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RESEARCH

Pulsed Electric Field–Assisted Processing of Whole Red Beetroot: A Sustainable Approach to Natural Colorant Production

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Abstract

Growing concerns over synthetic colorants have accelerated the shift toward natural sources. Among red pigment sources, red beetroot (*Beta vulgaris* L.) stands out for its superior pH stability and strong coloring capacity, making it increasingly popular in the food, medical, and cosmetic industries. Extraction is the first step in producing red colorant from this plant, yet there is a research gap regarding the use of pulsed electric field (PEF) pretreatment on whole red beetroots for continuous commercial processing possibilities. In this study, whole red beetroots were treated with PEF at different specific energy levels (0.5, 1.0, and 1.5 kJ/kg). After pretreatment, the whole red beetroots were freeze-dried for 24 h at − 30 °C under vacuum. PEF pre-treatment, particularly at 0.5 kJ/kg, significantly enhanced several quality attributes compared to the control sample, including a 20% increase in redness (a^* value), 66% in total phenolics, 45% in flavonoids, 14% in DPPH antioxidant capacity, 93% in ABTS antioxidant capacity, and 77% in betanin content (determined via HPLC) of the powder form of freeze-dried samples. Powder properties, such as dispersibility, were also enhanced according to the control group due to the cell rupture effect of PEF treatment at 0.5 kJ/kg. Higher electric fields caused deterioration of the properties of the samples. Scanning electron microscopy (SEM) images demonstrated microstructural changes in the plant tissue induced by PEF treatment. These findings highlight that PEF pretreatment to whole red beetroots is a promising approach for improving techno-functional properties of the powder samples.

Keywords Red beetroot · Pulsed electric field · Freeze-drying · Betalains · Bioactive compounds

Introduction

Beta vulgaris L., commonly known as red beetroot, is a flowering plant belonging to the *Amaranthaceae* family, with a historical presence dating back to ancient times. The distinctive red color of red beetroot is attributed to betalains, a class of pigments present in the plant. Based on their chemical structure, betalains can be categorized into betacyanins, responsible for imparting a red-violet hue, and betaxanthins, contributing to a yellow-orange coloration. The high content of betalains and bioactive components within red beetroot makes it a sought-after natural colorant in the food industry (Akan et al., 2021; Calva-Estrada et al., 2022; Tekin et al., 2023). According to recent reports, Türkiye produces approximately 25,000 tons of red beetroot annually, the majority of which is processed into concentrates and powdered derivatives. The levels of bioactive constituents in red beetroots are influenced by factors such as harvest time and cultivar, including betanin (300–600 mg/kg). Furthermore, the application of suitable pretreatments before processing has been shown to enhance extraction efficiency and improve the recovery of these valuable compounds (TÜİK, 2024). Beyond its role as a natural colorant in the food industry, red beetroot offers plenty of health benefits. Due to its high content of antioxidants and bioactive compounds, the red beetroot has been associated with various positive effects on human health such as red beetroot's improved cardiovascular health, enhanced exercise performance, and potential anti-inflammatory properties. Its nutritional profile, including vitamins (such as folate, vitamin C, and vitamin B6), minerals (including potassium, manganese, magnesium, and

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iron), and dietary fiber, adds to its appeal as a nutritious addition to a balanced diet (Chen et al., 2021; Sentkowska & Pyrzyńska, 2023).

During postharvest periods of fruits and vegetables, coloring substances undergo decomposition, leading to a decline in quality. To resist this degradation, the drying methods are extensively utilized in the food industry. The drying plays a basic role in reducing water content in raw materials, leading to desirable outcomes such as extended shelf life, reduced weight, and enhanced product quality during storage (Calín-Sánchez et al., 2020; ElGamal et al., 2023; Ma et al., 2023). Various drying methods, including hot air drying, vacuum drying, freeze drying, and osmotic dehydration, could be employed. However, it is worth noting that traditional drying methods are often regarded as time-consuming processes. The prolonged drying may also result in diminished color values and reduced biological activity, such as phenolic and antioxidant levels. To address these challenges, recent years have seen the development of innovative approaches, with a specific emphasis on leveraging advanced technologies to enhance drying processes. Over the past two decades, pulsed electric fields (PEF) have been extensively studied as a pre-treatment method for drying processes and enhance the overall quality of the end product (Giancaterino et al., 2024).

The betalains, a class of red pigments present in red beetroots, exhibit heightened resilience to variations in pH and temperature when compared to their counterparts, the anthocyanins. This characteristic renders betalains particularly sought after in various culinary applications, including but not limited to dairy products, toppings, smoothies, and confectionery items (Sadowska-Bartosz & Bartosz, 2021). However, the incorporation of red beetroot extracts or powders into food matrices initiates a transformation in their inherent techno-functional attributes during the preparatory stages (Novais et al., 2022). Consequently, post-production assessments not only necessitate the evaluation of colorimetric parameters but also demand an intricate analysis of the physical properties that influence their formulation compatibility and transportation dynamics during pre-processing or processing stages. These parameters encompass traits such as flowability and dispersibility, whose modulation can be attributed to processing techniques like pulsed electric field (PEF) treatment. Thus, a comprehensive understanding of these multifaceted properties becomes imperative for optimizing the utilization of red beetroot derivatives in food formulations and processing methodologies.

PEF treatment represents a nonthermal methodology involving the application of brief pulses characterized by high electric field intensity to a sample positioned between two electrodes. This electroprocessing induces permeability variations in food membranes, resulting in the formation of a pore structure. Primarily employed for the treatment of high-quality food products, PEF serves to preserve or minimize the loss of sensory and health-promoting attributes inherent in these products (Visockis et al., 2021). Notably, the PEF process exerts discernible effects on the structural composition of amino acids, proteins, polysaccharides, and their associated weak bonds. A review of existing literature suggests that PEF applications have been subject to evaluation as an alternative technology for sustainable food processing, particularly emphasizing its environmental friendliness (Ammelt et al., 2021; Souli et al., 2023). In addition to the PEF process, the freeze-drying method is one of the best drying methods in terms of preserving bioactive components. Drying the products by sublimation under pressure not only preserves the color and nutritional values of the products but also has a very high rehydration ability (Kılıç et al., 2024). Previous studies on the application of pulsed electric field (PEF) to red beetroots have primarily focused on investigating sliced or fragmented samples (Ammelt et al., 2021; Luengo et al., 2016; Nowacka et al., 2019). However, the potential practical and industrial impact of this process has not been examined on whole red beetroots. In this context, the present study was designed with the aim of identifying a pretreatment strategy capable of enhancing pigment recovery and overall process efficiency. Since in commercial practice, PEF can realistically be applied only to whole roots, the treatments were structured accordingly and conducted at varying PEF energy levels. Red beetroots subjected to PEF treatment were subsequently lyophilized and converted into powder form. The impact of PEF application was demonstrated by assessing the physical, chemical, and visual characteristics of the samples, comparing them with those untreated by PEF.

Materials and Methods

Materials

The red beetroot samples were purchased from a local market in Karaman, Türkiye, and washed with tap water to remove mud, soil, etc., on the day before PEF treatments. The samples were stored at 4 °C until processing. The chemicals and solvents used were obtained from Merck (Germany) and Sigma-Aldrich (USA).

Methods

Pulsed Electric Field Treatment

PEF treatment was performed with a pilot scale batch PEF system (PEF PilotTM) (Elea GmbH, Germany), which provides a voltage of up to 28 kV by monopolar and exponential decay pulses. The pulse number varied between 7 and 33 according

to the mass amount in the treatment cell with the required specific energy (kJ/kg) (Eq. 1) (Visockis et al., 2021). Pulse width was kept constant at 0.5 µs. The distance between the electrodes (made of stainless steel) was 28 cm. The whole red beetroot samples were weighed and placed inside the treatment cell between two parallel electrodes. Then, tap water ($\sigma = 907$ µS/cm, $T_{in} = 18.8$ °C, $\Delta T \leq 5$ °C) was added until the samples were completely covered. Three different specific energies of 0.5, 1.0, and 1.5 kJ/kg with a constant field strength of 1.0 kV/cm were applied to the whole red beetroot samples (Fig. 1).

$$\text{Specific Energy } (\frac{\text{kJ}}{\text{kg}}) = \frac{N_p \times 0.5 \times C \times U^2}{m \times 1000} \quad (1)$$

where N_p is the number of pulses, 0.5 is the factor in the capacitor energy equation, C is the capacitance of the PEF system (1 µF), U is the applied voltage (V), m is the sample mass in the treatment cell (kg), and 1000 is the unit conversion factor to obtain kJ/kg.

Freeze-Drying Process

Untreated red beetroots were used as a control. Both PEF-treated and untreated samples were sliced at 1.0 cm thickness and frozen at − 20 °C prior to lyophilization. The prepared samples were dried at − 30 °C for 24 h (Liyolife Freeze Dryer) with a shelf temperature of 50 °C. At the beginning of the process, the chamber pressure was > 300 Pa. Drying was continued until the chamber pressure reached < 40 Pa, resulting in a final dry matter content of 95 ± 0.5 (g/100 g) (Fig. 1). After drying, the samples were ground to a fine powder using a miller. Then, the freeze-dried red beetroot powders were stored at 4 °C in a glass jar until further analyses.

Analyses

Color Values

Colorimeter PCE-CSM 1 (Germany) was used to determine the CIE Lab L^*, a^*, b^* values in which L^* is the lightness (100 = white, 0 = black), a^* is the redness or greenness ($+a^*$ = red, $-a^*$ = green), and b^* is the yellowness or blueness ($+b^*$ = yellow, $-b^*$ = blue) of red beetroot powders. Chroma (C^*) and Hue (h°) values were expressed by Eqs. (2) and (3) (Demirci et al., 2023; Tekin et al., 2023).

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

$$h^o = \tan^{-1}\frac{b^*}{a^*} \quad (3)$$

Extraction of Bioactive Compounds

The samples were initially mixed with distilled water at a ratio of 1:10 (w/v) and homogenized using an Ultra-turrax homogenizer at 12,000 rpm for 5 min. Additional distilled water was then added to adjust the final ratio to 1:20 (w/v). The mixture was transferred to a glass-covered bottle and subjected to heat treatment in a rotating water bath at 50 °C and 50 rpm for 60 min. Following centrifugation at 4200 × g for 10 min, the supernatant was collected to be used for bioactive compound analysis (total phenolic content, total flavonoid content, antioxidant capacity, and betanin content) and stored at − 20 °C until analysis.

Total Phenolic Content

Total phenolic substance analysis was carried out according to the spectrophotometric Folin–Ciocalteu method. A 30 µL of red beetroot powder extract was taken and mixed with 2.37 mL deionized water and 150 µL Folin–Ciocalteu reagent at room temperature and incubated for 8 min in the dark. Then, 450 µL of saturated sodium carbonate solution was added and mixed by vortex and incubated at 40 °C for 30 min. The absorbance value of the mixture at 750 nm wavelength was measured with a UV–VIS spectrophotometer (Shimadzu V-1800, Japan). Different concentrations of gallic acid solutions (50–500 mg/L) were used to create the standard calibration curve and the analysis was carried out under the same conditions. The results were calculated as "mg gallic acid equivalent (GAE)/g" (Yılmaz et al., 2019; Yılmaz & Ersus Bilek, 2018).

Total Flavonoid Content

The colorimetric method recommended by Kim, Jeong, and Lee (2003) was used to assess the total flavonoid content. The results were reported as mg catechin equivalent per g dry weight sample (mg CE g − 1 d.b.) (Kim et al., 2003; Yılmaz & Zungur Bastıoğlu, 2020).

Antioxidant Capacity

Antioxidant capacity values of the samples were determined by both DPPH and ABTS methods. Trolox equivalent antioxidant capacity (TEAC) values were determined as described by Görgüç et al. (2019), and results were expressed as µmol trolox equivalent (TE) per kg dry weight basis sample (Görgüç et al., 2019).

Betanin Content

The amount of betanin in red beetroot powders was determined by the HPLC method as described by Gençdağ et al.

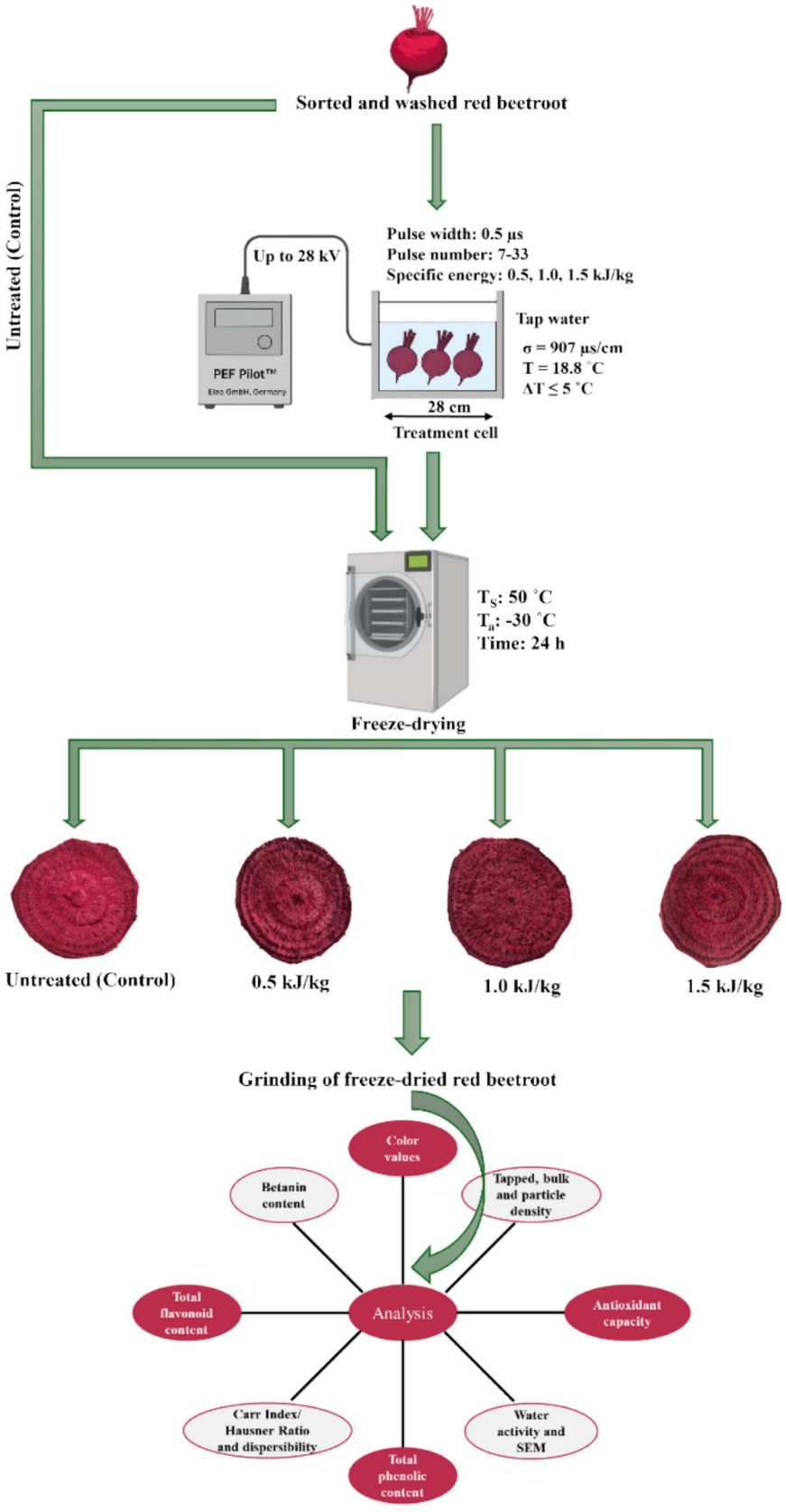

Fig. 1 Flow chart of PEF pre-treated freeze-dried red beetroot powders

(2019). In the study where a UV detector (Shimadzu SPD-20A) and a reversed-phase C18 column (250 mm × 4.60 mm × 5 µm) were used, the isocratic mobile phase was 0.5% trifluoroacetic acid solution and acetonitrile 90:10 (v:v). Analysis at 540 nm, 1 mL/min was carried out at flow rate and 20 °C column temperature. Identification and quantification were performed using the betanin standard, and the results were calculated as mg/g (Yilmaz et al., 2019).

Bulk and Tapped Density

The bulk density (ρ_{bulk}) was calculated by dividing the weight of the red beetroot powders (2 g) by the volume occupied in a graduated cylinder (10 mL). To determine the tapped density (ρ_{tap}), the cylinder was manually tapped on the surface until the volume did not change any further (Demirci et al., 2023).

Particle Density

The red beetroot powder samples' particle density (ρ_p) was determined using Eq. (4), in accordance with the methodology suggested by Demirci et al. (2023), using a pycnometer with 2-propanol.

$$\rho_p = \frac{(m_s - m_0) \times \rho}{(m_l - m_0) - (m_{sl} - m_s)} \quad (4)$$

where m_s is the weight of the pycnometer with powder product (g), m_0 is the weight of the empty pycnometer (g), ρ is the density of 2-propanol (0.785 g/mL), m_l is the weight of the pycnometer with 2-propanol (g), and m_{sl} is the weight of the pycnometer with 2-propanol and red beetroot powder product (g) (Demirci et al., 2023).

Carr Index (Flowability) and Hausner Ratio (Cohesiveness)

The Carr Index (CI) (flowability) and Hausner Ratio (HR) (cohesiveness) were calculated according to Eqs. (5) and (6) below (Akyüz & Ersus, 2021).

$$\text{Carr Index (CI)}(\%) = \frac{\rho_t - \rho_b}{\rho_t} \times 100 \quad (5)$$

$$\text{Hausner Ratio (HR)} = \frac{\rho_t}{\rho_b} \quad (6)$$

Dispersibility

Dispersibility was determined, as described by Demirci et al. (2023), by placing approximately 1 g of red beetroot powders in 10 mL of distilled water. The mixture was manually stirred for 1 min, and the reconstituted powder was poured through a sieve (212 µm). The sieved powder (1 mL) was transferred onto a weighed and dried aluminum pan and dried for 2 h in a vacuum oven at 70 ± 1 °C. The dispersibility of the powder was calculated by Eq. (7) (Akyüz & Ersus, 2021; Demirci et al., 2023).

$$\text{Dispersibility}(\%) = \frac{(10 + a) \times b}{a \times \frac{100-c}{100}} \quad (7)$$

where a is the amount of powder product (1 g), b is the % dry matter value of filtrate after treatment, and c is the % moisture content of powder product.

Water Activity

The water activity value of the red beetroot powders was measured by the Testo (Germany) brand device (25 °C).

Scanning Electron Microscopy

The microstructures of both PEF-treated and control red beetroot powders were examined by scanning electron microscope (SEM) (Zeiss Gemini Sigma 300 VP, Germany). The samples were coated with a thin layer of gold before imaging and photographed under a high vacuum at an operating voltage of 3.0 kV (Tekin et al., 2023).

Statistical Analysis

All treatments were carried out in triplicate, and each analysis was conducted in at least triplicate. The results were expressed as mean and standard deviation. The obtained data were analyzed using the SPSS 20.0 package program. The one-way analysis of variance (ANOVA) followed by Duncan's multiple range test was used to determine the differences among the groups. A probability level of 5% ($P < 0.05$) was considered significant.

Results and Discussion

Effect of Energy Levels on Color Values

Color is considered a crucial quality parameter in processed food products. It reflects the efficiency of processing methods and product stability (Novais et al., 2022). Chemical reactions such as the Maillard reaction, caramelization, and enzymatic oxidation, which occur during thermal, nonthermal processing, drying, or storage, can significantly change product's color. In this context, color alteration is critical not only for consumer acceptance but also for its impact on the nutritional quality and safety of the product (Nowosad et al., 2021). The pulsed electric field had different effects on

Table 1 Color properties of red beetroot powders

Sample	L^*	a^*	b^*	C^*	h^*
Control	43.00 ± 0.20^{a}	4.25 ± 0.34^{b}	0.43 ± 0.09^{a}	4.27 ± 0.15^{b}	5.70 ± 0.80^{a}
0.5 kJ/kg	43.50 ± 0.40^{b}	5.09 ± 0.36^{c}	1.18 ± 0.10^{d}	5.23 ± 0.05^{d}	12.90 ± 1.40^{d}
1.0 kJ/kg	43.10 ± 0.50^{ab}	3.92 ± 0.19^{a}	0.80 ± 0.07^{b}	4.00 ± 0.09^{a}	11.30 ± 2.10^{b}
1.5 kJ/kg	43.20 ± 0.30^{ab}	4.26 ± 0.13^{b}	0.94 ± 0.12^{c}	4.36 ± 0.06^{c}	12.30 ± 1.20^{c}

Data represent the mean values and standard deviations

[a, b, c, d] Different letters regarding each analysis represent statistically significant differences (P<0.05)

the color properties of the samples depending on the energy levels (Table 1). The L^* value did not change significantly with the applied electric field, and the lightness remained generally constant, indicating that the energy level had a low effect on the lightness. The a^* value showed a significant increase at the 0.5 kJ/kg level, indicating more red color, but a decrease was observed at the 1.0 and 1.5 kJ/kg energy levels. This fluctuation is due to different energy levels affecting the structure of the pigments and the chromophore groups differently. Lower energy levels reveal the colors of the pigments more, while higher energy levels may cause pigment degradation. The observed changes in the a^* value can largely be attributed to the enzymatic browning reaction, which is likely a result of the release of intracellular contents caused by electroporation. Electroporation, which involves applying an electrical field to cells, can disrupt cellular membranes and facilitate the escape of compounds that contribute to browning (Grimi et al., 2010; Wiktor et al., 2015). Additionally, similar trends were noted in the b^* parameter, indicating that these phenomena are not isolated to the a^* value alone. This suggests a broader impact of electroporation on the color parameters of the substance being examined, reflecting changes in both the underlying biochemical reactions and the physical properties of the material.

The chroma value serves as an indicator of a color's purity or saturation, whereas the hue angle determines its position on the color scale. A higher chroma value signifies a vibrant and saturated color, while a lower chroma value indicates a pale or pastel color (Hedjar et al., 2025). Upon examining the changes in chroma and hue values of red beetroot powders subjected to varying energy treatments at an energy level of 0.5 kJ/kg, there is a noteworthy increase in chroma from 4.27 ± 0.15 to 5.23 ± 0.05, and hue angle from 5.70 ± 0.80 to 12.90 ± 1.40, reflecting a significant enhancement in color intensity. Conversely, at 1.0 kJ/kg, there is a decrease in chroma by 23.5%, along with a 12.4% decline in the hue angle, indicating some degradation of color characteristics. At 1.5 kJ/kg, a partial recovery is noted, with chroma increasing by 9% and an 8% recovery in the hue angle. This suggests that higher energy levels may restore some color intensity, although they do not surpass the effects observed at 0.5 kJ/kg.

Table 2 Bioactive properties of red beetroot powders

Sample	TPC (mg GAE/g)	TF (mg CE/g)	DPPH (μmol TE/kg)	ABTS (μmol TE/kg)
Control	25.70 ± 5.80^{a}	2.11 ± 0.12^{a}	28.30 ± 2.30^{a}	9.50 ± 0.70^{b}
0.5 kJ/kg	42.60 ± 4.20^{d}	3.06 ± 0.09^{c}	32.30 ± 2.40^{c}	18.30 ± 3.10^{d}
1.0 kJ/kg	41.50 ± 3.70^{c}	2.92 ± 0.08^{b}	32.10 ± 1.90^{c}	11.20 ± 1.40^{c}
1.5 kJ/kg	23.80 ± 2.70^{b}	2.91 ± 0.08^{b}	30.30 ± 1.80^{b}	8.40 ± 0.80^{a}

Data represent the mean values and standard deviations.

TPC, total phenolic content; TF, total flavonoid content; GAE, gallic acid equivalent; CE, catechin equivalent;TE, trolox equivalent

a, b, c, d Different letters regarding each analysis represent statistically significant differences (P<0.05).

Effect of Energy Levels on Bioactive Properties

The bioactive properties of red beetroot powders were significantly affected by the pulsed electric field, depending on the energy levels (Table 2). Compared to the fresh sample, all treated groups exhibited an increase in total phenolic content (TPC), with the highest value determined at 0.5 kJ/kg as 42.60 ± 4.20 mg GAE/g. This finding demonstrated that a mild energy level for PEF treatment could assist in the release or preservation of phenolic compounds due to cell rupture, which enhances the extractability of these compounds (Eyshi et al., 2024; Rashvand et al., 2025). However, the increase in energy level to 1.5 kJ/kg led to a statistically significant reduction in TPC (23.80 ± 2.70 mg GAE/g). This effect may be attributed to the degradation of phenolic compounds caused by excessive processing stress over electric current or thermal effects (Eyshi et al., 2024). A similar trend was observed in total flavonoid content (TF), where the 0.5 kJ/kg group showed the highest value (3.06 ± 0.09 mg CE/g), followed by a gradual decline with increasing energy levels. Although the differences among treated samples were relatively minor, they were statistically significant ($P < 0.05$). These results indicate that low-energy levels PEF treatment can enhance flavonoid preservation, whereas higher energy levels may lead to their degradation or transformation (Liu et al., 2024; Rastorhuiev et al., 2024).

After the PEF pretreatment, all samples were cut into 1 cm-thick slices and then freeze-dried, a technique known to preserve thermolabile bioactive compounds due to the

low-temperature processing conditions. This drying technique likely preserved phenolic and flavonoid compounds in the treated samples, minimizing degradation that may occur with conventional thermal drying methods. The observed increase in TPC and TF, particularly at lower energy levels, can be attributed to two main factors: the enhanced extractability resulting from PEF-induced cell rupture and the protective effects of freeze-drying on these compounds. However, the decrease in bioactive compound levels at 1.5 kJ/kg indicates that excessive PEF intensity may negate the protective benefits of freeze-drying. This decline could be due to oxidative stress or irreversible damage to sensitive phytochemicals (Jedlińska et al., 2025; Thiruvengadam et al., 2024).

A similar trend was observed in antioxidant activity, which was measured using the ABTS and DPPH assays. All samples treated with PEF exhibited significantly higher antioxidant capacities compared to the fresh sample, with the highest values recorded at 0.5 kJ/kg (ABTS: 18.30 ± 1.30 µmol TE/kg, DPPH: 32.30 ± 2.40 µmol TE/kg). This enhancement may be attributed to the improved preservation and release of phenolic and flavonoid compounds under mild PEF conditions, which are known contributors to antioxidant activity (Athanasiadis et al., 2023; Martín-García et al., 2020).

However, a decline in antioxidant activity was observed at the highest energy level (1.5 kJ/kg). This suggests that, according to the energy level, excessive PEF intensity might induce oxidative stress or lead to degradation of sensitive bioactives, despite the protective role of freeze-drying (Martín-García et al., 2020; Yu et al., 2017).

Effect of Energy Levels on Betanin Content

Betanin is one of the most abundant betalains in red beetroot. It also plays a critical role as an important dietary component contributing to the nutritional and health benefits of red beetroot (Stoica et al., 2025). In this study, a significant increase in betanin levels was detected with PEF application compared to the control at different energy levels (Fig. 2). The highest increase was determined at the 0.5 kJ/kg energy level. This finding indicates that low-energy PEF treatment effectively increases membrane permeability, thereby promoting the release of intracellular pigments (Jedlińska et al., 2025; Luengo et al., 2016; Rastorhuiev et al., 2024). Due to that reason, extraction efficiency increases, which promotes the better-quality extracts gained in industrial-level production. In this point of view, in the control group, the betanin content was measured at 3.50 µg/g. Following treatment at 0.5 kJ/kg, the betanin content increased to 6.20 µg/g (Fig. 2). This difference was statistically significant, as reflected by the distinct letter groupings assigned to each treatment. This approximately two times more betanin gains gives higher

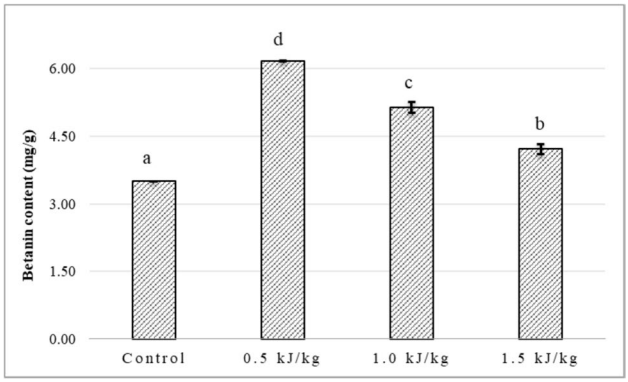

Fig. 2 Betanin content of red beetroot powders

natural potential for coloring to the extracts in food products. Betanin content was higher than in the control group at 1.0 and 1.5 kJ/kg; however, these values were still below those achieved at 0.5 kJ/kg. As it was known, this indicates that while pulsed electric field (PEF) treatment promotes pigment extraction, high energy input can adversely affect pigment stability, potentially due to structural changes or mild thermal degradation (Athanasiadis et al., 2023; Jedlińska et al., 2025; Luengo et al., 2016; Rastorhuiev et al., 2024).

Effect of Energy Levels on Density and Physical Properties of Freeze-Dried Red Beetroot Powder

Red beetroot powder has potential as a natural colorant in food products, particularly in cold instant drinks, and its technological properties are therefore of critical importance, as PEF treatment at different energy levels significantly affected the density and physical properties of the powders. As shown in Fig. 3, PEF treatment had a significant impact on bulk, tapped, and particle densities. Particularly at 0.5 kJ/kg, the increase in tapped density may be due to the structural disruption of plant tissues, which may reduce the porosity of the particles and promote tighter packing of the particles. Compaction of the powder reduces the amount of interstitial air between particles, thereby promoting a tighter packing arrangement and increasing bulk density (Ding et al., 2020; Jedlińska et al., 2025). The relatively high particle density at the 1.5 kJ/kg energy level suggests the formation of harder and less porous particles or further collapse of the cellular structure. However, higher energy inputs may lead to the formation of irregular or aggregated particles with poor packing behavior, as evidenced by the simultaneous decrease in volume and tapped densities at this level. Local temperature increases due to the high energy level or surface hardening caused by electroporation effects may cause such structural changes that would hinder powder flow and compaction (Lebovka et al., 2005; Suhag et al., 2024).

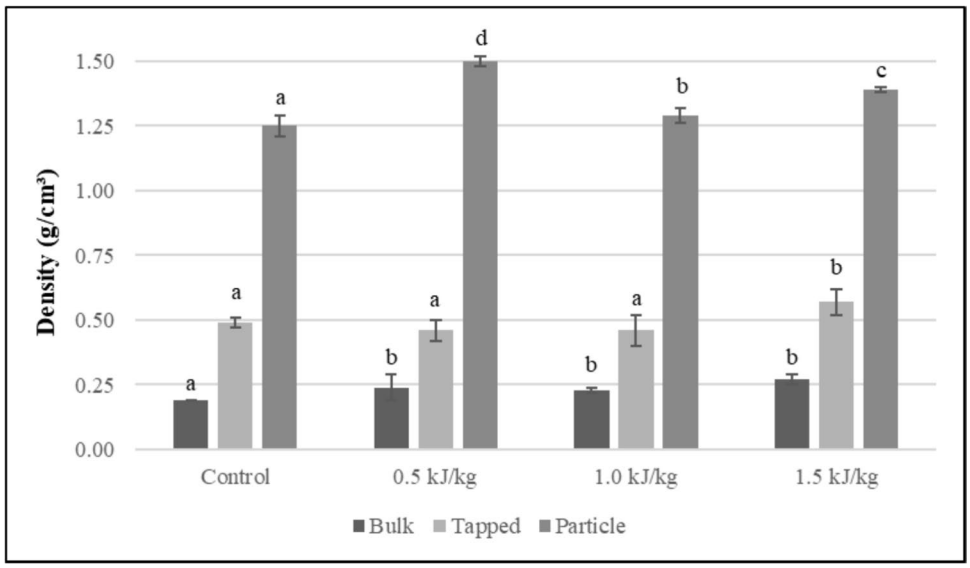

Fig. 3 Density properties of red beetroot powders

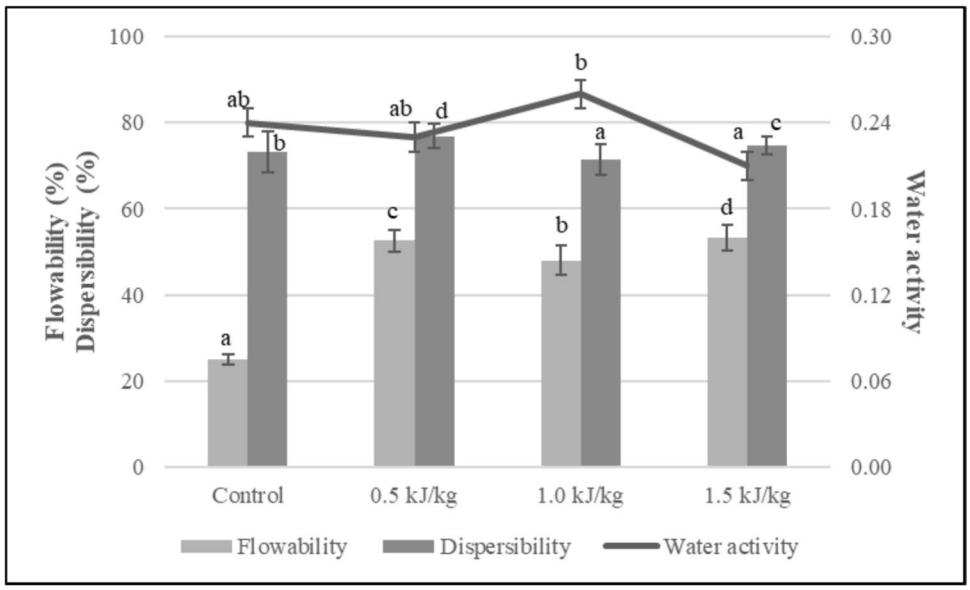

Fig. 4 Physical properties of red beetroot powders

The physical properties of the red beetroot powders, including flowability and dispersibility, were affected by PEF treatment, as shown in Fig. 4. Compared with the control sample, PEF treatment at 0.5 kJ/kg increased the CI from 25.00 to 52.60%, indicating reduced flowability. This suggests that although particle size distribution became more uniform at this energy level, the overall cohesiveness between particles increased (Suhag et al., 2024). Similarly, the CI remained high at 1.0 kJ/kg (48.00%) and 1.5 kJ/kg (53.30%), demonstrating that all PEF treatments led to poorer flowability than the control sample, likely due to structural modifications causing partial aggregation or stronger interparticle attractions. In contrast, dispersibility values exhibited a different trend. Compared with the control sample, dispersibility improved from 73.20 to 76.90% at the 0.5 kJ/kg energy level, slightly decreased at 1.0 kJ/kg (71.40%), and increased at 1.5 kJ/kg (74.60%). The enhancement at 0.5 and 1.5 kJ/kg may be attributed to a more homogeneous particle structure resulting from cell disruption, which promotes better interaction with water during rehydration. The slight decrease at 1.0 kJ/kg could be related to surface modifications or localized moisture redistribution caused by excessive electromechanical stress, reducing the particles' ability to disperse efficiently (Jedlińska et al., 2025; Rezaee et al., 2019).

Water activity values showed limited differences according to the energy levels. The lowest recorded water activity value at the 1.5 kJ/kg energy level suggests more efficient

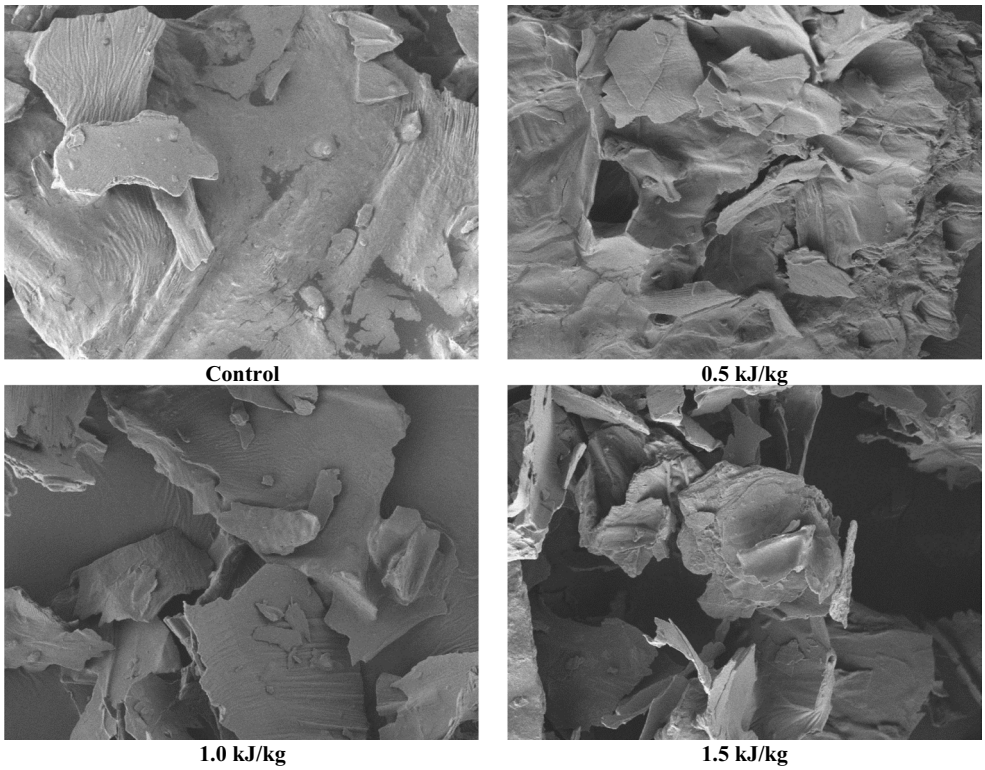

Fig. 5 Scanning electron microscopy (SEM) images of red beetroot powders at 2500 × magnification level

drying, likely due to a possible reduction in surface moisture or PEF-induced microstructural changes that increase moisture migration during dehydration. Conversely, the slight increase at 1.0 kJ/kg could be explained by structural collapse or increased moisture retention capacity due to internal void formation or water binding in denatured cellular matrices (Jedlińska et al., 2025).

Effect of Energy Levels on Morphology

Scanning electron microscope (SEM) images revealed significant changes in the surface morphology of red beetroot powders depending on the PEF energy levels (Fig. 5). The control group exhibited smoother, more compact, and layered structures compared to the other samples. This suggests that cell integrity was largely preserved during freeze-drying without PEF treatment (Jedlińska et al., 2025). At the 0.5 kJ/kg energy level, significant changes in surface structure were observed. Signs of cellular fragmentation were detected in the samples, with more fragmented and irregular surfaces. These changes indicate that, even at lower energy levels, PEF treatment facilitates electroporation and partial disruption of cell walls, facilitating structural loosening and increased surface area. These properties increase the accessibility of intracellular components, making them suitable for mass transfer processes such as extraction or drying (El Khayat Driaa et al., 2025; Jedlińska et al., 2025).

Morphological differences were even more pronounced at the 1.0 kJ/kg energy level. The samples exhibited more extensive fragmentation, increased porosity, and the presence of deformed particles. This may be attributed to the cumulative effects of electrical stress, which increases tissue rupture and internal channel formation. Although these properties facilitate mass transfer processes such as the extraction of intracellular pigments and bioactive compounds, increasing energy levels have been reported to have a degradative effect on these components (Ben Ammar et al., 2011; Carpentieri et al., 2022; Rashvand et al., 2025).

At the highest energy level of 1.5 kJ/kg, the structure appeared more collapsed and compacted, with clustered or fused particle formations. This suggests that excessive energy input may have reduced the integrity and porosity of the red beetroot powders by causing local heating or structural collapse. The presence of packed and folded structures suggests that a higher PEF energy level may cause intense mechanical and thermal stress in the plant matrix, potentially leading to reduced rehydration or solubility properties (Ben Ammar et al., 2011; Carpentieri et al., 2022; Jedlińska et al., 2025; Rashvand et al., 2025).

Conclusion

PEF pretreatment at 0.5 kJ/kg markedly improved color retention, betalain content, and antioxidant activity in both extracts for concentrate production and freeze-dried red beetroot powder, highlighting its potential as an effective non-thermal method for producing high-quality natural colorants and functional food ingredients. PEF treatment, particularly at an energy level of 0.5 kJ/kg, significantly enhanced, including a 20% increase in redness (a^* value), 66% in total phenolics, 45% in flavonoids, 14% in DPPH radical scavenging activity, 93% in ABTS antioxidant activity, and 77% in betanin content of freeze-dried red beetroot powder. Applying PEF to whole red beetroot shows strong potential as a pretreatment step in industrial production lines for concentrated natural colorants. Furthermore, the techno-functional properties of freeze-dried red beetroot powders, especially dispersibility, were positively affected, potentially enhancing their applicability in diverse food matrices. However, it was determined that applying higher PEF energy levels (1.0 and 1.5 kJ/kg) had a detrimental effect on several quality parameters, likely due to excessive membrane disruption and compound degradation. The use of PEF not only supports the development of value-added red beetroot-based ingredients but also aligns with sustainable food processing strategies by minimizing thermal degradation.

Future studies could focus on a more comprehensive optimization of PEF process parameters, including pulse width, pulse number, frequency, and electric field strength, to better understand their combined effects on cell disintegration efficiency, pigment stability, and techno-functional properties of beetroot powders. The integration of PEF with complementary technologies such as ultrasound, ohmic heating, or membrane concentration systems could also be explored to enhance pigment yield and improve process sustainability. From a scale-up perspective, pilot-scale and continuous-flow PEF systems could be investigated to assess throughput capacity, energy consumption, operational costs, and cleaning requirements under industrial conditions. Life cycle assessment (LCA) and techno-economic analysis (TEA) would further help determine the environmental and economic feasibility of adopting PEF as a pretreatment in commercial natural colorant production lines. Overall, such future work will be critical in transforming the promising laboratory-scale findings of this study into robust industrial applications.

Author Contribution İT: conceptualization, methodology, software, visualization, formal analysis, investigation, writing original draft, writing-review & editing. AA: conceptualization, methodology, software, visualization, formal analysis, investigation, writing-review & editing. AG: methodology, formal analysis, investigation, writing-review & editing. FMY: conceptualization, supervision, methodology, formal analysis, investigation, writing-review & editing, validation. SE: conceptualization, supervision, methodology, writing-review & editing, funding acquisition, resources, validation.

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Data Availability Data will be made available on request.

Declarations

Consent for Publication All authors agree to publish.

Conflicts of Interest The authors declare no competing interests.

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