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ORIGINAL PAPER

A Laboratory IGBT-Based High-voltage Pulsed Electric Field Generator for Effective Water Diffusivity Enhancement in Chicken Meat

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Abstract

Enhancing water diffusivity shortens meat processing time and saves energy and costs. One of the processes that can enhance water diffusivity in tissues is high-voltage, short-pulsed electric fields (PEF). However, for industrial PEF process development, there is a need in adaptable laboratory instruments. Here we report on a laboratory PEF generator, based on insulated-gate monopolar transistor switching, coupled with sliding positive electrode for the enhancement of water diffusivity in chicken breast muscle. The system generates rectangular monopolar pulses with a voltage amplitude up to 1000 V, current up to 160 A, pulse duration of 5 to 100 μs, and a frequency of pulse repetition of 1–16 Hz. The energy conversion efficiency of the developed PEF generator is 88%. We found that applying 120 pulses at 1000 V (~ 500 V mm^{-1}), and a pulse duration of 50 μs at 1 Hz, on the chicken breast muscle, increased the effective diffusivity of water by 13–24% and reduced convective air drying time by 6.4–15.3%. These results provide new information on the design of laboratory equipment to improve and optimize meat pre-processing on a small scale. Flexible, small-scale PEF equipment is a necessary step for the industrial development of new processes which could reduce equipment size and process energy consumption in the meat industry.

Keywords Meat processing · Drying · Pulsed electric field · Electroporation · Effective diffusivity · IGBT pulsed-field generator

Introduction

Water diffusion is important for meat processing (Hallström 1990). Controlling water diffusion is essential for meat preservation and processing during drying (Arnau et al. 2007), salting (Gómez et al. 2015), fermentation (Arnau et al. 2007), and heat cooking (van der Sman 2013). Thus, enhancing water diffusion kinetics is expected to shorten the time for meat processing (Apple and Yancey 2013; den Hertog-Meischke et al. 1997; Huff-Lonergan 2009), saving energy and monetary costs. One of the technologies that could enhance water diffusion in biological tissues is high-voltage, pulsed electric fields (PEF) (Amami et al. 2008; Janositz et al. 2011).

Application of PEF on biological cells and tissues leads to increased membrane permeability, a phenomenon known as electroporation (Golberg et al. 2016). Current consensus describes electroporation as the formation of aqueous pores in the lipid bilayer that enable molecular transport of usually impermeable molecules (Kotnik et al. 2012; Spugnini et al. 2007; Weaver and Chizmadzhev 1996). PEF-based technologies are used in multiple medical, food, and biotechnology applications (Golberg et al. 2016; Tadej Kotnik et al. 2015; Yarmush et al. 2014). Although the impacts of PEF on mass transport have been investigated for biomedical applications, such as electrochemotherapy and gene electrotransfer (Golberg and Rubinsky 2013; Granot and Rubinsky 2008), and in the food industry for multiple plant tissues (Knorr 2018; Puértolas et al. 2012; Vorobiev and Lebovka 2011), information describing the impact of PEF on animal tissues in the food industry is scarce (Alahakoon et al. 2017; Bhat et al. 2018a).

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Previous work reported on the ability of PEF to improve meat safety, organoleptic qualities (Ma et al. 2016; O'Dowd et al. 2013), tenderization (Bekhit et al. 2014; Suwandy et al. 2015), and supercooling and brining (Arroyo et al. 2014; Faridnia et al. 2014a, 2014b; McDonnell et al. 2014). PEF modified meat texture, color, and water holding capacity (Arroyo et al. 2015; Gudmundsson and Hafsteinsson 2001). Most recently, PEF has shown a capacity to modify the cooked beef protein profile leading to high and faster digestion kinetics in vitro (Bhat et al. 2018b, 2019). Nevertheless, to achieve its full technological and economic potential, detailed information on PEF-induced changes in meat products is still needed (Bhat et al. 2018a).

To generate this information, there is a need for versatile laboratory-scale equipment that would allow for testing and optimization of different electrical and mechanical protocols for PEF. Several topologies of the laboratory PEF scale systems were developed in previous studies (Pirc et al. 2017; Hofmann 2000; Novickij et al. 2014; Puc et al. 2004; Reberšek et al. 2014; Reberšek et al. 2010; Sack et al. 2016, 2017; Stankevič et al. 2013). The drawbacks of the available commercial laboratory systems (Puc et al. 2004; Reberšek et al. 2010) are their costs, limitation on supplied current and voltage, and limited opportunities for coupling with sliding electrodes, needed for the development of the continuous processes at which tissue volume changes with electroporation.

The goal of this work is to develop a PEF device for the treatment of chicken muscle and to determine the impact of PEF with microsecond pulse duration on the effective diffusivity of water in the chicken breast muscle. For this purpose, we developed an insulated-gate monopolar transistor switching (IGBT)–based pulse generator and electroporation treatment chamber with sliding positive top electrode. We chose to work with IGBT technology as in comparison with other methods for high-voltage rectangular pulse formation, semiconductor high-voltage power elements, including IGBT transistor, have more opportunities for controlling the process of pulse formation of different durations, as well as the frequency of their repetition (Sack et al. 2016).

Using the developed PEF system, we found that PEF increases the effective water diffusivity and decreases the convective air drying time of the chicken breast muscle in comparison with untreated controls. These results provide new information on the design of laboratory-scale equipment to improve meat preprocessing with PEF. This information is important for the development of applications for the enhancement of chicken breast meat processing, such as drying or cooking (Toepfl and Heinz 2007).

Materials and Methods

Meat Biomass

The chicken breast meat (500 g) was purchased in a local supermarket (Tel Aviv, Israel) in several batches in 2017–2019. For experiments, cylindrical samples (2.5 cm diameter) were randomly cut for PEF treatment and controls.

IGBT-Based Pulsed Electric Field Generator for Chicken Breast Biomass Treatment

In this work, we developed a laboratory PEF device for meat biomass electroporation. The circuit (Fig. 1) of the pulse generator has the following specifications: output voltage in the range from 0 to 1000 V, the maximum current of 160 A, a pulse duration of 5 to 100 μs, the frequency of pulse delivery of 1–16 Hz, the maximum number of pulses of 1000.

The main components of the PEF generator are energy storage capacitor (ESC) with a capacity of 50 μF for voltage 1.25 kV; high-voltage source of charge of energy storage capacitors (CCM1KW); parallel-connected high-voltage IGBT switches (M. Sack et al. 2016) (IXYN120N120C3 with parameters of 1200 V, 120 A); driver of high-voltage switch with electrical circuits of control of transistor gates and own power supply (Gate Driver Optocoupler FOD3184); DC-DC converter ITB0515S for voltage 5/15 V with high-voltage insulation between primary and secondary voltage circuits; high-power current-limiting resistors; circuit node for manual control of high-voltage switch and high-voltage power supply in testing mode; microcontroller; and low-voltage power supply for control circuits and fans of the device.

The resistance of current-limiting resistors, connected to the emitters of each of the transistors, is determined by the value of a single permissible current pulse. For the transistor IXYN120N120C3, it is equal to I_{CM} = 700 A. Thus, the magnitude of the current-limiting resistance (R_l) in the circuit of each of the IGBT transistors is calculated as in Eq. 1:

$$R_l = U_m / I_{CM} = 1000/700 = 1.429\ \Omega \quad (1)$$

where U_m (V) is the maximum allowed operation voltage. The required dissipation power (P_R) of the current-limiting resistance is determined based on the maximum current of each of the transistors (I = 80 A), the current-limiting resistance (R_l = 1.429 Ω), the pulse duration (t_i = 100 μs), and the pulse repetition rate (F = 10 Hz) (Eq. 2):

$$P_R = I^2 \cdot R_l \cdot t_i \cdot F = (80)^2 \cdot (1.429)^2 \cdot 100 \cdot 10^{-6} \cdot 10 = 13.07\ \mathrm{W} \quad (2)$$

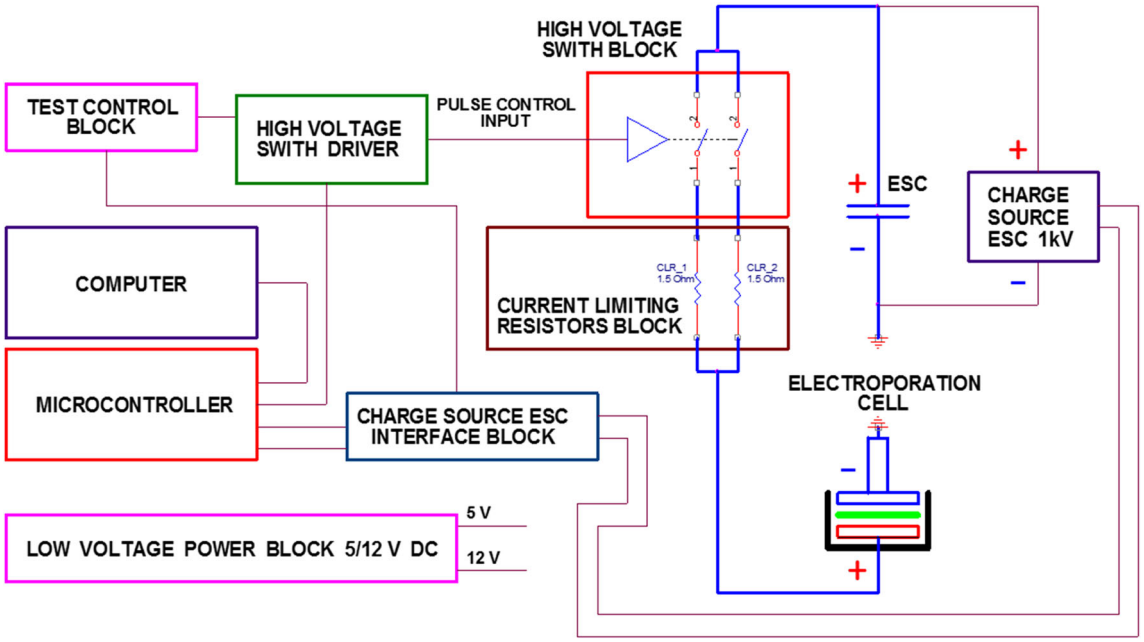

Fig. 1 Functional scheme of the high-voltage pulse electric field generator

A matrix of 8 resistors (RR02–3 Ω–2 W) with a total resistance of 1.5 Ω and total power dissipation, P_R, of 16 W was used for current limitation inside the PEF generator. The total power dissipation of two such matrices is 32 W, and their parallel connection determines the resistance $R_L = R_l / 2 = 0.75$ Ω. Therefore, with a pulse duration of $t_i = 100$ μs and a pulse current of $I = 160$ A, the permissible pulse repetition rate will be as in Eq. 10:

$$F = P_R/I^2 \cdot R_L \cdot t_i = 32/(160)^2 \cdot 0.75 \cdot 100 \cdot 10^{-6} = 16.666 \text{ Hz} \quad (3)$$

At the maximum pulse current, $I = 160$ A, and maximum applied voltage of 1000 V, the resistance of the discharge circuit must be at least $R = 1000/160 = 6.25$ Ω. From this resistance, 0.75 Ω is the resistance of the current-limiting resistors. Therefore, the minimum efficiency η of the device will be as in Eq. 4:

$$\eta = [1-(R_L/R)] \cdot 100\% = [1-(0.75/6.25)] \cdot 100\% = 88\% \quad (4)$$

For safety, the high-voltage is blocked and the storage capacitor is discharged when the chamber in which the experiments are conducted is opened. It is also possible to immediately terminate the experiment clicking on the "STOP" button or directly by switching the "TEST/WORK" switch on the front panel (Fig. 2b) to the "TEST" position. In addition, in an emergency, the device operation can be terminated by turning off the high-voltage charge source, pressing the "STOP HV" button, or by turning off the device general switch. Under all conditions, the high-voltage capacitor is discharged.

The software that controls the device and application algorithms is described in Supplementary Material 1. The complete developed experimental setup included the mechanical chamber with the sliding top electrode for meat electroporation (Fig. 2a). The moving positive top electrode generates the constant contact and inter-electrode pressure between electrodes and the meat when the volume of the electroporated sample changes. A load weighing up to 10 kg can be placed on the load-receiving platform to create the necessary inter-electrode pressure on the biomass (Fig. 2b). The PEF generator is shown in Fig. 2 b and c and the controlling software is described in Fig. 2d and Supplementary Material 1 and an example of the calibration procedure is shown in Supplementary Material 2.

Impedance Measurements

The bioimpedance measurement system was created by connecting an electroporation cell that holds the biomass sample in electrodes to a bioimpedance meter (ScioSpec, ISX-3, Germany). Multi-frequency electrical impedance was measured injecting a 100-mV peak potential difference in the frequency range of 100 Hz to 1 MHz and then measuring the current to estimate the impedance of the system. Impedance meter programming and storage data were developed by a personal computer.

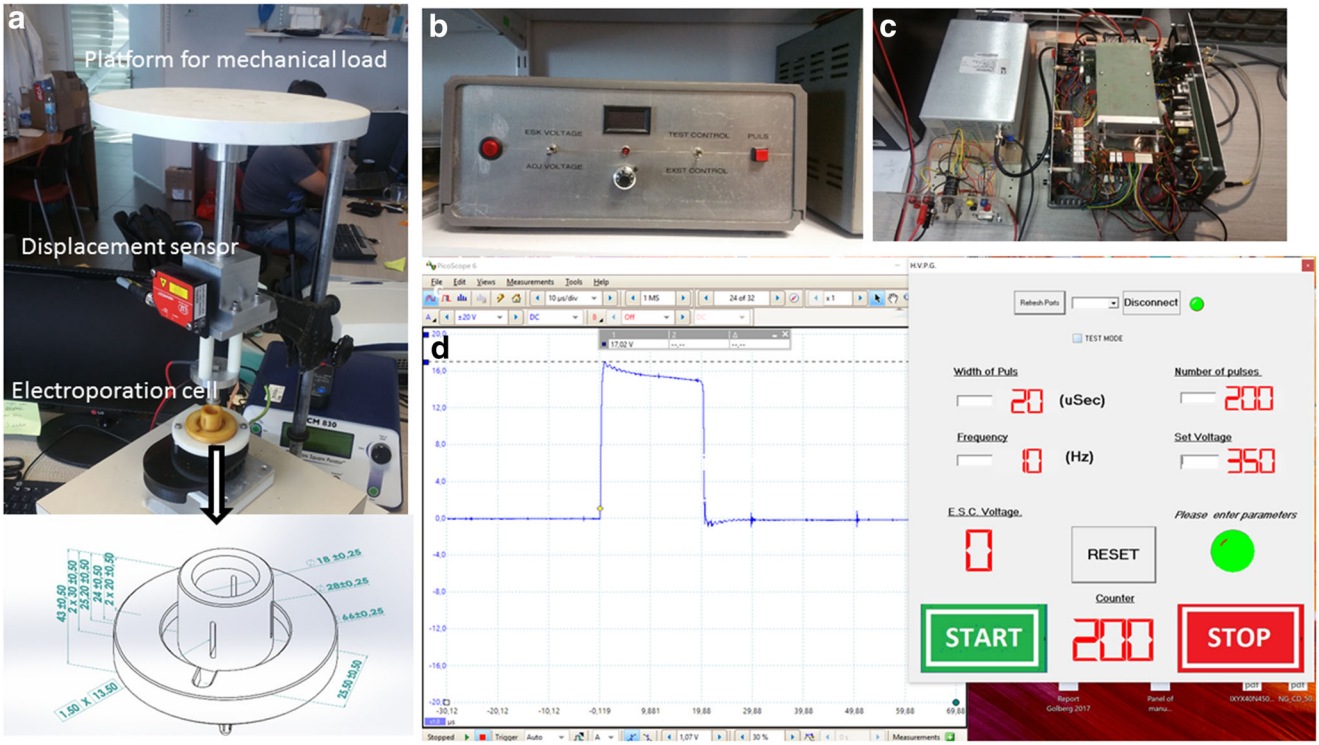

Fig. 2 The developed pulsed electric field system for meat biomass electroporation. **a** Mechanical electroporation chamber with slider electrodes. **b** Pulse generator box. **c** Digital image of the assembled pulse generator components. **d** Controlling software interface

Disintegration Index Z_p

The cell disintegration index (Z_p) was calculated on the basis of the measurement of the absolute impedance value of control (Z_c) and PEF-treated meat (Z_{tr}) in the low (1 kHz) and high (150 KHz) frequency ranges as reported in Bobinaitė et al. (2014) and Donsì et al. (2010), as follows:

$$Z_p = \frac{|Z_{c(1\ \mathrm{kHz})}| - |Z_{tr(1\ \mathrm{kHz})}|}{|Z_{c(1\ \mathrm{kHz})}| - |Z_{tr(150\ \mathrm{KHz})}|} \quad (5)$$

where the value of Z_p varies between 0 for intact tissue and 1 for fully permeabilized tissue.

For disintegration studies, approximately 2 g of chicken breast (single piece of a chicken breast muscle) was loaded into the electroporation cell between two flat circular (2.5 cm diameter) electrodes made from stainless steel. The distance between the two electrodes was measured continuously with the displacement sensor (optoNCDT, Micro-Epsilon, NC). Three protocols were tested: 10 pulses, 120 pulses, and 1000 pulses. The additional 4-kg load was applied to the top electrode. In all protocols, we used a voltage amplitude of 800 V, a pulse duration of 50 μs, and a pulse repetition frequency of 1 Hz. Three replications were done for all experimental groups (n = 9). Impedance was measured for each sample before and after electroporation

Pulsed Electric Field Treatment of the Chicken Breast for Drying Experiments

Approximately 0.5 g of a chicken breast muscle (single piece of a chicken breast muscle) was electroporated as described above. The starting distance between the electrodes was 1.97 ± 0.01 mm. The voltage was applied using the custom-made PEF generator. The currents were calculated from the voltage drop on the current-limiting resistor measured with a PicoScope TA044 70 MHz 7000 V differential oscilloscope probe 100:1/1000:1, PicoScope 4224 Oscilloscope, Pico Scope 6 software (Pico Technology Inc., UK). Immediately after the PEF treatment, the biomass was weighed again using analytical scale (repeatability of 0.5 mg, Metler Toledo XS, OH). For controls, the procedure was repeated exactly: the cut chicken breast biomass was loaded into the electroporation cell for the same time required for the PEF treatment without the application of the electric fields. In all PEF experiments, 120 pulses with a voltage amplitude of 1000 V and a pulse duration of 50 μs, at 1 Hz, were used. The additional 4-kg load was applied on the sliding top electrode. Five replications were done for a PEF treatment and five replications were done for a control group.

Drying Experiments

After unloading from the electroporation cell, the meat was dried with air convection at 105 °C for 30 min (to achieve a

constant weight < 5% change per minute) using a moisture analyzer (BM-50-5, Biobase Biodustry, Shandon Co. Ltd., China). We chose 105 °C as this temperature is used to determine the dry weight content and is expected to remove most of the liquid (Mujumdar 2014). The weight of the sample was measured continuously.

Under the assumption that the tissue is isotropic with respect to water transport, water diffusivity in the chicken muscle can be described with Fick's second law of diffusion (Eq. 6):

$$\frac{dw}{dt} = \nabla D_{\text{eff}} \nabla w \tag{6}$$

where D_{eff} ($m^2\ s^{-1}$) is the effective diffusivity of water in the sample, t (s) is drying time, and w is the dimensionless moister content calculated as in Eq. 7:

$$w = \frac{M(t) - M_e}{M_0 - M_e} \tag{7}$$

where $M(t)$ is the moisture content at drying time t (s), M_e is the moisture content at equilibrium (final), and M_0 is the initial moisture content.

Assuming uniform moisture distribution, negligible external resistance, constant diffusivity, and negligible shrinkage through the drying process, the solution of Eq. 6 for the chicken slab is given by Eq. 8 (Crank 1975):

$$w(D_{\text{eff}}, t, l) = \frac{8}{\pi^2} \sum_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left(-\frac{(2i+1)^2 \pi^2 D_{\text{eff}} t}{4l^2}\right) \tag{8}$$

where l (m) is the half thickness of the infinite slab.

Statistical Analysis

Comparison of Drying Kinetics of PEF and Control Meat Samples

The comparison between PEF and control meat drying kinetics was performed in two steps.

In the first step, we performed a point-wise comparison of the dimensionless moisture content at each time point during drying. To this end, we employed both parametric (Student's t test) and non-parametric (threshold number of misclassifications, TNoM) methods (Ben-Dor et al. 2001; Bittner et al. 2000). In a nutshell, the Student t test analyzes wherever two sets of points originate from the distribution with the same mean, while the TNoM finds the optimal threshold value separating both populations and evaluates the probability of obtaining such separation at random.

In the second stage, we combined all the drying time point–based statistics into a single p value according to Fisher's combined probability test (Fisher 1932) (Eq. 9):

$$\chi^2_{Test} = -2 \sum_{t=1}^{T} \ln\left[p_t^{Test}\right] \tag{9}$$

where t is the time point during drying for each comparison subset (T = 8 time points during drying: 1 min, 2 min, 5 min, 7 min, 11 min, 15 min, 20 min, 25 min), Test refers to the performed test (either t test or TNoM), and p is the 2-tailed p value statistics of the test. The resulting score is of χ^2 distribution with $2T$ = 16 degrees of freedom.

Estimation of the Diffusion Coefficient

The diffusion coefficient D_{eff} was estimated separately for each experiment by three different numerical approximation approaches, which minimize (i) the mean square error (MSE; Eq. 10); (ii) the mean absolute error (MAE; Eq. 11); and (iii) the mean relative error (MRE; Eq. 12) between the measured and the predicted dimensionless moisture contents, w, across the experimental replicate time points,

$$\text{MSE} = \frac{1}{T} \sum_{t=0}^{T} \left(w_t^{measured} - w_t^{predicted}(D_{\text{eff}}, l, t)\right)^2 \tag{10}$$

$$\text{MAE} = \frac{1}{T} \sum_{t=0}^{T} \left|w_t^{measured} - w_t^{predicted}(D_{\text{eff}}, l, t)\right| \tag{11}$$

$$\text{MRE} = \frac{1}{T} \sum_{t=0}^{T-1} \left|\frac{w_t^{measured} - w_t^{predicted}(D_{\text{eff}}, l, t)}{w_t^{measured}}\right| \tag{12}$$

where t is the measurement time point id; T = 10 is the total number of measurements and time, t is the measurement time in seconds. The $w_t^{measured}$ refers to the measured, normalized dimensionless moisture content, which is always equal to 1.00 at the $t[0]$ = 0 s and equal to 0.00 at the $t[T]$ = 30 min = 1800 s. The $w_t^{predicted}(D_{\text{eff}}, h, t)$ refers to the predicted dimensionless moister content calculated with Eq. 8 using the predicted value of D_{eff}, measurement t and l, which is the half thickness of the infinite slab in meters.

Results and Discussion

Validation of the IGBT-Based Pulsed Generator

To validate the developed pulsed generator performance, we tested it on resistors with known loads. For this, we applied 20 pulses with 20-μs pulse durations and with a fixed voltage, on the energy storage capacitor (U_{ESC}) on a load (R_{L}) with a known resistance (Table 1, Fig 3a). The internal resistance was calculated as $R_{\text{i\_measured}} = (U_{\text{ESC}} - U_{\text{L}}) / I_{\text{L}}$. The error was calculated as $R_{\text{i}}\%\text{Error} = 100\% \cdot (R_{\text{i\_measured}} - R_{\text{i\_designed}})$

Table 1 Pulse generator test on known loads. Averages of 20 pulses for each load are shown

R (Ω)	I_L (A)	U_{ESC} (V)	U_L (V)	$R_{i\_measured}$ (Ω)	$R_{i\_designed}$ (Ω)	R_i%Error
5	18.6	107	93.00	0.75	0.75	0.36
5	35.46	205	177.30	0.78	0.75	4.15
17	11.88	205	196.02	0.76	0.75	0.79
33	6.07	205	200.31	0.77	0.75	3.02
50	4.04	205	202.00	0.74	0.75	0.99
100	2.04	205	203.50	0.74	0.75	1.72

/ $R_{i\_designed}$. The error of the internal resistance estimation, using fixed 5–100 Ω resistors, was between 0.36 and 4.15% (Table 1). This suggests that the pulse generator provides a stable voltage on the output at this range of external loads.

Breast Muscle Disintegration as a Function of the Number of Applied Pulses

Increasing the number of pulses from 10 to 120 increased the cell disintegration index (Z_p) from 0.51 ± 0.22 to 0.95 ± 0.01. Further, an increase in the number of pulsed to 1000 leads to the same Z_p of 0.94 ± 0.01. These results suggest that 120 pulses were sufficient to achieve the maximum electropermeabilization and disintegration of the breast muscle. Therefore, we used 120 pulses in the following drying experiments.

Pulsed Electric Field Enhances Air Drying Rate of the Chicken Breast

Applying PEF at 1000 V (~ 500 V mm^{-1}), a pulse duration of 50 μs, 120 pulses at 1 Hz on the chicken breast biomass led to 99.8 ± 5.1 A currents (specific applied energy). The moisture removing curves (M_0–$M(t)$) during post-treatment drying for all treated and untreated samples are shown in Fig. 3b. Both parametric (based on Student's t test) and non-parametric (based on TNoM test) comparisons of PEF-treated and control experimental sets showed a significant difference between the two groups with the combined $p = 3.19 \cdot 10^{-5}$ and $2.75 \cdot 10^{-2}$ respectively. This longitudinal comparison of two samples shows that the applied PEF protocol enhances the convective air drying rate of the chicken breast meat. Previous work on PEF with more mild treatment parameters of 1.36 kV cm^{-1}, 40 pulses, each pulse duration of 2 μs, on the chicken muscle

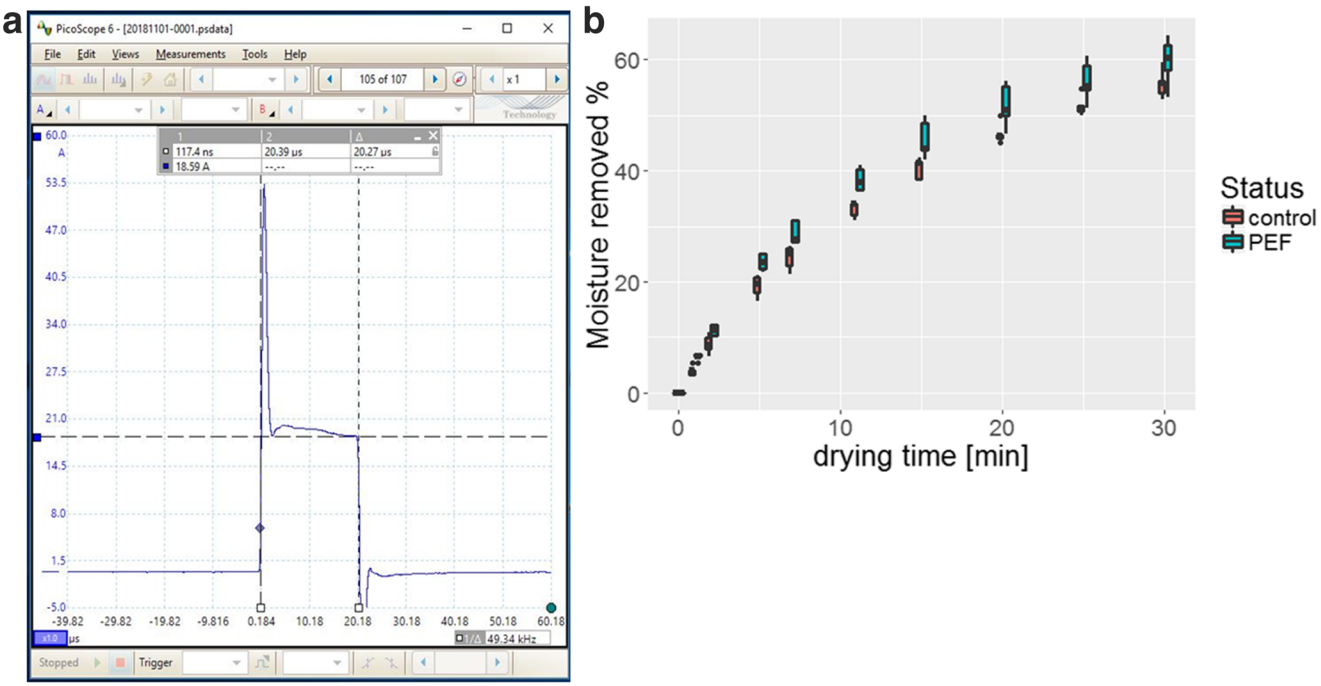

Fig. 3 **a** The experimentally measured oscillogram of a 20-μs pulse with 107 V amplitude applied on a known resistor of 5 Ω. **b** Moisture removed from the chicken breast muscle. 5 repetitions of control vs 5 repetitions of PEF-treated samples

demonstrated a reduction in the size of the cells in comparison with untreated controls (Gudmundsson and Hafsteinsson 2001). This cell size reduction could provide some mechanistic insights into the impact of PEF on the drying rate—smaller cells could provide large intracellular pathways for water to move and could also increase the time of the muscle shrinking during drying. Shrinking leads to the crust formation and, thus, reduces the water movement. Increasing the space between cells could slow down the shrinkage time (Srikiatden and Roberts 2007). Future work should address the structural changes in the meat following PEF treatment.

The Impact of Pulsed Electric Field on the Effective Diffusivity Coefficient of the Chicken Breast Meat

PEF can enhance meat drying by two major mechanisms: (1) the direct extraction of liquids from the biomass and (2) increasing the effective diffusivity (Toepfl and Knorr 2006). The direct extraction of liquids shortens the drying time and reduces the energy needed for evaporation. Increasing the effective diffusivity coefficient shortens the drying time, but does not reduce the total energy required for water evaporation, as the total volume of water does not change. Under the described PEF treatment conditions, we did not see a significant difference in the extracted water between PEF and the respective controls. Control groups lost 7.7 ± 1.1% of water and PEF groups lost 8.2 ± 0.6% (t test $p = 0.36$).

Next, we determined the effective diffusivity coefficient w in the control and PEF-treated chicken breast samples. The experimental data for w appears in Fig. 4a for control and Fig 4b for PEF-treated samples (error bars reflect minimal and maximal values, while dots reflect the median measurements). Using numerical approximation with three different error-estimating approaches (Eqs. 9–11), we determined the D_{eff} (Table 2) for both controls (Fig. 4a, solid lines) and PEF samples (Fig. 4b, solid lines). The predicted vs measured data for w is shown in Fig. 4a for control and Fig. 4b for the PEF-treated samples. These results show that PEF treatment increased the effective diffusivity coefficient of the chicken breast by 13–24% (depending on the error model), explaining the observed experimentally drying enhancement (Fig. 3b).

The absolute and relative differences in the moisture content between the control and PEF samples during drying are shown in Fig. 5 a and b respectively. For all time points, the moisture content removed from the chicken breast sample was higher in the PEF-treated samples (Fig. 5a, b). In other words, PEF-treated samples require less time to achieve the same moisture levels (Fig. 5c, d). We also observe (Fig. 5d) that the achieved relative time improvement is constant for all moisture levels, suggesting the PEF led to permanent structural changes in the treated meat that permanently increased the porosity and, thus, available for water movement area. The initial fluctuations (Fig. 5d) could be explained by variance in extraction by PEF to surface water.

This difference is important as it leads to shorter operational times required from the same oven to achieve the expected moisture levels in the dried biomass (Fig. 5c). Our results show that PEF decreased drying time by 6.4–15.3% (Fig. 5d), reducing the energy consumption of the process, which is an important target in this industry (Colak and Hepbasli 2009; Xu et al. 2015). Previous protocols to increase the energy efficiency of meat drying achieved 5–20% energy reduction by using reduced amounts of circulated air or using external thermal energy for the processes (Alcazar-Ortega et al. 2011; Bantle et al. 2015; Mujumdar 2014). Here we propose a complementary tool for increasing energy efficiency of drying using pretreatment with PEF. PEF has already been shown in other studies to save energy in biomass processing (Golberg et al. 2016). The combined impact of both process-enhancing approaches is yet to be determined.

In this work, we do not provide a mechanistic explanation of the PEF-induced changes in the chicken breast that can justify the increased effective diffusivity. Additional studies on structural and physicochemical (for example, water holding capacity and fat holding capacity) changes within the chicken breast muscle following PEF are needed. Our previous work using a potato model suggested the PEF could change the diffusion of salts and water by affecting tissue tortuosity for molecular flow (Golberg et al. 2010). This finding was corroborated by additional work on rat liver ablation with PEF (Golberg et al. 2009, 2011) and another work that investigated the acceleration of pork salting with PEF, which suggested myofibril structural changes (McDonnell et al. 2014; O'Dowd et al. 2013) and gaps created within muscle structure (Gudmundsson and Hafsteinsson 2001) as a result of PEF, which could lead to higher diffusion coefficients (McDonnell et al. 2014). Similar observations were made when studying the effects of PEF on the texture of salmon; gaps in the microstructure of salmon caused collagen leaks into the extracellular space (Gudmundsson and Hafsteinsson 2001). An additional study reported an increase in the number of ruptured myofibrils along the Z-lines in PEF-treated beef (F. Faridnia et al. 2016). This rupture resulted in muscle tissue with a more porous structure, which accounted for the observed increase in electrical conductivity (F. Faridnia et al. 2016). In addition, in previous work in vivo, we reported on the complete loss of striation and fragmentation of fibers in electroporated muscle in rats (Alexander Golberg et al. 2017). These preliminary studies support the hypothesis that PEF causes structural changes in muscle leading to a higher diffusion coefficient of water and accelerating meat drying rates, reported in this work.

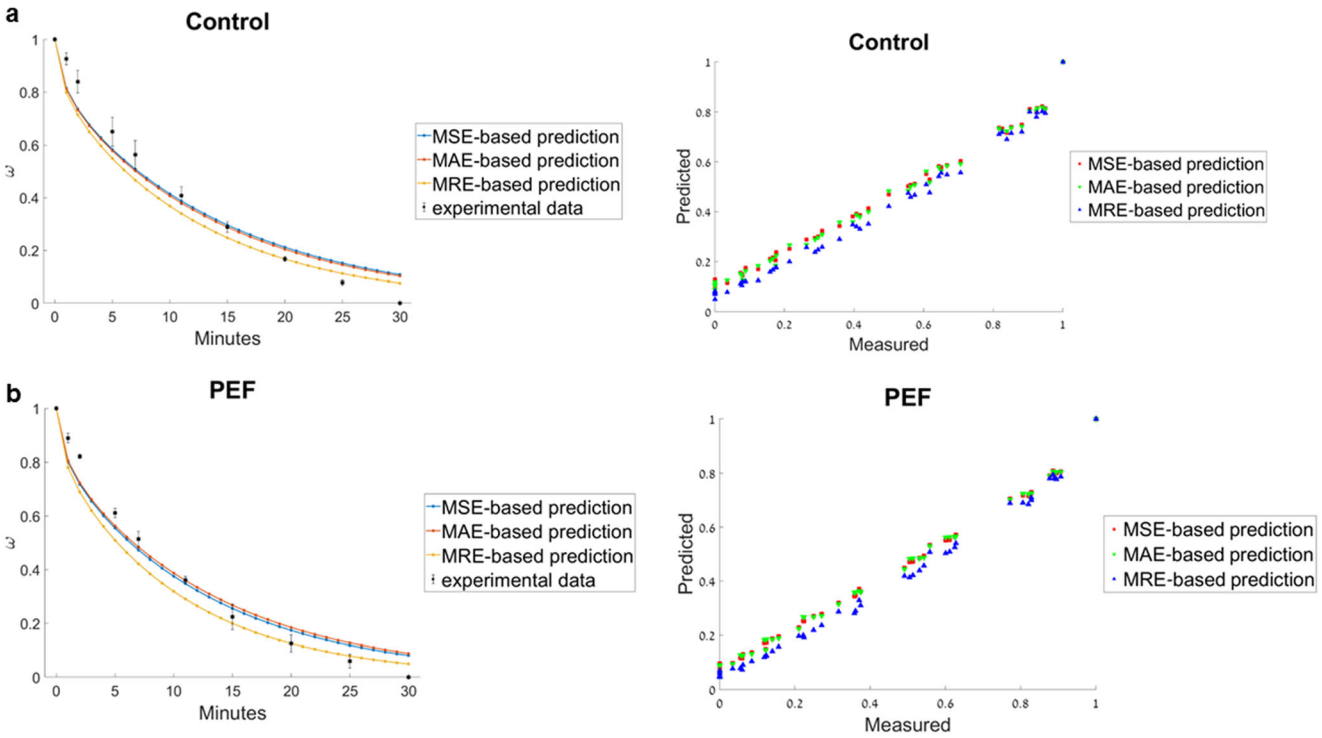

Fig. 4 Kinetics of the chicken breast drying. Experiment and predicted values based on the mean square error (MSE); the mean absolute error (MAE); and the mean relative error (MRE). Left panels (**a**, **b**) show kinetic-based comparison (error bars reflect minimal and maximal measured values, while dots reflect the median measurements), while right panels (**c**, **d**) show the measured vs predicted values for dimensionless moisture content *w*

One of the limitations of this work is the limited number of PEF condition used. We applied the electric field strength and pulse duration that were shown in other studies to cause muscle irreversible electroporation (Gehl et al. 1999). However, muscle is an anisotropic tissue and different parts of the muscle of other parts of meat could require additional parameters optimization (Čorović et al. 2010, 2012; Schertzer et al. 2006). In addition, as low energy consumption is an essential component required for PEF pre-drying treatment adaptation, additional optimization studies are needed to find the PEF protocol with the lowest energy inputs that can still enhance drying and reduce the total energy consumption of the process. Such a process could combine mechanical pressing with PEF to physically remove part of the water, thus saving the energy required for evaporation. A similar approach has been already been shown to be useful in the drying of plant tissues (Amami et al. 2008; Lebovka et al. 2007; Martin Sack et al. 2008), where PEF was applied for both electroporation and dewatering of the biomass (A Golberg et al. 2016). Future applications of PEF technology in the meat industry can include accelerated drying, frying, tendering, accelerated bringing, or extraction of high-value compounds from the waste meat.

Conclusions

Non-thermal, chemical-free processing is an emerging field in the meat industry with a clear need for new technologies and devices. In this work, we developed a laboratory-scale PEF device that consists of an IGBT-based pulsed generator that delivers up to 1000 V, 160 A pulse current, with 5- to 100-μs pulse duration, with 1–16 Hz frequency of pulse delivery and

Table 2 Water effective diffusivity calculated using the mean square error (MSE); the mean absolute error (MAE); and the mean relative error (MRE). Both parametric (based on Student's *t* test) and non-parametric (based on TNoM test) comparisons of PEF and control experimental sets showed a significant difference between the two groups with the combined *p* value of $3.19 \cdot 10^{-5}$ and of $2.75 \cdot 10^{-2}$ respectively

Method	$D_{eff\_control}$ ($m^2\ s^{-1}$)	Error_Control	D_{eff_PEF} ($m^2\ s^{-1}$)	Error_PEF
Mean square error (MSE)	$3.64\ 10^{-10}$	0.0050	$4.40\ 10^{-10}$	0.0037
Mean absolute error (MAE)	$3.73\ 10^{-10}$	0.0589	$4.23\ 10^{-10}$	0.0520
Mean relative error (MRE)	$4.28\ 10^{-10}$	0.1521	$5.34\ 10^{-10}$	0.1384

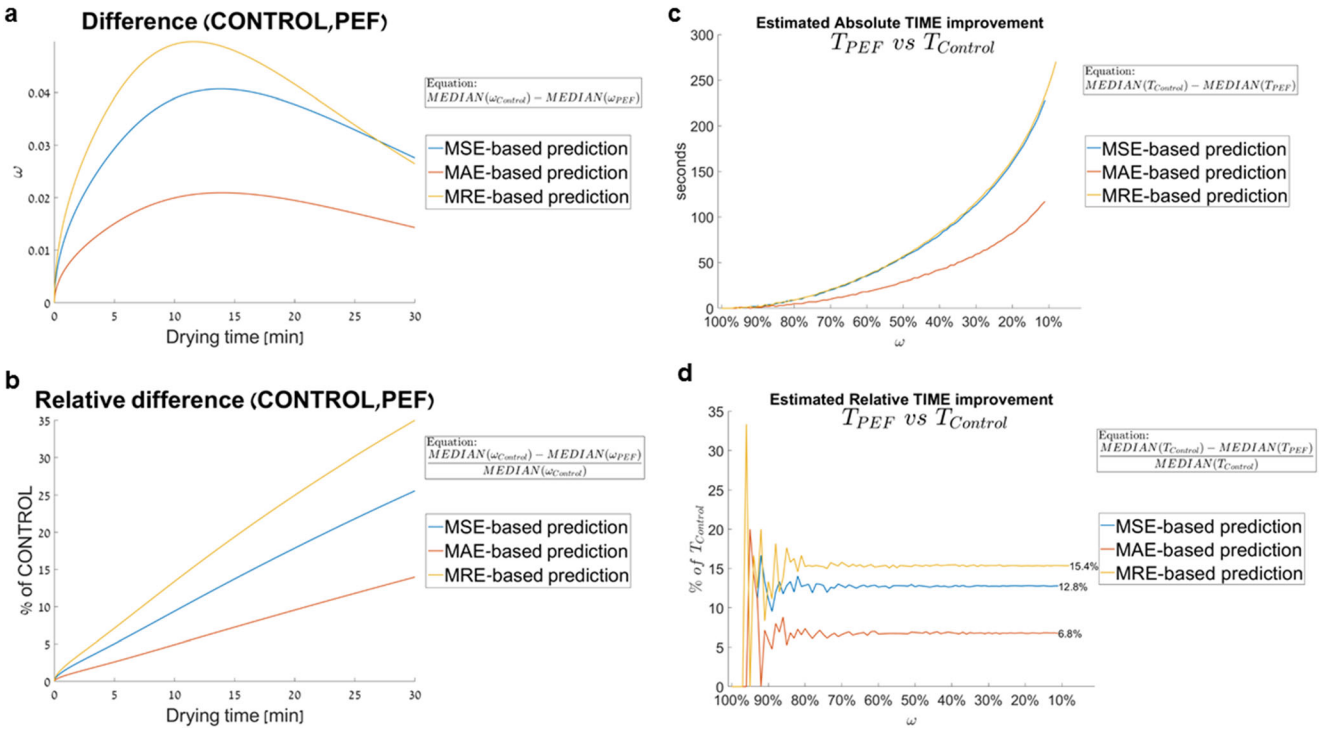

Fig. 5 **a** Absolute and **b** relative differences between median moisture contents in control and PEF-treated chicken breast muscle in time. **c** Absolute and **d** relative time enhancement of chicken drying expressed as the reduced time to achieve the same level of moisture in the control vs PEF-treated samples

1000 maximum number of pulses at a single charge—coupled with sliding press electrodes. Device validation on the chicken breast showed that applying 1000 V (~ 500 V mm^{-1}), a pulse duration of 50 μs, and 120 pulses at 1 Hz on the chicken breast enhanced the post-treatment drying rate in comparison with untreated controls. We found that the applied PEF protocol did not remove the water from the biomass but increased the effective diffusivity of water by a constant value through the whole convective air drying process. Our results show that PEF enhances drying by about 6.4–15.3%. Additional studies on the mechanisms of PEF impact on the chicken muscle are needed. Furthermore, optimization of the PEF protocol for minimum invested energy and de-watering is also still needed. Our results show that further development of PEF technology is a promising direction to improve meat processing and reduce its environmental impact by reducing the consumed energy.

The proposed technology could be used in industrial chicken meat processing such as deep-fried chicken products.

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