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Development and Characterization of a Laboratory-Scale Pulsed Electric Field System for Solid-Food Pretreatment

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ABSTRACT

Pulsed electric field (PEF) is a non-thermal food-processing technology that increases cell-membrane permeability, thereby facilitating mass transfer and the movement of biomolecules across the membrane. Although PEF has been widely applied to liquid foods, its use in solid food matrices remains limited because of challenges in designing treatment systems and controlling process parameters. This study aimed to develop and characterize a laboratory-scale PEF system for solid-food pretreatment and to evaluate its application for oxalate reduction in taro (*Colocasia esculenta*) tubers. The developed PEF system consists of five components: a high-voltage power supply based on a flyback converter, a capacitor bank for energy storage, a high-voltage SiC MOSFET switch, and an ESP32 microcontroller for pulsed control and a treatment chamber with stainless steel electrodes. Electrical characterization showed that the PEF system successfully generated monopolar rectangular pulses with a maximum output of 3 kV, pulse widths from 400 ns to 19.2 *μ*s, and frequencies from 5.9 kHz to 1.98 MHz. The treatment chamber was designed with adjustable electrode spacing (0.5–3.5 cm), enabling a wide range of electric field strengths while maintaining the same pulse-generation system. Application of the PEF system at 1.08 kV/cm for 10 s reduced oxalate content in taro tubers by up to 39%. These results demonstrate the laboratory-scale PEF system's capability to generate controllable, high-voltage pulses suitable for solid-food pretreatment.

Keywords: food pretreatment, high-voltage generator, non-thermal food technology, pulsed electric field, rectangular pulsed

INTRODUCTION

A pulsed electric field (PEF) is a non-thermal food processing technique that temporarily applies a high-voltage electric field to biological material sandwiched between two electrodes. It increases membrane permeability to facilitate mass transfer, such as molecular extraction and microbial inactivation (Nabilah *et al.,* 2022). Both temporary and permanent cell electroporation can be produced with PEF (Kotnik *et al.,* 2019). The typical electric field range for temporary electroporation is 0.5–1.5 kV/cm. Microbial inactivation requires higher electric field strengths, ranging from 15–40 kV/cm, whereas permanent electroporation in plant or animal tissue occurs at 1.0–3.0 kV/cm (Yarmush *et al.*, 2014). In food processing, electroporation can nonthermally damage cellular membranes, thereby eliminating the cellular turgor component of texture and altering the tissue's viscoelastic properties, particularly in solid plant-based matrices (Asavasanti *et al.,* 2011). This phenomenon has been widely utilized to enhance mass transfer processes, including extraction, drying, and the removal of undesirable compounds from plant tissues.

To improve extraction efficiency, reduce antinutritional compounds, and alter the textural characteristics of plant-based foods, PEF has been thoroughly investigated as a pretreatment technique. Prior research has shown that PEF treatment lowers the oxalate content in oca tubers (Liu *et al.,* 2018) and enhances the extraction of important chemicals from potatoes (Frontuto *et al.,* 2019). These results demonstrate the potential of PEF as a pretreatment approach for enhancing the functional and nutritional

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qualities of solid food matrices, especially underutilized indigenous tuber crops.

However, the effectiveness of PEF depends strongly on both the food matrix and treatment conditions. Cell size, morphology, orientation within the electric field, pulse duration, treatment time, and electric field strength are among the factors that influence electroporation efficiency (Kandušer and Miklavčič, 2008). Therefore, optimization of PEF treatment across different food materials requires a system with controllable pulse parameters and adjustable electrode spacing. A PEF system generally consists of a pulse generator and a treatment chamber. For solid-food applications, the design of the treatment chamber is particularly important because electrode geometry and spacing directly influence electric field distribution and treatment uniformity (Nowosad *et al.,* 2021). The chamber should provide consistent treatment conditions while minimizing undesirable effects such as overheating and electrolysis (Nithya and Sudheer, 2023).

In Indonesia, a number of underutilized tuber crops, such as cassava (*Manihot esculenta Crantz*), yams (*Dioscorea alata*), and taro (*Colocasia esculenta*), function as substitute sources of carbohydrates (Ferdaus *et al.*, 2023). However, oxalates often limit their use since they might irritate skin and reduce mineral absorption (Bradbury and Nixon, 1998). Oxalate levels can be decreased by boiling and other conventional processing techniques, but extended thermal treatment may result in the loss of heat-sensitive nutrients (Catherwood *et al.,* 2007). These restrictions have brought attention to non-thermal processing methods like PEF, which may reduce heat damage while enhancing food safety and quality (Anwar *et al.,* 2021).

Despite growing interest in PEF technology, information on the development and characterization of adaptable laboratory-scale systems for solid-food pretreatment remains limited. Therefore, a PEF system with controllable pulse parameters and adjustable treatment conditions is needed to support research and pretreatment applications involving solid food matrices. This study aimed to develop and characterize a laboratory-scale PEF system for solid-food pretreatment and to evaluate its applicability by assessing oxalate reduction in taro (*Colocasia esculenta*) tubers.

MATERIALS AND METHOD

Design and development of pulsed electric equipment

The pulsed electric field (PEF) system is designed to generate high-voltage pulses for solid food preprocessing. A flyback transformer-based high-voltage power supply, a bank of capacitors for energy storage, a SiC-MOSFET switching circuit for pulse generation, an ESP32 microcontroller for control, and a treatment chamber with stainless steel electrodes are the system's five primary components. The overall configuration of the developed PEF system is shown in Figure 1, while the specifications and functions of each component are described in the following sections.

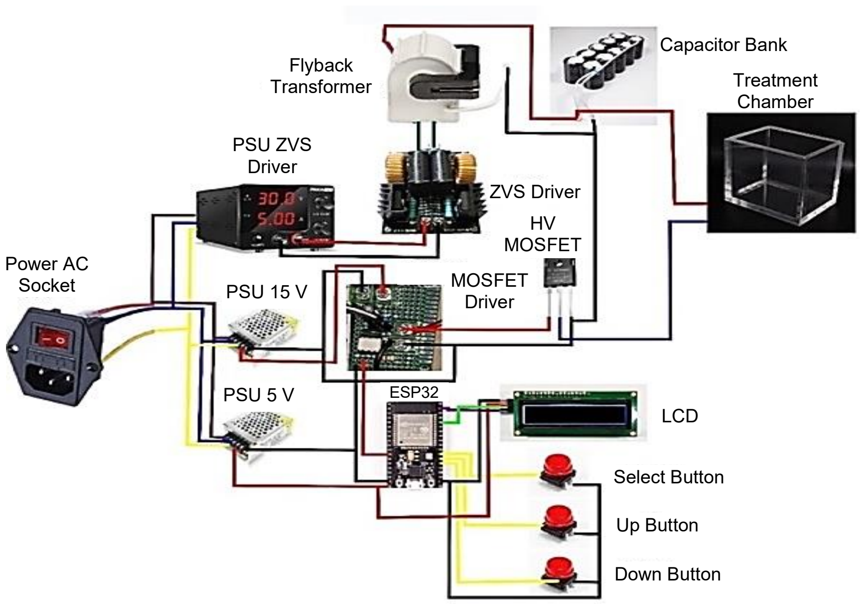

Figure 1. Overall configuration of the developed laboratory-scale pulsed electric field (PEF) system for solid-food pretreatment. The system comprises a flyback transformer-based high-voltage supply, ZVS driver, capacitor bank, SiC-MOSFET pulse generator, ESP32-based control unit, LCD interface, and a treatment chamber with adjustable electrode spacing

The high-voltage power supply used a flyback transformer driven by a zero voltage switching (ZVS) driver to step up the input voltage and charge a capacitor bank. The bank consisted of seven series-connected capacitors, each rated at 330 μF and 450 V, yielding a maximum voltage of 3150 V. The energy stored was released through a high-voltage switching circuit featuring a SiC MOSFET (IXTX4N300P3HV, Littelfuse Inc., USA), rated at 3000 V. Pulse generation and parameter control were performed using an ESP32-WROOM-32 microcontroller (Espressif Systems, China). The microcontroller regulated pulse width and frequency by controlling the SiC MOSFET's switching operation. The generated pulses were subsequently delivered to biological samples placed between two electrodes inside the treatment chamber.

A digital oscilloscope (DSO5102P, Hantek Electronic Co., China) coupled to a high-voltage probe (P6015A, Tektronix Inc., USA) was used to characterize the created PEF system electrically. The system's output voltage, pulse width, pulse frequency, and waveform properties were assessed using the oscilloscope. To accommodate diverse solid food matrices and treatment settings, the system was designed with configurable pulse parameters and electrode spacing.

Treatment chamber design

The treatment chamber was built to use polymethyl methacrylate (PMMA) to process solid food samples in batches. PMMA was chosen due to its electrical insulation, strength, and ease of manufacturing. The chamber design is shown in Figure 2.

The treatment chamber contained two parallel stainless-steel 316 plate electrodes, each measuring 5×5 cm and 0.1 mm thick. The electrodes were installed within the chamber and linked to the output terminals of the PEF generator. Because of its corrosion resistance and suitability for food-contact applications, stainless steel 316 was selected.

The electrode spacing was designed to be adjustable to accommodate various food matrices and treatment conditions. Food samples were placed directly between the electrodes during treatment. Electrode gaps of 0.5, 1.0, 2.0, and 3.5 cm were used in this study to obtain different electric field intensities. The electric field strength (E) applied to the sample was calculated according to Equation 1.

$$E=\frac{V}{d} \qquad (1)$$

E= the electric field strength (kV/cm), V= the applied voltage (kV), d= the distance between electrodes (cm).

Characterization of pulsed electric field

The designed PEF system was electrically characterized to assess the waveform properties, output voltage, pulse width, and pulse frequency. A digital oscilloscope coupled to a high-voltage probe was used for the measurements.

The oscilloscope ground was linked to the circuit ground, and the output terminal of the PEF generator was connected to the high-voltage probe for waveform measurements. The resulting voltage waveforms were then displayed and recorded for analysis.

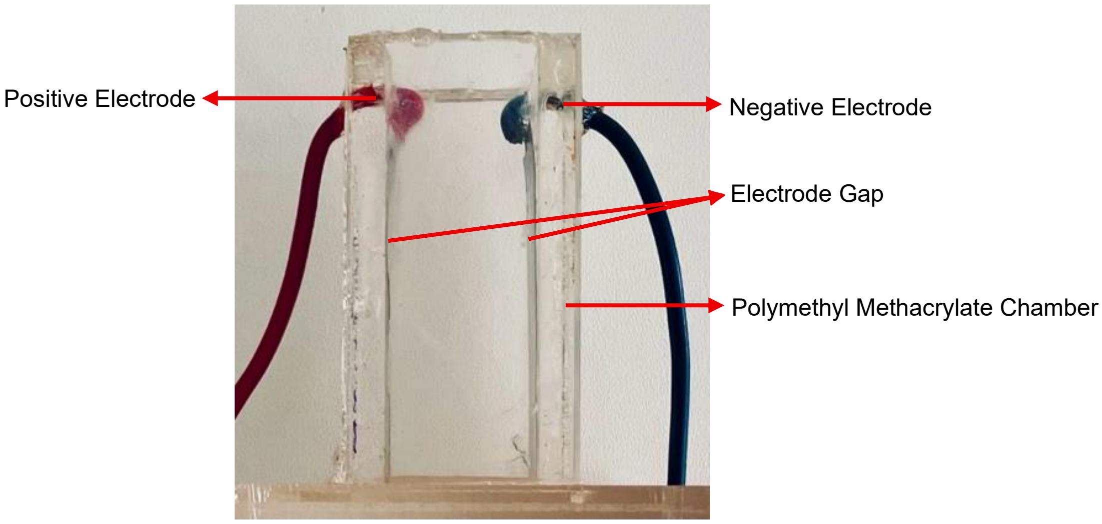

Figure 2. Representative batch-type treatment chamber fabricated from polymethyl methacrylate (PMMA) and equipped with two parallel stainless-steel 316 electrodes. The photograph shows one of four chambers used in this study. Identical chambers with electrode spacings of 0.5, 1.0, 2.0, and 3.5 cm were constructed to generate different electric field strengths during PEF treatment

Preliminary experiments were conducted over a wider input-voltage range; however, only the operating range between 6.7 and 8.0 V generated output voltages suitable for PEF treatment and this range was therefore selected for detailed characterization. For each operating condition, the peak output voltage was recorded. Pulse-width and pulse-frequency measurements were performed by adjusting the microcontroller's programmed settings and measuring the corresponding output signals on the oscilloscope. The waveform characteristics were analyzed to verify the pulse shape and stability of the developed PEF system.

Electrical characterization was performed prior to food-treatment experiments to verify the operating performance of the developed PEF system.

Application of pulsed electric field to taro tuber

Distilled water was used as the treatment medium and added to the treatment chamber until the taro samples were completely submerged. The conductivity of the distilled water was measured prior to treatment using a portable conductivity meter (Mediatech PH-TDS-EC Temp meter, China) and was approximately 3 μS/cm.

Taro tubers were grated using a coarse cheese grater to obtain thin strip-shaped samples. Approximately ten strips, with a total sample mass of 1.25 g, were used in each PEF treatment run. Air bubbles trapped between the sample and electrodes were removed prior to treatment to ensure uniform electric field distribution and uninterrupted current flow.

PEF treatment was performed using monopolar rectangular-wave pulses generated by the developed system. Treatment was conducted at an electric field strength of 1.08 kV/cm for 10 s. Pulse characteristics were determined from the electrical characterization of the developed PEF system. After treatment, samples obtained under identical operating conditions were pooled and homogenized prior to oxalate analysis.

Evaluation of oxalate content

Oxalate content was determined according to the method described by Sangketkit *et al.* (2001). After PEF treatment, samples obtained under identical treatment conditions were pooled and homogenized using a mortar. Total oxalate extraction was performed using 5 g of accurately weighed sample mixed with 2 M hydrochloric acid (HCl). Three independently weighed aliquots were prepared and analyzed separately.

The mixture was then placed in a water bath at 80 °C for 15 min. After cooling, the solution was transferred to a 100 mL volumetric flask and diluted to volume with 2 M HCl. The mixture was centrifuged at 3000 rpm for 15 min, and the supernatant was carefully filtered through a 0.45 μm cellulose acetate membrane.

A 5 μL sample of the filtrate was injected into an HPLC system comprising an LC-10AT VP pump and an SPD-10AV VP UV–Vis detector (Shimadzu Corporation, Japan), which was set to operate at 210 nm. Chromatographic separation was performed using an Aminex HPX-87H ion-exclusion column (300×7.8 mm, Bio-Rad Laboratories, USA) with isocratic elution at 0.6 mL/min, utilizing 0.0125 M H_2SO_4 as the mobile phase. The column was maintained at room temperature. Oxalic acid concentrations were deter-mined using an external calibration curve generated from standard solutions.

RESULTS AND DISCUSSION

Development of the pulsed electric field system

A laboratory-scale pulsed electric field (PEF) system was successfully developed for solid-food pretreatment applications. The system consists of five main components: a high-voltage power supply, a capacitor bank, a SiC-MOSFET switching circuit, an ESP32-based control unit, and a treatment chamber. The overall configuration of the developed PEF system is presented in Figure 3.

Figure 3. Photograph of the developed laboratory-scale PEF system and experimental setup used for electrical characterization and solid-food treatment. The setup consists of a high-voltage generator, a treatment chamber, a DC power supply, a digital oscilloscope, and a high-voltage probe

A Zero Voltage Switching (ZVS) circuit powers the flyback transformer in the high-voltage generation unit. Because of its compact size, straightforward construction, and ability to deliver high-voltage outputs suitable for electroporation treatment, this arrangement was selected (Raghavendra *et al.,* 2023).

The energy storage unit was a capacitor bank consisting of seven capacitors connected in series, each with a capacitance of 330 μF and a voltage rating of 450 V, yielding an equivalent capacitance of 47.1 μF and a maximum voltage rating of 3150 V. During treatment, the capacitor bank played a crucial role in maintaining voltage stability. Initial testing revealed that when a load was applied, direct application of the flyback transformer's output caused a noticeable voltage drop. The maximum output power of the flyback transformer used in this investigation was approximately 40 W, which was insufficient to consistently meet the energy demand for producing high-voltage pulses. As a result, the capacitor bank was utilized to store electrical energy before the pulse discharge and to supply the treatment chamber with sufficient power during operation. Similar energy-storage approaches have been reported to improve the reliability of energy delivery and reduce voltage fluctuations in pulsed-power systems (Khan *et al.,* 2023).

The capacitor bank's contribution to system performance was further evaluated by comparing system voltage stability with and without capacitor bank integration (Figure 4). Without the capacitor bank, the output voltage dropped to zero after approximately 10 s under unloaded conditions and after approximately 1 s when a sample was placed in the treatment chamber. However, after 15 s of operation, a detectable output voltage was still observed when the capacitor bank was integrated into the system. The experiment was terminated after 15 s; therefore, the maximum voltage-sustaining duration of the capacitor-assisted system was not determined. These findings demonstrate that, especially when the treatment chamber was connected to a load, the capacitor bank successfully compensated for voltage loss and helped maintain voltage availability during pulse generation.

A high-voltage switching circuit based on an IXTX4N300P3HV SiC-MOSFET with a maximum voltage rating of 3000 V was the third part of the developed PEF system. The electrical energy stored in the capacitor bank was directed into the treatment chamber by the MOSFET, which functioned as a fast electronic switch. The MOSFET was connected in series between the capacitor bank and the treatment chamber and was controlled by the ESP32 micro-processor. The capacitor bank's electrical energy was isolated from the treatment chamber with the switch open, enabling charging. In the closed-switch condi-tion, the stored energy was rapidly discharged through the treatment chamber, generating a high-voltage pulse. Monopolar rectangular-wave pulses, which are frequently used in electroporation applica-tions because of their reproducibility and con-trollability, were generated using the SiC-MOSFET. SiC-MOSFETs are widely used in modern pulsed-power systems because of their high breakdown voltage, fast switching capability, and low switching losses, making them suitable for generating high-voltage pulses for electroporation applications (Kang *et al.,* 2024). Similar MOSFET-based switching systems have been reported to produce high-voltage pulses with durations ranging from nanoseconds to microseconds, making them suitable for biological applications (Novickij *et al.,* 2014).

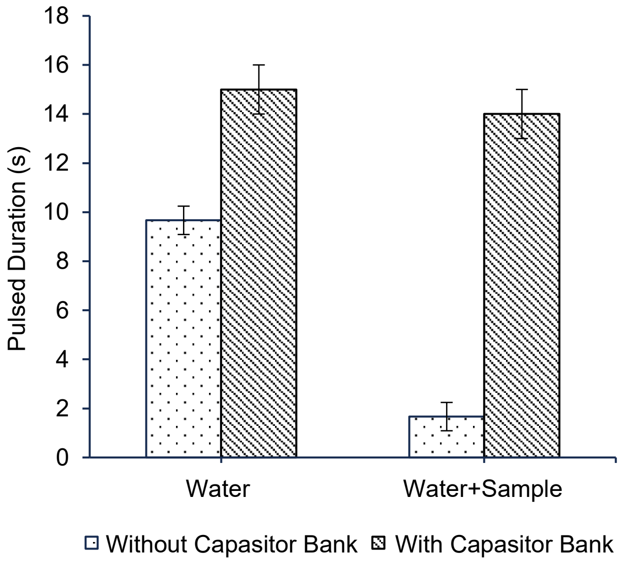

Figure 4. Effect of capacitor-bank integration on voltage sustainability during PEF operation under unloaded and sample-treatment conditions

The effect of MOSFET integration on pulse generation is shown in Figure 5. Without the MOSFET switching circuit, the output signal from the flyback transformer exhibited irregular voltage fluctuations and failed to form discrete high-voltage pulses (Figure 5A). After integration of the SiC-MOSFET, the system successfully generated monopolar rectangular pulses suitable for PEF treatment (Figure 5B). Enlarged views of the waveform revealed the pulse width, overshoot, ringing, and pulse cycle used for subsequent pulse-width and frequency characterization (Figure 5C–D). These results demonstrate the essential role of the MOSFET switching circuit in generating controllable high-voltage pulses and are consistent with previous MOSFET-based PEF systems reported for electroporation applications (Achour *et al*., 2021).

The pulse parameters were controlled using an ESP32 microcontroller. Using the microcontroller, pulse width, pulse frequency, and treatment duration could be adjusted to meet the desired operating conditions. The ESP32 has been widely used in embedded control systems because of its low cost, reliability, and ability to generate precise timing signals (Maier *et al.,* 2017). This programmable control architecture provided flexibility for investigating different treatment conditions while maintaining consistent pulse generation.

A batch-type treatment chamber was developed for solid-food applications. The chamber employed two parallel stainless-steel electrodes and was designed with adjustable electrode spacing of 0.5, 1.0, 2.0, and 3.5 cm. This configuration enabled the generation of different electric field strengths without modifying the high-voltage source. The adjustable electrode design increased the system's versatility, enabling its use on a variety of solid-food samples with different dimensions and electrical properties. Parallel-plate electrodes are commonly employed in PEF treatment of solid foods because they provide a relatively uniform electric field distribution and facilitate sample placement (Luengo *et al.,* 2016).

The design of the developed PEF system was guided by the electrical requirements for electroporation of plant tissues, which typically occur at electric field strengths of 1–3 kV/cm (Yarmush *et al.*, 2014). The system combined an ESP32 microcontroller for pulse control, a SiC-MOSFET switching circuit for pulse generation, a capacitor bank for energy storage, and a flyback transformer-based high-voltage supply to satisfy these demands. The technology produced adjustable high-voltage pulses and electric field strengths appropriate for solid-food preparation when combined with the treatment chamber's varied electrode spacings. All things considered, the created laboratory-scale PEF system effectively integrated energy storage, pulse regulation, high-voltage production, and treatment-chamber design into a single platform for further electrical characterization and application research.

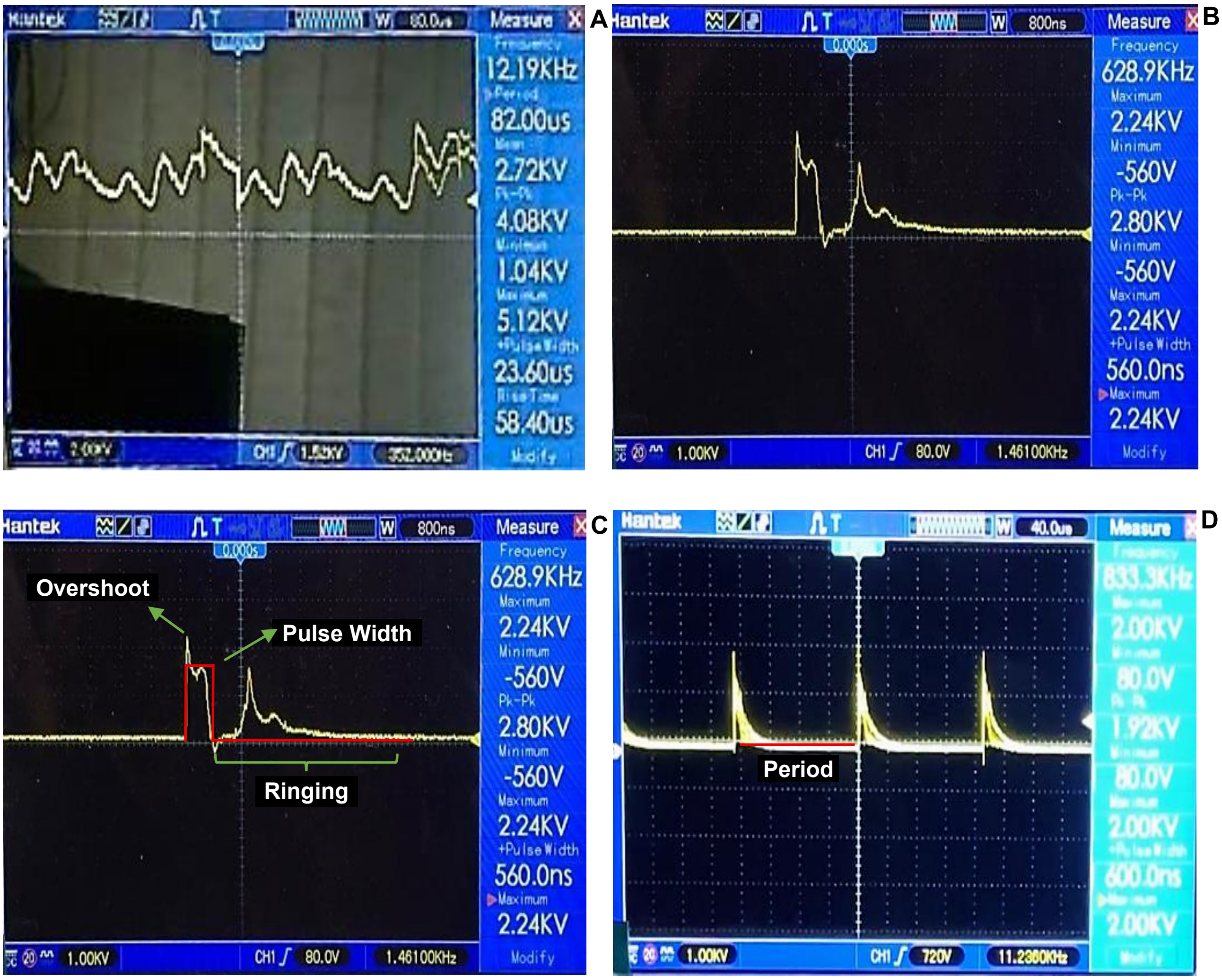

Figure 5. Representative waveforms generated by the developed PEF system: (A) without MOSFET switching, (B) with MOSFET switching, (C) enlarged view of a single pulse, and (D) pulse cycle used for frequency determination

Characteristics of output voltage and electric field

The developed PEF system was designed to operate at output voltages up to 3 kV. Voltage characterization was conducted by varying the input voltage supplied to the ZVS driver from 1 to 8 V. The corresponding output voltage measured under open-circuit and treatment conditions is presented in Table 1. These results indicated that the output voltage increased with increasing input voltage. However, a voltage drop was observed both under open-circuit conditions and during treatment. Under open-circuit conditions, the voltage reduction was approximately 20–30%, whereas a larger reduction of approximately 30–40% was observed when a food sample was placed in the treatment chamber. Similar voltage-stability challenges have been reported in compact pulsed-power systems, where the load impedance changes dynamically during treatment (Cvetkoska *et al.*, 2020).

Table 1. Output-voltage characteristics of the developed PEF system under open-circuit conditions

V_{in} (volt)	I (A)	V_{max} (kV)	V_{min} (kV)	Average Vout (kV)	% V Drop
6.7	0.38	2.44	1.88	2.16	23
7.0	0.41	2.52	1.88	2.20	25
7.4	0.43	2.76	2.04	2.40	26
8.0	0.47	2.84	2.16	2.50	24

Among the tested operating conditions, an input voltage of 6.7 V resulted in the lowest voltage drop (23%) while still producing an average output voltage of approximately 2.16 kV. Therefore, this operating condition was selected for subsequent electrical characterization and application experiments.

A further reduction in voltage occurred during treatment due to interactions between the pulsed electric field and the sample's electrical properties. Biological materials behave as dynamic electrical loads, where conductivity may change during treatment as electroporation progresses. Similar behavior has been reported in biological tissues exposed to pulsed electric fields, where changes in membrane conductivity contribute to variations in electrical response during treatment (Beitel-white *et al.,* 2020). These findings emphasize the need to include energy-storage components, such as capacitor banks, in order to preserve voltage stability and enable effective energy delivery during PEF treatment.

Equation 1 was used to determine the electric field intensity in the treatment chamber using the output voltage and electrode spacing. Treatment chambers with electrode spacings of 0.5, 1.0, 2.0, and 3.5 cm produced electric field strengths ranging from 0.62 to 3.32 kV/cm (Table 2). As expected, the electric field strength increased as the electrode spacing decreased. Electrode spacings of 1.0 and 0.5 cm generated electric field strengths of 2.05 and 3.32 kV/cm, respectively, which fall within or slightly exceed the range commonly used for electroporation of plant tissues (Yarmush *et al.,* 2014). In contrast, electrode spacings of 2.0 and 3.5 cm produced electric field strengths below 1 kV/cm and may therefore result in less extensive membrane permeabilization. The generated electric field strengths are comparable to those reported in previous PEF studies involving plant materials, including potato and oca tubers (Liu *et al.,* 2018b; Frontuto *et al.,* 2019). These results demonstrate that the developed PEF system can generate a wide range of electric field strengths suitable for investigating electroporation-based pretreatment of solid food materials.

Pulse waveform characteristics

The pulse waveforms generated by the developed PEF system are presented in Figure 5. Without the MOSFET switching circuit, the output signal from the flyback transformer exhibited irregular voltage fluctuations and failed to form discrete high-voltage pulses (Figure 5A). After integration of the SiC-MOSFET, the system successfully generated monopolar rectangular-wave pulses suitable for PEF treatment (Figure 5B). The ability to generate rectangular-wave pulses is particularly important because this waveform is widely used in modern electroporation systems due to its reproducibility and controllable energy delivery (Novickij *et al.,* 2022).

An enlarged view of the generated pulse revealed the presence of a positive overshoot followed by ringing at the beginning of the waveform (Figure 5C). These transient phenomena are commonly attributed to stray inductance and parasitic capacitance within high-voltage switching circuits (Liu *et al.*, 2020). Despite overshoot and ringing, the waveform remained predominantly rectangular throughout the pulse duration, indicating stable operation of the switching circuit and suitability for electroporation applications. The pulse cycle shown in Figure 5D was subsequently used to determine the pulse frequency and pulse width.

The rectangular pulses were primarily generated by the SiC-MOSFET switching circuit, which rapidly controlled the discharge of electrical energy stored in the capacitor bank. Similar waveform characteristics have been reported in MOSFET-based pulse generators developed for biological and electroporation applications (Novickij *et al.,* 2022). The successful generation of rectangular-wave pulses confirms the developed PEF system's capability to produce controlled high-voltage pulses required for electroporation-based food pretreatment.

Table 2. Voltage characteristics and electric field strength of the PEF system at different electrode spacings

Electrodes Distance (cm)	V_{in} (volt)	Average V_{max} (kV)	Average V_{min} (kV)	% V drop	Average V (kV)	Electric Field Strength (kV/cm)
3.50	6.7	2.6	1.7	33	2.16	0.62
2.00	6.7	2.4	1.5	40	1.95	0.98
1.00	6.7	2.4	1.7	30	2.05	2.05
0.50	6.7	2.0	1.3	36	1.66	3.32

Pulse width and frequency characteristics

The pulse width and frequency produced by the developed PEF system are summarized in Table 3. The system produced pulses with frequencies between 5.9 kHz and 1.98 MHz and widths between 400 ns and 19.2 μs. Both the nanosecond and microsecond pulse regimes commonly used in electroporation applications fall within this working range. The ability to produce a wide range of pulse durations and frequencies provides flexibility for examining various treatment conditions and food matrices.

Table 3. Pulse frequency and pulse width characteristics of the developed PEF system

Measurement Number	Frequency (kHz)		Pulse Width (ns)	
	Max	Min	Max	Min
1	1666	5.9	19200	400
2	1980	366	10460	415
3	1923	593	530	420
4	1818	552	540	440
5	1666	5.9	15200	400

Although they do so through distinct methods and with differing efficiency, prior research has shown that both nanosecond and microsecond pulses can successfully cause permeabilization in biological tissues (Rao *et al.,* 2022). The pulse properties found in this work are similar to those documented for contemporary high-voltage pulse generators utilized in electroporation and biotechnology applications. A high-voltage pulse generator that can generate pulses with widths between 100 ns and 100 μs at frequencies up to 5 MHz was described by Kandratsyeu *et al.* (2021). The comparable operating range observed in the present study indicates that the developed laboratory-scale PEF system possesses electrical characteristics suitable for food pretreatment and electroporation research. Furthermore, the obtained pulse range encompasses operating condi-tions commonly reported for tissue permeabilization, extraction enhancement, and food electroporation, demonstrating the versatility of the developed system for solid-food applications.

Overall, the developed PEF system generated output voltages, electric field strengths, pulse waveforms, pulse widths, and pulse frequencies that fall within ranges commonly reported in food electroporation studies. These results demonstrate that the developed laboratory-scale system possesses the electrical characteristics required for solid-food pretreatment applications and provides a suitable platform for subsequent validation using taro tubers.

Application of PEF for oxalate reduction in taro tubers

The developed PEF system was evaluated by applying it to the reduction of oxalate in taro tubers. Oxalate is a major antinutritional compound in taro because it can cause irritation and reduce mineral bioavailability. Therefore, reducing oxalate content is important for improving the quality and acceptability of taro-based food products.

PEF treatment was performed at an electric field strength of 1.08 kV/cm for 10 s. This electric field strength falls within the range commonly reported for electroporation of plant tissues (Yarmush *et al.*, 2014). The corresponding treatment chamber configuration (2 cm electrode spacing) also provided a practical treatment volume for handling taro samples during the experiment. Furthermore, a similar electric field strength was previously reported to be effective for oxalate reduction in tuber materials treated using a laboratory-scale PEF system (Anggraeni *et al.*, 2026). The results showed that the oxalate content of taro tubers decreased by up to 39% following treatment. The reduction is attributed to electroporation-induced disruption of cellular membranes, which increases cell permeability and facilitates the release of soluble intracellular compounds (Yarmush *et al.*, 2014), including oxalates, into the surrounding medium. Because oxalates in taro tissues are present in both soluble and insoluble forms, electroporation may promote the release of soluble oxalates from intracellular compartments, thereby contributing to the observed reduction in total oxalate content after treatment.

The reduction observed in the present study is consistent with previous reports demonstrating the effectiveness of PEF in reducing oxalates in tuber crops. Liu *et al.* (2018) reported greater oxalate reduction in Oca (*Oxalis tuberosa*) tubers than in this study, using lower electric field strengths. However, the effectiveness of PEF depends on tissue morphology, cell size, orientation within the electric field, pulse conditions, and the electrical properties of the treated material (Kandušer and Miklavčič, 2008). Therefore, species-specific differences in tissue structure and oxalate distribution may contribute to the differences in reduction efficiency observed between oca and taro tubers. Nevertheless, both studies support the ability of PEF-induced electroporation to facilitate oxalate reduction in tuber tissues.

The reduction achieved in this study is comparable to that reported for several conventional oxalate-reduction methods. Vulla and Mmanda (2025) reported that soaking taro leaves in water for 24 h reduced oxalate content by approximately 43%, while Marzuki *et al.* (2024) reported a reduction of approximately 58.7% after soaking taro tubers in a 6% NaCl solution for 120 min. Although the oxalate reduction achieved in this study was lower than that reported for prolonged soaking treatments, the developed PEF system accomplished the reduction within only 10 s of treatment. The substantially shorter processing time, combined with the absence of thermal treatment and chemical additives, highlights the potential of PEF as a rapid and environmentally friendly pretreatment technology for reducing anti-nutritional compounds in tuber crops. These findings demonstrate that the developed laboratory-scale PEF system generated sufficient electric field intensity to induce electroporation in taro tissues, thereby validating its applicability to solid-food pretreatment.

CONCLUSION

The development and characterization of a laboratory-scale pulsed electric field (PEF) system for solid-food applications has been accomplished. An ESP32 microcontroller, a SiC-MOSFET switching circuit, a bank of capacitors, a flyback transformer-based high-voltage power supply, and a batch-type treatment chamber with variable electrode spacing were all part of the designed system. The device could produce monopolar rectangular pulses with output voltages up to 3 kV, pulse widths between 400 ns and 19.2 *µ*s, pulse frequencies between 5.9 kHz and 1.98 MHz, and electric field intensities appropriate for electroporation of plant tissues, according to electrical characterization. PEF treatment at an electric field intensity of 1.08 kV/cm for 10 s reduced oxalate content by up to 39%, as validated using taro (*Colocasia esculenta*) tubers. The results confirmed that the developed system generated sufficient electrical conditions to induce electroporation and facilitate the reduction of anti-nutritional compounds in plant tissues. Overall, the developed PEF system provides a flexible laboratory-scale platform for investigating electroporation-based pretreatment of solid foods and may support future studies on extraction enhancement, drying pre-treatment, texture modification, and quality improvement of food materials.

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