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Saving energy on meat air convection drying with pulsed electric field coupled to mechanical press water removal

Supratim Ghosh[a], Amichai Gillis[a], Klimentiy Levkov[a], Edward Vitkin[b], Alexander Golberg[a,*]

[a] Porter School of Environment and Earth Sciences, Tel Aviv University, Israel
[b] IBM Watson Health, Haifa, Israel

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ABSTRACT

The present study analyses the effects of low intensity pulsed electric fields (PEFs), coupled to mechanical press dewatering on meat drying with air convection. Process parameter optimization using Taguchi design showed that the number of pulses had most significant effect on meat dewatering. A maximum effective diffusivity of 2.31×10^{-9} m^2 s^{-1} was observed for PEF assisted drying of chicken meat at 80 °C. An overall energy saving of 933.18 ± 22 J g^{-1} was observed for drying at 60 °C when the meat was treated with a voltage of 75 V with initial distance between electrodes of 6.917 ± 0.38 mm, pulse length 7 ms, 300 pulses with a frequency of 2 Hz under 125.44 kPa continuous mechanical load. Our study suggests that PEF coupled to mechanical dewatering saves energy in conventional meat drying with air convection. Such a strategy could provide a scalable model for PEF assisted drying of various food products with higher energy efficiency and improved diffusivity.

1. Introduction

The consumption of poultry meat has increased during the last decade (*OECD-FAO* Agricultural Outlook, 2018-2027, OECD-FAO Agricultural Outlook 2018). This is mainly due to the fact that it is a cheap source of protein for the general population as well as lower production costs as compared to other sources of meat along with various religious restrictions. It also has a very low-fat content with high nutritional content thereby categorizing as lean meats (Chouliara, Karatapanis, Savvaidis, & Kontominas, 2007).

Poultry meat is a highly perishable product. Longer periods of storage lead to various changes in the physicochemical properties (da Silva, de Arruda, & Gonçalves, 2017) as well as the alteration in the color and flavor of the meat (Del Olmo, Calzada, & Nuñez, 2012). This also leads to higher growth of microorganisms and enzymes which induce spoilage (Vaclavik, Christian, & Christian, 2008; Zhou, Xu, & Liu, 2010). The most efficient method of preservation for poultry meat is refrigeration which delays the spoilage. Alternative technologies such as High Hydrostatic Pressure (HHP) (Ros-Polski, Koutchma, Xue, Defelice, & Balamurugan, 2015), ionizing radiation (Zhou et al., 2010), supercritical fluids (Morbiato et al., 2019), and preservatives (Mulla et al., 2017) lead to higher maintenance costs as well as side effects on the meat tissues. Therefore, alternative methods to refrigeration of meat need to be developed.

Drying of meats has been regarded as one of the most efficient methods for preservation of meat at room temperature. The mechanism of action includes the reduction of water activity which in turn reduces the growth of microorganisms and activity of spoiling enzymes (Slade, Levine, & Reid, 2009). But traditional drying techniques for food preservation suffers from various demerits. They do not reduce the microbial load completely, which reappears on rehydration (Bourdoux, Li, Rajkovic, Devlieghere, & Uyttendaele, 2016). This sometimes leads to foodborne diseases and poisoning with consumption of dried food (Farakos & Frank, 2014). Also, industrial drying using heat requires huge amounts of energy thereby providing an economic and environmental disadvantage to the process (Ahn, Lee, & Mendonca, 2017). Combinations of various innovative methods have been suggested along with traditional drying methods in order to reduce the drying time of meat samples. Methods such as microwave, irradiation, and ultrasound technologies have been utilized to reduce the drying time and temperature (Baeghbali, Niakousari, & Ngadi, 2019). But high energy consumptions render these processes inefficient for scale-up. An efficient alternative to these innovative techniques could be the use of Pulsed Electric Fields (PEFs) (Golberg et al., 2016) for effective drying of meat samples.

During the application of PEF, specific electric fields increase the membrane permeability to usually nonpermeable molecules, a phenomenon known as electroporation (Golberg et al., 2016). Currently,

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[*] Corresponding author at: Porter School of the Environment and Earth Sciences, Faculty of Exact Sciences Tel Aviv University, Israel.
E-mail address: agolberg@tauex.tau.ac.il (A. Golberg).

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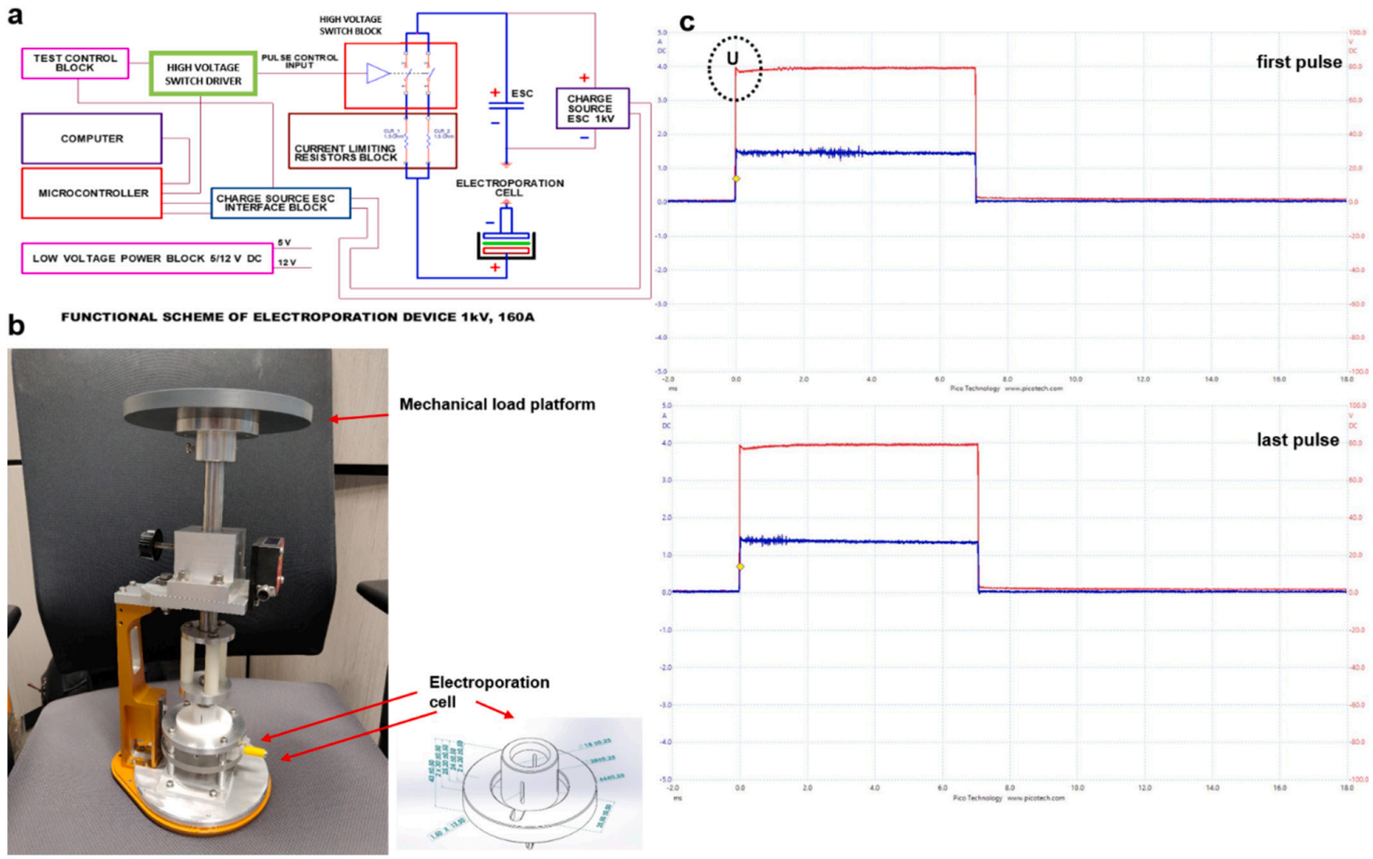

Fig. 1. a) Functional circuit diagram of the pulse generator; b) Device for PEF and mechanical press dewatering of chicken meat with the electroporation cell diagram as insert; and c) Initial and final pulses showing the electroporation residual cell voltage (U).

electroporation describes the formation of aqueous pores in the lipid bilayer that enable molecular transport (T. Kotnik, Kramar, Pucihar, Miklavčič, & Tarek, 2012; Spugnini et al., 2007; Weaver & Chizmadzhev, 1996). Thermodynamic considerations led to a current electroporation model, which describes the formation of aqueous pores as started by penetration of water molecules into the lipid bilayer of the membrane. Such a penetration leads to the reorientation of the adjacent lipids with their polar headgroups towards the polar water molecules (Weaver & Chizmadzhev, 1996). Unstable pores with nanosecond lifetimes can form even in the absence of an external electric field, but the presence of an external field induces an additional voltage across the lipid bilayer, reducing the energy required for penetration of water into the bilayer (Weaver & Chizmadzhev, 1996). This activation energy decrease increases both the probability of pore formation and the pores' average lifetime, resulting in a larger number of pores formed in the bilayer per unit of area and per unit of time, with the pores more stable than in the absence of the electric field.

Electroporation-based technologies are used in multiple medical, food and biotechnology applications (Golberg et al., 2016; Kotnik et al., 2015; Yarmush et al., 2014). Although the impacts of PEF on the mass transport have been investigated for biomedical application, such as electrochemotherapy and gene electro transfer (Golberg & Rubinsky, 2013; Granot & Rubinsky, 2008), and in the food industry for multiple plant tissues (Knorr, 2018; Puértolas, Luengo, Álvarez, & Raso, 2012; Vorobiev & Lebovka, 2011), and agricultural plant waste (Poojary et al., 2017), and meat treatment (Alahakoon, Faridnia, Bremer, Silcock, & Oey, 2017; Arroyo et al., 2015; Z. F. Bhat, Morton, Mason, & Bekhit, 2019; Cummins & Lyng, 2016; Ghosh, Gillis, Sheviryov, Levkov, & Golberg, 2019; Töpfl, 2006).

Previously published works showed the impact of PEF on meat structure and properties and on the enhancing of mass, transport to accelerate drying, accelerate the uptake of molecules substances in marinating/curing processes, enhance the water-binding characteristics through the diffusion of water binding molecule (Zuhaib F. Bhat, Morton, Mason, & Bekhit, 2018). However, the reports on applications of PEF on drying chicken meat, although proposed by some authors as the future application of PEF, are scarce (Smetana et al., 2019). In addition, to be best of our knowledge there are no reports that describe the combined effects of PEF assisted drying in order to reduce the energy consumed.

The goal of the present study was to analyze the effect of low intensity PEF pretreatment on the drying efficiency of poultry meat and meat products. The chicken breast was chosen due to its higher consumption and availability with high moisture content. A customized, insulated-gate bipolar transistor (IGBT) based PEF device was utilized for the study. PEF in combination with the mechanical press was applied to the meat sample for dewatering. The conditions for PEF (Electric field strength, Frequency, No. of pulses and Pulse duration) were optimized using the Taguchi method for efficient extraction of moisture from the chicken meat. The modified by PEF water diffusivity was studied at different temperatures. Finally, the energy efficiency of the drying with air convection after PEF treatment was determined. PEF pre-treatment coupled with the mechanical press for dewatering could provide a sustainable and energy-efficient alternative for the production of various dried meat products.

2. Materials and methods

2.1. Meat biomass

The chicken breast meat was purchased in a local supermarket in Tel Aviv, Israel in August 2018, cut into small pieces with a size of

Table 1

Taguchi L9 orthogonal array for experiment design, distances between the two electrodes and energy invested in each experimental condition.

Exp. No.	Pulselength (ms)	No. of Pulses	Voltage (V)	d_1* (mm)	d_2* (mm)	Frequency (Hz)	Energy consumed (J g^{-1})
1	2	75	25	7.08	6.82	1	104.77 ± 0.86
2	2	150	50	6.53	6.29	2	209.65 ± 0.54
3	2	300	75	6.91	6.67	3	416.18 ± 0.28
4	5	75	50	7.02	6.87	3	105.02 ± 0.26
5	5	150	75	6.42	6.17	1	209.23 ± 0.14
6	5	300	25	6.67	6.42	2	414.58 ± 0.47
7	7	75	75	6.23	5.87	2	104.17 ± 0.34
8	7	150	25	6.20	5.82	3	208.97 ± 0.95
9	7	300	50	6.79	6.44	1	415.67 ± 0.21

* d_1 (mm) is the initial distance between the two electrodes inside the electroporation chamber. d_2 (mm) is the final distance between the two electrodes inside the electroporation chamber.

about 25 mm and a weight of 2.0 ± 0.005 g. The meat was stored in the refrigerator at 4 °C and brought to room temperature before use. The breast meat used was from a single chicken and the experiments were performed in triplicates for each statistical design parameter.

2.2. Pulsed electric field setup for treatment of meat

A custom made pulsed electric field generator was developed and utilized for chicken biomass PEF treatment (Levkov, Vitkin, González, & Golberg, 2019; Rubin, Levkov, Usta, Yarmush, & Golberg, 2019). The generator provides at a maximum voltage of 1000 V and current of 120 A at the 5 Ohm load. The maximum pulse duration, the number of pulses and pulse frequencies are limited by the permissible heating of the used IGBT transistors. In our system, described below, for 5 Ohm load and 1 Hz pulse repetition rate the maximum pulse duration, limited by the heat dissipation, is 100 μs. The functional circuit diagram of the developed pulsed generator is shown in Fig. 1a. The main functional nodes of the system include: 1) energy storage capacitor (ESC) with a capacity of 50 μF for voltage 1.25 kV; 2) high-voltage source of charge of energy storage capacitors (CCM1KW (Spellman, NY)); 3) parallel-connected high-voltage switches for pulsed discharge of ESCs (IXYN120N120C3 (IXYS, CA) with parameters of 1200 V, 120 A; 3) driver of high-voltage switch with electrical circuits of control of transistors gates and own power supply (Gate Driver Optocoupler FOD3184 (Fairchild, CA)); 4) high-power current-limiting resistors (RR02–3 OHM-2 W); 5) circuit node for manual control of high-voltage switch and high-voltage power supply in testing mode; 6) microcontroller for controlling the process of PEF treatment, calculating the current at the treated biomass, and transferring the results of calculations to the computer for writing to the experiment file; 7) low-voltage power supply for control circuits and fans of the device. The device is connected by a USB interface to a computer for input the experiment parameters in the microcontroller, displaying the current state of the process and record the received data in the experiment file. Currents were measured using a PicoScope 4224 Oscilloscope with a Pico Current Clamp (60A AC/DC), (Pico Technologies Inc., UK). The voltage was measured with PicoScope TA044 70 MHz 7000 V differential oscilloscope probe 100:1/1000:1. Currents and voltages were analyzed with Pico Scope 6 software (Pico Technologies Inc., UK).

The press-electrode device (diameter 2.5 cm), for the separation of solid and liquid phases, is shown in Fig. 1b. A load weighing up to 10 kg can be placed on the load-receiving platform connected to the sliding electrode to create the necessary inter-electrode pressure on the biomass (Fig. 1b). A displacement sensor (optoNCDT, Micro-Epsilon, NC), is used to monitor volume change of the biomass during electroporation. For continuous liquid extraction, narrow slit-like openings were made in the lateral part of the electroporation cell. The extracted liquid is collected and discharge through a groove at the base of the cell. The pulse shapes (initial and final) along with the residual cell voltage are shown in Fig. 1c.

2.3. Taguchi orthogonal array to determine the impact of different pulsed electric fields parameters on the drying efficiency

The goal in these series of experiments was to determine the effects of pulsed electric field parameters such as duration of the pulses (t), number of pulses (N_t), Voltage applied (V_{app}) and frequency of pulsed (f) coupled with mechanical press on the dewatering of the chicken breast muscle. The range of parameters and their combinations is large; therefore, to decrease the number of experiments but still be able to evaluate the impact of each parameter independently, we applied the Taguchi robust design method for the experimental design (Kacker, Lagergren, & Filliben, 1991; Taguchi, 1988). The key feature of the Taguchi method is the design of the experiment where process factors are tested with orthogonal arrays (Ghosh et al., 2019).

Our previous study on extraction of value added proteins from chicken biomass suggested that a combination of high voltage long pulses followed by low voltage short pulses could extract more protein from the biomass (Ghosh et al., 2019). Another recent study on chicken biomass drying studied the effect of various PEF parameters on increasing the effective diffusivity of the biomass sample (Levkov et al., 2019). We leveraged these previous results to study the combined effect of various PEF parameters, especially with low voltages, on dewatering of chicken biomass. We tested the impact of the following range PEF settings using L9 Taguchi matrix: t of 2, 5, 7 ms; N_t of 75, 150, 300; V_{app} of 25, 50, 75 V; and f of 1, 2, 3 Hz. The initial gap between the electrodes was 6.917 ± 0.38 mm. Table 1 summarizes the experiments conducted for the L9 orthogonal Taguchi array which is needed to determine the individual effects of each of the tested parameters on the drying efficiency. At least 3 repeats were performed for each experimental condition. Analysis for maximizing the best target function, following (Golberg et al., 2016), was done using Minitab 18 (Minitab Inc., USA).

In Taguchi design of experiment algorithm, the best parameter setting is determined using signal-to-noise ratio (SN). In our experiments, we used the algorithm of "the larger the better" type. The ratio SN is determined independently for each of the process outcomes (OUT_max) to be optimized (Jiang et al., 2016). In this study, the single process outcome is the water weight released during application of the mechanical load after PEF. Maximizing SN corresponds to obtaining the maximum amount of water extracted. The ratio SN was calculated by:

$$SN^{OUT-max}(j) = -10 * \log\left[\frac{1}{\#R}\sum_{R=1}^{\#R}\frac{1}{(m_{rep})^2}\right] 1 \le j \le K \tag{1}$$

where K is the number of experiments (in our case K = 9; #R is the number of experiment repetitions (in our case $\#R = 3$) and m_{Rep} is the measurement of the process outcome (OUT) in the specific repetition R of experiment j.

Consider a process parameter P (t, N_t, V_{app}, f) and assume that P has a value of V (among n(P, V) experiments). Let J (P, V) be the set of experiments in which process parameter P was applied at level L. Let:

$$SN^{OUT}(P, V) = \frac{1}{n(P, V)} \sum_{j\in J(P,V)} SN^{OUT} \tag{2}$$

be the average ratio SN for concrete level V of parameter P. The sensitivity (Δ) of each outcome (OUT) with respect to the change in a parameter P is calculated as:

$$\Delta^{OUT}(P) = Max\{SN^{OUT}(P, V)\} - Min\{SN^{OUT}(P, V)\} \tag{3}$$

Ranking (on the scale of 1–4, where 1 is the highest) was assigned to the process parameters according to the ranges obtained.

2.4. *Drying by air convection efficiency at different temperatures*

The efficiency of PEF pretreatment for conventional drying by air convection was studied at different temperatures. The best conditions for PEF were determined using the Taguchi method of optimization. Using those conditions, the modified water diffusivity coefficients were determined during air convection drying at different temperatures (50 °C, 60 °C, 70 °C, and 80 °C) in an oven (Ex-Lab Scientific, Israel) until constant weight was obtained. The airflow in the oven was maintained uniformly by natural convection. The drying samples were kept at the centre of the oven for uniform temperature distribution on the sample. The temperature accuracy was ± 0.1 °C with a fluctuation of ± 1 °C. The reduction in moisture content was observed for 10 min using a moisture analyser ((BM50–5, Biobase Biodustry (Shandong) Co. Ltd., China). The moisture ratio (MR) was defined as follows (Touil, Chemkhi, & Zagrouba, 2014):

$$MR = \frac{(X - X_e)}{(X_0 - X_e)} \tag{4}$$

where X_e is the equilibrium moisture content, X_0 is the initial moisture content and X is the moisture content at time t.

Assuming that the tissue is isotropic with respect to water transport, water diffusivity in biomass (chicken, seaweed, etc.) can be described with the Fick's second law of diffusion (Levkov et al., 2019; Polikovsky et al., 2016) (Eq. 5):

$$\frac{dMR}{dt} = \nabla D_{eff} \nabla \mathrm{MR} \tag{5}$$

where D_{eff} ($m^2\ s^{-1}$) is the effective diffusivity of water in the sample, t (s) is drying time, and MR is the dimensionless moister content calculated as in Eq. 4.

Under the assumption of the equal distribution, negligible external resistance, constant diffusivity, and negligible shrinkage through the drying process, the solution of Eq. 5 for the chicken slab is given by Eq. 6 (Crank, 1975):

$$MR(D_{eff}, t, l) = \frac{8}{\pi^2} \sum\nolimits_{i=0}^{\infty} \frac{1}{(2i+1)^2} \exp\left(-\frac{(2i+1)^2\pi^2 D_{eff}\, t}{4l^2}\right) \tag{6}$$

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

2.5. *Determination of energy consumed during drying*

The total energy consumed for the PEF treatment was calculated based on the energy stored in the pulse capacitor with the following Eq. 7:

$$E_t = V \times I \times dt/m \tag{7}$$

where E_t (J) is the total energy consumed for the treatment, V is the discharging electroporation cell voltage, I is the current, and m is the mass of the chicken sample (Fig. 1c) and N is the total number of pulses. Additional losses of the capacitor charger have not been considered. All combinations of charging voltage and number of pulses were applied on at least two replicates. The energy saved is the difference between total energy saved on evaporation and the total energy consumed for PEF pretreatment.

The total energy saved on evaporation (Q) can be determined as

$$Q = C_P M \Delta T + L_{vaporization} M \tag{8}$$

Where, C_p is the specific heat of water (4.2×10^3 J kg^{-1} °C^{-1}), M is the mass of water evaporated, ΔT is the change in temperature (°C) and $L_{vaporization}$ is the latent heat of vaporization of water (2.3×10^6 J kg^{-1}).

2.6. *Statistical analysis*

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. 9); (ii) the Mean Absolute Error (MAE, Eq. 10); and (iii) the Mean Relative Error (MRE, Eq. 11) between the measured and the predicted dimensionless moisture content, *w,* across the experimental replicate timepoints,

$$MSE = \frac{1}{T} \sum_{t=0}^{T} (MR_t^{measured} - MR_t^{predicted}(D_{eff}, l, t))^2 \tag{9}$$

$$MAE = \frac{1}{T} \sum_{t=0}^{T} |MR_t^{measured} - MR_t^{predicted}(D_{eff}, l, t)| \tag{10}$$

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

where t is the measurement time point id; $T = 26$ is the total number of measurements and time, t is the measurement time in minutes The $MR_t^{measured}$ refers to the measured, normalized dimensionless moisture content, which is always equal to 1.00 at the $t[0] = 0$ min and equal to 0.00 at the $t[T] = 120$ min. The $MR_t^{predicted}(D_{eff}, h, t)$ refers to the predicted dimensionless moisture content calculated with Eq. 5 using the predicted value of D_{eff}, measurement t and l, which is the half-thickness of the infinite slab in meters.

3. Results and discussion

3.1. *Optimization of PEF pretreatment parameters using Taguchi*

The effect of PEF parameters was studied on the dewatering efficiency of chicken meat. According to Taguchi ranking, the parameter of no. of pulses (N_t) has the most prominent impact on moisture removal (Taguchi Rank 1, Table 2). The increase in the number of pulses might increase pore distribution in the biomass which in turn leads to more moisture loss (Liu, Esveld, Vincken, & Bruins, 2019). In addition to this, longer pulse durations may assist in tissue lysis by generation of some chemical species via electrolysis (Arevalo, Ngadi, Bazhal, & Raghavan, 2004; de Vito, Ferrari, Lebovka, Shynkaryk, & Vorobiev, 2008; Ersus, Oztop, McCarthy, & Barrett, 2010; Ghosh et al., 2019). Further investigation is required in order to quantify electrolytic events and its impact on drying of biomass. The voltage applied (V_{app}) is ranked second (Taguchi Rank 2) in significance on moisture removal followed by the frequency (f, Taguchi Rank 3). The pulse length (t_p) has the smallest effect on moisture release from the meat (Taguchi Rank 4).

The sensitivity of moisture removal during PEF to the tested process

Table 2
Response Table for Signal to Noise Ratios and ranking of PEF parameters using the Taguchi approach.

Level	Pulselength (ms)	No. of Pulses	Voltage (V)	Frequency (Hz)
1	5.27	4.812	3.316	3.839
2	5.38	4.121	6.69	7.537
3	6.461	8.178	7.105	5.735
Δ	1.192	4.057	3.789	3.698
Rank	4	1	2	3

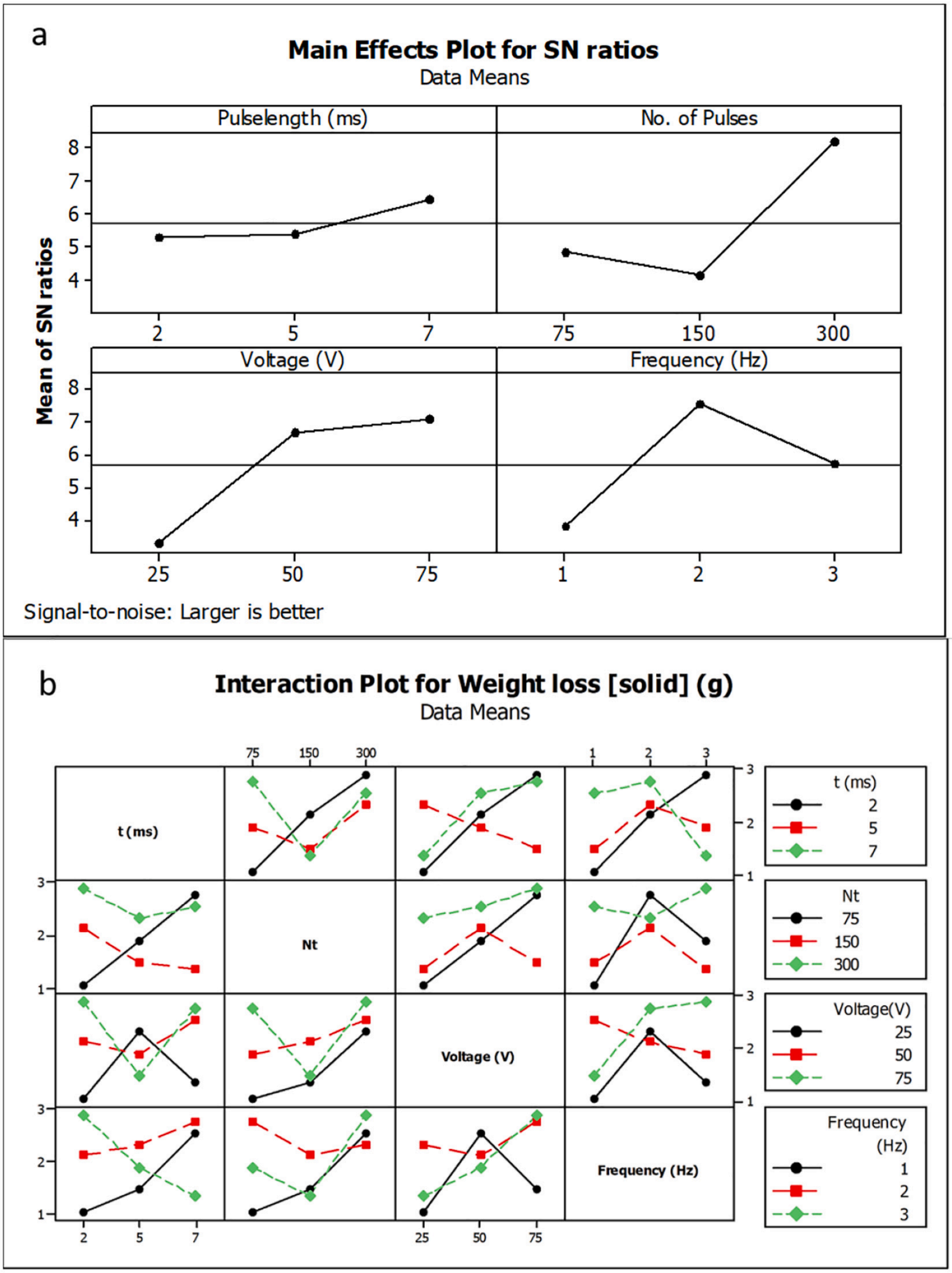

Fig. 2. a. Taguchi analysis of the impact of 4 PEF parameters on the moisture removal from the chicken breast biomass. The effects of pulsed electric field parameters such as duration of the pulse (t), number of pulses (N_t), Voltage (V) and frequency (f) and were tested. b. Interaction plots for the effect of different factors on the moisture removal from chicken meat using Pulsed Electric fields.

parameters that can be controlled was analyzed (Fig. 2). The number of pulses significantly influenced the drying process (Fig. 2a). The signal to noise ratio (S/N) of different factors indicated that number of pulses, as well as voltage, played a key role in moisture removal. Therefore, controlling the number of pulses may lead to an increase in moisture removal from the chicken muscle biomass. This was in contrary to our previous study of protein extraction from chicken biomass where the pulse duration played a major role (Ghosh et al., 2019). The interaction plots that show the impact of various tested parameters on the moisture removal appears in Fig. 2b. Interaction between two factors is signified by angles between two lines whether they intersect or not. If the interaction plots run parallel to each other, it signifies that there is no interaction between the two factors (Ball, Das, Roy, Kisku, & Murmu, 2019). This can be observed by studying the interaction plots between pulse length and number of pulses. At pulse length 5 and 7 s, no interaction was observed between pulse length and number of pulses but the factors interacted at pulse lengths 2 s. The other factors showed relations between them as observed by the interaction plots. At lower voltage values (25 and 50 V), an interaction between voltage and pulse length could be observed. But at higher voltage values, there was no

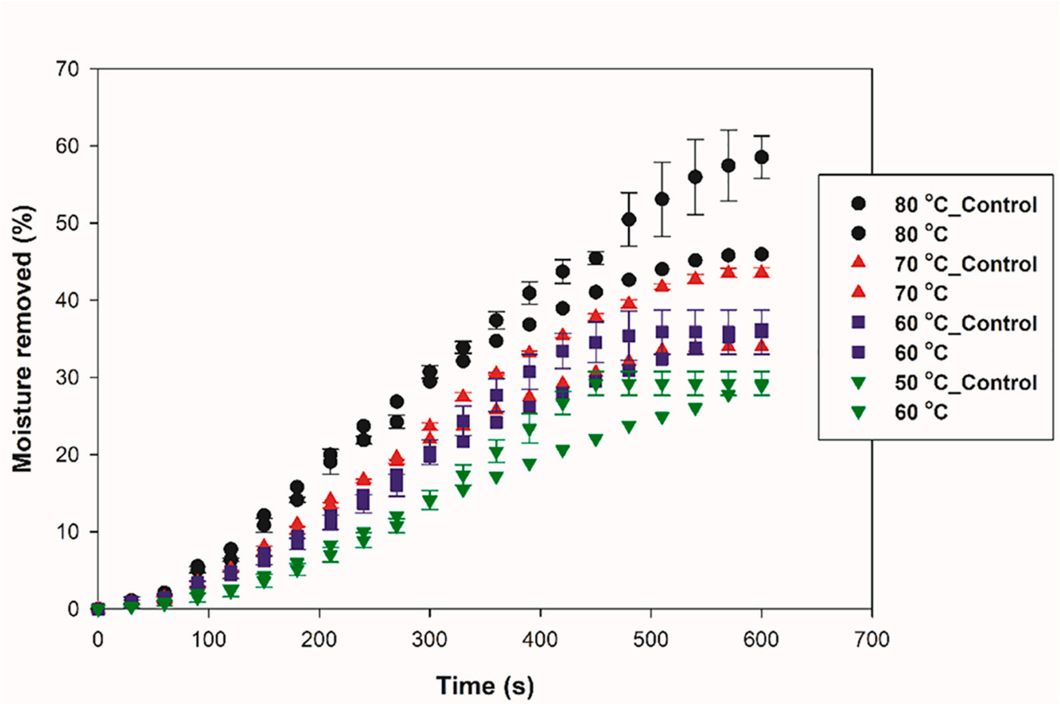

Fig. 3. Moisture removal from the chicken breast at different temperatures. 3 repetitions of control vs 3 repetitions of PEF-treated samples.

Table 3
Effective diffusivities (D_{eff}) at different drying temperatures.

Temperature [°C]	Treatment	D_{eff} (MSE) [$m^2\ s^{-1}$]	Error (w^2)	D_{eff} (MAE) [$m^2\ s^{-1}$]	Error (w^2)	D_{eff} (MRE) [$m^2\ s^{-1}$]	Error (w^2)
50	Control	8.74×10^{-10}	0.005	8.47×10^{-10}	0.064	1.30×10^{-9}	0.314
	PEF treated	1.10×10^{-9}	0.015	1.39×10^{-9}	0.011	1.59×10^{-9}	0.242
60	Control	3.50×10^{-10}	0.007	2.87×10^{-10}	0.049	3.40×10^{-10}	0.215
	PEF treated	1.13×10^{-9}	0.011	1.10×10^{-9}	0.009	1.88×10^{-9}	0.348
70	Control	1.18×10^{-9}	0.004	1.44×10^{-9}	0.051	1.94×10^{-9}	0.352
	PEF treated	1.30×10^{-9}	0.007	1.31×10^{-9}	0.008	1.75×10^{-9}	0.436
80	Control	1.18×10^{-9}	0.001	1.18×10^{-9}	0.031	1.37×10^{-9}	0.193
	PEF treated	1.43×10^{-9}	0.008	1.50×10^{-9}	0.007	2.31×10^{-9}	0.282

interaction observed. This could be due to the fact that higher voltage had no effect on the output of the process when the pulse length was increased. Similar interactions could be observed between pulse length and number of pulses at lower pulse lengths. Further studies are required in order to determine the exact nature of interaction between two as well as multiple factors involved in the process. This could be done by using other experimental designs using the optimized values obtained from the present study. The optimum parameters for the maximum liquid extraction (the maximum SN ratio) were determined as 75 V, 7 ms, 300 pulses with a frequency of 2 Hz. The electric field strength was calculated and was found to be 11.4 V mm^{-1}. The electric field intensity was low as compared to other studies. Low PEF intensities often lead to reversible results. But due to the increase in ratio of pore size to membrane surface area, the membrane undergoes breakdown (Zuhaib F. Bhat et al., 2018). Similar results for treatment of plant and animal tissues at low PEF intensities have been reported for pore formation which led to disintegration of cells (Corrales, Toepfl, Butz, Knorr, & Tauscher, 2008; Toepfl, Siemer, & Heinz, 2014; Zimmermann, Pilwat, Beckers, & Riemann, 1976). Owing to their larger cell size, a lower electric field strength and energy input is required for pore formation in plant and animal cells (Zuhaib F. Bhat et al., 2018).

The effect of PEF parameters on energy saving was also studied and was calculated using Eq. 7 and represented in Table 1. The amount of energy invested was dependent on the number of pulses. Energy invested in the process increased with the rise in the number of pulses. Also, a higher combination of voltage and number of pulses led to higher energy inputs for PEF. The highest energy invested was calculated to be 416.18 ± 0.28 J g^{-1} while the lowest energy investment was 104.17 ± 0.34 J g^{-1}. The best Taguchi parameter (Experiment No. 3) for PEF assisted drying had an energy investment of 416.18 ± 0.28 J g^{-1}. This was further utilized to calculate the energy saved using PEF assisted drying at different temperatures (Eq. 8).

The ranges of voltage applied for the present study could be characterized as moderate intensity rather than high intensity pulsed electric fields. The observed effects could be explained by the combined effects of electroporation and ohmic heating which in turn affected the drying rate of the biomass. High intensity PEFs are utilized for minimal thermal effects but the temperature of biomass increases due to ohmic heating thereby reducing the quality (Timmermans et al., 2019). This problem could be overcome by utilizing the strategy of moderate intensity PEFs for drying of meat thereby reducing the effect of temperature on the biomass.

3.2. *Using the best parameters to study drying at various temperatures*

The levels of parameters which were obtained after Taguchi optimization were further utilized to study the effect of temperature on the air convection drying process. The PEF treated biomass had reduced moisture content. The air drying was studied under various drying temperatures (50 °C, 60 °C, 70 °C and 80 °C). Higher temperatures were

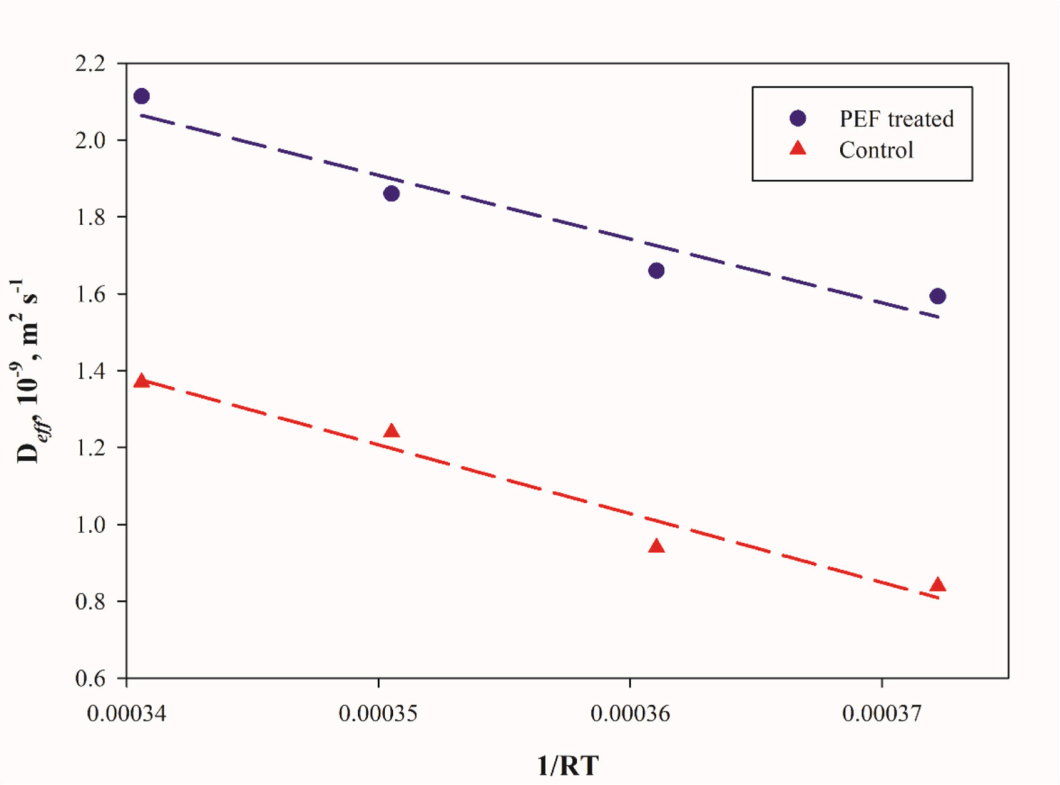

Fig. 4. Arrhenius plots of the effective diffusion coefficient D_{eff} versus 1/RT for intact and PEF pre-treated chicken meat.

Table 4
Energy saving on combined methods of drying at different temperatures.

Temperature (°C)	Energy saved during Evaporation (J g^{-1})	Energy used during PEF (J g^{-1})	Total energy saved (J g^{-1})
50	1294.95 ± 34	416.18 ± 0.28	878.77 ± 27
60	1349.37 ± 27	416.18 ± 0.28	933.18 ± 22
70	1256.06 ± 24	416.18 ± 0.28	839.88 ± 20
80	1257.32 ± 18	416.18 ± 0.28	841.14 ± 15

not chosen so that there was no damage to the nutritional quality of the dried biomass. The major factor which determines the drying efficiency of any process is the diffusion coefficient. Thus, the diffusion coefficient at different temperatures was calculated in order to study the efficiency of the process.

The effect of PEF on drying was observed with varying temperatures. The drying curves at different temperatures are given in Fig. 3. The time of drying was reduced at higher temperatures. The increase in porosity was caused by the effect of PEF coupled with mechanical pressing. This in turn helped in better moisture removal at higher temperatures. This observation was also supported by calculating the effective diffusivities at different temperatures which are discussed below.

The effective diffusivities (D_{eff}) were also determined at various temperatures. The effective diffusivities ($m^2 s^{-1}$) were found to be in the range of 1.1–2.31 × 10^{-9} with a maximum of 2.31 × 10^{-9} at 80 °C. The higher temperatures were probably responsible for higher water activity of the meat sample which in turn led to higher effective diffusivity values (Shi et al., 2008). But higher temperatures could also lead to higher energy inputs for drying. So, in order to determine the suitable parameters for PEF assisted drying, the consideration of energy-saving is important which has been discussed in the next section. The obtained values were within standard range of effective diffusivity values for various food products (10^{-9}–10^{-11}) (Zogzas & Maroulis, 2007). Previous studies on solar drying of beef have reported effective diffusivities of 1.775 × 10^{-10} m^2 s^{-1} (Mewa, Okoth, Kunyanga, & Rugiri, 2019). Our results could also be compared for solar drying of organic tomato (1.31 × 10^{-9} m^2 s^{-1}) (Sacilik, Keskin, & Elicin, 2006) and pumpkin (1.07 × 10^{-9} m^2 s^{-1}) (Sacilik, 2007). The values of D_{eff} calculated using the various models (Eq.9–11) have been shown in Table 3.

Fig. 4 shows the D_{eff} values for untreated and PEF treated meat at different drying temperatures. The values of D_{eff} were fitted according to the Arrhenius equation:

$$D_{eff} = D_{\infty} \exp\left(-\frac{\Delta U}{RT}\right) \tag{12}$$

where D_{eff} is the calculated effective diffusivity, D_{∞} is the limiting diffusion coefficient at an infinitely high temperature, ΔU is the activation energy, R is the universal gas constant and T is the temperature in Kelvins. The activation energies estimated from this equation are: $\Delta U = 16 \pm 2$ kJ mol^{-1}, $\Delta U = 14 \pm 0.5$ kJ mol^{-1} and the limiting diffusion coefficients are $D_{\infty} = (11 \pm 5) \times 10^{-6}$ m^2 s^{-1}, $D_{\infty} = (13 \pm 2) \times 10^{-6}$ m^2 s^{-1} for intact and PEF treated meat biomass respectively. Our values were similar to reported values of Lebovka, Shynkaryk, & Vorobiev, 2007 where they studied pulsed-field enhanced drying of potato tissue (Lebovka et al., 2007).

3.3. How PEF can save energy for chicken biomass drying

Energy consumption is an important factor in determining the process efficiency. The conventional drying processes at higher temperatures utilize a higher amount of energy thereby rendering the process inefficient. Thus, innovative methods for drying need to be developed in order to be energy efficient.

The energy required for PEF of 1 g of chicken meat with our optimized parameters was calculated to be 416.18 ± 0.28 J g^{-1}. The PEF pre-treatment provided with moisture removal of 40 ± 2% at optimized conditions without a need for evaporation. The energy saved on evaporation of water was calculated and was found to be different for varying temperatures. The best results were obtained at 60 °C with a maximum energy saving of 933.18 ± 22 J g^{-1} followed by 50 °C with a saving of 878.77 ± 27 J g^{-1}. The energy savings as different temperatures are shown in Table 4. The energy savings were almost similar at higher temperature ranges suggesting that higher temperatures do not influence the drying efficiency when combined with PEF. This also supported our assumption that PEF decreases the total energy involved for the drying process. It is also possible that PEF affects dewatering thereby accelerating the drying process.

Dewatering is always better than evaporation as there is no phase transition. PEF as a pretreatment to dehydration can improve water removal without substantial influence on solid gain (Amami, Vorobiev, & Kechaou, 2006; Wiktor, Schulz, Voigt, Witrowa-Rajchert, & Knorr, 2015). Therefore, PEF treatment can be applied when it comes to reducing the water content without increasing the sugar concentration in the material (which are the main osmotic agents) – for example, in the production of dietary products. This could provide a basis for further development of energy-efficient drying processes. Recent applications of PEF pretreatment have been on drying and freezing of food products. Most of the studies have focused on drying of fruits and vegetables (Barba et al., 2015; Wiktor et al., 2015) but have not explored the possibilities of drying chicken meat. Our studies could provide an insight into the efficacy of PEF on production of dried chicken meat products.

4. Conclusions

Preservation of perishable food products such as poultry meat by drying is an energy-intensive process. The aim of the present study was to combine modern techniques of food preservation with conventional techniques in order to reduce the energy consumption of the process. Pulsed Electric Field (PEF) technology was used in combination with temperature-based drying for chicken meat. The various parameters of the PEF process were optimized using Taguchi method. The number of pulses had a significant effect on the PEF process. The PEF treated meat was then dried at different temperatures. The maximum effective diffusivity was found to be $2.31 \times 10^{-9}\ m^2\ s^{-1}$. Energy consumption for various processes involved was also calculated. The best results were obtained at 60 °C with a maximum energy saving of 933.18 ± 22 J g^{-1}. Our studies suggested that pulsed electric field could be used in combination with conventional drying processes thereby extending the shelf life of the sample. These low energy-consuming processes are scalable and thus could be further used for various other food products in order to increase their shelf life.

Declaration of Competing Interest

The authors declare no conflict of interest.

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