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Applications of pulsed electric fields for processing potatoes: Examples and equipment design

Oleksii Parniakov[1], Nikolai Lebovka[2], Artur Wiktor[3], Martina Comiotto Alles[1], Kevin Hill[1], Stefan Toepfl[1]*

[1]*Elea Technology GmbH, Quakenbrück, Germany*
[2]*Institute of Biocolloidal Chemistry named after F.D. Ovcharenko, NAS of Ukraine, Kyiv, Ukraine*
[3]*Department of Food Engineering and Process Management, Institute of Food Sciences, Warsaw University of Life Sciences, Warsaw, Poland*

**Corresponding author: o.parniakov@elea-technology.com*

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Abstract: In the last two decades, pulsed electric fields (PEF) have successfully been introduced into the food industry, as one of the most promising and "game changing" technologies. This review is devoted to the recent applications of pulsed electric fields used in processing potatoes. The potato processing market size was estimated to be ca. USD 24.83 billion (2018) and with an annual growth rate of 5.2%. The physicochemical characteristics of potatoes and the specificity of potato processing lines makes a pulsed electric field very versatile and flexible allowing one to achieve different technological aims by its implementation into technological lines. In this paper, a short analysis of the potato structure and its nutritional properties, applications of moderate electric fields, ohmic heating, and pulsed electric fields are presented. Moreover, the basic electroporation effects, metabolic responses, texture modification and different PEF assisted processes applied to the potato are discussed. Finally, some examples of commercial applications and a brief description of the available equipment for the PEF processing of potatoes are presented.

Keywords: commercial applications; electrical treatments; electroporation; extraction; metabolic responses

In the last two decades, pulsed electric fields (PEFs) have intensively been used for the non-thermal treatment in different food processing operations (Dourado et al. 2019). In particular, examples of PEF applications to assist with the texture modification (Fauster et al. 2018), solid/liquid extraction (Liu et al. 2018b; Ricci et al. 2018; Nowacka et al. 2019), osmotic dehydration (Wiktor et al. 2014; Tylewicz et al. 2017), juice expression (Jaeger et al. 2012; El Kantar et al. 2018), cooling, freezing, thawing and crystallisation (Wiktor et al. 2015; Parniakov et al. 2016), drying and freeze-drying (Lammerskitten et al. 2019; Liu et al. 2019; Wiktor and Witrowa-Rajchert 2020), have been demonstrated. Processes assisted by PEF have the potential to improve the retention of the nutritional and sensorial quality characteristics of foods. In many scientific works, potatoes have been used as model object to study the PEF effects.

The aim of this paper is to present a review on the electroporation phenomenon, the effects of the electrical treatment on the potato tissue (including moderate electric fields, ohmic heating and pulsed electric fields), an analysis of the metabolic responses, changes in the texture, and the effects of PEF on the extraction, solid liquid expression, drying, frying, and freezing. Some examples of commercialised PEF applications in the potato industry are also presented.

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ELECTROPORATION PHENOMENON

The efficiency of PEF for assisting with the above-mentioned processes can be explained by the electroporation of the cytoplasmic membranes (electrically induced perforation of the membranes) (Kotnik et al. 2019). PEF assumes the application of short duration pulses (from several nanoseconds to several milliseconds) at a high pulse amplitude (from $E = 100–300\ \text{V·cm}^{-1}$ to $10–50\ \text{kV·cm}^{-1}$). For plant cells, the response of the cell membranes can be observed at $E = 100–1\,000\ \text{V·cm}^{-1}$, and the total duration of the PEF treatment of $t_{PEF} = 10^{-4}–10^{-1}$ seconds (Vorobiev and Lebovka 2008). However, for microbial inactivation the larger fields of the order of $E = 20–50\ \text{kV·cm}^{-1}$ and PEF time of $t_{PEF} = 10^{-5}–10^{-4}$ s are commonly required (Barbosa-Canovas et al. 1998). In an ensemble of cells with different sizes, the electroporation effects are maximal for the largest cells.

Depending on the intensity of the PEF treatment (values of E and t_{PEF}), the electroporation can be distinguished into sub-lethal, intermediate, and over-lethal (Figure 1). A sub-lethal injury with recovery or resealing effects develops at a moderate PEF treatment (low electric field strength and/or low total duration of the PEF treatment) (Saulis 1997). Typically, the duration of resealing is in the order of 1–100 µs, and it significantly depends on the temperature and composition of the lipid membrane (Sugar et al. 1987). At this stage, electroporated cells can release some portion of the interior biomolecules (ionic contents, proteins, pigments, proteins etc.), but these cells keep their viability even after leakage. Such an extraction process with the survival of the culture after the treatment is called biocompatible (Srivastava et al. 2019). For an intermediate PEF treatment, the prolonged resealing (seconds, minutes and even hours or days) has also been observed (Rols and Teissie 1990; Pakhomov et al. 2009). It has been demonstrated that partially injured cell membranes can recover the ATPase activity (which uses the chemical energy of ATP) during the long-term physiological process (Arora and Palta 1991). For an intermediate treatment, the lipid peroxidation (oxidative degradation of the lipids) has been observed (Rems et al. 2019). It can be speculated that, after an intermediate PEF treatment, some cells are killed whereas others are recovered (Figure 1). At severe PEF conditions (high electric field strength and/or long total duration of the PEF treatment), the complete killing of majority of the cells in the tissue and the maximum extraction efficiency can be observed.

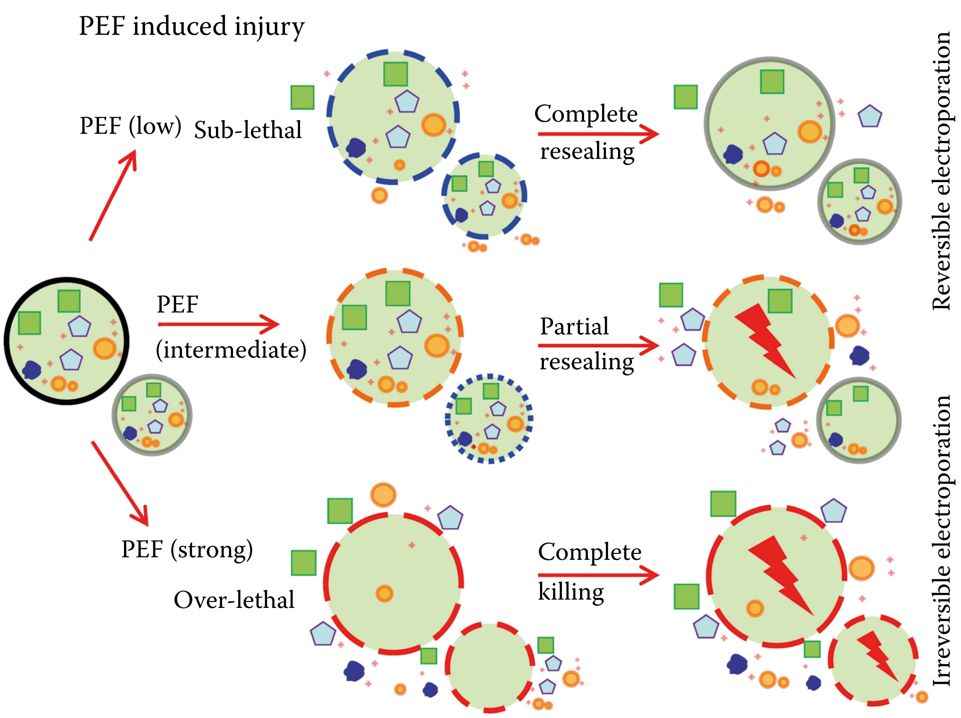

Figure 1. Illustration of irreversible and reversible electroporation with the complete and partial resealing and complete killing of cells – the increase in the PEF induced injury results in an increase in the quantity of extracted biomolecules

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The electroporation effects are dependent on many different factors related to the process itself (parameters of the electric field, temperature, pH, design of the treatment chamber, etc.) or to the treated product (electrical conductivity, cell diameter, type of the microorganism, etc.).

The technological aims that can be achieved by reversible and irreversible electroporation could be different. For instance, since the cell has the capability to restore its integrity after reversible electroporation, the PEF treatment can be used to administrate the inside of specific substances or compounds. Hence, it has been used in biomedicine to deliver cytotoxic drugs into tumour cells (Kotnik et al. 2015), whereas reversible electroporation has been utilised to introduce cryoprotectants in food technology and, thus, improve the frozen-thawed spinach leaves quality (Phoon et al. 2008; Demir et al. 2018). In turn, the irreversible electroporation that has led to the disintegration of the cellular structure can facilitate heat and/or mass transfer based unit operations, as aforementioned, or can lead to the inactivation of microorganisms (Barba et al. 2015).

POTATOES: STRUCTURE AND NUTRIENTS

Most cultivated varieties of potatoes belong to the species *Solanum tuberosum*. Potatoes are, economically, the fourth most produced food crop in the world and their production amounted to 388 million tonnes in 2017 (Potato Production and Consumption 2019). In 2019, the leading potato producing countries were (in million tonnes) China (99.2), India (48.6), Ukraine (22.2) and the USA (20).

Figure 2A schematically represents the structure of a potato tuber. The potato is a typical stem tuber. It includes the outer medulla, inner medulla or pitch, vascular zones, and a cortex. The bulk of potato tubers contain parenchyma cells filled with the starch granules (~20% of the fresh weight) and covered with thin, non-lignified, primary cell walls (~1% of the fresh weight) (Singh and Kaur 2016). The parenchyma cells have a size of approximately 100–200 μm (Figure 2B) (Ben Ammar et al. 2010). The potato cell-wall can be represented as an independent pectic polysaccharide (determines the wall porosity) and cellulose–xyloglucan (main load-bearing structure) networks (Singh and Kaur 2016).

The starch granules have a size of approximately 10–100 μm in diameter (Bertoft and Blennow 2016). The granules are built up by two polysaccharides, major amylopectin and minor amylose components. The starch macromolecules inside the granules are organised in amorphous and semi-crystalline 100–400 nm thick granular rings ("growth rings"). The crystallinity of the starch granules depends on the water content and the melting (or gelatinisation) of the crystals appears at a temperature range of 59–70 °C.

Moreover, potatoes are rich in essential macronutrients (carbohydrates, proteins, lipids, sugars and fatty acids), micronutrients (vitamin C, vitamin B6, folate, riboflavin, thiamine, potassium, phosphorus, magnesium and iron), and phytonutrients/antioxidants (carotenoids, polyphenols, anthocyanins, and phenolic acids) (McGill et al. 2013; Zaheer and Akhtar 2016; Brar et al. 2017). Freshly harvested potato tubers contain from 16% to 26% dry matter. Figure 3 presents an example of the average nutrition composition of potato tubers (A) (Mu et al. 2017) and

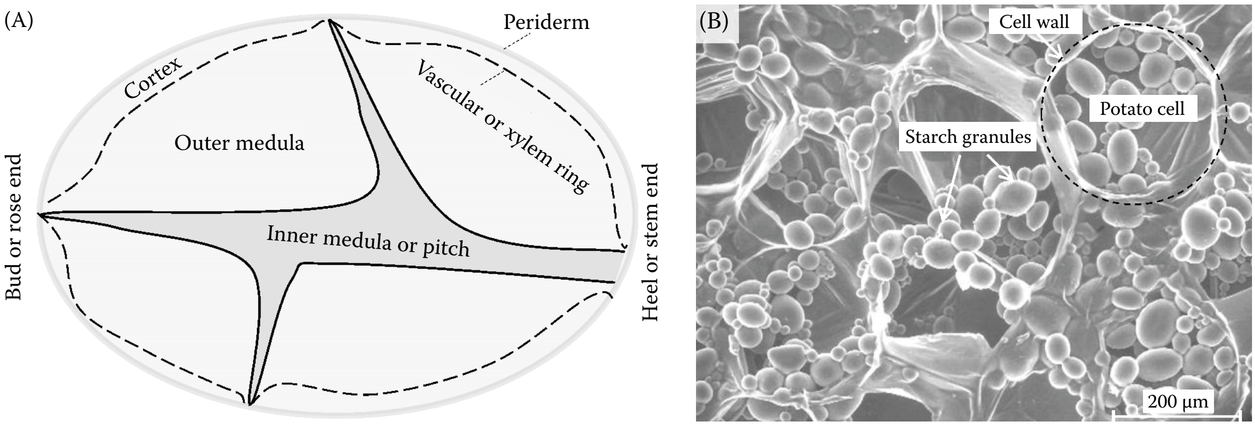

Figure 2. Structure of a potato tuber (A) (compiled from Friedman 1997; Talburt and Smith 2018) and SEM image of potato tuber cells (B) (compiled from Ben Ammar et al. 2010)

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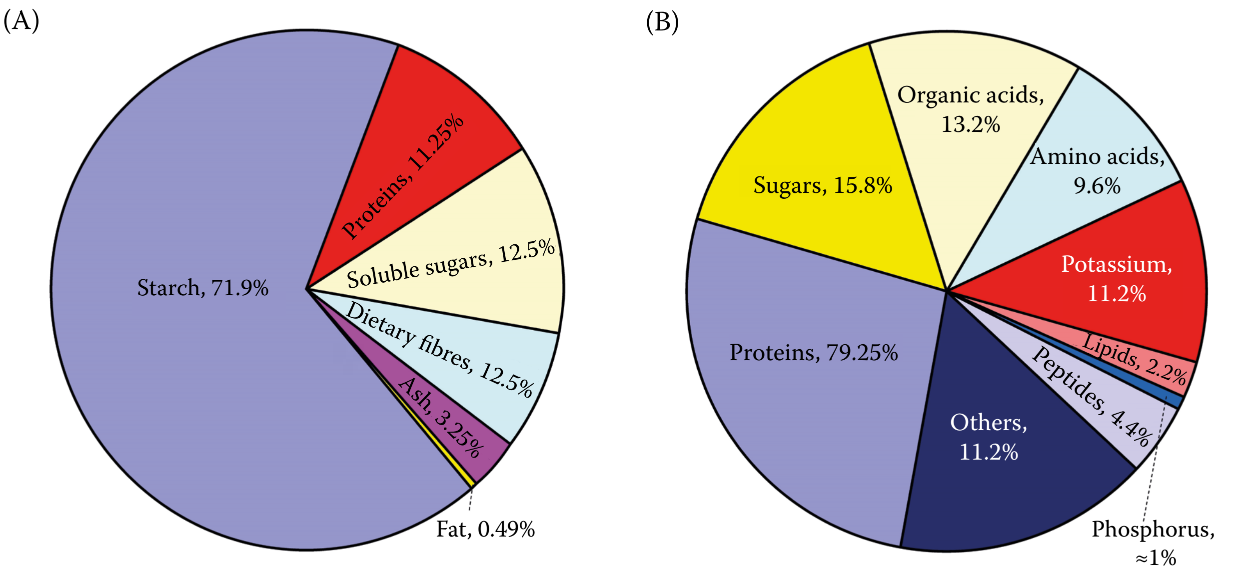

Figure 3. Average nutritional composition of (A) potato tubers (% of dry matter) (Mu et al. 2017) and (B) potato juice (% of dry matter) (van Koningsveld 2001; Løkra and Strætkvern 2009)

potato juice (B) (van Koningsveld 2001; Løkra and Strætkvern 2009).

The starch [≈71.9% of the dry matter (DM)] presents the main body of the total carbohydrate content (≈72.7% of the DM). The ash (non-volatile inorganic residue) constitutes about 3.25% of the DM and contains the different aforementioned minerals and trace elements. Phenolic compounds are distributed mostly between the cortex and the skin (peel) tissues of the potato (Figure 2A) (Friedman 1997). About 50% of the phenolic compounds are located in the potato peel and adjoining tissues, whereas the remainder decreases in concentration from the outside towards the centre of the potato tuber.

STUDIES ON THE ELECTRICAL TREATMENTS OF POTATOES

In early works, potatoes were used in numerous studies on the electrical properties of foods (Mudgett 1986), the correlations between electrical conductance and firmness of entire potato tubers (Meredith 1988), electrical impedance analyses of the effect of freeze-thaw injuries (Zhang and Willison 1992), and electroporation of protoplasts (Jones et al. 1989; Joersbo and Brunstedt 1991). What is more, treatment by a high frequency alternating electric current for the prevention of enzymatic discolouration of potatoes was patented (Schade 1951).

MODERATE ELECTRIC FIELDS AND OHMIC HEATING

Commonly, electric fields with a field strength E below 100 $V \cdot cm^{-1}$ are referred to as moderate electric fields (MEF). Moderate direct current (DC) or alternating current (AC) electric fields can be used for ohmic heating. During ohmic heating, the electric current passes through materials and the electric energy is volumetrically dissipated directly into the food without a large temperature gradient within the product (Hayden et al. 1969; De Alwis and Fryer 1990b; Ruan et al. 2001; Knirsch et al. 2010; Varghese et al. 2014; Kaur and Singh 2016).

The changes in the electrical conductivity of potatoes after an MEF treatment or ohmic heating have been studied in several works (Hayden et al. 1969; Halden et al. 1990; Palaniappan and Sastry 1991). Potato tissue modifications caused by small pulses of alternating current have been detected by the electrical impedance technique (Hayden et al. 1969). The effects were related to the changes in the conductivity of the water inside the channels of the cell walls of the potato tubers. The observed differences in the behaviour of the electrical conductivity of the potato product during conventional heating and ohmic heating were explained by the electro-osmotic effects (Halden et al. 1990; Palaniappan and Sastry 1991). Additionally, potato tissues were used for the experimental verification of the mathematical model of ohmic heating of liquid-particle

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mixtures (Sastry and Palaniappan 1992). It has been demonstrated that the orientation to the field and the electrical conductivity of the two phases (liquid and solid) of the potato particles with an anisotropic shape can have a great effect on the ohmic heating efficiency (De Alwis and Fryer 1990a).

Later on, during an MEF treatment, significant non-thermal electroporation effects in the potato tissue were demonstrated (Lebovka et al. 2005b). The application of long lasting ohmic heating at low electric fields can result in incomplete electroporation and a high level of electroporation can be only obtained at E >70 V·cm^{-1}. The measurements of the dielectric spectra (from 100 Hz to 20 kHz) confirmed the effect of the MEF treatment on the electropermeabilisation of cell membranes (Kulshrestha and Sastry 2006). The non-thermal effects of an MEF treatment on changes in the permeability of potato tissue were demonstrated by salt diffusion experiments (Kulshrestha and Sastry 2010). The combined MEF (E = 30–80 V·cm^{-1}) and thermal (50 °C) treatments significantly accelerated the low-temperature permeabilisation of the potato (Lebovka et al. 2008).

Literature data also presents the ohmic-assisted induced texture softening of potato tissues in comparison with microwave and conventional heating (Kamali and Farahnaky 2015). Also, the combined effects of ohmic heating and blanching on the texture of the potato have been studied (De Alwis and Fryer 1990a). Positive effects of ohmic heating of potatoes on the blanching (Vigerstrom 1975), acceleration of convective air drying (Lima and Sastry 1999; Wang and Sastry 2000; Lebovka et al. 2006), vacuum drying (Zhong and Lima 2003), enhanced expression of juice (Praporscic et al. 2006), recovery of phytochemical compounds from coloured potatoes (Pereira et al. 2016) have been reported. The published articles provided some data about the effects of an ohmic pre-treatment (E = 35.5 V·cm^{-1}) on the oil uptake during frying and subsequent cooling of potato slices (Salengke and Sastry 2007). As reported, the oil uptake was decreased by the ohmic treatment without involving a liquid medium.

Some works have been devoted to possible industrial applications of MEF treatments of potatoes (Vigerstrom 1975; Cousin et al. 2003). An MEF pre-treatment (E = 2–200 V·cm^{-1}) as a part of new blanching step in a process of deep-fried potato products, such as chips or French fries, was patented (Vigerstrom 1975). The application of MEF treatments (E = 30–75 V·cm^{-1} at a frequency of 50 or 60 Hz) of vegetables and fruits including potato tubers for manufacturing French fries, in order to reduce the resistance to cutting, was also patented (Cousin et al. 2003).

The effects of ohmic heating on potato starch gelatinisation have been also reported (Wang 1995; Wang and Sastry 1997; Li et al. 2004). Particularly in these studies, the non-linear changes in the electrical conductivity of the starch suspension in the gelatinisation temperature range were observed. The effects of ohmic heating on the water holding property of potato starch was discussed (Cha 2014). It was demonstrated that potato starch could bind more water after an ohmic heating treatment compared to the non-treated one.

PULSED ELECTRIC FIELDS

Basic electroporation effects. Potato tissue has frequently been used to test the different effects provoked by PEF treatments. In pioneering research, the effects of PEF (E = 150–800 V·cm^{-1}) on the electroporation of membranes in potatoes were studied (Angersbach et al. 2000). The critical transmembrane potential required for the electroporation of the potato was estimated as 1.7 volts. Membrane rupture occurred within 1 ms after the pulse initiation. For a cell size of 50–120 µm, the critical electrical field strength required for significant electroporation was estimated as E = 400–800 V per centimeter.

The synergy between PEF and thermal treatments on the electroporation effects in potato tissue has been revealed (Lebovka et al. 2005a). In many works, the potato has been used as a model tissue for the experimental determination of the temporal evolution of the electroporation (Cima and Mir 2004), studies of electric field distribution during electroporation (Ivorra et al. 2009), visualisation of irreversible electroporation by magnetic resonance imaging techniques (Hjouj and Rubinsky 2010; Kranjc et al. 2016; Suchanek and Olejniczak 2018), comparison of electroporated and intact potatoes by electrical resistivity measurements (Bullo et al. 2016), studies of effects of "cold" electroporation induced by PEF (Boussetta et al. 2013), and determination of the PEF effects on the structure of potato tubers (Oey et al. 2017). The potato tissue was also selected in order to study the relationships between the PEF electroporation efficiency, the size of the cells and the electro-physical properties of the tissue (Ben Ammar et al. 2010; Ben Ammar et al. 2011). Differ-

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ent numerical models of "*in vitro* simulations" of the electroporation effects in potato tissue were compared (Berkenbrock et al. 2017). The extent of brown areas in the potato after electroporation was estimated and it was concluded that the potato is a useful model tissue for the prediction of the electroporation effectiveness.

The potato tissue was also used to reveal the effects of PEF treatments (E = 0.2–1.1 kV·cm^{-1} with energy levels W = 1–10 kJ·kg^{-1}) on the microstructure of potato tubers (Faridnia et al. 2015). In this study, the cell viability was visualised using tetrazolium salt staining. The leakage of the ionic species was tested using atomic absorption spectrophotometry, cryogenic scanning electron microscopy and energy dispersive spectroscopy analysis. It was demonstrated that the orientation of the tuber towards the electrodes and the presence of the peel greatly affected the impact of the PEF. The PEF treatment with a strength of 300 V·cm^{-1} and above induced more damage in the cells located in the pith (inner medulla) compared to the cells located in the outer medulla (Figure 2A).

Metabolic responses. Additionally, the potato has been used in studies of reversible electroporation and metabolic responses induced by PEF treatments (Galindo 2008; Soliva-Fortuny et al. 2009). The PEF treatment of potato tissue with a low electrical field strength (E = 150–200 V·cm^{-1}) resulted in the resealing of the conductive channels across the electroporated membranes within a short time while preserving the cell vitality and metabolic activity (Angersbach et al. 2000).

The resealing processes after a PEF treatment (E = 30 V·cm^{-1} to 500 V·cm^{-1}, t_p = 1, 10, or 100 ms, one pulse) of potato tissue were studied using isothermal calorimetry, changes in the electrical resistance during the delivery of the pulse and impedance measurements (Galindo et al. 2008b). The metabolic responses involved the oxygen consuming pathways and they were strongly dependent on the pulsing conditions. In a few minutes after the PEF treatment, the resealing processes were accompanied by oxidative stress with the production of reactive oxygen species (ROS) and adenosine triphosphate (ATP) hydrolysis. The reversible electroporation in a potato tissue after a PEF treatment (E = 200–400 V·cm^{-1}, t_p = 1 ms, n = 1) was tested using propidium iodide staining of the cells (Galindo et al. 2009). The metabolic responses in the 24 h after the PEF were related to the changes in the hexose pool, and the degradation of the starch and ascorbic acid.

The effects of a PEF treatment (E = 30–500 V·cm^{-1}, t_p = 1 ms, one pulse) on the diffusion of the fluorescent dye FM1-43 through the cell walls of potato tissue have been studied and reported in the literature (Galindo et al. 2008a). A slower diffusion rate of the dye in electroporated tissues was explained by the decreased cell wall permeability on a nanometre scale. These changes were linked with the production of H_2O_2 by the cell wall associated peroxidases. The resealing processes can be accompanied by oxidative stress with production of ROS (Teissie et al. 2005) and associated with a decrease in the cell wall porosity for a PEF treated potato (Arevalo et al. 2004).

Texture. Potato tissue softening after a PEF treatment has been reported in many experimental works. Different stress-deformation, compression-to-failure and stress-relaxation tests were applied to study the effects of the softening (Fincan and Dejmek 2003; Lebovka et al. 2004b; Praporscic 2005; Shynkaryk 2006; Grimi 2009). The studies revealed significant effects of mild heating at 50 °C on the textural softening of the potato (Lebovka et al. 2004b) and juice expression from the tissue (Lebovka et al. 2004a). Changes in the viscoelastic properties of the potato caused by the PEF treatment (E = 500–1 500 V·cm^{-1}, t_p = 10–1 000 μs, n = 1–90 pulses) have been reported in the literature (Fincan and Dejmek 2003). Compression stress relaxations of PEF treated and untreated potato tissue with or without an osmotic treatment were modelled using the five parameter generalised Maxwell model. The changes in the PEF-induced mechanical properties were explained by the partial loss of the turgor pressure. No synergetic effects between the osmotic and PEF treatments were found. The relationships between the transient permeabilisation caused by a PEF treatment (E = 30–500 V·cm^{-1}, t_p = 10, 100, 1 000 μs, one pulse) and changes to the viscoelastic properties of potato tissue have been discussed (Pereira et al. 2009). The viscoelastic properties were monitored using small amplitude oscillatory dynamic rheological measurements of the elastic and viscous modulus compared with the changes to the electrical resistance during the delivery of the pulse. The changes in these properties were attributed to a partial loss in turgor pressure as a consequence of electroporation.

Textural investigations (stress–deformation and relaxation tests) have shown that the potato tissue loses a part of its textural strength after a PEF treatment, and both the elasticity modulus and the fracture stress decreased with an increase in the damage de-

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gree (Praporscic 2005; Shynkaryk 2006; Grimi 2009). The tissue structure was less affected by the PEF treatment when compared to the freeze-thawing or heating effect. The observed compression characteristics for PEF treated potatoes were intermediate between those of the fresh and freeze-thawed tissues. Uniaxial force textural investigations (stress-deformation and relaxation tests with unconfined potato samples) have shown that the tissue was losing part of its textural strength after the PEF treatment, and both the elasticity modulus and the fracture stress decreased with an increase in the damage degree (Praporscic 2005). These data were confirmed by textural and solid–liquid expression investigations into PEF-treated potato tissues (Chalermchat et al. 2004). The PEF treatment alone was not sufficient for the complete destruction of the textural strength, however, a mild thermal pretreatment at 45–55 °C allowed for an increase in the PEF efficiency (Praporscic 2005). Three-dimensional (3D) textural investigations have shown that the fracture pressure was approximately the same for PEF-treated and untreated specimens, but the PEF-treated tissues exhibited higher stiffness (Grimi et al. 2009; Grimi 2009). The fracture pressure (P_c), estimated from these experiments, was approximately the same for the untreated and PEF-treated potato samples, $P_c \approx 4.5 \pm 0.4$ MPa and it was noticeably larger than the fracture pressure $P_c \approx 1.5$–1.6 MPa under uniaxial compression.

The PEF induced softening effects on the potato tissue can be useful for improving cutting and/or slicing operations, thus decreasing the energy required for cutting and extending the durability of the knives (Ignat et al. 2015).

Recently, it has been investigated that potatoes with a longer storage time were more sensitive to PEF pre-treatments. It has been shown that the potato texture after the PEF pre-treatments with total specific energy inputs between 0 and 0.6 kJ·kg^{-1} was softer after prolonged storage compared to the normal storage duration (Moens et al. 2021).

Solvent extraction. A device for the electroporation of potatoes and potato products and for the application of PEF treatments to enhance the mass transfer in potatoes has been patented (Lindgren 2005). The device described in the patent can be used in the process of preparing deep-fried potato products, such as chips and French fries. The PEF treatment (E = 1.5–5 kV·cm^{-1}, t_p = 100–400 µs, n = 20–40 pulses) was tested to evaluate the potential application of PEFs in potato processing (Janositz et al. 2011). The PEF treatment accelerated the release of the intracellular molecules and improved the uptake of molecules into the sample that can be useful for the introduction of the colour and flavour carrier into the potato tissue. The effects of a PEF treatment (E = 250–1 000 V·cm^{-1}, t_{PEF} = 15–1 500 µs) on the ethanol extraction of steroidal alkaloids from potato showed (Faridnia et al. 2015) the maximum concentration of this compound (1 856.2 µg·g^{-1} dried potato peels) after the PEF treatment at E = 0.75 kV·cm^{-1} and t_{PEF} = 600 µs. What is worth emphasising is that it was 99.9% higher in comparison to the untreated peels. For a more intensive PEF treatment, performed at E = 1 000 kV·cm^{-1}, the extraction yield was lower. Such results can be associated with a degradation of the aglycone alkaloids.

Solid/liquid expression. The solid/liquid expression for PEF treated (E = 200–300 V·cm^{-1}, t_p = 100 µs) potato slices has been investigated as well (Lebovka et al. 2003). The juice yield and compression curves at a constant pressure (P = 5 bars) revealed the existence of complex multi-exponential behaviour with three different expression periods. After the PEF treatment, an excess of juice was released from the electroporated cells and the compression developed more intensively. An increase in the PEF intensity and duration accelerated the expression kinetics. It was demonstrated that an intermediate PEF treatment at the initial period of compression is desirable for the best expression. The effects of a PEF treatment (E = 130–680 V·cm^{-1}) on the solid–liquid expression from potato tissue have been studied (Chalermchat and Dejmek 2005). The juice yield was noticeably enhanced in the case of the PEF treated samples and it was strongly dependent on the pressing speed. The PEF-assisted expression experiments for potato disks in constant velocity regimes have been also performed (Grimi et al. 2009). The quantity of expressed juice from the electroporated cells was significantly higher when compared to that from the undamaged cells. The effects of ohmic heating (OH) and a PEF treatment on the juice expression from potato slices have been compared (Praporscic et al. 2005). The OH samples were pre-treated using alternating currents (E = 30 V·cm^{-1} or E = 50 V·cm^{-1} for 45 s). The interrupted heating-cooling OH mode of the treatment was applied when the temperature of the slices reached 50 °C. The PEF treatment (E = 850 V·cm^{-1}, t_p = 100 µs, n = 100 pulses) was performed at an ambient temperature. The highest juice yield was observed for the PEF treated samples.

https://doi.org/10.17221/90/2021-RAE

Drying. The course of the drying, as a heat and mass transfer-based process, is mainly limited by the cellular structure of food. As such, the electroporation that is induced by the PEF treatment can intensify this process and, in consequence, reduce its time and energy consumption and improve the quality of the food. The reduction in the drying time through the application of a PEF as a pre-treatment before drying has been evidenced in many different scientific papers using potato tissue as a model example. The effects of the PEF treatment (E = 350–3 000 V·cm^{-1}) on fluidised bed drying (T = 55 and 70 °C) of potatoes have been studied (Angersbach and Knorr 1997). A significant reduction in the drying time (by up to 20–25%) was reported. This conclusion has been confirmed in different studies on the PEF effects on convective air drying of potatoes (Arevalo et al. 2004; Lebovka et al. 2007; Janositz et al. 2011). The drying experiments (T = 70 °C) revealed the increased diffusivity (by up to 40%) for the PEF-treated (E = 0.75–1.5 kV·cm^{-1}, t_p= 100–300 ms, n ≤120 pulses) potato samples (Arevalo et al. 2004). The effects of the PEF treatment (E = 400 V·cm^{-1}) and drying temperatures (T = 30–70 °C) on the convective air drying of potatoes were investigated (Lebovka et al. 2007). The PEF treatment accelerated the moisture transport and, hence, increased the drying rate. Before the final falling drying rate period, the internal temperature was noticeably smaller for the PEF-treated sample than for the untreated one. The diffusivity (D), at different drying temperatures was estimated. The electroporation significantly increased the diffusivity. It was concluded that strong electroporation has the potential to decrease the drying temperature approximately by 20 °C without any adverse effects on the kinetics or quality.

Frying. A PEF treatment (E = 200–10 000 V·cm^{-1}) was applied prior to a frying step for controlling the content of reducing the sugars without affecting the cell wall or starch structure (Andersson et al. 2008). The sugar (precursor of the Maillard reaction and acrylamide formation) content was noticeably decreased in the PEF treated (E = 1.5–5 kV·cm^{-1}, t_p = 100–400 μs, n = 20–40 pulses) potatoes (Janositz et al. 2011). The positive effects of PEF treatment on the drying and frying processing were discussed. Particularly, the PEF treatment allowed the distinct reduction in the fat content in the processing of potato chips or French fries. The effect of PEF treatments (E = 750 kV·cm^{-1} and 2 500 kV·cm^{-1}, W = 18.9 kJ·kg^{-1}) prior to deep frying potato cubes on the quality aspects have been evaluated (Ignat et al. 2015). The PEF treatments softened the samples and decreased the oil uptake upon frying in a bigger extent than the blanched and water-dipped control samples. The accelerated leaching of reducing sugars and the decreased browning tendency during frying were also observed. The different effects of PEF treatments on the structural properties that affect the texture of French fries during processing were recently reviewed (Botero-Uribe et al. 2017). The effects of a combined preliminary PEF treatment (E = 600 V·cm^{-1}, t_p = 100 μs, n = 100 pulses) and convective air-drying (T = 50 °C) on the characteristics of fried potatoes (T = 130 °C) were studied (Liu et al. 2018a). The PEF treatment induced significant reductions in the drying and frying time. The combined treatments significantly affected the oil uptake and texture of the samples. During the frying, the upper layer of the PEF treated potato strips became denser and, thus, hindered the oil penetration. The impacts of preliminary vacuum drying and a PEF treatment on characteristics of fried potatoes were also recently studied (Liu et al. 2020). The vacuum drying was performed at a sub-atmospheric pressure of P = 30 kPa, and two different drying temperatures, 40 °C and 70 °C. The effects of the PEF included a significant reduction in the vacuum drying time and resulted in the absence of starch gelatinising. For the PEF treated samples, the moisture and oil contents were significantly smaller than for the untreated ones. Moreover, the preliminary dehydration assisted by the PEF allowed the preservation of the starch granules in the fried potato. The effects of a PEF treatment (E = 1 000, 1 250, and 1 500 V·cm^{-1}; t_p = 60, 90, and 120 μs, n = 15, 30, and 45 pulses) on the freeze-drying of potato tissues were also studied (Wu and Zhang 2014). Under optimum PEF treatment conditions, the drying time was shortened by 31.47%, and the drying rate improved by 14.31% compared to the untreated sample. The obtained data evidenced that the PEF treatment allowed a noticeable decrease in the vacuum drying time, and it resulted in a more uniform shape, clear colours, smaller shrinkage, a lower browning level and the visually better quality of the dried potato samples.

The impacts of a PEF treatment on the process performance of industrial French fry production have extensively been discussed (Fauster et al. 2018). The clear benefits of PEF assisted processing related to the improved cutting behaviour, resulting in a smoother cutting surface, a reduction of the

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breaking loss, starch loss and fat uptake, and clear economic benefits were demonstrated.

Freezing. The effects of PEF treatments on the freezing behaviours of potatoes have been studied (Jalte et al. 2009). Water crystallisation in the untreated and PEF treated samples was observed at the same temperatures, $T \approx -1$ °C, but the PEF treatment noticeably accelerated the freezing process. In this study, the reduction in the freezing time for the electroporated potato was explained by the creation of additional nucleation centres due to the residue of the electroporated membranes. Removing diffusion barriers inside the electroporated tissue also accelerates mass exchange processes that can critically affect the crystallisation. The scanning electron microscopy (SEM) images revealed a noticeable deformation in the polyhedrally shaped cells with embedded starch granules in the freeze-thawed potato (Jalte et al. 2009). PEF osmotic treatments that assisted freezing has also been studied (Ben Ammar et al. 2010). Potato samples treated by a PEF (E = 400 V·cm^{-1}) were then osmotically dehydrated (OD) using salted water. The freezing curves were highly different for the PEF or PEF + OD samples in comparison to the untreated material (U), and the effective freezing time was decreased in the order: U > PEF > PEF + OD. The force relaxation tests revealed noticeable tissue softening for the PEF treated samples and a more rigid texture for the PEF + OD samples. Both the PEF and PEF + OD treatment resulted in the enhancement of the process. These samples also exhibited better sensorial properties as expressed by the appearance. The estimated porosity of the freeze-dried samples was significantly higher for the PEF + OD (≈0.89) and PEF (≈0.84) samples when compared with that of the U (≈0.71) sample (Ben Ammar et al. 2010). The SEM analysis of the freeze-dried PEF + OD samples revealed a high disorder of the starch surface morphology and redistribution of the starch matter inside the cells.

EXAMPLES OF COMMERCIAL APPLICATIONS

Nowadays, continuous pulsed electric field systems are already used in industrial scale potato processing. Prominent examples of commercialised PEF utilisation in the potato and snack industry (Fauster et al. 2018) have also been demonstrated. The two main applications are related with the production of French fries and chips. The potential of a pulsed electric field pre-treatment on potato tubers for the production of French fries and the effects on the structural changes (Fauster et al. 2018), fat uptake (Janositz et al. 2011; Ignat et al. 2015), sugar release (Jaeger et al. 2010) and drying (Lebovka et al. 2007) have already been described.

Presently, PEFs are complementing the existing production consisting of various processing steps (Fauster et al. 2018). In the deep-fry potato industry, potatoes can be subjected to PEF immediately after the sorting, washing and peeling step prior to the cutting/slicing step. The delivery of short electric pulses through the whole potatoes where the PEF processing alters the structural integrity of tuber tissues, results in tissue softening and in the release of small intracellular compounds. For example, it helps to release the reducing sugars and low-molecular substrates that are involved in the Maillard reaction and, hence, reduces the tendency of deep-fry potatoes to brown. The PEF technology replaces the classic pre-heater, therefore, reducing the amount of water and energy consumption by up to 90 percent. In the process, the product is not heated, therefore, its results in the reduction of the microorganisms' load and starch concentration being present in the processing water. It should be noted that depending on the line capacity, the dwell time in the PEF system is a total of just 5–8 seconds. This technology also offers improvements in the processing efficiency as the softer texture induced by the PEF makes the potatoes more flexible and easier to cut, which increases the durability of the cutting knives, resulting in fewer broken products leading to less waste, and provides the ability to develop new cut shapes (Oey et al. 2016) (Figure 4).

The utilisation of PEFs also offers other advantages. As the method is a volumetric treatment, all potatoes – regardless of whether they are large or small – are treated uniformly. In the past, small potatoes were already cooked soft after pre-heating, while large potatoes were still hard inside. Additional quality advantages in the final product are an approximately 10% lower oil absorption during deep-frying, more even browning and longer French fries.

In the production of chips, the advantages are similar to those for French fry processing; however, the quality improvement of the final product is even more pronounced. The cutting pattern improves, resulting in a reduced loss of raw materials and starch during cutting, leading to a significantly increased yield. The reduced loss of starch is primar-

https://doi.org/10.17221/90/2021-RAE

Figure 4. PEF treated sweet potato sticks

ily due to the fact that the products softened by the PEF treatment are easier to cut. This, in turn, results in less mechanical damage by the knives and, as a result, less starch wash-out on the surface. In addition, fewer chips stick together during deep-frying, eliminating the need to reject them.

As chips have a considerably larger surface relative to their weight than French fries and are deep-fried longer, the oil reduction is even higher with up to 20%, depending on the cut, the raw product and the deep-frying process. The latter plays a special role in improving the product quality. The opening of the cells and the increased amount of water given off enable the deep-frying parameters, such as oil temperature and time, to be optimised. The increased efficiency of the deep-frying process has a major effect on the oil content, the colour and the crunchiness of the final product. Especially the colour, and the accompanying acrylamide content, for the currently popular vegetable chips made, for example, of sweet potatoes, carrots, parsnips or red beets, is an important quality characteristic which can be improved by optimising the deep-frying process.

In addition, the uniform softening of the raw product opens up new possibilities for cutting the products. In the production of French fries, now-

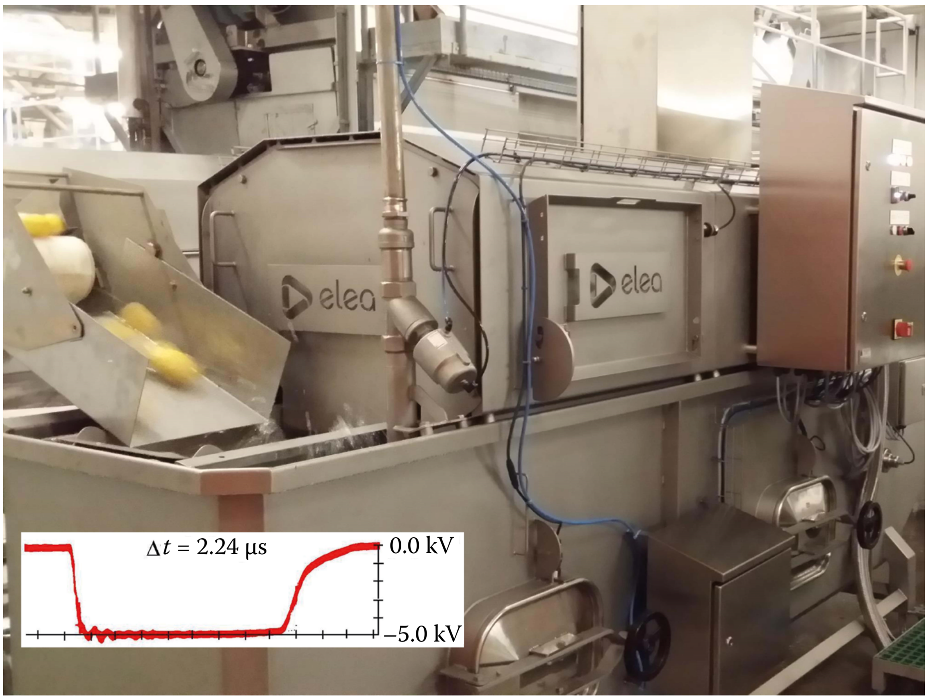

Figure 5. Example of an industrial PEF system in operation; insert shows a typical shape of the PEF pulse (Elea 2019)

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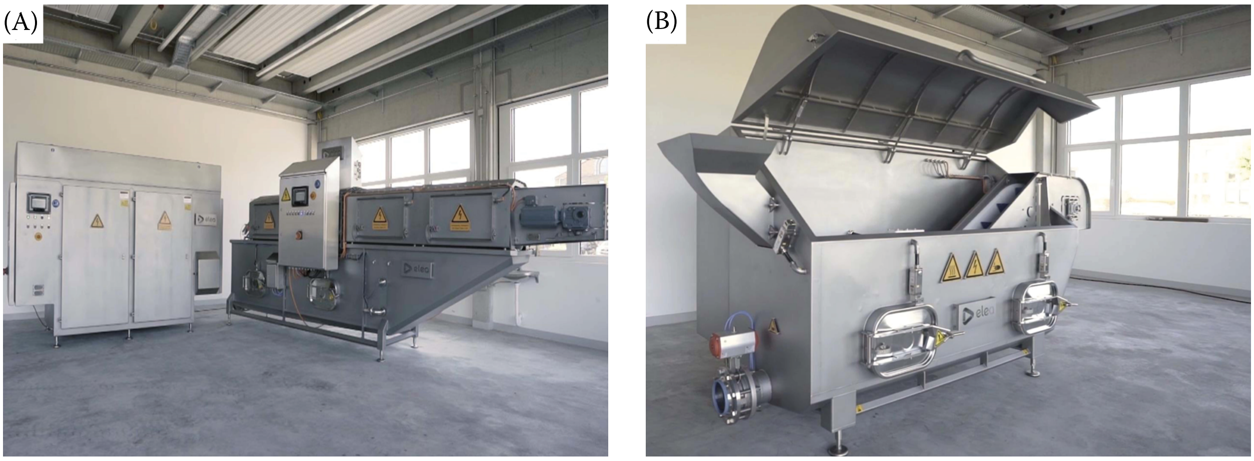

Figure 6. Examples of an industrial PEF system for the treatment of solid products: Large scale (10–60 $t \cdot h^{-1}$) (A) and small scale (1–6 $t \cdot h^{-1}$) (B) systems (Elea 2019)

adays, new shapes like a spiral/twister, waffle or wavy-cut can be obtained with considerably reduced losses for a broad range of raw products. In the production of chips, even greater alternatives are opened up, as now harder vegetables like sweet potatoes, parsnips or red beets can also be processed to form unusual shapes (Figure 4) without breaking. In both cases, the greater product diversity, therefore, results in improved competitiveness and the production of unusual cuts and/or products is more efficient.

The company Elea from Germany (Elea 2019) manufactures different large scale PEF machines and generators suitable for the treatment of a wide range of food types including the potato. The industrial equipment can be used for potato chips, French fries or other snacks (sweet potato, taro, cassava and parsnip) production. Today, more than 100 PEF systems are used in the potato-processing industry worldwide (Figure 5).

Typical throughputs for systems in the chips industry ranges between 1 and 10 $t \cdot h^{-1}$, and, in French fry processing, the line capacities are considerably higher with an efficiency of 10–60 t per hour. Industrial PEF equipment for solid food products that typically consists of a pulse modulator and a treatment belt which contains the electrodes (Figure 6A).

These two parts are connected with a coaxial cable of <15 m in length. The pulse modulator creates the electric pulses that are required for the treatment by converting the 400 V AC to pulses to around 30 kV DC and a pulse width of less than 10 microseconds. These pulses are then applied to the product in the treatment area. The treatment belt is easily integrated into the production line applying the pulses while the product is continuously transported through the system. Depending on the treatment intensity and raw material, the energy and water consumption can be expected to be around 1 $kWh \cdot t^{-1}$ of raw material and 30 $L \cdot t^{-1}$ of raw material, respectively.

Different small scale system models suitable to process 1–6 $t \cdot h^{-1}$ raw materials are also available (Figure 6B).

CONCLUSION

The potato represents a significant crop for human consumption, and it has most frequently been used as a model tissue to test the electroporation effects. The most common techniques applied in food processing (such as solid/liquid extraction and expression, drying, frying, freezing and free-drying) were tested using only PEF treated potatoes. The PEF treatment allows one to avoid undesirable changes in the textural, chemical, colour, flavour and nutritional properties. Moreover, particularly for the potato, the PEF improves the processing conditions, reduces the time and energy, decreases the media consumptions related to the slicing and cutting. PEF assisted processing of potato peels and biowaste skins can open, in the future, important perspectives for the production of phytochemical antioxidant nutraceuticals, which are nutritionally and pharmacologically interesting compounds (Schieber and Saldaña 2009; Al-Weshahy and Rao 2012; Wu 2016; Fritsch et al. 2017). Interesting future perspectives of PEF applications may be related to the production of the modified potato starches with improved nutritional (Szabó-Révész and Szepes 2009;

https://doi.org/10.17221/90/2021-RAE

Dupuis and Liu 2019) and glycaemic digestibility (Lynch et al. 2007; Hong et al. 2018). Therefore, there is great potential, in the future, for the further implementation of PEF treatments in the potato industry.

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