



A Numerical Approach to Analyze the Performance of a PEF-Ohmic Heating System in Microbial Inactivation of Solid Food

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Pulsed Electric Fields (PEF) technology has been recently proposed as a new ohmic-heating system for the heat treatment of solid products in short periods (less than 1 min). However, similar to traditional ohmic heating, non-homogeneous distribution of temperature has been observed and cold points appeared in the interphase between the solid treated product and the electrodes, which can limit the technology for assuring food safety for treated solid products. In this investigation, a computational axisymmetric model of a lab-scale PEF system for a solid product (agar cylinder) was developed. This model was used to predict the temperature and the electric field distribution, treatment time, and the microbial inactivation (*Salmonella* Typhimurium 878) in the solid product after a PEF-ohmic treatment. Using a factorial analysis, a total of 8 process conditions with different settings of applied field strength levels (2.5–3.75 kV/cm), frequencies (100–200 Hz), and initial agar and electrode temperature (40–50°C) were simulated for the agar cylinder in order to identify the effect and optimal values of these parameters, which offer the most temperature homogeneity. The results showed that the initial temperature of the agar and the electrodes was of great importance in achieving the best temperature uniformity, limiting the occurrence of cold points, and therefore, improving the homogeneity in the level of inactivation of *Salmonella* Typhimurium 878 all over the agar cylinder. A treatment of 2.3 s would be enough at 3.75 kV/cm, 200 Hz with an initial temperature of 50°C of the agar and the electrodes, for a 5-Log₁₀ reduction of *Salmonella* Typhimurium 878 in the whole product with a deviation of 9°C between the coldest and hottest point of the solid.

Keywords: microbial inactivation, ohmic heating, *Salmonella*, numerical simulation, pulsed electric fields

INTRODUCTION

Numerical simulation is a useful and complementary method for solving physical processes described by differential equations. It is a helpful tool for evaluating scenarios that sometimes are difficult or impossible to carry out experimentally (Wölken et al., 2017), such as the evaluation of microbial inactivation by thermal treatment in a solid food product, as in the pasteurization process. In this case, all parts of the product have to be treated with at least the minimum process criteria (a

combination of time and temperature) to assure that a certain level of inactivation of the pathogenic target microorganisms is achieved (i.e. 5-Log₁₀ reductions for pasteurization of liquid food products), minimizing the impact on quality (Smelt & Brul, 2014). When using traditional heating systems, heat is transferred slowly from outside to inside the solid product using convection and/or conduction processes. During this process, heat can affect the nutritional and sensorial quality of the solid food product, where its surface could be over-treated.

Due to the possible loss of food quality, interest in novel thermal processing technologies (ohmic heating, dielectric heating, microwave and radio frequency, and inductive heating) as alternatives for the application of traditional thermal treatments in food has increased. These technologies have the advantage that the heat is generated from the inside to the outside of the food, reducing the overheating of the surface of the product (Sastry et al., 2014; Alkanan et al., 2021). However, in these techniques, heating uniformity is dependent on the composition of the product, and the same heating rates are not always observed in all parts of the product, occurring randomly in some cases (Ravishankar et al., 2002; Yildiz-Turp et al., 2013; Astráin-Redín et al., 2022). In addition, experimentally monitoring the temperature evolution in a non-known cold point of the product can be a challenge. In these situations, numerical simulations can be very helpful for predicting the temperature evolution of the whole product. These computational models could allow us to determine the coldest point and evaluate the influence of different parameters to limit overheating treatment (Jun and Sastry, 2005; Jun and Sastry, 2007; Salengke and Sastry, 2007; Marra et al., 2009). Moreover, the inactivation level could also be predicted in the whole volume of the product. Additionally, this technique results in an advantage, since sometimes the experimental measuring equipment itself disturbs the process under consideration when using electric heating systems such as ohmic heating (Shim et al., 2010; Wölken et al., 2017).

Ohmic heating consists of the application of electric potentials up to 0.1 kV/cm in food, which works as an electrical resistance by heating itself internally (De Alwis and Fryer, 1990). The generation of heat in this type of system is based on the Joule Effect described by the following equation:

$$W = \int_0^{\omega} \sigma E^2 dt \quad (1)$$

where σ is the electrical conductivity of the treated medium or product (S/m), E is the electric field strength (V/m); and dt is the time (s) during which the field strength is applied (Sastry and Li, 1996).

Based on this equation, the electric field strength is an important parameter since slight modifications square the transferred energy to the treated product (Eq. 1). On the other hand, the application of an electric field (0.1–0.5 kV/cm) can cause the permeation of eukaryotic cell membranes (Fincan and Dejmek, 2002; Lebovka et al., 2002; Toepfl et al., 2006), favoring the release of intracellular material (ionic compounds), increasing the electrical conductivity of the food during the heating process. The result is a more rapid and uniform heating (Sastry, 2005). This has been described by

applying Moderate Electric Fields (MEF) at intensities up to 1 kV/cm (Wang and Sastry, 2002; Yoon et al., 2002), and more recently by Pulsed Electric Fields (PEF) as a new ohmic heating system for solid products (Ariza-García et al., 2020).

Ariza-García et al. (2020) showed that PEF applied over 1 kV/cm, which could be a new way of applying ohmic heating in solids using a technical agar cylinder. Nevertheless, even though this type of heating is considered a uniform and volumetric process, cold points were detected as has been described in traditional ohmic systems in the contact zone between the electrodes and the product (De Alwis and Fryer, 1990; Ito et al., 2014; Marra, 2014). This represents a limitation of the technology when applying heat treatments to guarantee the safety of food since the cold points do not receive the required minimum treatment to achieve a certain level of microbial inactivation compromising the food safety. On the other hand, conversely, for cold areas to be adequately treated, other parts would be extremely over-treated, affecting the quality of the food. Due to this, any evaluation or strategy that reduces this difference between zones would be of interest to improve the heating uniformity of the solid product. Therefore, in this article, a sensitivity analysis of the main PEF parameters involved in the ohmic heating process of the agar product (field strength, frequency, number of pulses, and initial temperatures) has been conducted. This analysis enabled us to obtain the optimal parameter combination that reduces the apparition of cold points in the contact zone between the product and the electrodes. Since several parameters are involved in the process, finite element simulations have been used not only to provide detailed knowledge of the temporal and spatial distribution of the product's field strength and temperature (Gerlach et al., 2008; Schroeder et al., 2009; Pataro et al., 2011; McLaren et al., 2019) but also to estimate the degree of microbial inactivation in an inhomogeneous or homogeneous PEF process, which has hardly been investigated to date.

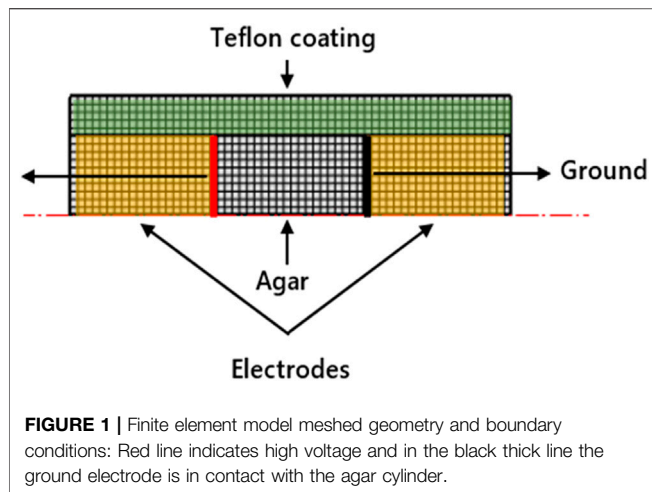
FINITE ELEMENT MODEL OF PEF ON LAB-SCALE

Ohmic Heating Model, Initial and Boundary Conditions

In ohmic heating, there is a coupled thermo-electrical problem: Laplace equations solve the intensity of the electric field applied over the domain, and Joule's equation determines the internal energy generated by the electric field (Ariza-García et al., 2020). According to Joule's equation, the heat generated Q (J) during ohmic heating is proportional to the square of the electrical current that flows through the sample, its resistance, and the time on which such current is flowing. The governing equation for heat transfer is shown in Eq. 2.

$$\rho C_p(T) \frac{\partial T}{\partial t} - \nabla \cdot (k(T) \nabla T) = Q \quad (2)$$

where $C_p(T)$ (J·kg⁻¹·K⁻¹) represents the specific heat and $k(T)$ (W·m⁻¹·K⁻¹) is the thermal conductivity.



The term Q is the conversion of electrical to thermal energy, caused by the Joule's heating (Eq. 3):

$$Q = \sigma(T) E^2 \quad (3)$$

where $\sigma(T)$ (mS/cm) represents electrical conductivity, and E is the electric field strength (kV/cm). This variable can be written as a function of the electrical potential, V (V) (Eq. 4), and based on charge conservation, the governing equation for the electrical potential can be written as shown in Eqs 4, 5.

$$E = \nabla V \quad (4)$$

$$\nabla \cdot J = \nabla J \cdot [\sigma(T)\nabla V] = 0 \quad (5)$$

where J (A) represents the current density.

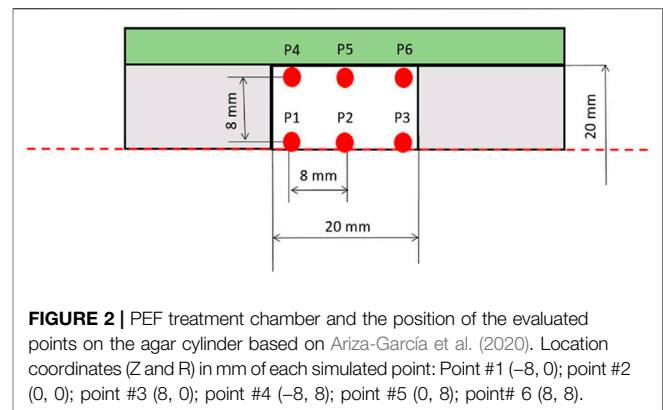
Due to the thermo-electrical character of the problem, two different types of boundary conditions were introduced in the model: electrical and thermal. In the first approach, the electric potential between electrodes was defined as a squared electric pulse of 3 μ s of duration and a load amplitude of 2.5 kV/cm. The frequency of this pulse was established at 50 Hz. One electrode was set as the high voltage electrode (red line in Figure 1) and the other as the ground electrode (black line in Figure 1).

Natural convection was set in the boundary of the Teflon to reproduce the heat transfer between the treatment chamber and the surrounding media according to Eq. 6:

$$\vec{n} \cdot (k_{teflon}\nabla T = h \cdot (T_{amb} - T) \quad (6)$$

where k_{teflon} ($W \cdot m^{-1} \cdot K^{-1}$) is the thermal conductivity for the insulator material; T_{amb} is the initial room temperature condition, set up at 20°C; and h is the heat transfer coefficient of air, set in $5 W m^{-2} \cdot K^{-1}$.

Regarding initial conditions, two scenarios have been considered for the study. Consequently, it depends on the working conditions in which each trial was carried out: cases on which an initial room temperature condition (20°C) was set on the agar and the electrodes or cases on which a previous initial temperature of the electrodes was set. The thermophysical properties mentioned in the section were implemented in the numerical model.



FE Model

For this study, a parallel electrode treatment chamber was used for the simulations based on the one described by Ariza-García et al. (2020), which was already validated in that research (Figure 2). The chamber consists of a parallel electrode chamber composed of two stainless steel cylinders of 20 mm in diameter with a space between them of 20 mm (gap) where the sample (an agar cylinder of 20 mm length) would be placed. The sample and the electrodes are introduced in a hollow cylinder made of polytetrafluoroethylene (Teflon, insulating material) with an internal diameter of 20 mm.

A computational axisymmetric model was developed to reproduce the ohmic heating in the cylindrical agar when applying PEF treatments in the commercial software COMSOL Multiphysics 5.3, assuming that the treatment chamber shown in Figure 2 presents a perfect symmetry of revolution.

Geometry meshed with quadrilateral elements using a quadratic approximation. A mesh sensitivity analysis was carried out to set the optimal mesh size. A set of case studies were run with different mesh sizes. Finally, the one for which the results converged and from which the refinement did not improve the results was chosen. The total number of degrees of freedom and elements was 6,050 and 720, respectively (120 elements for the Teflon coating, 200 for each electrode, and 200 elements for the agar).

To evaluate the accuracy of the predictions done with the model, it was compared with that described by Ariza-García et al. (2020). The results in temperature were the same in both models for the same operating conditions.

In a second step, sensitivity analysis of the main parameters governing the numerical response of the ohmic heating (electric field strength, frequency of the pulses, and initial temperature of the electrodes) was undertaken. Based on those conditions, a FEM analysis was carried out to evaluate the uniformity of the PEF heating in the agar cylinder. Based on the agar temperature distribution, a longitudinal and radial temperature difference between pairs of points were evaluated in the FE model when applying PEF. Longitudinal temperature difference evaluated the heating from the inside to the outside of the cylinder caused by the PEF treatment, and in radial examined the temperature difference due to the proximity of the cylinder surface points to the coating.

TABLE 1 | Properties of stainless steel and Teflon: Thermal conductivity k , electrical conductivity σ , specific heat c_p , and density ρ .

	Stainless Steel	Teflon
k (W/(m·K))	12	0.25
σ (S/m)	1.45×10^6	10^{-24}
c_p (J/(kg·K))	502	1450
ρ (kg/m)	7850	970

To avoid overheating in the product, which would produce a deterioration in quality, the simulations were stopped when any point on the agar reached 80°C (the central point is always the first one that reaches that temperature). The total simulation time was divided into different steps to consider the applied voltage at the given frequency.

Finally, the theoretical inactivation of *Salmonella* Typhimurium 878 in the agar cylinder was numerically simulated for cases with greater homogeneity in temperature distribution, and for cases that showed less homogeneity.

Material Properties

Three different materials were considered in the FE model based on the described treatment chamber: the sample (technical agar), the electrodes (stainless steel), and the insulating material (Teflon). Technical agar with 0.24% of NaCl was employed to enhance the transmission of electric current through them. The electrical (electrical conductivity, $\sigma(T)$, expressed in mS/cm, Eq. (7)), and thermal properties (thermal conductivity, $k(T)$ (W/mK), Eq. 8; and specific heat, $C_p(T)$ (J/kgK), Eq. 9) of this material were determined experimentally in a previous study (Ariza-García et al., 2020). Regarding the rest of the components, Table 1 shows the material properties for the electrodes, stainless steel, and for the insulating material, which separates the electrodes (Teflon).

$$\sigma(T) = 0.433 - 0.0096 \cdot T + 3.192 \cdot 10^{-5} \cdot T^2 \quad (7)$$

$$k(T) = -0.732 + 0.007 \cdot T - 9.492 \cdot 10^{-6} \cdot T^2 \quad (8)$$

$$C_p(T) = 3.991 \cdot 10^{-4} - 423.184 \cdot T + 1.880 \cdot T^2 - 0.004 \cdot T^3 + 2.762 \cdot 10^{-6} \cdot T^4 \quad (9)$$

Sensitivity Analysis

A sensitivity analysis of the three main parameters governing the numerical response of the ohmic heating was addressed. Two different values or levels were considered for each one of them to study its influence. The parameters were: the frequency of the applied pulses (100 and 200 Hz), the electric field strength of the pulses (2.5 and 3.75 kV/cm), and the initial temperature of the electrodes (40 and 50°C). The temperatures at certain points of the agar volume after PEF treatments when the central point achieves 80°C (Figure 2) were used to determine the radial and longitudinal temperature differences. The longitudinal one was obtained from the temperature difference between points #4 and #5 or between points #6 and #5. The radial one was obtained from points #1 and #4 or between points #3 and #6.

The influence of the investigated parameters was performed by means of a 2^k full factorial design (Montgomery, 2017), with k being the number of selected parameters at two different levels (Low and High). The output variables considered in the analysis were the radial temperature difference and the longitudinal temperature difference. Therefore, the full factorial analysis of the selected three parameters (frequency, f ; field strength, E ; and initial temperature of the electrodes, T) at two different levels implies 8 simulations.

After completing the simulations, the main effect and interactions of each parameter were analyzed by multiple regression. The results were fitted to a general lineal model that accounted for the influence of the individual factors and their interactions. A backward regression procedure was used, systematically removing the effects that were not significantly associated ($p > 0.05$) with the response until a model with only significant effects was obtained.

The sensitive analysis including the response fit analysis, regression coefficient estimations, and model significance evaluations were performed with Minitab 19 software (Minitab Inc.) through the numerical results obtained in Comsol Multiphysics 5.3.

Simulated Microbial Inactivation

The D_t value means the time to inactivate 90% of the microbial population, and the z value is the temperature increase to reduce the D_t value by 90%. To estimate the inactivation of *Salmonella* Typhimurium 878 in the different zones of the agar cylinder when applying PEF heat treatments, the thermal resistance values ($D_{60°C} = 0.39 \pm 0.04$ min and z value = 5.0 ± 0.1 °C) described by Ariza-García et al. (2020) obtained in isothermal conditions in McIlvaine buffer of pH 6.8 were used. The lethal effect (L , Log₁₀ cycles of inactivation of the microbial population) of the treatment on the different zones of the agar was calculated by the following equation:

$$L = \int_0^t \frac{t}{D_{T_{ref}} \cdot 10^{\frac{T_{ref}-T}{z}}} \cdot dt \quad (10)$$

where t is the PEF heating time (s), $D_{T_{ref}}$ is the D_t value at a reference temperature (T_{ref}), in this study 60°C, obtained under isothermal conditions, and T (°C) is the temperature of the agar at a determined point.

Taking advantage of the steps taken by the simulation along the total time, this equation was implemented in the FE model. Since each simulation considered 1 s, the model was programmed to calculate the integral in every time step based on the computed temperature. In this way, the lethal effect was obtained in each second of calculation and added throughout every second of the simulation time. Total simulation time stops when the central point of the agar reaches 80°C in each case.

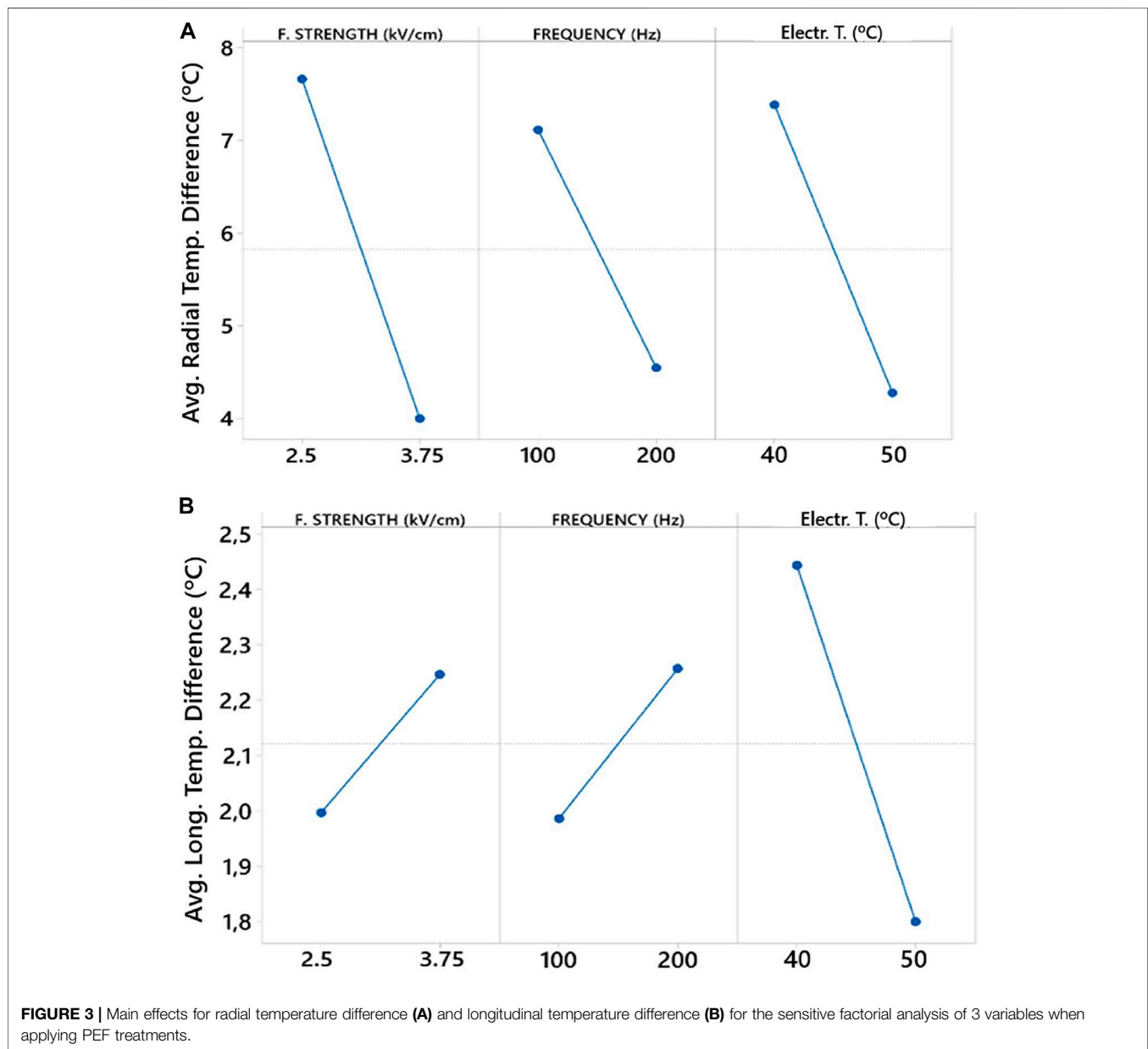
RESULTS AND DISCUSSION

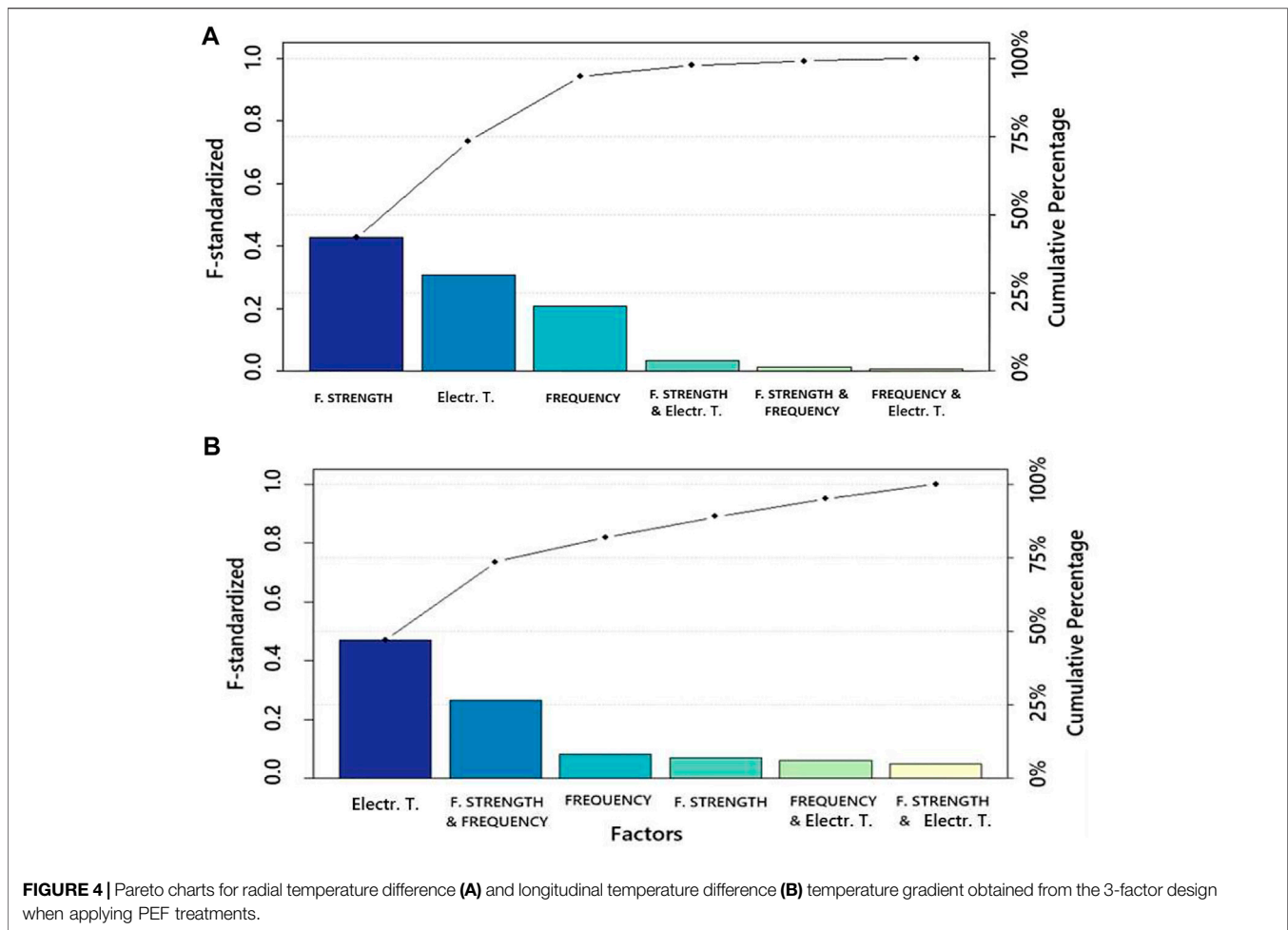
Sensitive Analysis of PEF-Ohmic Heating

Table 2 shows the different tested combinations for the FEM simulations and the resulting temperature differences for the

TABLE 2 | List of experiments carried out for the 3 variable-sensitive factorial analyses and the obtained temperature differences for the longitudinal and radial axes of the treatment chamber.

Case	Electric Field Strength (kV/cm)	Frequency (Hz)	Initial Electrode Temperature (°C)	Longitudinal Temperature Difference (°C)	Radial Temperature Difference (°C)
1	3.75	200	50	1.630	2.111
2	3.75	100	40	2.696	6.125
3	2.5	200	40	2.738	7.740
4	3.75	200	40	2.650	3.950
5	2.5	100	40	1.690	11.720
6	2.5	200	50	2.010	4.380
7	2.5	100	50	1.550	6.820
8	3.75	100	50	2.010	3.790





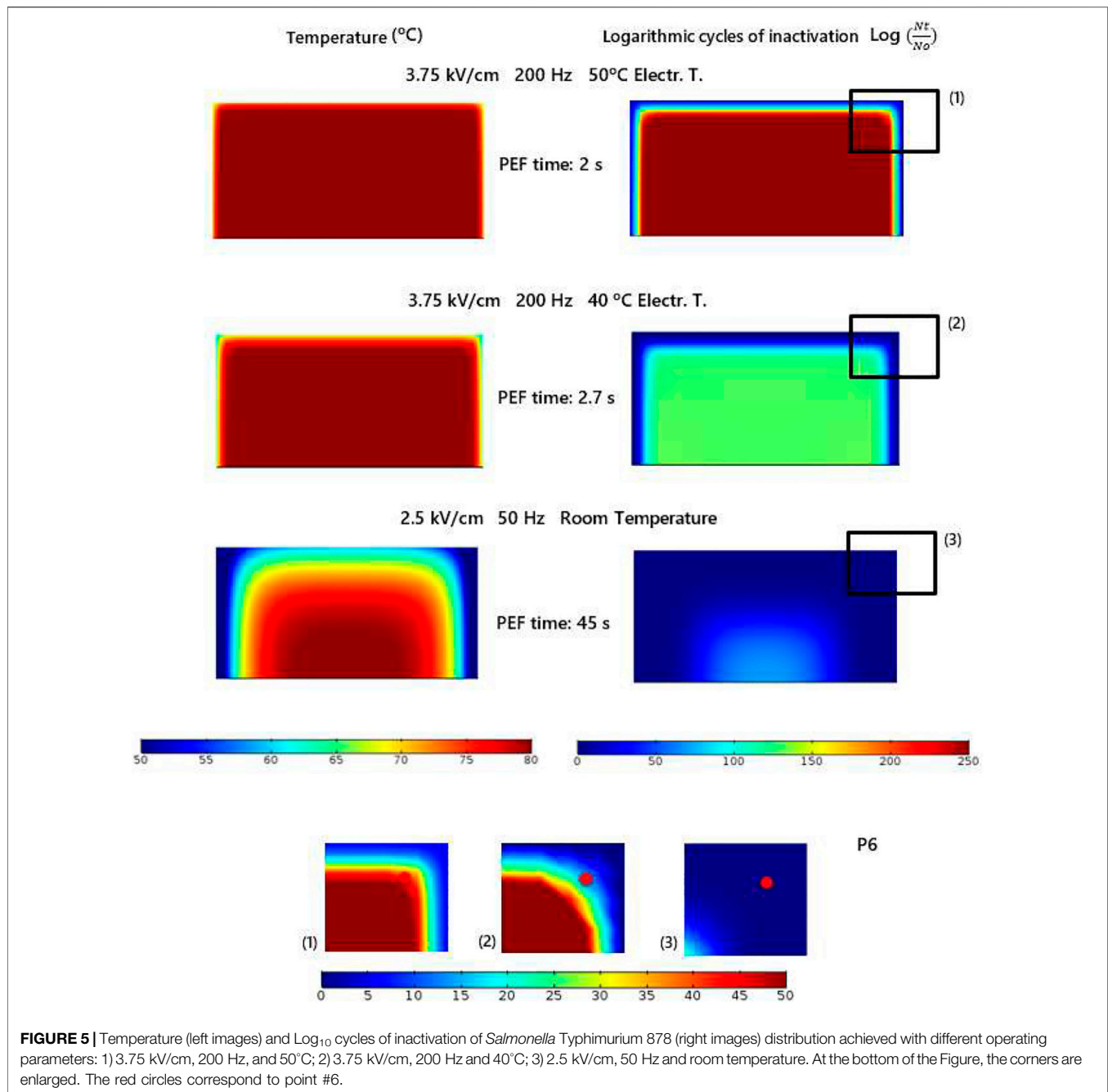
radial and longitudinal directions in terms of the three processing conditions evaluated (field strength, frequency of the pulses, and initial temperature of the electrodes). Each FEM simulation lasts approximately 12 h. Based on these results, the following equations were obtained by multiple regression ($R^2 = 0.99$) to describe the longitudinal ($\Delta T_{\text{longitudinal}}$) and the radial (ΔT_{radial}) temperature variation in the agar for the three variable-sensitivity analysis:

$$\begin{aligned} \Delta T_{\text{longitudinal}} = & 91.96 - 9.456 \cdot E - 0.2392 \cdot fr - 1.366 \cdot T \\ & + 0.02601 \cdot E \cdot fr + 0.1444 \cdot E \cdot T + 0.003628 \\ & \cdot fr \cdot T - 0.000418 \cdot E \cdot fr \cdot T \end{aligned} \quad (11)$$

$$\begin{aligned} \Delta T_{\text{radial}} = & -12.77 + 2.280 \cdot E + 0.08168 \cdot fr + 0.2048 \\ & \cdot T - 0.008948 \cdot E \cdot fr - 0.03200 \cdot E \cdot T - 0.001096 \cdot fr \\ & \cdot T + 0.000102 \cdot E \cdot fr \cdot T \end{aligned} \quad (12)$$

Based on these equations, the main effects of this 3-factor study and both directions were obtained (Figure 3). As observed, electric field strength and frequency follow different trends for each

direction: increasing field strength and frequency between the two study levels, radial temperature difference decreases between 3 and 4°C, while in the case of longitudinal temperature difference, it increases by 0.25°C. However, increasing the initial temperature of the electrodes from 40 to 50°C leads to a decrease of 3°C in the radial direction and 0.7°C in the longitudinal one. This different behavior in the radial and longitudinal axis could be explained by the fact that increasing the electric field and the frequency accelerates the heating rate and thus reduces the time for the heat generated in the center of the food to be transmitted to the ends of the electrodes, which is why no improvements are observed in the longitudinal axis. On the other hand, when the electrodes are at room temperature, the behavior is the same in both directions, as the critical zone for this type of heating, i.e. the area where the electrodes are in contact with the food, is improved (data not shown). An increase in the temperature gradient within the food when the applied electric field is increased was also observed by Salengke and Sastry (2007). They simulated the ohmic heating of a solid immersed in a saline medium (1 mS/cm) and evaluated the application of two electric fields (0.8 kV/cm and 1.28 kV/cm). It was observed that the longitudinal gradient was smaller in the electric field at 0.8 kV/cm i.e. after 90 s the temperature gradient was 34°C while at 0.8 kV/cm after 350 s the gradient was 14°C.



To define the parameters or combination of them with the most influence on the evaluated temperature difference, **Figure 4** shows the Pareto charts for the radial and longitudinal temperature differences obtained from the factorial regressions (**Eqs 11, 12**). For the radial direction, the most important parameter was the applied field strength, but also followed by the initial temperature of the electrodes. For the longitudinal direction, this temperature was the most decisive when it comes to reducing this difference since in this direction the cold spots located in the proximity of the electrodes were considered. With these results, it could be concluded that tempering the electrodes to obtain an initial temperature throughout the

treatment chamber is fundamental in order to achieve the established objectives of temperature uniformity after applying PEF treatments. This approach for direct contact PEF-ohmic application systems is similar to that proposed by Gratz et al. (2021a) for systems where the solid is immersed in a liquid medium. However, they observed that starting with the liquid medium at 90 °C did not improve the uniformity of heating in the solid food, indicating the need for more research to optimize the process. More recently, Astráin-Redín et al. (2022) demonstrated an improvement in temperature uniformity when tempering the electrodes. However, these results were only tested under a unique

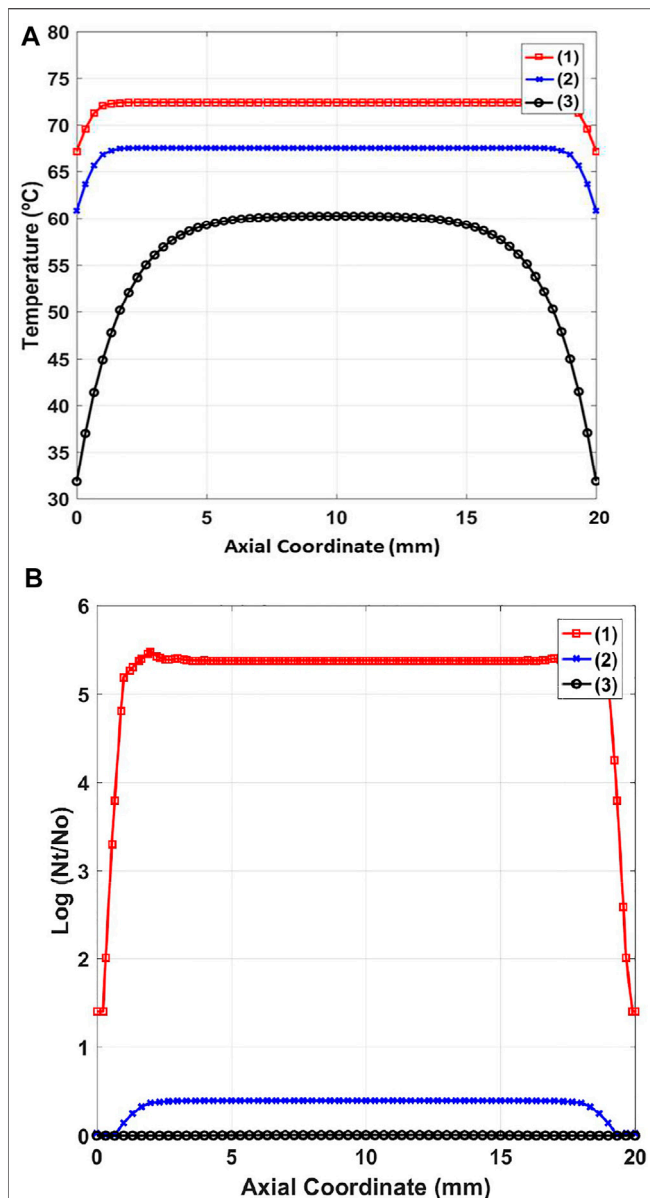


FIGURE 6 | Temperature (A) and Log₁₀ cycles of inactivation of *Salmonella* Typhimurium 878 (B) in the contact zone between the Teflon and the agar along coordinate z for each operating condition: 1) 3.75 kV/cm, 200 Hz, and 50°C; 2) 3.75 kV/cm, 200 Hz and 40°C; 3) 2.5 kV/cm, 50 Hz and room temperature.

ohmic heating treatment through PEF conditions (2.5 kV/cm, 50 Hz), not permitting them to evaluate the influence of the other parameters on the temperature uniformity or microbial lethality.

Based on the results from **Figure 4**, the higher the temperature of the electrode, the lower the temperature differences obtained. Moreover, an increase in the electric field strength would decrease the radial temperature difference without compromising the longitudinal one. On the other hand, the joint effect of frequency and the electric field strength is not negligible. If it is also taken into account that these parameters determine the duration of the electric

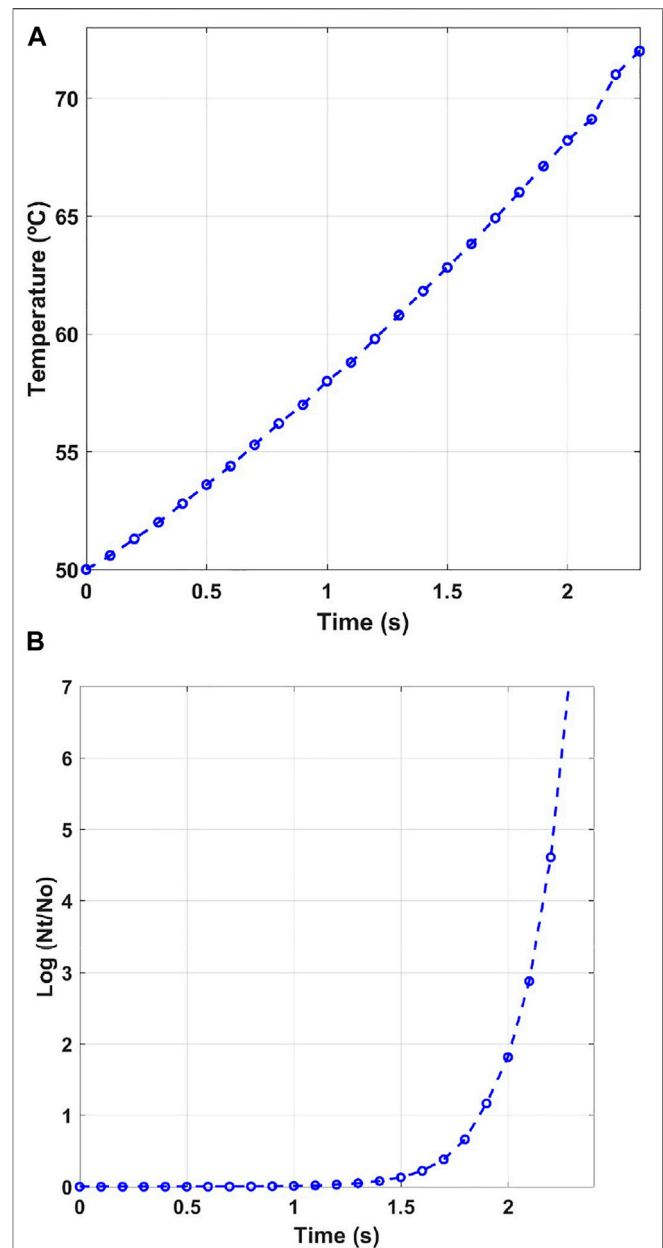
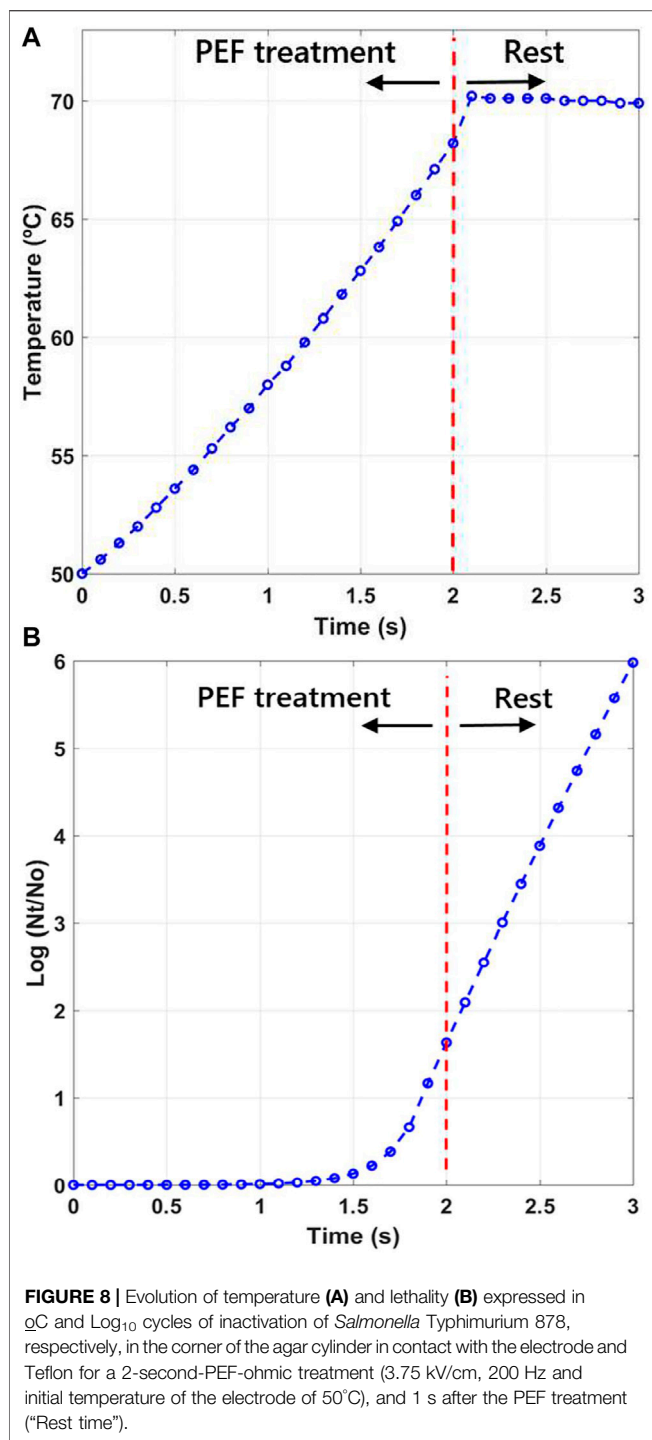


FIGURE 7 | Evolution of temperature (A) and lethality (B) expressed in oC and Log₁₀ cycles of inactivation of *Salmonella* Typhimurium 878, respectively, in the corner of the agar cylinder in contact with the electrode and Teflon when applying PEF-ohmic treatment at 3.75 kV/cm, 200 Hz and initial temperature of the electrode of 50°C.

pulse treatment, it is just as important as maintaining a higher temperature in the electrodes during this stage.

According to the results after the sensitivity analysis, it is possible to choose a combination of factors that lead to an acceptable degree of temperature homogenization. The highest possible initial temperature of the electrodes was chosen because it provided lower temperature differences in both directions: in this case 50°C. Finally, for the electric field and frequency, a compromise between the two was sought to guarantee a reduction in the



longitudinal temperature difference without notably increasing the radial temperature difference: 3.75 kV/cm and 200 Hz.

Numerical Simulation of Microbial Inactivation

Microbial inactivation depends on the time and the temperature applied in the product, so depending on the received treatment in

the different parts of the agar, the same inactivation may not be achieved in the whole sample. Based on this, microbial inactivation of a certain microorganism, *Salmonella* Typhimurium 878, was evaluated to determine the influence of the investigated parameters on the microbial inactivation in all parts of the agar and to evidence the effect of the lack of temperature uniformity in the mortality of this microorganism. To the best of our knowledge, this is the first time that microbial inactivation by ohmic heating treatment through PEF is simulated in a solid product by considering the investigated parameters, although there are studies for traditional ohmic heating (Zell et al., 2009).

Figure 5 shows the temperature distribution (left images) and the Log_{10} cycles of inactivation (L) of *Salmonella* Typhimurium 878 (right images) after different PEF-ohmic treatment conditions. The tested conditions were those estimated as the ones which offered the best temperature uniformity based on the previous sensitivity study (3.75 kV/cm, 200 Hz, and initial electrodes temperature of 50°C, case 1); and that previously described by Ariza-García et al. (2020), in which PEF-ohmic conditions did not achieve a temperature homogeneity (2.5 kV/cm, 50 Hz and with electrodes at room temperature, case 3). This figure also includes the case of 3.75 kV/cm at 200 Hz, but with an initial electrode temperature of 40°C (case 2), to analyze the effect of the agar temperature on microbial lethality. The bottom of Figure 5 shows a more detailed image of the lethality at the agar-electrode-Teflon area (point #6 is indicated with a red circle). Simulations were represented when a final temperature of 80°C in the center of the agar was achieved. This time was 2, 2.7, and 45 s when the initial temperature of the electrodes was 50°C, 40°C, and room temperature, respectively. As observed, temperature distribution was more uniform when the initial temperature of the electrodes was the highest (case 1), observing a noticeable temperature variation of more than 30°C (80°C in the center and 50°C in the edge) when the electrodes initial temperature is the same as the room (case 3). The consequence is a great variation in microbial lethality (L) compared to the best scenario. However, in this case, less than 5- Log_{10} reductions would be achieved at the coldest point, when the final temperature was around 66°C.

To more easily compare the results, the inactivation levels at the area of point #6 (the red point at the bottom of Figure 5) are pointed out. Theoretical inactivation values were only higher than 20 Log_{10} cycles in case 1. In cases 2 and 3, lethality was 15 and 2.5 Log_{10} cycles, respectively.

Although point #6 enables comparisons, a dramatic situation was observed in the contact line between the insulation, electrode, and the sample. Figure 6 shows the temperature (6A) and Log_{10} cycles of inactivation of *Salmonella* Typhimurium 878 (6B) in that contact line for the three cases previously described in Figure 5 (case 1: 3.75 kV/cm, 200 Hz, and 50°C; case 2: 3.75 kV/cm, 200 Hz and 40°C; case 3: 2.5 kV/cm, 50 Hz and room temperature). As expected, in cases 2 and 3, inactivation was below food safety target level of 5- Log_{10} reductions (Peng et al., 2017). In case 1, the central area of contact (agar and Teflon) was just above this level (71.9°C and 5.35 Log_{10} cycles of inactivation), but the corner areas would not reach the desired standards of $L = 5\text{-Log}_{10}$ reductions of the target microorganism.

To ensure that even those areas in the corner L would be at least 5- Log_{10} reductions, we studied the exact duration of treatment under these conditions (200 Hz and 50°C electrodes temperature) that would reach the L target. **Figure 7**, shows the temperature (**Figure 7A**) and the Log_{10} cycles of inactivation of *Salmonella* Typhimurium 878 (**Figure 7B**) just in the most unfavorable point (the one corresponding to the corner between agar, Teflon, and electrode) with constant increments of 0.1 s. As a result, treatment would take 2.3 s to reach $L = 5\text{-Log}_{10}$ reductions at this point with a final temperature of 72.5°C. Therefore, the other points of the agar cylinder would be achieving at least this lethality. In the case of the other scenarios, longer treatment times would have been necessary with a greater variation in the temperature (data not shown).

Although at the coldest point 5- Log_{10} reductions would be achieved (**Figure 7B**), in the center of the agar, temperatures over 80°C (92°C) would be reached after 2.3 s at the simulated conditions. This could result in a possible thermal impact on quality even though treatments would be very short, lasting only 2.3 s. Due to this, we evaluated an alternative solution for reaching adequate lethality levels by limiting the internal heating of the sample. For this purpose, the lethality was assessed several seconds after the PEF treatment was stopped. Immediately after applying the ohmic heating treatment through PEF, even the reached temperatures at the coldest point were lethal (68°C). Therefore, inactivation occurs only a few seconds after the application of the pulses. **Figure 8** shows the inactivation at the same corner as previously studied in **Figure 7**, including a resting period of 1 s after the P ohmic heating treatment through PEF. As observed, after the 2-second-PEF treatment and 1 s of resting time without applying PEF, temperature slightly increased due to heating inertia and then maintained (**Figure 8A**), and inactivation would exceed 5- Log_{10} reductions of *Salmonella* Typhimurium 878 (**Figure 8B**). This would limit the increment of the temperature in the center of the agar cylinder to 80°C, but achieve the target level of inactivation in all parts of the cylinder with a maximum temperature difference of 9°C between the hottest and coldest point with a total processing time of 3 s.

Although ohmic heating of food is faster than conventional heating, never before has it been shown that solid food can be heated in such a short time. Shim et al. (2010) simulated ohmic heating (214–890 V/cm) of 1 cm³ cylinder of carrots, meat, and potatoes immersed in a NaCl salt solution, which took 230, 180, 200 s respectively, to reach 80°C. Moreover, Gratz et al. (2021b) investigated the application of high frequencies (12 and 300 kHz) to improve the uniformity and reduce the ohmic heating time (300–1000 V) of 3 cm³ potato cubes. They observed an improvement in heating uniformity when applying 300 kHz, but the time to reach 80°C in the center of the potato was 130 s.

CONCLUSION

In this study, a numerical model that reproduced treatment by PEF in solid food was implemented including, for the first time, the simulation of microbial inactivation by thermal-ohmic

heating caused by PEF. The study theoretically demonstrated the potential of PEF as a system capable of rapidly achieving microbial inactivation in a solid product thanks to a higher heat transfer when applying electric fields over 1 kV/cm.

Based on the results, the initial temperature of the electrodes resulted in the most significant parameter for achieving the most uniform heating of the product including the coldest point, which corresponded to the contact zone between the product, the electrode, and the insulator. Nevertheless, the influence of electric field strength and frequency should not be neglected, determining the highest heating rates and heating uniformity when increasing both parameters.

The obtained simulations indicated that starting the treatment with the electrodes at the highest non-lethal agar temperature (in our case, 50°C) would mean a better temperature uniformity, with very short processing times (2–3 s) achieving 5- Log_{10} reductions of a determined target microorganism, in our case *Salmonella* Typhimurium 878 in the whole tested solid product. These results showed the potential of ohmic heating treatment through PEF as a quick heating system to pasteurize solid products in seconds, and that the tempering of the electrodes, similar to that described in Saldaña et al. (2010) for liquid products, is an efficient and relatively simple way of considerably improving temperature uniformity in the peripheral zones of the sample. More research, for example examining the physical construction of a PEF chamber that allows for validating the thermostating process, is necessary in order to experimentally confirm the simulated obtained results.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusion of this article will be made available by the authors, without undue reservation.

AUTHOR CONTRIBUTIONS

JM: Methodology, Software, Investigation, Writing—Original Draft. LA-R: Investigation, Methodology, Writing—Review and Editing. JG: Formal analysis, Visualization. GC: Formal analysis, Project administration. BC: Software, Data Curation, Writing—Review and Editing, IA: Conceptualization, Resources, Writing—Original Draft, Writing—Review and Editing, Supervision, Project administration.

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