\]](#) [\[PubMed\]](#)
34. Silva, D.S.N.; Silva, M.D.S.; Coelho, T.L.S.; Dantas, C.; Lopes Júnior, C.A.; Caldas, N.M.; Vieira, E.C. Combining High Intensity Ultrasound and Experimental Design to Improve Carotenoid Extraction Efficiency from Buriti (*Mauritia flexuosa*). *Ultrason. Sonochem.* **2022**, *88*, 106076. [\[CrossRef\]](#) [\[PubMed\]](#)
35. Andrade, A.C.; Borsoi, F.T.; Saliba, A.S.M.C.; De Alencar, S.M.; Pastore, G.M.; Arruda, H.S. Optimization of Ultrasonic-Assisted Extraction of Phenolic Compounds and Antioxidant Activity from Araticum Peel Using Response Surface Methodology. *Plants* **2024**, *13*, 2560. [\[CrossRef\]](#) [\[PubMed\]](#)
36. Peng, S.; Zhu, M.; Li, S.; Ma, X.; Hu, F. Ultrasound-Assisted Extraction of Polyphenols from Chinese Propolis. *Front. Sustain. Food Syst.* **2023**, *7*, 1131959. [\[CrossRef\]](#)
37. Da Silva Donadone, D.B.; De Castro França, I.A.; Silva, D.L.G.; Faria, M.G.I.; Ruiz, S.P.; Barros, B.C.B. Enhancement of Phenolic Recovery by Probe-Type Ultrasound-Assisted Extraction of Acerola By-Product and Evaluation of Antioxidant and Antibacterial Activities. *Appl. Sci.* **2025**, *15*, 9154. [\[CrossRef\]](#)
38. Prawira-Atmaja, M.I.; Puangpraphant, S. Effects of Ultrasound-Assisted Bath, Probe, and Extraction Time on Bioactive Compounds and Antioxidant Activity in White Tea (*Camellia sinensis*) Extracts from Purple- and Green-Leaf Cultivars. *J. Saudi Soc. Agric. Sci.* **2025**, *24*, 10. [\[CrossRef\]](#)

39. Nithya, C.; Sudheer, K.P.; Abdullah, S.; Jayachandran, L.E. Enhancing Juice Yield and Bioactive Compounds in Red Dragon Fruit Juice through Pulsed Electric Field and Ultrasonic Pre-Treatments: Process Optimization and Comparative Evaluation. *Food Chem.* **2025**, *496*, 146709. [CrossRef] [PubMed]
40. Harish, S.; Sandhya, K.; Hema, V.; Rawson, A.; Natarajan, V. Comparative Evaluation of Pulsed Electric Field and Assisted Technology Alkalization on the Quality Characteristics of Cocoa Powder. *Innov. Food Sci. Emerg. Technol.* **2025**, *106*, 104245. [CrossRef]
41. Barba, F.J.; Parniakov, O.; Pereira, S.A.; Wiktor, A.; Grimi, N.; Boussetta, N.; Saraiva, J.A.; Raso, J.; Martin-Belloso, O.; Witrowa-Rajchert, D.; et al. Current Applications and New Opportunities for the Use of Pulsed Electric Fields in Food Science and Industry. *Food Res. Int.* **2015**, *77*, 773–798. [CrossRef]
42. Puértolas, E.; Barba, F.J. Electrotechnologies Applied to Valorization of By-Products from Food Industry: Main Findings, Energy and Economic Cost of Their Industrialization. *Food Bioprod. Process.* **2016**, *100*, 172–184. [CrossRef]
43. Chiorcea-Paquim, A.-M.; Enache, T.A.; De Souza Gil, E.; Oliveira-Brett, A.M. Natural Phenolic Antioxidants Electrochemistry: Towards a New Food Science Methodology. *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 1680–1726. [CrossRef] [PubMed]
44. Chemat, F.; Rombaut, N.; Sicaire, A.-G.; Meullemiestre, A.; Fabiano-Tixier, A.-S.; Abert-Vian, M. Ultrasound Assisted Extraction of Food and Natural Products. Mechanisms, Techniques, Combinations, Protocols and Applications. A Review. *Ultrason. Sonochem.* **2017**, *34*, 540–560. [CrossRef] [PubMed]
45. Vilku, K.; Mawson, R.; Simons, L.; Bates, D. Applications and Opportunities for Ultrasound Assisted Extraction in the Food Industry—A Review. *Innov. Food Sci. Emerg. Technol.* **2008**, *9*, 161–169. [CrossRef]
46. WHO. *Vitamin and Mineral Requirements in Human Nutrition*, 2nd ed.; WHO: Geneva, Switzerland, 2004. Available online: <https://www.who.int/publications/i/item/9241546123> (accessed on 14 May 2026).
47. Ministério da Saúde. Available online: <https://coffito.gov.br/nsite/wp-content/uploads/2016/08/resoluo-rdc-n-269-2005-ingesto-diria-recomendada-idr-de-protenas-vitaminas-e-minerais.pdf> (accessed on 14 May 2026).
48. Office of Dietary Supplements. Nutrient Recommendations and Databases. Available online: <https://ods.od.nih.gov/HealthInformation/nutrientrecommendations.aspx> (accessed on 14 May 2026).
49. European Food Safety Authority (EFSA). Dietary Reference Values: Vitamin A Advice Published. Available online: <https://www.efsa.europa.eu/en/press/news/150305> (accessed on 14 May 2026).
50. Nascimento-Silva, N.R.R.; Silva, M.R. Physicochemical Composition and Antioxidants of Buriti (*Mauritia flexuosa* Linn. F.)—Pulp and Sweet. *J. Bioenergy Food Sci.* **2020**, *7*, 1–12. [CrossRef]
51. Rudke, A.R.; Mazzutti, S.; Andrade, K.S.; Vitali, L.; Ferreira, S.R.S. Optimization of Green PLE Method Applied for the Recovery of Antioxidant Compounds from Buriti (*Mauritia flexuosa* L.) Shell. *Food Chem.* **2019**, *298*, 125061. [CrossRef] [PubMed]
52. Leite, P.I.P.; Barreto, S.M.A.G.; Freitas, P.R.; de Araújo, A.C.J.; Paulo, C.L.R.; de Almeida, R.S.; de Assis, C.F.; Padilha, C.E.A.; Ferrari, M.; de Sousa Junior, F.C. Extraction of Bioactive Compounds from Buriti (*Mauritia flexuosa* L.) Fruit by Eco-Friendly Solvents: Chemical and Functional Characterization. *Sustain. Chem. Pharm.* **2021**, *22*, 100489. [CrossRef]
53. Pelosi, M.S.; Leite, I.; Passos, L.; Ferreira, C.; Sabaa-Srur, A.U.O.; Fialho, E. Avaliação físico-química e capacidade antioxidante do extrato de buriti (*Mauritia flexuosa* L.) e atividade antitumoral em linhagem celular de câncer de mama MDA-MB-231/Physico-chemical evaluation and antioxidant capacity of buriti extract and antitumor activity in breast cancer cell line MDA-MB-231. *Braz. J. Dev.* **2020**, *6*, 17493–17515. [CrossRef]
54. Nobre, C.B.; Sousa, E.O.; Camilo, C.J.; Machado, J.F.; Silva, J.M.F.L.; Filho, J.R.; Coutinho, H.D.M.; Costa, J.G.M. Antioxidative Effect and Phytochemical Profile of Natural Products from the Fruits of “Babaçu” (*Orbignia speciosa*) and “Buriti” (*Mauritia flexuosa*). *Food Chem. Toxicol.* **2018**, *121*, 423–429. [CrossRef] [PubMed]
55. Popescu, M.; Iancu, P.; Pleșu, V.; Bîldea, C.S.; Todasca, C.M. Different Spectrophotometric Methods for Simultaneous Quantification of Lycopene and β -Carotene from a Binary Mixture. *LWT* **2022**, *160*, 113238. [CrossRef]
56. Biehler, E.; Mayer, F.; Hoffmann, L.; Krause, E.; Bohn, T. Comparison of 3 Spectrophotometric Methods for Carotenoid Determination in Frequently Consumed Fruits and Vegetables. *J. Food Sci.* **2010**, *75*, C55–C61. [CrossRef] [PubMed]
57. Roohinejad, S.; Everett, D.W.; Oey, I. Effect of Pulsed Electric Field Processing on Carotenoid Extractability of Carrot Purée. *Int. J. Food Sci. Tech.* **2014**, *49*, 2120–2127. [CrossRef]
58. López-Gámez, G.; Elez-Martínez, P.; Quiles-Chuliá, A.; Martín-Belloso, O.; Hernando-Hernando, I.; Soliva-Fortuny, R. Effect of Pulsed Electric Fields on Carotenoid and Phenolic Bioaccessibility and Their Relationship with Carrot Structure. *Food Funct.* **2021**, *12*, 2772–2783. [CrossRef]
59. Graça, J.S.; Furtado, M.M.; Freire, L.; Watanabe, C.A.; Rocha, R.S.; Sant’Ana, A.S. Impact of pre-exposure stress on the growth and viability of *Lactobacillus acidophilus* in regular, buriti pulp and orange byproduct fermented milk products. *Food Microbiol.* **2025**, *125*, 104660.
60. Barboza, N.L.; Cruz, J.M.D.A.; Corrêa, R.F.; Lamarão, C.V.; Lima, A.R.; Inada, N.M.; Sanches, E.A.; Bezerra, J.D.A.; Campelo, P.H. Buriti (*Mauritia flexuosa* L. f.): An Amazonian Fruit with Potential Health Benefits. *Food Res. Int.* **2022**, *159*, 111654. [CrossRef] [PubMed]

61. Delekta, P.C.; Shook, J.C.; Lydic, T.A.; Mulks, M.H.; Hammer, N.D. Staphylococcus Aureus Utilizes Host-Derived Lipoprotein Particles as Sources of Fatty Acids. *J. Bacteriol.* **2018**, *200*, e00728-17. [[CrossRef](#)] [[PubMed](#)]
62. Zhou, B.; Pathania, A.; Pant, D.; Halpern, D.; Gaudu, P.; Trieu-Cuot, P.; Dias-Leao, A.; Pagot, C.; Solgadi, A.; Gruss, A.; et al. Prophages Divert Staphylococcus Aureus Defenses against Host Lipids. *J. Lipid Res.* **2024**, *65*, 100693. [[CrossRef](#)] [[PubMed](#)]
63. Lee, J.-E.; Kim, M.J.; Park, J.; Cho, Y.S. Environmental Triggers of Enterotoxin Production in Foodborne Staphylococcus Aureus: A Focus on Growth-Dependent Risk. *LWT* **2025**, *234*, 118590. [[CrossRef](#)]
64. Santos, C.I.A.D.; Salgado, C.A.; Vanetti, M.C.D. Lipases Bacterianas: Impactos Na Qualidade de Produtos Lácteos e Potencial Biotecnológico. *Res. Soc. Dev.* **2021**, *10*, e230101321213. [[CrossRef](#)]
65. Xin, L.; Zhang, L.; Meng, Z.; Lin, K.; Zhang, S.; Han, X.; Yi, H.; Cui, Y. Development of a Novel Loop-Mediated Isothermal Amplification Assay for the Detection of Lipolytic Pseudomonas Fluorescens in Raw Cow Milk from North China. *J. Dairy Sci.* **2017**, *100*, 7802–7811. [[CrossRef](#)] [[PubMed](#)]
66. Javidi, P.; Salari, D.; Montaseri, M.; Hosseinzadeh, S.; Shekarforoush, S.S. Diversity of Pseudomonas Spp. Isolated from Raw Milk in Iran: Growth, Proteolytic, and Lipolytic Characteristics. *Int. Dairy J.* **2026**, *172*, 106416. [[CrossRef](#)]
67. Santos, J.S.; Escher, G.B.; Da Silva Pereira, J.M.; Marinho, M.T.; Prado-Silva, L.D.; Sant’Ana, A.S.; Dutra, L.M.; Barison, A.; Granato, D. 1H NMR Combined with Chemometrics Tools for Rapid Characterization of Edible Oils and Their Biological Properties. *Ind. Crops Prod.* **2018**, *116*, 191–200. [[CrossRef](#)]
68. Koolen, H.H.F.; Da Silva, F.M.A.; Gozzo, F.C.; De Souza, A.Q.L.; De Souza, A.D.L. Antioxidant, Antimicrobial Activities and Characterization of Phenolic Compounds from Buriti (*Mauritia flexuosa* L. f.) by UPLC–ESI-MS/MS. *Food Res. Int.* **2013**, *51*, 467–473. [[CrossRef](#)]
69. Zanatta, C.F.; Ugartondo, V.; Mitjans, M.; Rocha-Filho, P.A.; Vinardell, M.P. Low Cytotoxicity of Creams and Lotions Formulated with Buriti Oil (*Mauritia flexuosa*) Assessed by the Neutral Red Release Test. *Food Chem. Toxicol.* **2008**, *46*, 2776–2781. [[CrossRef](#)] [[PubMed](#)]
70. Zanatta, C.F.; Mitjans, M.; Ugartondo, V.; Rocha-Filho, P.A.; Vinardell, M.P. Photoprotective Potential of Emulsions Formulated with Buriti Oil (*Mauritia flexuosa*) against UV Irradiation on Keratinocytes and Fibroblasts Cell Lines. *Food Chem. Toxicol.* **2010**, *48*, 70–75. [[CrossRef](#)] [[PubMed](#)]
71. Reis, L.V.d.C.; Leão, K.M.M.; Ribeiro, A.P.B.; de Jesus, M.B.; Macedo, G.A.; Macedo, J.A. Evaluation of Cytotoxicity of Nanolipid Carriers with Structured Buriti Oil in the Caco-2 and HepG2 Cell Lines. *Bioprocess Biosyst. Eng.* **2020**, *43*, 1105–1118. [[CrossRef](#)] [[PubMed](#)]

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