Effect of pulsed electric field treatment on cell-membrane permeabilization of potato tissue and the quality of French fries

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Abstract

The effect of pulsed electric field (PEF) treatment on the cell membrane permeabilization of potato tissue and the quality of French fries was investigated. Pulses with an electric field strength of 0.5, 1.5, and 2.5 kV/cm and a width of 20 μs were applied to the potato. PEF treatment permeabilized the membrane of potato cells. The magnitude of cell-membrane permeabilization was estimated by ion leaching and biological impedance tests and verified by microscopic observation. As the PEF field strength increased, the accumulation of neutral red dye decreased due to increased cell rupture. The index Z-values (relative cell membrane breakdown values) for 0.5-, 1.5-, and 2.5-kV/cm PEF-treated samples were 0.01, 0.28, and 0.52, respectively. PEF treatment at 2.5 kV/cm reduced the cutting force of potatoes by 33%; it also increased the degree of the crispness of French fries by 64% and decreased crude fat content by 28%. The total reducing sugar content was decreased by PEF treatment, which could be attributed to increased lightness and yellowness after frying. Therefore, PEF treatment improved the quality of French fries by increasing crispness, improving color, and reducing crude fat content.

Keywords: cell membrane permeabilization; fat content; French fries quality; potato; pulsed electric field

Introduction

Potato is one of the most available foods worldwide and can contribute to the daily supply of carbohydrates, minerals, vitamins, and proteins. French fries are among the most popular potato products because of their texture and characteristic taste. Frying is a complicated process that involves the heat and mass transfer between fried foods and the surrounding oil. The frying process results in developing a thin outer layer and crust, which are essential in heat and mass transfer during frying and for the sensory characteristics (Moreira *et al*., 2009). Dehydration toward the center of the potato causes pore creation and shrinking, resulting in the production of this thin layer (Kalogianni and Smith, 2013). During crust development, complex chemical and physical events have been reported such as starch gelatinization, cell shape and size changes, and tissue disruption (Pedreschi and Aguilera, 2002).

In the French-fry industry, blanching is a widely used thermal process. It is usually performed in water at 70–90°C for 3–10 min to inactivate the polyphenol oxidase enzyme and soften the tissue (Ignat *et al*., 2015). Starch is partially gelatinized during blanching, and cell walls are weakened (Moyano *et al*., 2007). However, blanching is time-consuming and requires a large amount of water. In addition, chlorogenic acid and iron in potatoes may form a colorless compound, ferrichlorogenic acid, resulting in an undesirable darkening of the blanched tissue (Wang-Pruski and Nowak, 2004). Sulfate is added to the blanching solution to prevent this

process. However, the sulfate may leave a chemical residue in the product, which can cause an allergic reaction in sensitive humans. Therefore, improving the quality of French fries while minimizing chemical additives and reducing the excessive usage of energy and water are important considerations.

The food industry has focused on nonthermal processing technologies for reducing energy consumption and shortening the treatment duration (Shahbaz *et al*., 2018). PEF is a nonthermal processing technology that involves electrical stimulation using pulsations of high voltage and short intervals (1–100 μs) to food or food ingredients (Hill *et al*., 2022; Vorobiev and Lebovka, 2009). The processing parameters for PEF include the pulse width (μm), pulse number (n), pulse frequency (Hz), and electric field strength (kV/cm). Membrane conductivity increases immediately after PEF treatment, and membrane permeability increases with increasing conductivity (Angersbach *et al*., 2000; Pereira *et al*., 2009). PEF damages only the cell membrane (Vorobiev and Lebovka, 2009), having lipid components as the site of electric interaction. The degree of cell-membrane permeability is determined by the cell membrane's properties and the electrical pulse (Kandušer *et al*., 2008). PEF treatment can induce reversible or irreversible membrane permeability, depending on the conditions. In general, reversible breakdown occurs when pores stay small in proportion to the membrane area and can lead to variations in metabolic responses by increasing the development of secondary metabolites, causing sublethal stress to cells. PEF-induced irreversible permeability can significantly improve the transfer of mass in various processes, such as drying (Parniakov *et al*., 2016), extraction, and concentration (Gagneten *et al*., 2019). PEF treatment induces softening of plant tissues such as in apples, carrots, and potatoes (Boussetta *et al*., 2013). PEF treatment has also been used to improve mass-delivery processes, e.g., drying, extraction, and cooking of various fruits and vegetables (Amami *et al*., 2008; Donsì *et al*., 2010). However, little data are available on the comprehensive results of the PEF processing effects on fresh potatoes such as membrane permeabilization, textural properties, and PEF-frying effects of French fries, including texture, color, fat contents, and reducing sugar contents. In this study, we examined the PEF processing impact on the physical properties of raw potatoes and determined whether it affects the final quality of French fries.

Materials and Methods

Reagents

All chemicals used were purchased from Sigma-Aldrich, South Korea.

Potato samples

Fresh potatoes (superior) were obtained from a local marketplace in Anseong, South Korea, and before use, were stored at 4°C. Potatoes were sliced into quarters, and the two cut pieces were placed in the batch chamber for PEF treatment.

PEF treatment

PEF treatment was done using a pulse generator of 5-kW (HVP-5; DIL, Quakenbrueck, Germany) with batching equipment and continuous treatment chambers. The pulse generator creates bipolar and rectangular pulses. The batch chamber had parallel stainless-steel electrodes (10 × 5 cm) separated by 8 cm. Potato samples were submerged in the PEF treatment chamber containing 300 mL tap water. PEF was performed using an out voltage of 1–70%, frequency electrical, 500 pulses, 20 μs pulse width, and electrical field strengths of 0.5 to 2.5 kV/cm. The strength of the electric field in the treatment chamber was estimated by the following Equation (1) (Zhang *et al*., 2021):

$$\text{Electrical field strength}\left(\text{E},\frac{\text{kV}}{\text{cm}}\right)=\frac{\text{Output voltage}\left(\text{kV}\right)}{\text{Distance between the electrode}\left(\text{cm}\right)} \quad (1)$$

The electric field strengths ([E] 0.5–2.5 kV/cm) were used to attain irreversible cell disruption—an E of > 1 kV/cm leads to permanent pore development in the membranes of plant cells. PEF treatment was conducted at room temperature. Untreated samples were immersed in tap water for 1 min. The PEF treatment conditions are listed in Table 1. PEF-treated potato pieces were sliced into cuboids (1 × 1 × 4 cm) using a commercial cutter with an adjustable frame (JG-04, ChromeCater, South Africa).

Blanching

Blanching was performed at 90°C for 3 min by immersing 50 g of raw potato slices in 100 mL of tap water. For 20 min, the blanched potato was immersed in 300 mL of

Table 1. PEF treatment conditions.

Size (g)	Field Strength (kV/cm)	out voltage (%)	Pulse width (μs)	Frequency (Hz)	Pulse number
40 ± 2	0.5	14	20	50	500
	1.5	42			
	2.0	70			

tap water at room temperature. Untreated samples were immersed in tap water for 20 min.

Microscopic observation of potato tissue

Sample thickness was determined to be 300 µm using a hand microtome (FB1262, Finn Science). Neutral red solution (0.5% aqueous neutral red) diluted to 0.04% with 0.2 M mannitol–0.01 M 4-(2-hydroxyethyl)-1-piperazineethanesulfonic acid (HEPES) buffer at pH 7.8 was used for visualization (Caine *et al*., 2003). Tissue was immersed in a 0.04% diluted dye solution for 2 h and rinsed for 1 min in 0.2 M mannitol–0.01 M HEPES buffer (pH 7.8). Neutral red staining tissue was examined by using an optical microscope (CX22LEDRFS1, Olympus, Japan). The stained cells were observed using an electron microscope at magnifications of 40× and 100×.

Estimation of cellular damage based on potato tissue conductivity measurements

Electrical conductivity (S/m) was measured to estimate the PEF-induced membrane permeabilization of potatoes. Samples of potatoes were cut into cylinders (diameter of 1 cm, thickness of 1 cm) using a cork borer and measured with an LCR meter (LCR-8000G, GW Instek, Taiwan) at 1 kHz to 1.9 MHz frequencies. The electrical conductivity of potato samples was estimated by the following Equation (2) (Angersbach *et al*., 2000):

$$\sigma(\omega)^s = \frac{l}{A\left|Z(j\omega)^s\right|} \quad (2)$$

where l is the length of the sample, A is the area perpendicular to the electrical field, and $Z(j\omega)^s$ is the system impedance.

Tissue rupture was estimated from the electrical conductivity index Z-value calculated by the following Equation (3) (Vorobiev and Lebovka, 2009):

$$Z = \frac{\sigma - \sigma_i}{\sigma_d - \sigma_i} \quad (3)$$

where σ (S/m) is the measured electrical conductivity and subscripts i and d indicate intact and damaged tissue (freeze-thaw or heat treatment), respectively. The value is the electrical conductivity of untreated potato tissue, and value is obtained by thawing after freezing for 24 h in the refrigerator and measuring the electrical conductivity. The Z-value of the intact tissue is 0 and that of damaged tissue is 1.

Ion leaching measurement

Cell membrane permeabilization of potato tissue was estimated indirectly by measuring ion leaching. Potato samples were cut into cuboids (1 × 1 × 3 cm) and submerged in 250 mL of deionized water. A conductivity meter (CM-21P, TOA-DKK, Japan) was used to measure water conductivity at room temperature for 6 h.

Texture properties

Texture profile analysis

A texture analyzer (TA-XT, Stable Micro Systems Ltd., Surrey, UK) and a cylindrical probe (20 mm diameter, P/20) performed texture profile analysis. Samples were cut into cubes (1 × 1 × 1 cm) in two cycles, and compressed to 15% of their initial height. The test was performed at a pretest speed of 5 mm/s, posttest speed of 5 mm/s, and during test speed of 1 mm/s. The obtained data were analyzed using Texture Expert Software (Stable Micro Systems, UK) and expressed as chewiness, hardness, cohesiveness, springiness, and resilience values.

Cutting force

Cutting force was evaluated using a texture analyzer (TAHDi/500, Godalming, UK) and a Warner-Bratzler flat blade (Caine *et al*., 2003). Samples were sliced into cuboids (1 × 1 × 4 cm), and the maximum shear force (N) was measured. The test was performed at a pretest speed of 5 mm/s, a posttest speed of 5 mm/s, and a test speed of 10 mm/s.

Frying conditions

A commercial deep-fat fryer (DK-201, DELKI, China) was used for frying. Potato cubes were cut into cuboids (1 × 1 × 4 cm) and fried in soybean oil at 180°C for 5 min (potato–oil ratio 1:30, w/w). After frying, potato cubes were drained for 3 min in a frying sieve to remove excess oil.

Moisture content of French fries

The oven-drying method was used to measure the moisture content of fries at 105°C temperature for 18 h. The moisture content of the French fries was measured at 1-min intervals from 1 to 5 min during frying.

The crispness of French fries

A texture analyzer (TAHDi/500, TAHD, Godalming, UK) equipped with a Warner-Bratzler flat blade was used for measuring crispness. The crosshead speed was 10 mm/s.

Color measurement of French fries

A colorimeter (Ultra Scan Pro, Hunter Lab) was used to determine the color differentiation of the French fries. A standard whiteboard was used to calibrate the colorimeter, and values for the L* (lightness), a* (+, redness/–,

greenness), and b* (+, yellowness/−, blueness) were determined. The color differentiation between untreated and PEF-treated samples was shown as ΔE, calculated by the following Equation (4):

$$\Delta E = \sqrt{(\Delta L)^2 + (\Delta a)^2 + (\Delta b)^2} \quad (4)$$

Total reducing sugar content of potato tissue

Five grams of raw potato sample was homogenized in 50 mL of distilled water for 1 min and centrifuged at 4°C for 20 min at 8000 rpm. The supernatant was filtered through a membrane filter (0.45 μm; Millipore) and diluted two-fold with distilled water. Samples were inserted into a test tube containing 1 mL of dinitroalicylic acid (DNS), and heated for 10 min. After cooling, 3 mL of distilled water was added, and 200 μL of every sample was transferred to a 96-well plate. At 550 nm, the absorbance was measured using a spectrophotometer.

Total crude fat content of French fries

The Folch method with several modifications was used to extract crude fat from milk powder to allow fat to be removed without being affected by moisture. Chloroform-methanol (300 mL; 2:1, v/v) was added to 15 g of homogenized sample and shaken. Next, 60 mL of distilled water was added, shaken, and impurities in the lower layer were removed using filter paper (Whatman No. 4). The filtered solvent was concentrated using a decompression condenser and the crude fat content was calculated by weighing.

Preference evaluation of French fries

Preference was evaluated by examining the color, texture, and overall acceptability of French fries on a 9-point hedonic scale by 20 panelists. The panelists comprised students and graduate students at the Department of Food Science and Biotechnology, Chung-Ang University who were 20–30 years of age and trained in the inspection method. The sample was placed in a white dish to evaluate color, followed by assessing texture and overall preference. Color, texture, and overall acceptability were rated from very disliked (1 point), neither good nor bad (5 points), to very good (9 points).

Statistical analysis

Data were analyzed using analysis of variance (ANOVA) in IBM SPSS Statistics 19. Results were expressed as means ± standard deviation. Differences in means were assessed by Duncan's multi-range test and considered significant at $P < 0.05$.

Results and Discussion

Microscopic observation of potato tissue

Neutral red (NR) staining visualized cell membrane permeabilization of potato tissue. In the control (i) and blanched (ii) samples, NR remained in the cytoplasm because the cell membrane was intact (Figure 1). The

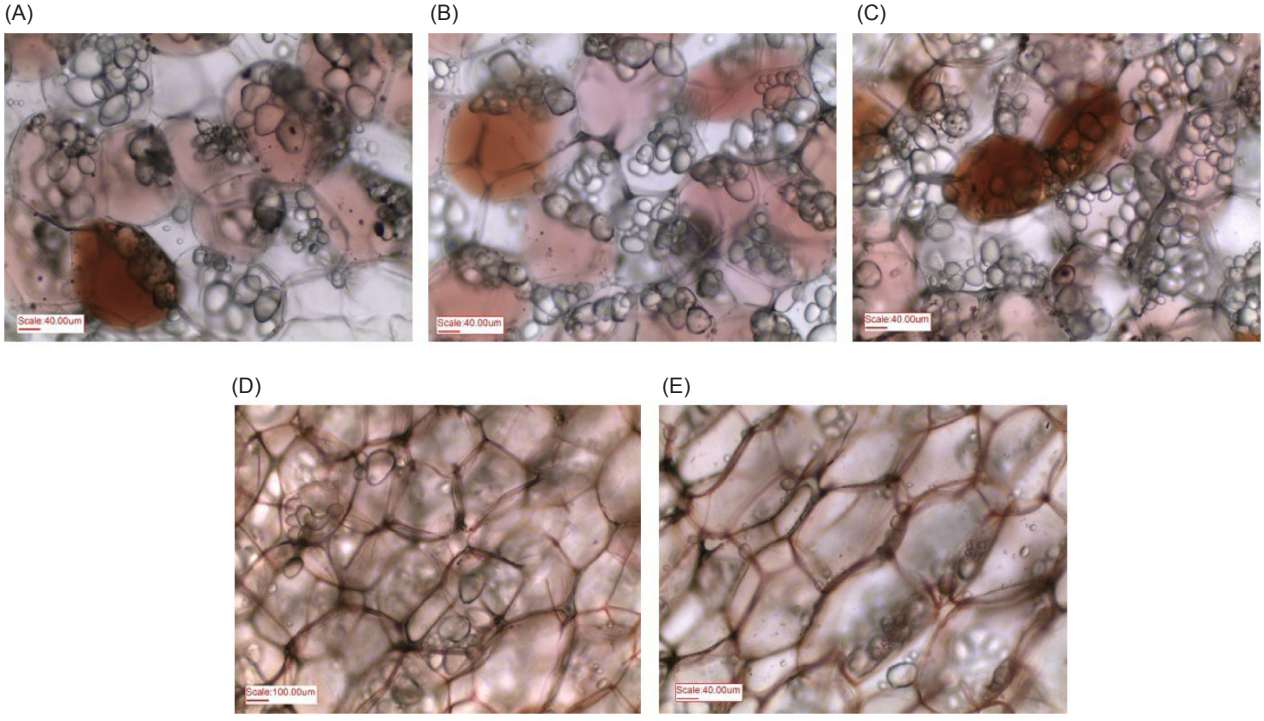

Figure 1. Microscopic observation of potato tissue. (A) Control, (B) blanched, and PEF-treated at (C) 0.5 kV/cm, (D) 1.5 kV/cm, and (E) 2.5 kV/cm.

samples subjected to PEF treatment at 0.5 kV/cm also showed NR-stained cells, implying an intact membrane (Figure 1c). PEF treatment at 1.5 to 2.5 kV/cm exhibited unstained areas (Figure 1d, e). This is consistent with a previous report on onions treated with PEF (Ersus and Barrett, 2010). Therefore, PEF treatment may induce membrane breakdown and be affected by membrane permeability.

Electrical conductivity of potato

Figure 2 shows potato samples' frequency-dependent electrical conductivity spectrum from 1 kHz to 1.9 MHz. Increased membrane permeability reduces the electrical resistance, altering the impedance of plant cells. Therefore, determining the impedance of plant samples enables the assessment of the magnitude of PEF-induced damage (Oey *et al*., 2016). The conductivity-frequency spectrum of the potato samples treated at 0.5 kV/cm was similar to those of the untreated control and blanched pieces. Conductivity is degraded by the electrical resistance of an intact cell membrane. However, samples subjected to PEF at 1.5 and 2.5 kV/cm had high conductivity, indicating membrane damage.

Figure 3 shows the Z-values obtained by measuring electrical conductivity (S/m). The Z-value reflects the degree of disintegration of tissue (Lebovka *et al*., 2002). The index Z-value of freeze-thawed tissue is 1.0, and that of untreated tissue is 0. The Z-values of the control, blanched, and 0.5-, 1.5-, and 2.5-kV/cm PEF-treated samples were 0, 0.01, 0.01, 0.28, and 0.52, respectively. The low Z-values of the control blanched and 0.5-kV/cm-treated potato samples indicate intact tissues. However, 1.5- and 2.5-kV/cm PEF treatment increased Z-values, indicating tissue destruction. Similarly, the Z index values of red beet were 0.6 and 0.9, following PEF at 375 and 1000 V/cm, respectively (Loginova *et al*., 2011).

Ion leaching from potato

The breakdown of the potato cell membrane was assessed by measuring the elution of ionic materials (Figure 4). The conductivity values of the control, blanched, and 0.5-, 1.5-, and 2.5-kV/cm PEF-treated samples after 6 h of immersion were 0.006, 0.01, 0.02, 0.06, and 0.07 S/m, respectively. Untreated potato showed very slowly increasing conductivity, indicating little leaching of ionic materials and intact cell membranes. By contrast, the PEF-treated samples showed rapidly increasing solution conductivity, indicating that disrupted cell membranes accelerated the release of ionic materials. This finding is consistent with a prior report on PEF-treated red pepper (Won *et al*., 2015). Therefore, membrane permeabilization of potato cells was increased by PEF treatment.

Effect of PEF treatment on potato textural properties

The maximum N values of the control, blanched, and 0.5-, 1.5-, and 2.5-kV/cm PEF-treated samples were 43.14, 37.88, 36.30, 32.45, and 28.75, respectively (Figure 5).

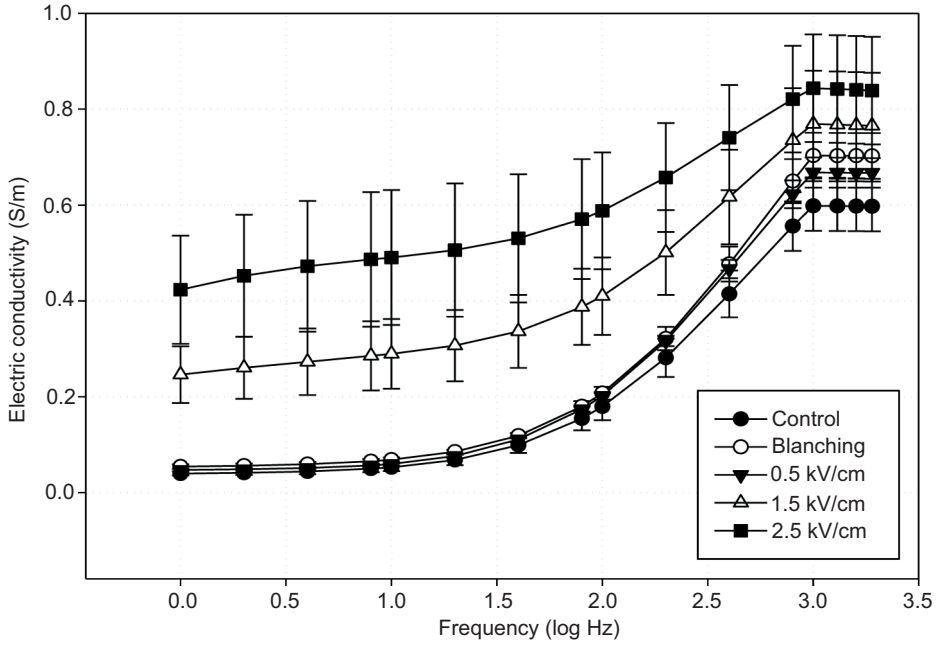

Figure 2. Electrical conductivity spectra of potato samples. Bars are standard errors of the mean.

The PEF-treated samples had significantly decreased maximum N values ($P < 0.05$); the 2.5-kV/cm PEF-treated sample was reduced by 33%.

The hardness values [N] of the control, blanched, and 0.5-, 1.5-, and 2.5-kV/cm PEF-treated samples were 21.05, 21.62, 18.96, 17.09, and 14.06, respectively (Table 2). The hardness value decreased as the PEF-treated field strength increased; the 2.5-kV/cm PEF-treated sample decreased by 33%. Similarly, the chewiness value of 2.5-kV/cm PEF-treated potato significantly decreased from 12.96 ± 2.94 to 7.86 ± 1.40 ($P < 0.05$). However, PEF treatment did not significantly affect the springiness, cohesiveness, and resilience values.

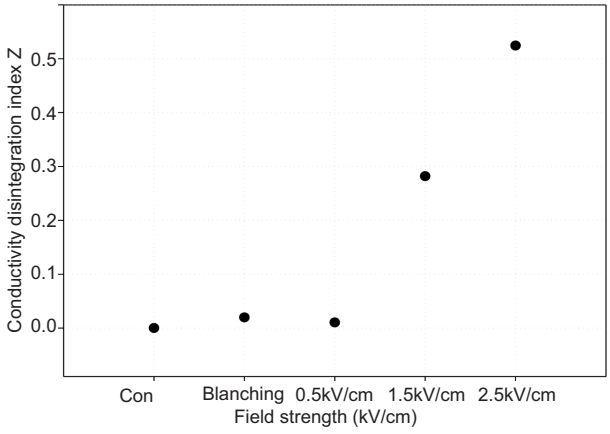

Figure 3. Cell membrane disintegration index Z values of potato samples. The conductivities of 1-kHz PEF-treated, intact, and freeze-thawed samples were used.

The tissues became weaker, and the elastic modulus decreased with increasing PEF treatment time (Lebovka *et al.*, 2004). Indeed, the hardness and chewiness of potato samples reportedly decreased with increasing PEF field strength (Icier *et al.*, 2010). Therefore, PEF treatment of potatoes may change their textural properties and result in membrane breakdown.

Effect of PEF treatment on the moisture content of French fries

Figure 6 shows moisture content according to frying time (1–5 min). The moisture content of PEF-treated samples rapidly decreased compared to the control but without a significant difference. The moisture content of the control sample at 4 min was similar to that of the 2.5-kV/cm PEF-treated sample at 2.3 min. In PEF-treated pieces, diffusion of liquid from the core to the surface might be greater during frying because of increased cell membrane permeability. The blanched samples exhibited slow water diffusion from the core to the surface due to structural changes. Blanching promoted starch gelatinization and maintained the integrity of the native pectin network by deactivating pectolytic enzymes (Pedreschi and Moyano, 2005). Therefore, PEF increased the rate of water diffusion from the core to the surface during frying.

Effect of PEF treatment on the crispness of French fries

The crispness of potato chips is the most critical indicator of their freshness, which is also reflected by their

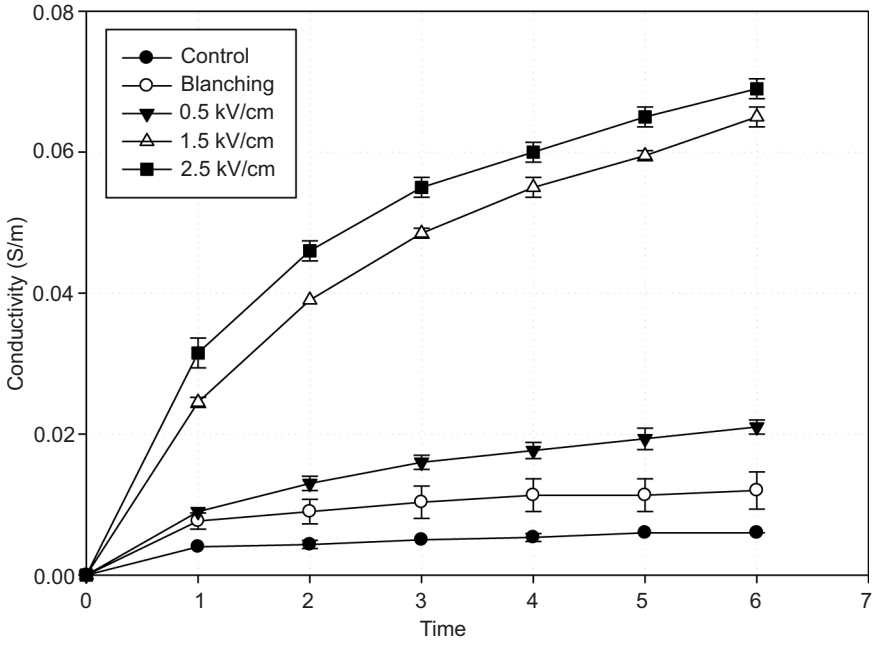

Figure 4. Effect of PEF treatment on ion release from potato. Bars are standard errors of the mean.

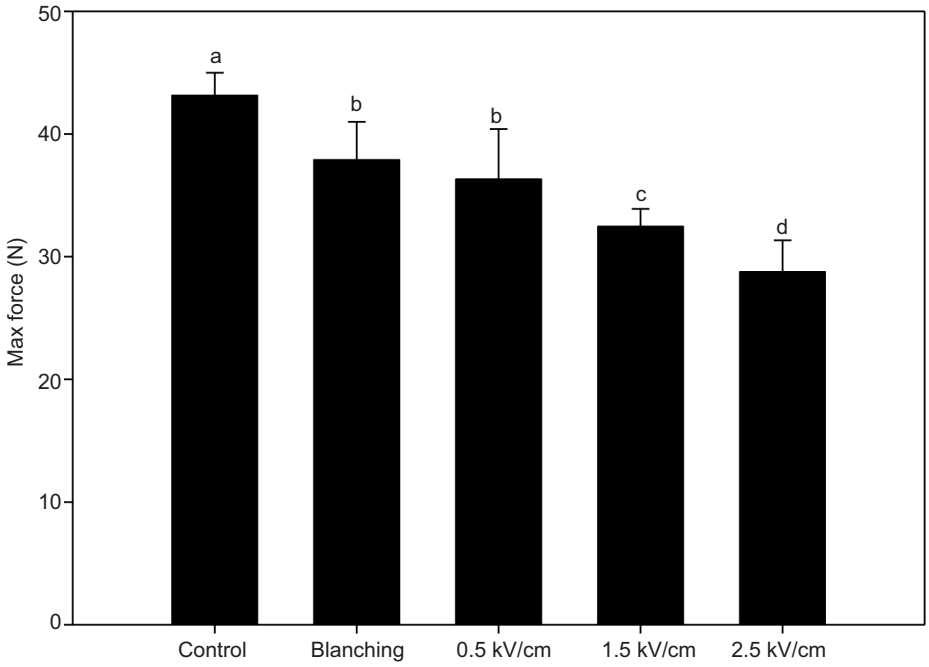

Figure 5. Maximum cutting force [N] of potato. Bars are standard errors of the mean; means with different letters are significantly different (P < 0.05).

Table 2. Texture profile analysis of potato samples.

	Hardness	Springiness	Cohesiveness	Chewiness	Resilience
Control	21.05 ± 1.39^{a}	0.82 ± 0.16^{a}	0.75 ± 0.04^{a}	12.96 ± 2.94^{ab}	0.96 ± 0.10^{b}
Blanched	21.62 ± 1.76^{a}	0.85 ± 0.11^{a}	0.74 ± 0.02^{a}	13.57 ± 1.70^{a}	0.99 ± 0.05^{b}
0.5 kV/cm	18.96 ± 1.80^{b}	0.74 ± 0.11^{a}	0.73 ± 0.02^{a}	10.45 ± 2.73^{bc}	1.03 ± 0.06^{b}
1.5 kV/cm	17.08 ± 1.76^{b}	0.75 ± 0.12^{a}	0.72 ± 0.01^{a}	9.19 ± 1.44^{c}	1.04 ± 0.03^{b}
2.5 kV/cm	14.06 ± 0.94^{c}	0.75 ± 0.11^{a}	0.75 ± 0.02^{a}	7.86 ± 1.40^{c}	1.13 ± 0.08^{a}

*Values are means ± standard deviation.
*Means with different superscript letters within the same column indicate significant difference (P < 0.05).

hardness (Salvador *et al.*, 2009). The crispness of French fries is influenced by their desirable quality characteristics (Kita *et al.*, 2007). The crispness values of French fries are shown in Figure 7. The crispness value increased with increasing PEF field strength. It was the highest for 2.5-kV/cm PEF and significantly lower for the untreated control and blanched samples. Although the moisture content of samples was varied but without a statistically significant difference (Figure 6), it cannot be the only reason for the difference in crispness. During frying, moisture evaporates due to the difference in partial vapor pressure between the product and the frying oil. The diffusion of liquid from the core to the surface in PEF-treated potato cubes was enhanced by cell membrane permeabilization. PEF treatment increases the water vapor pressure, thickens the surface vapor layer, and increases the crispness (Janositz *et al.*, 2011).

Effect of PEF treatment on the appearance and color values of French fries

An image of fried potato cubes is shown in Figure 8. PEF treatment led to uniform and brightly colored French fries. The untreated control and blanched samples showed uneven dark colors with brown edges. The color of fried potato is affected by its sugar content.

Most consumers expect French fries to be golden-brown in color, and higher L* and b* values are preferable for French fries. Table 3 shows the L* (lightness), a* (green-to-red), and b* (yellow-to-blue) color values of the French fries. PEF-treated French fries showed higher lightness and b* values than the untreated control and blanched samples. The French fries treated with 2.5-kV/cm PEF showed significantly increased brightness (51.49 ± 1.21

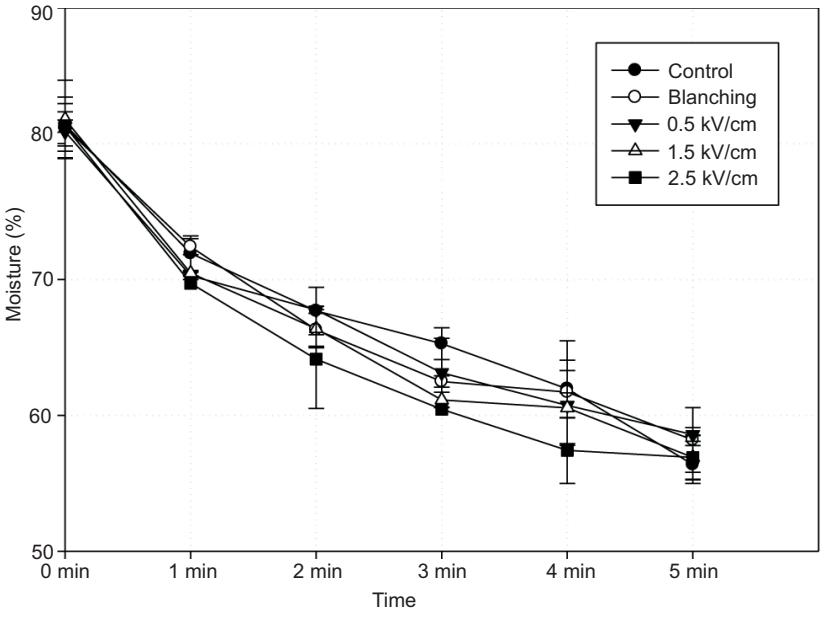

Figure 6. The moisture content of French fries according to frying time. Bars are standard errors of the mean.

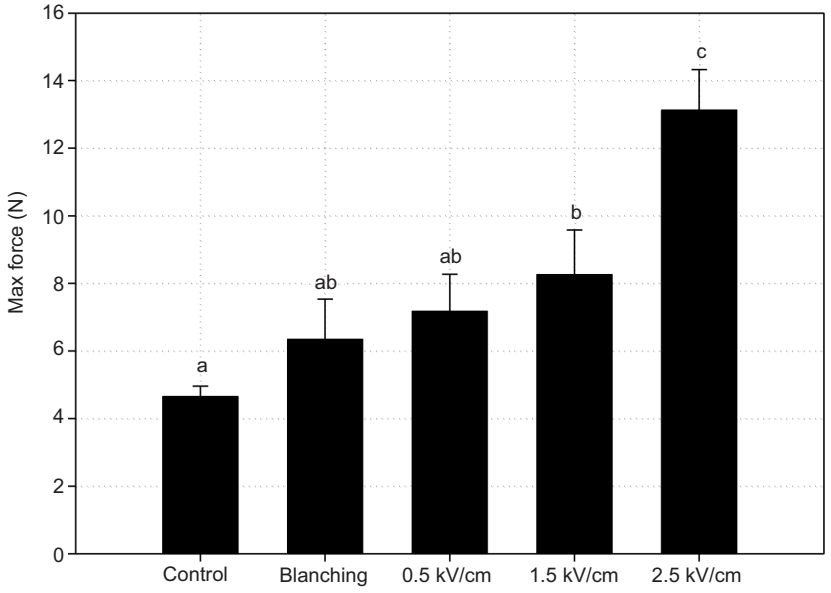

Figure 7. The crispness of French fries. Bars are standard errors of the mean; means with different letters are significantly different (P < 0.05).

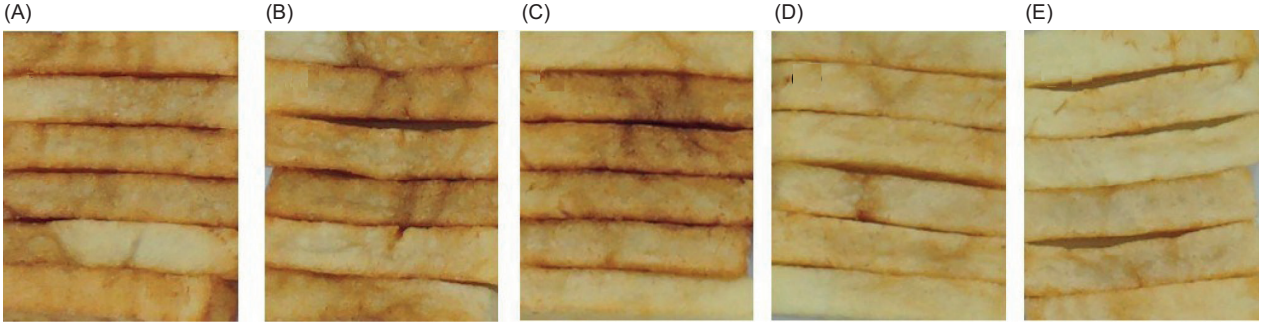

Figure 8. Appearance of French fries after frying at 180°C for 5 min. (A) Control, (B) blanched, and (C) 0.5-kV/cm, (D) 1.5-kV/cm, and (E) 2.5-kV/cm PEF-treated samples.

Table 3. Color values of French fries after frying at 180°C for 5 min.

	L*	a*	b*	ΔE
Control	51.49 ± 1.21^{d}	11.46 ± 0.81^{c}	15.80 ± 1.82^{c}	–
Blanching	57.29 ± 1.57^{b}	14.17 ± 0.87^{a}	23.71 ± 2.86^{b}	9.64
0.5 kV/cm	55.54 ± 1.28^{c}	13.29 ± 0.60^{ab}	23.04 ± 1.73^{b}	7.97
1.5 kV/cm	57.38 ± 0.90^{b}	12.88 ± 0.57^{b}	23.66 ± 1.60^{b}	9.44
2.5 kV/cm	65.81 ± 1.05^{a}	11.01 ± 0.93^{c}	28.51 ± 1.59^{a}	18.80

*Values are means ± standard deviation.
*Means with different superscript letters in the same column are significantly different (P < 0.05).

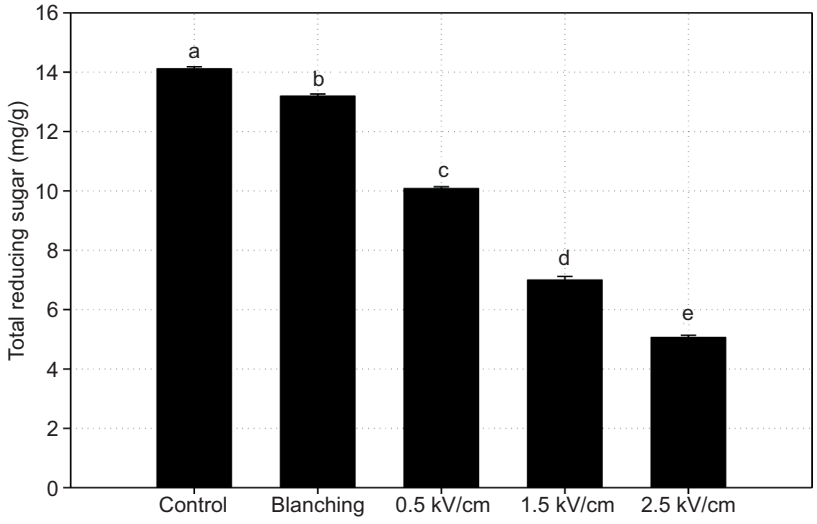

Figure 9. The total reducing sugar content of potato tissue before frying. Bars are standard errors of the mean; means with different letters are significantly different (P < 0.05).

to 65.81 ± 1.05; P < 0.05) and yellowness (15.80 ± 1.82 to 28.51 ± 1.59; P < 0.05). Therefore, PEF treatment affected the color of French fries, as indicated by the ΔE values.

Effect of PEF treatment on the total reducing sugar content of potato tissue

PEF treatment of potato cubes significantly decreased their reducing sugar content by disrupting cell membranes (Figure 9). Treatment of potato cubes with 2.5-kV/cm PEF decreased the total reducing sugar content from 14.11 ± 0.08 to 5.06 ± 0.08 (P < 0.05). In a previous study, PEF treatment at 1.5 kV/cm and 20 pulses stimulated glucose and fructose release (Janositz *et al*., 2011). Therefore, PEF treatment could be an adjunct to heat treatment for removing reducing sugars linked to the Maillard reaction and acrylamide formation. Acrylamide formation during French fries production is linked with Maillard reactions from reducing sugars and asparagine, as acrylamide precursors, and depends on the frying temperature (Yang *et al*., 2016). It was reported that during the processing, when the sugar concentration was relatively high, acrylamide formation was proportional to the sugar content. In contrast, when the sugar level was low, acrylamide formation was proportional to the asparagine content (Halford *et al*., 2012). Efforts are being made by researchers for the reduction of acrylamide content in potato chips. Ostermeier *et al.* (2021) reported that combining pretreatment of PEF with ultrasound-assisted frying caused a reduction of 66% in acrylamide content of potato chips. In another study, a reduction of 30% of acrylamide content was reported by PEF treatment (Genovese *et al*., 2019). Pretreatment with yeast followed by PEF was found useful in reducing the acrylamide content in potato chips (Schouten *et al*., 2020). A combined treatment of PEF and blanching reduced the acrylamide content of French fries (Zhang *et al*., 2021).

Effect of PEF treatment on the total crude fat content of French fries

The total crude fat contents of the untreated control, blanched, and 0.5-, 1.5-, and 2.5-kV/cm PEF-treated samples were 15.67, 16.00, 15.00, 12.67, and 11.33,

respectively (Table 4). The total crude fat content of PEF-treated samples decreased significantly with increasing field strength ($P < 0.05$). This is in agreement with a previous report (Ignat *et al*., 2015) that control and blanched samples had similar oil contents, which were significantly higher ($P < 0.05$) than those of PEF-treated pieces.

During frying, water vapor prevents oil penetration (Van Loon *et al*., 2007), and PEF treatment reduces oil uptake by enhancing water diffusion from the core to the surface of potato strips, creating a thicker water vapor layer and suppressing oil uptake. The decreased oil content of PEF-treated French fries may also result from their smoother surface, which promotes the draining of oil after frying (Thanatuksorn *et al*., 2005). Therefore, PEF treatment reduced the crude fat content of French fries.

Effect of PEF treatment on the preference scores of French fries

The maximum color, crispness, and overall acceptability scores of French fries were achieved by 2.5-kV/cm PEF treatment (Table 5). The control samples showed significantly lower scores for color, crispness, and overall acceptability. The scores of the blanched and 0.5-kV/cm PEF-treated samples were similar to those of the control. There is reportedly no difference in the color of French fries according to storage temperature and duration.

Table 4. The total crude fat content of French fries.

Sample	Total crude fat content (%)
Control	15.67 ± 2.31^{a}
Blanching	16.00 ± 1.00^{a}
0.5 kV/cm	15.00 ± 1.00^{a}
1.5 kV/cm	12.67 ± 0.58^{b}
2.5 kV/cm	11.33 ± 0.58^{b}

Values are means ± standard deviation.
*Means with different letters are significantly different ($P < 0.05$).

Table 5. Preference scores of French fries.

Sample	Color	Crispness	Overall acceptability
Control	4.42 ± 2.17^{c}	2.95 ± 1.31^{d}	3.47 ± 1.58^{c}
Blanching	4.68 ± 1.86^{bc}	3.74 ± 1.24^{c}	4.37 ± 1.38^{bc}
0.5 kV/cm	5.53 ± 1.95^{abc}	4.63 ± 1.34^{b}	5.16 ± 1.80^{b}
1.5 kV/cm	6.00 ± 2.00^{ab}	7.21 ± 0.98^{a}	7.26 ± 0.93^{a}
2.5 kV/cm	6.42 ± 2.19^{a}	7.89 ± 1.20^{a}	7.58 ± 1.46^{a}

*Values are means ± standard deviation.
*Means with different letters in the same column are significantly different ($P < 0.05$).

The color of French fries is closely linked to their freshness (Troncoso and Pedreschi, 2009). Also, the desirable characteristics of potato chips are influenced by their color and crispness, as is the overall taste (Salvador *et al*., 2009). Therefore, PEF treatment at 2.5 kV/cm increased the overall preference scores of French fries.

Conclusions

PEF treatment increased cell membrane permeability in potato tissue proportionately with field strength. The neutral red dye did not accumulate in the cytoplasm after PEF treatment, and cell membrane permeability increased with increasing field strength. PEF treatment also reduced the maximum cutting force and hardness of potato tissue. The increased cell membrane permeability improved the quality of French fries, which were of uniform and bright color, because of the decreased sugar content resulting from PEF treatment. During frying, water rapidly diffused from the core to the surface, thickening the surface vapor layer and reducing oil uptake, and increasing the crispness of French fries. In conclusion, PEF treatment could prevent the need for blanching and chemical treatment and reduce the processing time and water and energy consumption.

Conflicts of Interest

The authors declared no potential conflict of interest with respect to the research, authorship, and/or publication of this article.

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Data Availability

Data will be available on request.

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