

Article

Factors Influencing the Sterilization of *E. coli* in a High-Voltage Electric Field: Electric Field Strength, Temperature and Humidity

Di Pan, Diya Wen, Xuan Guo, Hua Song * and Shupeai Bai *

State Key Laboratory of NBC Protection for Civilian, Beijing 102205, China; pandiy@163.com (D.P.); wdy-wdy2008@163.com (D.W.); xuan.guo@siat.ac.cn (X.G.)

* Correspondence: huasww@163.com (H.S.); baishp@263.net (S.B.)

Abstract: The application of a high-voltage electric field (HVEF) is crucial for mitigating the growth and reproduction of pathogenic microorganisms on solid surfaces. However, the electric field distribution of HVEF in the undischarged state and bactericidal effect remain largely unexplored. Herein, a unipolar wire–plate HVEF device was developed and its field strength distribution was simulated by COMOSL software (version 6.2). The simulation analysis revealed that the electric field strength and space charge density of HVEF in the undischarged state reached a maximum at the discharge electrode and a minimum at the middle of the two electrode wires. The electric field strength and the inhomogeneity of electric intensity distribution also decreased with the increase in electrode spacing. The sterilization effect of *E. coli* was positively correlated with voltage and treatment time, but negatively correlated with electrode spacing, which was consistent with the change in the field strength of the simulation results. When the voltage was -12.5 kv and electrode spacing 2.7 cm, the sterilization rate was 98.03% at 60 min. In addition, the increase in treatment temperature and relative humidity also affected the electric field distribution, thereby improving the bactericidal effect. Our results revealed that the electric field distribution was the main factor affecting the sterilization effect of HVEF, which provided theoretical support for the design of HVEF sterilization equipment and the optimization of sterilization performance



Academic Editor: Vijaya Raghavan

Received: 10 January 2025

Revised: 12 February 2025

Accepted: 14 February 2025

Published: 15 February 2025

Citation: Pan, D.; Wen, D.; Guo, X.; Song, H.; Bai, S. Factors Influencing the Sterilization of *E. coli* in a High-Voltage Electric Field: Electric Field Strength, Temperature and Humidity. *Processes* **2025**, *13*, 551. <https://doi.org/10.3390/pr13020551>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: high-voltage electric field; a unipolar wire–plate apparatus; undischarged state; electric field simulation; inactivation

1. Introduction

Generally, microorganisms intercepted by filter materials or contaminated within gas pipelines during gas protection processes can accumulate and secrete substances, forming biofilms under suitable conditions [1]. These biofilms offer protection, enabling microorganisms to proliferate, migrate, and spread rapidly, potentially causing widespread damage and posing risks to human health [2]. Therefore, it is of great significance and necessity to effectively kill pathogenic microorganisms on the surface of objects and inhibit their growth. Traditional sterilization techniques have certain limitations, such as equipment damage and high price, chemical residue, secondary pollution and toxicity [3]. The application of many heat-sensitive and protective materials, especially filter fiber materials, has further led to a search for non-thermal methods of microbial inactivation. Nonthermal sterilization technologies such as high pressure, ultraviolet light, pulsed light, ultrasound, pulsed electric field, ozone and cold plasma have received great attention [4]. Amongst these novel methods, electric field as a non-thermal technology has proven its capability to

kill microorganisms without a temperature increase, with spatially stereoscopic antibacterial effect, safety, low energy consumption, environmental friendliness and economic feasibility, which has a very broad development prospect in the field of environmental sterilization [5]. High-voltage electric field (HVEF) technology, as a novel sterilization technology with safety, low temperature and lower energy consumption, induces cell membrane electroporation, increasing membrane permeability, compromising cellular integrity and causing content leakage [6,7]. Additionally, HVEF disrupts enzymes and proteins, impairing cellular homeostasis and physiological processes, ultimately leading to microbial inactivation [8,9]. Additionally, the HVEF equipment is very simple and mainly consists of a direct current (DC) power supply and a treatment chamber with the electrode structures of plate–plate, pick–plate, or wire–plate for different uses [10]. Therefore, it has been considered a relatively mild electric field technique. Nevertheless, the exploitation of this sterilization potential requires a better understanding of the electric field characteristics of HVEF and its effects on micro-organisms.

HVEF discharge involves several complex physical processes. The exact assessment of the electric field and charge density distribution is essential to understand the particle behavior inside the high-voltage electric field. To date, substantial experiments and numerical modeling studies of a wire–plate electric field have mainly focused on the solution of the governing equations involving the complex corona discharge for small-laboratory-scale electrostatic precipitators (ESPs), with two parallel grounded collecting plates, including electric field distribution, airflow field, particle trajectories [11–14] and the influence of the design parameters on dust removal efficiency [15–18]. However, due to the relatively simple electric field distribution of a unipolar wire–plate HVEF in static systems and undischarged states, complex experimental conditions of high voltage and few practical application scenarios, there is a scarcity of simulation analysis research in this field.

In electric field sterilization research, microbial resistance is influenced by factors such as electric field strength, treatment time, electrode spacing, medium parameters (e.g., conductivity, pH) and environmental conditions [19–23]. While the impact of these factors on PEF resistance has been widely studied [24–27], research on HVEF resistance remains limited. Notably, current HVEF sterilization methods primarily focus on discharge-based approaches, which generate ozone (O_3), electromagnetic pollution and high energy consumption, making them unsuitable for residential environments and sensitive materials [28,29]. However, in practical HVEF applications, air ionization inevitably occurs around the wire electrodes due to the applied voltage, leading to O_3 generation, thus necessitating its monitoring [28]. Furthermore, to the best of our knowledge, there is not so much knowledge about the effect of the electric field parameters and environmental factors on the inactivation of *E. coli* by HVEF in the undischarged state, and research on the wire–plate HVEF is still limited.

Therefore, this study integrated electric field simulation and sterilization experiments to comprehensively explore the field strength distribution of a unipolar wire–plate HVEF in the undischarged state, as well as the influence of electric field parameters and environmental factors on the inactivation of *E. coli*. The research aims to fill the gap in the research of HVEF sterilization in the undischarged state, advance the practical application of HVEF technology, and provide theoretical foundations and practical guidance for optimizing electric field design and developing safe, energy-efficient sterilization methods.

2. Materials and Methods

2.1. Bacterial Culture

The Gram-negative bacterium *Escherichia coli* BN8099 (*E. coli*) utilized in this investigation was procured from Daogene Technology (Beijing, China) and stored at $-80\text{ }^{\circ}\text{C}$.

Initially, the freeze-dried strain was streaked onto a Luria–Bertani (LB) agar medium (Beijing Solarbio Science & Technology Co., Ltd., Beijing, China) and incubated for 18 h at 37 °C. The cultured plates were then stored at 4 °C for preservation. Subsequently, a single isolated colony was inoculated onto an LB broth (Beijing Solarbio Science & Technology Co., Ltd., Beijing, China) and incubated overnight at 2000 rpm in a shaking incubator (HZQ-F100, Suzhou Peiying Experimental Equipment Co., LTD, Suzhou, China) at 37 °C. Following subculture to the second generation, 0.4 mL of this culture was inoculated into 40 mL of fresh LB broth and incubated at 37 °C until reaching an optical density (OD₆₀₀) of 0.3. Afterward, the cell pellets were harvested by centrifugation at 8000 rpm for 5 min in a refrigerated centrifuge (5810R, Ditu (Shanghai) Biotechnology Co., Ltd., Shanghai, China), followed by triple washing with sterile phosphate-buffered saline (1 × PBS, pH 7.2, Beijing Solarbio Science & Technology Co., Ltd., Beijing, China). The resulting pellets were finally resuspended in PBS to prepare bacterial suspensions with concentrations of $3\text{--}5 \times 10^8$ CFU/mL.

2.2. HVEF Sterilization Device

Utilizing a unipolar wire–plate apparatus showcased in Figure 1a, the process of HVEF sterilization was carried out. The HVEF device configuration encompasses a negative high-voltage DC power source with a voltage spectrum ranging from 0 to −20 kV (DW-N503-4ACH1, Dongwen High Voltage Power Supply (Tianjin) Co., Ltd., Tianjin, China), a wire–plate reactor (measuring 20 cm × 20 cm × 20 cm) containing three wire electrodes, a stainless steel plate serving as the sample platform, an oscilloscope (TDS 3012B, Tektronix, Beaverton, OR, USA), a DC microammeter (ZGF-Z2, 0–1999 µA, 0.5% ± 1 d, Wuhan Guodian Zhongxing Electric Power Equipment Co., Ltd., Wuhan, China), and an ozone detector (DPO-2024B, Tektronix, Beaverton, OR, USA). In the wire–plate reactor, three parallel nickel–chromium wires with a diameter of 0.2 mm and adjacent wire spacing of 5 cm function as the negative high-voltage electrode, consistently maintained at negative polarity for all measurements. A stainless steel plate (dimensions: 19.5 cm × 19.5 cm × 0.3 cm), detachable from the wire–plate reactor, served as the ground electrode. The actual applied voltage and current were monitored using a high-voltage probe connected to the oscilloscope and a DC microammeter, respectively. An ozone detector was utilized to ascertain the concentration of O₃ produced during the experiment. Electrode spacing, set at 0.7, 2.7, and 4.7 cm, was adjusted by varying the height of the stainless steel plate. The voltage regulation range under different electrode spacing was controlled by the negative high-voltage power supply.

2.3. Electric Field Simulation

The distributions of the electric potential and space charge density are controlled by a Poisson equation, given by

$$\nabla \cdot \bar{D} = \rho \quad (1)$$

$$\bar{E} = -\nabla V \quad (2)$$

where ∇ is the gradient operator, $\bar{D}$ is induced electric field (kV), ρ is space charge density (C/m³), $\bar{E}$ is electric field strength (kV/cm), and V is the applied voltage (kV). The above two equations were established simultaneously, and the COMSOL software (version 6.2) was used to solve the parameters by the finite element method (FEM) to study the electric field distribution inside the wire–plate HVEF. In the specific solution process, we used the “electrostatic module” in the software to simulate the electric field distribution, and combined with the “mesh generation tool” to discretize the geometric model to ensure the calculation accuracy and convergence. By setting appropriate boundary conditions

and material properties, the electric field intensity distribution and its variation law of the wire–plate HVEF system were obtained.

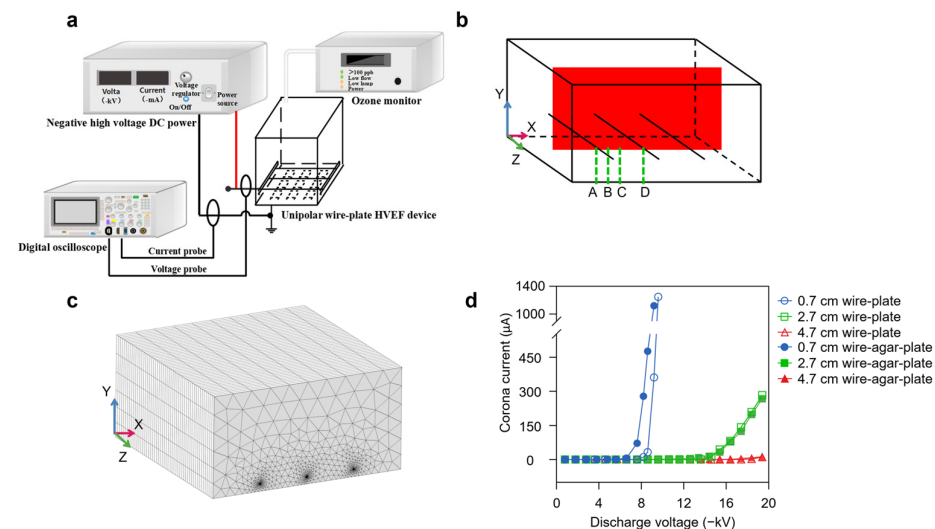


Figure 1. (a) Schematic diagram of the HVEF experimental setup. In the HVEF sterilization device, three parallel nickel–chromium wires served as the negative high-voltage electrodes, while a stainless steel plate functioned as the ground electrode. The samples were positioned directly beneath the three parallel electrode wires and evenly spread on the surface of a 1.5% agar layer (1 mm thick) placed above the stainless steel plate, with each sample covering an area of 3.5 cm × 2 cm. The electrode spacing was adjusted by changing the height of the stainless steel plate. (b) The unipolar wire–plate HVEF device and position distribution of A, B, C and D. A, B, C and D are located directly below the outer electrode line, below 1/4 of the adjacent electrode line, below 1/2 of the adjacent electrode line, and below the center electrode line. (c) Geometry and mesh grid of the HVEF with the wire–plate type. A prismatic grid was used for partitioning. (d) The volt–ampere characteristic curves of HVEF at different electrode spacings.

A cartesian coordinate system was established at the lower-left corner of a plane perpendicular to the three wire electrodes, as illustrated in Figure 1b. Notably, points A, B, C and D were located directly below the outer electrode line, below 1/4 of the adjacent electrode line, below 1/2 of the adjacent electrode line, and below the center electrode line, respectively. Additionally, the XY plane ($Z = 0$) served as the characterization plane for presenting the numerical outcomes. The entire geometry was discretized using unstructured mesh, with refined grids concentrated around the discharge electrodes to enhance simulation convergence and accuracy, as depicted in Figure 1c. Among them, 129,850 prisms, 5194 triangles, 4450 quadrangles, 978 edge elements and 32 vertex elements were used, respectively. With the above parameter settings, we simulated the field strength distributions for different electrode spacings and optimal electric field parameters to fully understand the electric field characteristics of the device.

2.4. HVEF Treatment

Before treatment, 50 μL of cell suspensions, with a concentration approximately of 10^8 CFU/mL, was uniformly applied onto the surface of 1.5% agar (1 mm thickness) above the stainless steel plate, with each sample occupying a coating area of 3.5 cm × 2 cm. Following a 15 min period of ventilation and drying on a sterile operating table, the electrode plate carrying the samples was exposed to different electric field parameters. Specifically, voltages of –8.1, –10.8 and –12.5 kV were applied at an electrode spacing of 2.7 cm, while electrode spacings of 0.7, 2.7 and 4.7 cm were set at a voltage of –6 kV, with a cumulative treatment time ranging from 0 to 60 min. The voltage chosen in our study

was the voltage in the undischarged state, which referred to the state before the corona discharge of the gas.

Additionally, the effects of treatment temperatures (10, 15, 20, 25, 30, 40 °C) and relative humidity (35%, 55%, 75%, 95%) on bactericidal efficacy were evaluated using the HVEF sterilization device within a mold incubator (model MJ-150-II, Shanghai Yiheng Scientific Instrument Co., LTD., Shanghai, China) according to the aforementioned sample preparation conditions.

Finally, the viability of *E. coli* following HVEF treatment was assessed via colony counting on agar plates. HVEF-treated and control samples were transferred to centrifuge tubes containing 10 mL of PBS, respectively, and the cells were then resuspended by shaking for 2 min. Subsequently, tenfold serial dilutions were prepared in PBS. From selected dilutions, 0.1 mL of the samples was plated onto an LB agar medium and incubated at 37 °C for 24 h to determine the total number of viable cells. The survival rate of *E. coli* was calculated using the following equation:

$$S (\%) = \frac{N1}{N0} \times 100 \quad (3)$$

where S [%] represents the survival rate, N0 [CFU/mL] denotes the number of viable cells in the control group and N1 [CFU/mL] signifies the number of viable cells in the HVEF-treated group.

2.5. Statistical Analysis

GraphPad Prism 9.5.0 software was used to analyze and draw the data obtained. The bactericidal experiments under different electric field positions were analysis using a one-way ANOVA followed by Dunnett's test in SPSS version 23, with $p < 0.05$ considered statistically significant. Each experiment was conducted at least three times, with the results presented as the mean values along with standard deviations.

3. Results

3.1. Electric Field Characteristics of the Unipolar Wire–Plate HVEF

3.1.1. Volt–Ampere Characteristic Curves

To explore the change rule of the current of the unipolar wire–plate HVEF device with the increase in voltage, the volt–ampere characteristic curves of the HVEF at different electrode gaps were measured, as shown in Figure 1d. The results showed that the six volt–ampere characteristic curves were all parabolic in the wire–plate (WP) device and the wire–agar plate (WAP) device. The current increased non-linearly with the voltage, and the smaller the electrode gap, the faster the current increased. This indicates that the electric field strength and current distribution can be optimized by adjusting the electrode gap, thereby improving sterilization efficiency and reducing energy consumption. These findings are significant for developing high-efficiency, low-energy HVEF sterilization equipment, particularly in healthcare, food processing and air purification. Optimized HVEF devices reduce ozone and electromagnetic pollution, making them suitable for sensitive environments and materials. Future research could focus on advanced electrode designs or multi-field coupling effects to enhance performance and broaden applications.

Moreover, the corona discharge characteristics of the WAP and WP systems vary with different electrode spacings. At the electrode spacing of 0.7 cm, the slope of the volt–ampere characteristic curve of the WAP system was steeper than that of the WP system under the same voltage, with corona onset voltages of −5 kV and −8 kV, respectively. The maximum corona currents reached 1120 µA and 1249 µA, while the breakdown voltages were −9.6 kV and −10.2 kV, respectively. However, with the electrode spacing of 2.7 cm, there was no

significant difference in the volt–ampere characteristic curves between the WAP system and the WP system, with the corona onset voltages registering at -11 kV and -13 kV, respectively, and the peak corona current reaching $267\text{ }\mu\text{A}$ and $283\text{ }\mu\text{A}$, respectively. When the electrode spacing was further extended to 4.7 cm, the volt–ampere characteristic curve of the WAP system remained virtually indistinguishable from those of the WP system, exhibiting corona onset voltages of -17 kV and -18 kV, respectively, and the maximum corona currents at a mere $13\text{ }\mu\text{A}$ and $11\text{ }\mu\text{A}$, respectively. These results indicated that the corona onset voltage increased with the increase of electrode spacing, resulting in weaker corona line discharge ability and smaller corona current, which provides a reference for the setting of the applied voltage range of HVEF in the undischarged state. Additionally, the WAP system of HVEF was more prone to corona discharge than the WP system under the small electrode spacing. Nevertheless, since corona discharge causes energy loss, radio interference, corona noise, wire corrosion and, most importantly, the production of large amounts of O_3 , the sterilization effect of HVEF in the undischarged state, which was before the gas corona discharge, was mainly explored in our next study.

3.1.2. Electric Field Strength and Space Charge Density Distribution

To further understand the electric field characteristics of the unipolar wire–plate HVEF in the undischarged state, the FEM was used to simulate and analyze the distribution of electric field intensity and space charge density using the COMSOL simulation tool. Figure 2a–c showed the simulated electric field intensity, space charge density and voltage value distribution characteristics of the XOY plane under different electrode spacing at a -6 kV applied voltage in the HVEF sterilization device. It can be clearly observed that the electric field intensity, space charge density and voltage values exhibited bilateral symmetry along the central electrode line, with the strongest near each electrode wire and gradually weakening from the center of each electrode wire to the surrounding. Due to the ground electrode below the electrode wires and the suspended electrode above it, the electric field intensity and space charge density mainly showed an elliptical distribution with the electrode wires as the vertex downward, and gradually decreased as it approached the ground electrode, while basically zero in the suspended electrode part (Figure S1a–c). Meanwhile, due to the same polarity, the region of low electric field intensity was formed between adjacent electrodes under the action of electrostatic field shielding.

Subsequently, from the perspective of the whole HVEF device, the electric field intensity and voltage were mainly distributed between the electrode wires and ground electrode plates (Figures 2d, S1d and S2a,b), and within the range of 0 – 2.7 cm electrode spacing, the electric field intensity gradually decreased with the increase in electrode spacing (Figure 2e). Importantly, there were differences in the electric field intensity at different locations near the electrode lines, with the lowest electric field intensity at point C located between adjacent electrode lines and higher electric field intensity at points A and D located on the electrode line (Figure 2e). Moreover, there were also some differences in the electric field intensity under different electrode spacings between point A directly below the outer electrode line and point D directly below the center electrode line. For example, at voltage of -12.5 kV and electrode spacing of 2.7 cm, the electric field strength at point D (166.45 kV/cm) was less than that at point A (174.08 kV/cm) when approaching the line electrodes; with the increase in electrode spacing, the electric field strength at point D (2.03 kV/cm) was gradually greater than that at point A (1.92 kV/cm , Figure 2e). The reason may be that in the vicinity of the electrode line, the D point was disturbed by the electric field of the left and right adjacent electrode lines, which led to the decrease in the electric field intensity. When far away from the electrode line, the shielding interference

gradually weakened, thereby increasing the electric field intensity of the D point. Note that the voltage at point D was always slightly greater than at point A (Figure S1e).

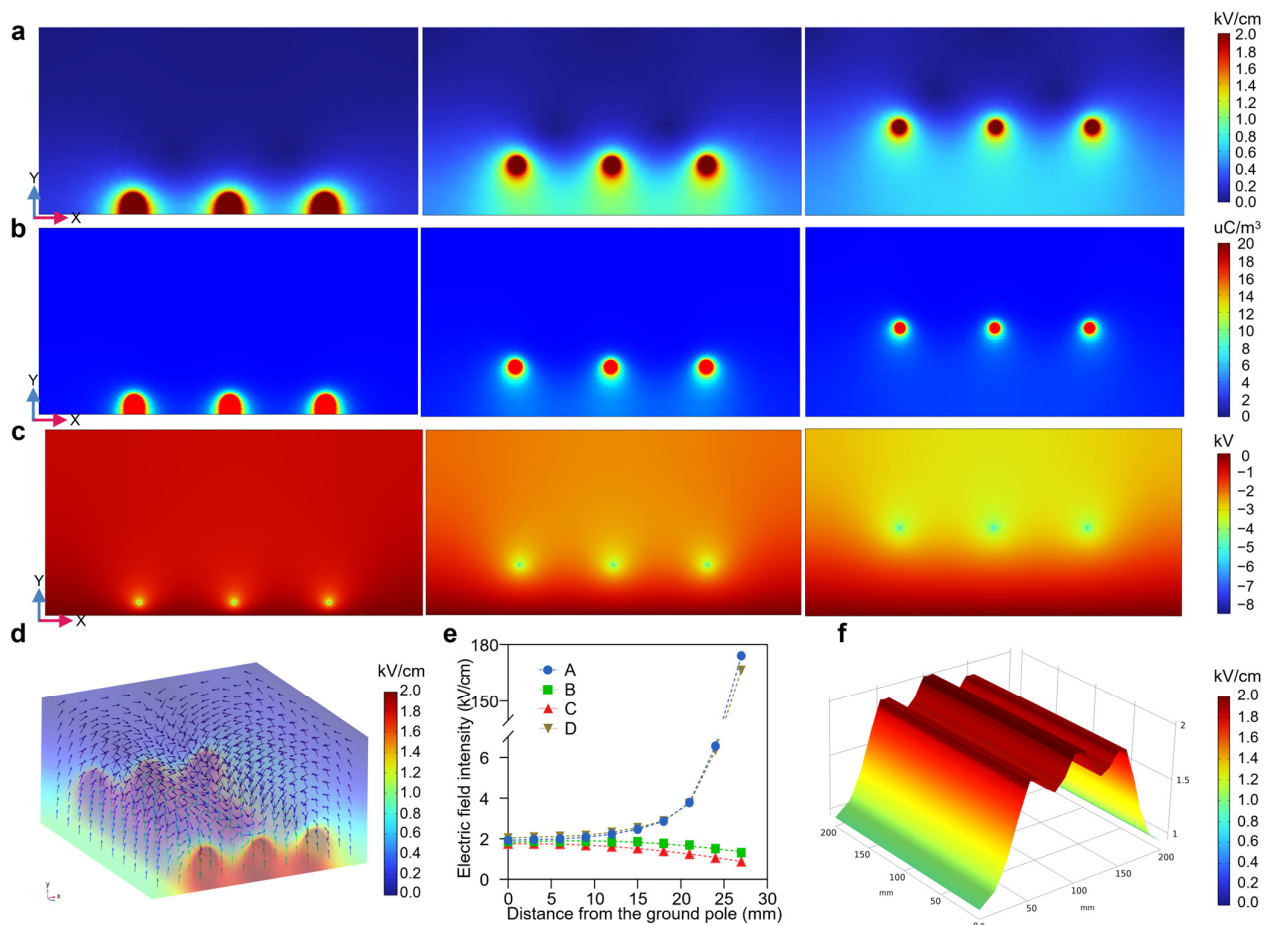


Figure 2. HVEF simulation. Electric field intensity (a), space charge density (b) and electrical potential (c) of the XOY plane at -6 kV with the electrode spacings of 0.7, 2.7 and 4.7 cm, respectively. (d) Electric field strength and field streamlines of the whole HVEF reactor at a voltage of -12.5 kV and electrode spacing of 2.7 cm. (e) Electric field intensity of A, B, C and D at different distances from the ground pole at a HVEF voltage of -12.5 kV and electrode spacing of 2.7 cm. A, B, C and D are located directly below the outer electrode line, below 1/4 of the adjacent electrode line, below 1/2 of the adjacent electrode line, and below the center electrode line. (f) Three-dimensional diagram of electric field strength distribution on the ground electrode surface at a HVEF voltage of -12.5 kV and electrode spacing of 2.7 cm.

To better elucidate the effect of the electric field on the inactivation of *E. coli*, the field strength distribution of the whole ground plate surface was also simulated. As can be seen from Figures 2f, S1f and S2c, the field intensity distribution on the surface of the whole ground plate was strongly non-uniform and mainly concentrated in the vicinity of the three parallel electrode wires, with a maximum at the center electrode line and a minimum at the edge of the ground electrode away from the electrode line. With increasing electrode spacing, the inhomogeneity of the electric field strength on the surface of the whole ground electrode gradually decreased, because the spacing between adjacent electrode lines was relatively small compared to the distance between the electrode wires and the ground plate (Figure S2c) [30,31]. Notably, when the electrode spacing was 2.7 cm, there was no significant difference in the bactericidal effect at different locations near the electrode line on the ground plate ($p > 0.05$), indicating that the HVEF field strength in the undischarged state was generally weak at the electrode spacing of 2.7 cm, and although the electric field

strength was different at different positions, it was not enough to cause significant changes in the number of bacteria (Figure S3a).

3.2. Effect of Electric Field Parameters on the Inactivation of *E. coli*

Electric field intensity and treatment time were the primary variables affecting the sterilization effect [32]. The electric field strength can be adjusted by changing the distance between the wire electrode and the ground electrode or the applied voltage. On this basis, we first investigated the antibacterial effect of HVEF at different electrode gaps and voltages against *E. coli*. The sterilization effect of *E. coli* decreased with the increase in electrode spacing under the same treatment time (Figure 3a). When the electrode spacing increased from 0.7 cm to 4.7 cm, the survival rate of *E. coli* at 60 min increased from 12.02% to 83.75%. This was because when the applied voltage was the same, the electrode spacing was smaller, the field strength increased and the sterilization effect was enhanced (Figures 2a and S2); as the electrode spacing increases, the breakdown voltage required for discharge increases, resulting in weaker ionization strength and lower sterilization effect, which was consistent with the voltammetry characteristics obtained in Figure 1d. Moreover, we found that the number of inactivated bacteria gradually increased with increasing applied voltage at a fixed electrode spacing of 2.7 cm (Figure 3b). When the negative voltage value was increased from 8.1 kV to 12.5 kV, the survival rate of *E. coli* decreased from 32.06% to 1.93% at 60 min, which was closely related to the increase in field strength. The above results showed that HVEF presented an inactivation effect on *E. coli*, and the sterilization rate had a highly positive correlation with the electric field strength and treatment time.

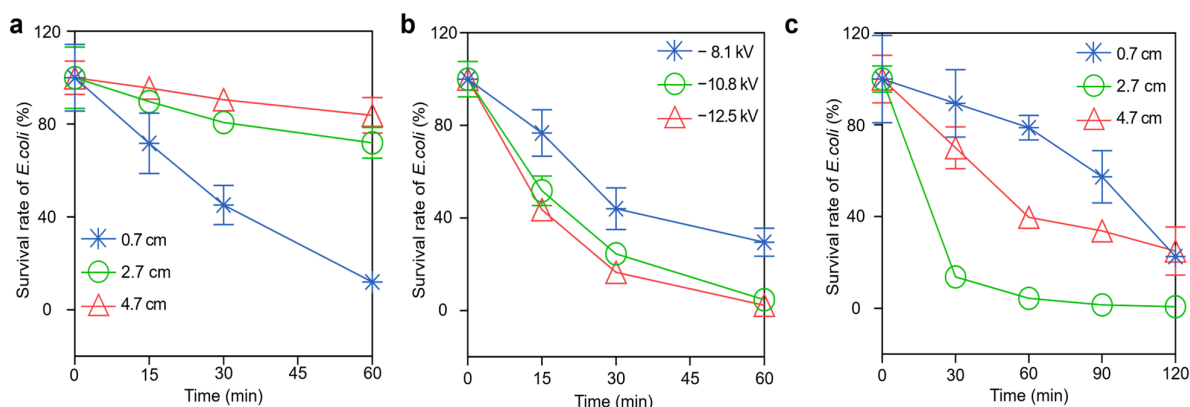


Figure 3. Effect of electric field intensity and treatment time on the inactivation of *E. coli* by HVEF. (a) *E. coli* survival rate at different electrode spacings with a voltage of -6 kV. (b) *E. coli* survival rate at different voltages with an electrode spacing of 2.7 cm. (c) *E. coli* survival rate at different electrode spacings and voltages with a field intensity of -4 kV/cm. The results are presented as the means $\pm$ s.d. of experimental replicates ($n = 3$).

Next, to further prove the relationship between the HVEF field strength distribution and the sterilization effect, the effect of different electrode spacing and voltage on the sterilization effect of HVEF at the same electric field intensity was investigated, as shown in Figure 3c. Under the electric field strength of -4 kV/cm, the sterilization rate was best at the electrode spacing of 2.7 cm, which was due to the uneven field strength distribution of the wire-plate device at different electrode spacing. Additionally, with the extension of treatment time, *E. coli* survival first decreased rapidly and then leveled off. This was mainly due to the fact that the energy injected into the reactor increased with the extension of treatment time at a certain field strength, resulting in more severe damage to *E. coli* by HVEF. However, as the number of viable bacteria decreased significantly with the extension of treatment time, the probability of HVEF interaction with them decreased,

ultimately flattening the downward trend in *E. coli* survival rates. Accordingly, in view of the high efficiency of the sterilization and the adjustable range of the applied voltage of the electrostatic field, a mild electrostatic field condition with an electrode spacing of 2.7 cm and a voltage of -12.5 kV was chosen for the next experiment.

3.3. Effect of Environmental Factors on the Inactivation of *E. coli*

In addition to influencing the bactericidal effect of *E. coli* via changing the electric field parameters, environmental factors, such as treatment temperature and relative humidity, can also affect the electric field characteristics and lead to differences in the bactericidal effect [33]. The findings demonstrated a significant increase in the sterilization efficiency of *E. coli* in the logarithmic growth phase with treatment temperature, which could be attributed to an increase in dielectric conductivity [34] and a decrease in transmembrane breakdown potential [35] (Figure 4a). Similar studies conducted on *Listeria innocua* in which PEFs were applied at high temperatures reported a considerable increase in the inactivation effectiveness [36]. Likewise, within a relative humidity range of 35–95%, the inactivation rate of *E. coli* in logarithmic growth phase increased from 26.12% to 92.11% with the increase in relative humidity (Figure 4b). This was due to the degradation of insulation between the electrode plates, where it was easy to produce corona discharge, resulting in current generation and breakdown effect [37].

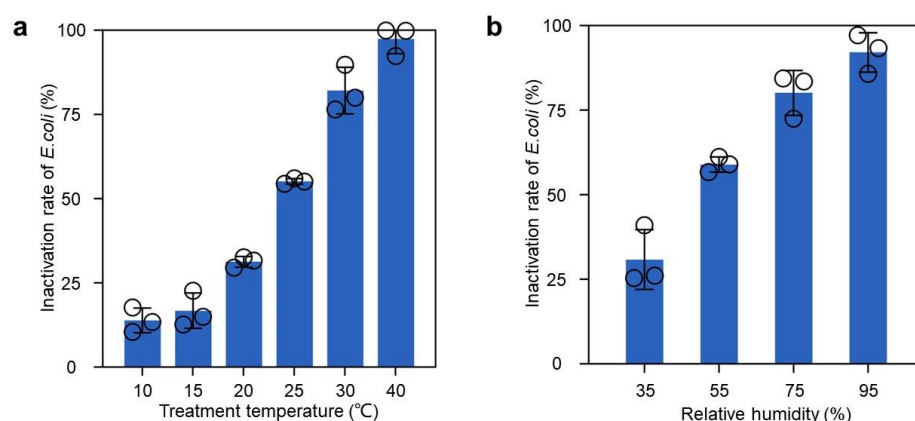


Figure 4. Effect of treatment temperature (a) and relative humidity (b) on the inactivation of *E. coli*. The results are presented as the means $\pm$ s.d. of experimental replicates ($n = 3$).

4. Discussion

As a relatively mild sterilization technology, HVEF has a great development potential in the field of gas protection. It is very important to fully understand the electric field characteristics of physics field to improve the performance of HVEF. The volt-ampere characteristic curve reflects the relationship between voltage and current, and illustrates the generation and development process of HVEF corona discharge [38]. Our results showed that at the same voltage, the increase in electrode gap not only reduced the corona current, but also decreased the slope of the volt-ampere characteristic curves and the rise rates of corona current with the increase in voltage. This was because the increase in interelectrode distance reduced the electric field strength and increased the difficulty of corona discharge caused by the local breakdown of the gas around the discharge electrode, which reduced the number of ions and charged particles emitted by ionization of the gas, resulting in a relative decrease in the number of charges reaching the ground electrode per unit time and a decrease in corona current [39].

Moreover, the distribution of space charge density and electric field strength between electrodes is the basis for calculating particle charge and motion trajectories, which can be used to characterize the physical field of HVEF [40]. In our study, the simulation analysis

showed that the electric field strength and space charge density of the unipolar wire–plate HVEF in the static system and undischarged state were mainly distributed between the three parallel electrode wires and the ground electrode, with the highest at the electrode lines and the lowest at the middle of the two electrode lines, which is consistent with most studies [41,42]. This was due to the electrostatic shielding effect, the field strength between the adjacent electrode lines did not overlap, but restricted each other. We found that space charge density was symmetrically distributed along the central electrode line at different electrode spacing. However, Arif et al. [16] showed that as the plate spacing increased from 100 mm to 220 mm, the space charge density caused by corona discharge in the central wire was significantly suppressed compared to the outer discharge wire, which was mainly caused by the shielding effect. More importantly, we found that the electric field strength and the inhomogeneity of electric field distribution gradually decreased with increasing electrode spacing. The field strength of HVEF on the surface of the ground plate was mainly concentrated near the position of three parallel electrode lines, but there was no obvious difference in the bactericidal effect near them. Therefore, the electrode spacing of 2.7 cm was chosen to perform the sterilization experiment directly below the electrode line to obtain a higher sterilization effect.

Based on the above electric field distribution characteristics, the effect of electric field parameters on the bactericidal effect was verified. We found that the antibacterial activity of HVEF in the undischarged state against *E. coli* was positively correlated with the treatment time and voltage, while it negatively correlated with the electrode spacing (Figure 3a–c). Combined with the simulation results of electric field in Section 3.1.2, it was not difficult to observe that the order of HVEF sterilization efficiencies at different electrode spacings and voltages was consistent with the order of the field strength and space charge density within the HVEF device (Figures 2a,b and S1a,b). It can be concluded that for the wire–plate HVEF, the change in field strength and space charge density was the main factor affecting the change of its sterilization efficiency, and the main factor affecting the field strength and space charge density was the electrode spacing and voltage, so when applying wire–plate HVEF for sterilization, the influence of the applied voltage and electrode spacing should be focused on. In addition, the sterilization experiment in Figure 3c further confirmed that the electrode spacing led to the uneven distribution of electric field intensity. Therefore, the electric field condition with an electrode spacing of 2.7 cm and voltage of -12.5 kV was used for the sterilization experiment in the subsequent study. Our results also found that ozone concentrations were low (1 ppm) throughout the sterilization process (Figure S3b). Considering that HVEF equipment was in an open environment, it can be considered that the electric field strength was one of the main factors leading to bacterial death.

The bactericidal effect of HVEF in this study was the result of the combined effect of the electric field between the electrodes and the electric field formed by the attached electrons. The ionization, adhesion and mobility of the particles in the electric field were directly related to temperature, so the treatment temperature would affect the electric field distribution of HVEF, which, in turn, led in the difference of sterilization effect. With the increase in air temperature, the effective ionization coefficient gradually increased and the corona onset voltage decreased [43]. This was because the air density decreased with the increase in temperature, which increased the degree of freedom of electrons in the air, improving the energy of electrons gained from the electric field and making ionization collisions more likely to occur [44]. Nevertheless, due to the substantial decrease in the number of collisions per unit length, excessive temperature ultimately impeded the extent of gas ionization to some degree. Bi et al. [45] used a rod–plate discharge model based on fluid dynamics to explore the effect of ambient temperature changes on electron density and electric field strength. The results showed that in the temperature range of 300–400 K, the

thermal motion of the particles was significantly enhanced by increasing the temperature, resulting in an increase in the electron density generated by the particle collision ionization and an increase in the electric field strength. However, in the range of 400 to 600 K, the distance between the gas molecules gradually increased due to the limitation of the constant pressure condition, which will lead to a decrease in the collision frequency and a downward trend in the electric field. On the other hand, the treatment temperature also influenced the cell membrane. Phospholipid molecules in cell membranes underwent temperature-related phase transitions, changing from a packed gel-like structure at low temperatures to a looser liquid–crystalline phase at higher temperatures, reducing the thickness and mechanical resistance of cell membranes [46]. In our study, the significant increase in bactericidal effect of HVEF at high treatment temperatures may be indicative of the occurrence of such phase transition on the cell membrane of *E. coli*, since it is possible to argue that a thinning of the bacterial membrane would render bacterial cells more susceptible to disruption by electric fields [47], as indicated by the dielectric breakdown theory [48], similar to most results obtained when cells were PEF-treated [27]. When bacteria were in an electric field, a potential difference was formed on both sides of the cell membrane. Under the action of an electric field of sufficient strength, electroporation of the cell membrane occurs, leading to an increase in the permeability of the cell membrane [49]. Substances inside the cell, such as ions, proteins, nucleic acids, etc., leak out of the cell through the pores, and, at the same time, some substances with larger molecules can enter the cell, resulting in a cellular imbalance, leading to cell death [50]. In addition, under the action of the external voltage, the reaction generates hydroxyl radicals and other strong oxidizing substances that oxidize and decompose organic molecules (transport proteins, synthetic enzymes, etc.) and bacteria, leading to cell death. Overall, high temperature not only increased the degree of HVEF ionization, but also transformed the phospholipid structure of the cell membrane to a liquid crystal state, thereby drastically enhancing the degree of microbial inactivation.

Changes in relative humidity also mainly affect the discharge characteristics of HVEF. The initial corona voltage of negative polarity wire is affected by water molecules in the air and water molecular film on the wire surface [51]. Water molecules in the air trap free electrons in space and inhibit the development of electrical discharges. The water molecular film on the wire surface can increase the secondary electron emission coefficient and increase the discharge intensity. For the 0.2 mm wires in our experiment, with the increase in relative humidity, the increase in the secondary electron emission coefficient of the water molecular film may be greater than the inhibition intensity of the discharge of water molecules in the air, so the corona onset voltage decreased overall, which was similar to the results of previous studies [52,53]. Moreover, when the relative humidity was high, the suspended droplets may appear in the space, which had a large radius compared with water molecules, making the charge of the suspended droplets in the air increase, and then the electric field intensity increases [54]. Notably, water molecules also have an adhesion effect on electrons. Excessive humidity leads to the adhesion rate exceeding the ionization rate, and the electron density decreases, which, in turn, reduces the electric field intensity [45]. At the same electric field intensity, the effective ionization coefficient also increases with the increase in relative humidity, which enhances the ionization capacity in space [55,56]. However, there were few studies on the effect of humidity on bacterial resistance to HVEF, most of which focused on the effect of water activity. Studies on the effect of water activity on PEF resistance showed that decreased water activity increased microbial resistance to PEF [23,57]. This was due to the cell shrinkage when the water activity value decreases, which may lead to the thickening of the cell membrane and subsequently to a decrease in cell membrane permeability and fluidity, making the bacteria more resistant to HVEF [58]. In summary, our results confirmed that the increase in relative

humidity reduced the HVEF resistance of *E. coli*, which was associated with a decrease in corona onset voltage, an increase in field strength and effective ionization coefficient, and an increase in the fluidity of the cell membrane.

To summarize, the field intensity and space charge density of HVEF changed with electrode spacing and voltage, which made *E. coli* show a large inactivation variation to HVEF. In addition, these differences were also changed under the influence of environmental conditions assayed. Our findings help to understand the HVEF electric field distribution under undischarged conditions to achieve higher levels of microbial inactivation of HVEF. Meanwhile, HVEF sterilization equipment is simple to operate, easy to integrate with existing industrial production lines, and can achieve efficient sterilization at lower temperatures. It has the advantages of low energy consumption, no chemical residues, and strong adaptability, demonstrating its potential application value in industrial production. However, there are also some limitations of HVEF sterilization technology, such as limited processing capacity, treatment efficiency affected by many factors, imperfect technical standards and insufficient research on its mechanism of action. These problems restrict the wide application of this technology in the industrial field, and further research and optimization are still needed to promote its practical application.

5. Conclusions

In this study, we designed a unipolar wire–plate HVEF device, comprehensively examined the effects of electric field characteristics and different factors such as electric field parameters and environmental conditions on the bactericidal performance of HVEF. The main results of the study are as follows:

- (1) The volt–ampere characteristic curve of HVEF was parabolic, and the corona current increased with the increase in voltage. As the electrode spacing increased, the corona onset voltage raised, which provides a reference for the voltage applied by electrostatic field.
- (2) The electric field strength and space charge density of HVEF in the undischarged state exhibited bilateral symmetry along the central electrode line and formed an elliptical distribution with the electrode line as the vertex downward, and all reached a maximum at the discharge electrode and a minimum at the middle of the two electrode wires. The electric field strength and the inhomogeneity of electric field distribution decreased with the increase in electrode spacing.
- (3) The electric field distribution is the main factor affecting the bactericidal effect. The sterilization effect of HVEF in the undischarged state was positively correlated with voltage and treatment time, and negatively correlated with electrode spacing. Due to the uneven electric field distribution, an optimal sterilization effect was achieved at an electrode spacing of 2.7 cm, with a sterilization rate of 98.07% at 60 min. Additionally, the increase in treatment temperature and relative humidity also enhanced the degree of HVEF ionization, thus improving the sterilization effect.

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/pr13020551/s1>, Figure S1: HVEF simulation analysis of the XOY plane at a voltage of -12.5 kV and an electrode spacing of 2.7 cm, including electric field intensity distribution (a), space charge density (b), voltage (c) and voltage distribution of the whole reactor (d). (e) The voltage of A, B, and C at different distances from the ground pole. A is located directly below the outer electrode line, B and C are directly located $1/4$ and $1/2$ of the adjacent line electrode, respectively, and D is located directly below the center electrode line. (f) Field intensity distribution diagram of ground plate surface; Figure S2: The distribution of potential (a), space charge density (b) and ground plate surface field strength (c) of HVEF under different electrode spacings at a voltage

−6 kV; Figure S3: (a) Bactericidal effect of *E. coli* at different locations on ground electrode surface. A: located at the left electrode line, C: located between the left electrode line and the center electrode line, D: located at the center electrode line, E: located between the center electrode line and the right electrode line, F: located at the right electrode line. (b) O₃ concentration under different treatment times at a HVEF voltage −12.5 kV and electrode spacing 2.7 cm. The results are presented as the means ± s.d. of experimental replicates ($n = 3$).

Author Contributions: Conceptualization, D.P., H.S. and S.B.; methodology, D.P., H.S. and X.G.; validation, D.P. and H.S.; formal analysis, D.P. and X.G.; investigation, D.P.; data curation, D.P.; writing—original draft preparation, D.P.; writing—review and editing, X.G. and D.W.; supervision, X.G. and S.B.; project administration, X.G., H.S. and S.B. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Key R&D Program of China (2021YFF0604000).

Data Availability Statement: The data presented in this study can be obtained upon request from the corresponding authors. These data will not be publicly disclosed due to privacy restrictions.

Acknowledgments: The authors gratefully acknowledge the funding support.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

HVEF	High-voltage electric field
PEF	Pulsed electric field
DC	Direct current
ESPs	Electrostatic precipitators
<i>E. coli</i>	<i>Escherichia coli</i> BN8099
LB	Luria–Bertani
FEM	Finite element method
WAP	Wire–agar plate

References

1. Brožková, I.; Červenka, L.; Mořková, P.; Frühbauerová, M.; Metelka, R.; Švancara, I.; Sýs, M. Electrochemical Control of Biofilm Formation and Approaches to Biofilm Removal. *Appl. Sci.* **2022**, *12*, 6320. [\[CrossRef\]](#)
2. Guzmán-Soto, I.; McTiernan, C.; Gonzalez-Gomez, M.; Ross, A.; Gupta, K.; Suuronen, E.J.; Mah, T.-F.; Griffith, M.; Alarcon, E.I. Mimicking Biofilm Formation and Development: Recent Progress in in Vitro and in Vivo Biofilm Models. *iScience* **2021**, *24*, 102443. [\[CrossRef\]](#)
3. Li, X.; Farid, M. A Review on Recent Development in Non-Conventional Food Sterilization Technologies. *J. Food Eng.* **2016**, *182*, 33–45. [\[CrossRef\]](#)
4. Lopes, S.J.S.; Sant’Ana, A.S.; Freire, L. Non-Thermal Emerging Processing Technologies: Mitigation of Microorganisms and Mycotoxins, Sensory and Nutritional Properties Maintenance in Clean Label Fruit Juices. *Food Res. Int.* **2023**, *168*, 112727. [\[CrossRef\]](#) [\[PubMed\]](#)
5. Wei, S.; Chen, T.; Hou, H.; Xu, Y. Recent Advances in Electrochemical Sterilization. *J. Electroanal. Chem.* **2023**, *937*, 117419. [\[CrossRef\]](#)
6. Tsong, T.Y. Electroporation of Cell Membranes. In *Electroporation and Electrofusion in Cell Biology*; Neumann, E., Sowers, A.E., Jordan, C.A., Eds.; Springer: Boston, MA, USA, 1989; pp. 149–163, ISBN 978-1-4899-2528-2.
7. Huo, Z.-Y.; Li, G.-Q.; Yu, T.; Feng, C.; Lu, Y.; Wu, Y.-H.; Yu, C.; Xie, X.; Hu, H.-Y. Cell Transport Prompts the Performance of Low-Voltage Electroporation for Cell Inactivation. *Sci. Rep.* **2018**, *8*, 15832. [\[CrossRef\]](#) [\[PubMed\]](#)
8. Zhang, Y.; Liang, Y.; Pan, D.; Bai, S.; Wen, D.; Tang, M.; Song, H.; Guo, X.; Han, H. Enhancing *Escherichia Coli* Inactivation: Synergistic Mechanism of Ultraviolet Light and High-Voltage Electric Field. *Foods* **2024**, *13*, 1343. [\[CrossRef\]](#) [\[PubMed\]](#)
9. Zhu, N.; Yu, N.; Zhu, Y.; Wei, Y.; Zhang, H.; Sun, A. Inactivation of *Pichia Rhodanensis* in Relation to Membrane and Intracellular Compounds Due to Microchip Pulsed Electric Field (MPEF) Treatment. *PLoS ONE* **2018**, *13*, e0198467. [\[CrossRef\]](#)

10. Dalvi-Isfahan, M.; Havet, M.; Hamdami, N.; Le-Bail, A. Recent Advances of High Voltage Electric Field Technology and Its Application in Food Processing: A Review with a Focus on Corona Discharge and Static Electric Field. *J. Food Eng.* **2023**, *353*, 111551. [\[CrossRef\]](#)
11. Lu, Q.; Yang, Z.; Zheng, C.; Li, X.; Zhao, C.; Xu, X.; Gao, X.; Luo, Z.; Ni, M.; Cen, K. Numerical Simulation on the Fine Particle Charging and Transport Behaviors in a Wire-Plate Electrostatic Precipitator. *Adv. Powder Technol.* **2016**, *27*, 1905–1911. [\[CrossRef\]](#)
12. Dong, M.; Zhou, F.; Zhang, Y.; Shang, Y.; Li, S. Numerical Study on Fine-Particle Charging and Transport Behaviour in Electrostatic Precipitators. *Powder Technol.* **2018**, *330*, 210–218. [\[CrossRef\]](#)
13. Lin, G.-Y.; Tsai, C.-J. Numerical Modeling of Nanoparticle Collection Efficiency of Single-Stage Wire-in-Plate Electrostatic Precipitators. *Aerosol Sci. Technol.* **2010**, *44*, 1122–1130. [\[CrossRef\]](#)
14. Chen, Y.-T.; Lu, C.-L.; Lu, S.-J.; Lee, D.-S. Electrostatic Precipitator Design Optimization for the Removal of Aerosol and Airborne Viruses. *Sustainability* **2023**, *15*, 8432. [\[CrossRef\]](#)
15. Li, J.; Duan, L.; Chen, J.; Li, D.; Bao, S.; Wang, Z.; Wang, J.; Liao, J. Research of the Effect of Different Corrugated Dust Collection Plates on Particle Removal in Electrostatic Precipitators. *Chem. Eng. Res. Des.* **2023**, *197*, 323–333. [\[CrossRef\]](#)
16. Arif, S.; Branken, D.J.; Everson, R.C.; Neomagus, H.W.J.P.; Arif, A. The Influence of Design Parameters on the Occurrence of Shielding in Multi-Electrode ESPs and Its Effect on Performance. *J. Electrostat.* **2018**, *93*, 17–30. [\[CrossRef\]](#)
17. Chen, B.; Li, H.; He, Y.; Liu, B.; Zhang, L. Study on Performance of Electrostatic Precipitator under Multi-Physics Coupling. *Environ. Sci. Pollut. Res.* **2019**, *26*, 35023–35033. [\[CrossRef\]](#) [\[PubMed\]](#)
18. Zhou, W.; Jiang, R.; Sun, Y.; Chen, B.; Liu, B. Study on Multi-Physical Field Characteristics of Electrostatic Precipitator with Different Collecting Electrodes. *Powder Technol.* **2021**, *381*, 412–420. [\[CrossRef\]](#)
19. Boudjema, N.; Kherat, M.; Drouiche, N.; Mameri, N. Investigation of the Mechanisms of Escherichia Coli Cells Sterilization by the Application of an Electric Field. *Int. J. Environ. Sci. Technol.* **2019**, *16*, 6259–6266. [\[CrossRef\]](#)
20. Yan, B.; Nakamura, T.; Katsuki, S.; Masuda, N.; Shimizu, Y.; Sasahara, R.; Kurihara, J. Optimization of Co-Linear-Type Pulsed Electric Field Treatment Chamber for Milk Pasteurization. *J. Food Eng.* **2025**, *388*, 112373. [\[CrossRef\]](#)
21. Tian, Y.; Fan, W.; Lu, W.; Zhang, G.; Chang, Z. Structure Optimization of Pulsed Electric Field Processor and Its Sterilization Effect. *Food Qual. Saf.* **2024**, *8*, fyad044. [\[CrossRef\]](#)
22. Wang, L.-H.; Wang, M.-S.; Zeng, X.-A.; Liu, Z.-W. Temperature-Mediated Variations in Cellular Membrane Fatty Acid Composition of Staphylococcus Aureus in Resistance to Pulsed Electric Fields. *Biochim. Biophys. Acta Biomembr.* **2016**, *1858*, 1791–1800. [\[CrossRef\]](#) [\[PubMed\]](#)
23. Alvarez, I.; Pagan, R.; Raso, J.; Condon, S. Environmental Factors Influencing the Inactivation of Listeria Monocytogenes by Pulsed Electric Fields. *Lett. Appl. Microbiol.* **2002**, *35*, 489–493. [\[CrossRef\]](#)
24. Timmermans, R.A.H.; Nierop Groot, M.N.; Nederhoff, A.L.; van Boekel, M.A.J.S.; Matser, A.M.; Mastwijk, H.C. Pulsed Electric Field Processing of Different Fruit Juices: Impact of pH and Temperature on Inactivation of Spoilage and Pathogenic Micro-Organisms. *Int. J. Food Microbiol.* **2014**, *173*, 105–111. [\[CrossRef\]](#) [\[PubMed\]](#)
25. Sepulveda, D.R.; Guerrero, J.A.; Barbosa-Cánovas, G.V. Influence of Electric Current Density on the Bactericidal Effectiveness of Pulsed Electric Field Treatments. *J. Food Eng.* **2006**, *76*, 656–663. [\[CrossRef\]](#)
26. Zhou, J.; Hung, Y.-C.; Xie, X. Application of Electric Field Treatment (EFT) for Microbial Control in Water and Liquid Food. *J. Hazard. Mater.* **2023**, *445*, 130561. [\[CrossRef\]](#)
27. Heinz, V.; Toepfl, S.; Knorr, D. Impact of Temperature on Lethality and Energy Efficiency of Apple Juice Pasteurization by Pulsed Electric Fields Treatment. *Innov. Food Sci. Emerg. Technol.* **2003**, *4*, 167–175. [\[CrossRef\]](#)
28. Zukeran, A.; Sawano, H.; Ito, K.; Oi, R.; Kobayashi, I.; Wada, R.; Sawai, J. Investigation of Inactivation Process for Microorganism Collected in an Electrostatic Precipitator. *J. Electrostat.* **2018**, *93*, 70–77. [\[CrossRef\]](#)
29. Qi, M.; Liu, Y.; Shi, S.; Xian, Y.; Liu, Q.; Yan, H.; Zhang, Y.; Yuan, Y. Inhibition Mechanism of High Voltage Prick Electrostatic Field (HVPEF) on Staphylococcus Aureus through ROS-Mediated Oxidative Stress. *LWT* **2022**, *155*, 112990. [\[CrossRef\]](#)
30. Guo, B.Y.; Guo, J.; Yu, A.B. Simulation of the Electric Field in Wire-Plate Type Electrostatic Precipitators. *J. Electrostat.* **2014**, *72*, 301–310. [\[CrossRef\]](#)
31. Chen, B.; Li, S.; Guo, Y.; Li, H.; Zhou, W.; Liu, B. Research on Electrostatic Shielding Characteristics of Electrostatic Precipitator. *J. Air Waste Manag. Assoc.* **2022**, *72*, 331–345. [\[CrossRef\]](#)
32. Wang, Q.; Li, Y.; Sun, D.-W.; Zhu, Z. Enhancing Food Processing by Pulsed and High Voltage Electric Fields: Principles and Applications. *Crit. Rev. Food Sci. Nutr.* **2018**, *58*, 2285–2298. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Ma, X.Q.; He, K.; Lu, J.Y.; Xie, L.; Ju, Y.; Zhao, L.X.; Gao, W.S. Effects of Temperature and Humidity on Ground Total Electric Field under HVDC Lines. *Electr. Power Syst. Res.* **2021**, *190*, 106840. [\[CrossRef\]](#)
34. Schwan, H.P. Electrical Properties of Tissue and Cell Suspensions. In *Advances in Biological and Medical Physics*; Elsevier: Amsterdam, The Netherlands, 1957; Volume 5, pp. 147–209, ISBN 978-1-4832-3111-2.
35. Zimmermann, U. Electrical Breakdown, Electroporation and Electrofusion. *Rev. Physiol. Biochem. Pharmacol.* **1986**, *105*, 176–256. [\[CrossRef\]](#) [\[PubMed\]](#)

36. Sepulveda, D.R.; Góngora-Nieto, M.M.; San-Martin, M.F.; Barbosa-Cánovas, G.V. Influence of Treatment Temperature on the Inactivation of *Listeria Innocua* by Pulsed Electric Fields. *LWT Food Sci. Technol.* **2005**, *38*, 167–172. [\[CrossRef\]](#)
37. Magne, L.; Pasquiers, S.; Blin-Simiand, N.; Postel, C. Production and Reactivity of the Hydroxyl Radical in Homogeneous High Pressure Plasmas of Atmospheric Gases Containing Traces of Light Olefins. *J. Phys. D Appl. Phys.* **2007**, *40*, 3112–3127. [\[CrossRef\]](#)
38. Li, Z.; Yu, X.; Jiang, S.; Wang, Y.; Rao, J. Characteristics and Spectral Analysis of the Back-Corona Discharge Using Different Power Supplies. *IEEE Trans. Plasma Sci.* **2023**, *51*, 3123–3130. [\[CrossRef\]](#)
39. Dorval, A.; Geraud, K.; Valensi, F.; Hamdan, A. Statistical Analysis of Pulsed Spark Discharges in Water: Effects of Gap Distance, Electrode Material, and Voltage Polarity on Discharge Characteristics. *J. Vac. Sci. Technol. A* **2022**, *40*, 043006. [\[CrossRef\]](#)
40. Zhu, Y.; Tao, S.; Chen, C.; Liu, J.; Chen, M.; Shangguan, W. The Experimental and Simulation Investigation of the Dynamic Characteristic of Submicron-Scale Aerosol in High-Voltage Electric Field by a Visualization Method. *J. Hazard. Mater.* **2021**, *416*, 126227. [\[CrossRef\]](#)
41. Liu, L.; Gu, X.; Zhang, L.; Sun, T.; Cao, Z.; Yu, B.; Li, J.; Zhang, L.; Xu, W.; Bu, S.; et al. Experiment and Numerical Simulation Investigation on Wire-Plate Electrostatic Precipitator with Expanded-Shrunk Spoilers. *Powder Technol.* **2022**, *395*, 60–70. [\[CrossRef\]](#)
42. Shen, H.; Yu, W.; Jia, H.; Kang, Y. Electrohydrodynamic Flows in Electrostatic Precipitator of Five Shaped Collecting Electrodes. *J. Electrostat.* **2018**, *95*, 61–70. [\[CrossRef\]](#)
43. Yan, P.; Zheng, C.; Xiao, G.; Xu, X.; Gao, X.; Luo, Z.; Cen, K. Characteristics of Negative DC Corona Discharge in a Wire-Plate Configuration at High Temperatures. *Sep. Purif. Technol.* **2015**, *139*, 5–13. [\[CrossRef\]](#)
44. Zeng, M.; Qu, Z.; Zhang, J. Negative Corona Discharge and Flow Characteristics of a Two-Stage Needle-to-Ring Configuration Ionic Wind Pump for Temperature and Relative Humidity. *Int. J. Heat Mass Transf.* **2023**, *201*, 123561. [\[CrossRef\]](#)
45. Bi, M.; Zhang, S.; Zhang, S.; Jiang, C.; Lei, S.; Jiang, T. Numerical Simulation Study on the Influence of Temperature and Humidity on Streamer Discharge in Rod-Plane Air Gap. *IEEE Trans. Plasma Sci.* **2024**, *52*, 134–143. [\[CrossRef\]](#)
46. Stanley, D.W. Biological Membrane Deterioration and Associated Quality Losses in Food Tissues. *Crit. Rev. Food Sci. Nutr.* **1991**, *30*, 487–553. [\[CrossRef\]](#) [\[PubMed\]](#)
47. Jayaram, S.; Castle, G.S.; Margaritis, A. Kinetics of Sterilization of *Lactobacillus Brevis* Cells by the Application of High Voltage Pulses. *Biotechnol. Bioeng.* **1992**, *40*, 1412–1420. [\[CrossRef\]](#)
48. Zimmermann, U.; Pilwat, G.; Riemann, F. Reversible Dielectric Breakdown of Cell Membranes by Electrostatic Fields (Author's Transl). *Z. Fur Naturforschung. Sect. C Biosci.* **1974**, *29*, 304–305. [\[CrossRef\]](#)
49. Huo, Z.-Y.; Liu, H.; Yu, C.; Wu, Y.-H.; Hu, H.-Y.; Xie, X. Elevating the Stability of Nanowire Electrodes by Thin Polydopamine Coating for Low-Voltage Electroporation-Disinfection of Pathogens in Water. *Chem. Eng. J.* **2019**, *369*, 1005–1013. [\[CrossRef\]](#)
50. Chang, D.C.; Reese, T.S. Changes in Membrane Structure Induced by Electroporation as Revealed by Rapid-Freezing Electron Microscopy. *Biophys. J.* **1990**, *58*, 1–12. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Li, Z.; Cui, J.; Wei, Y.; Huang, Y.; Xie, H.; Yao, W. Calculation Study of Ion Flow Field in ± 800 kV Transmission Lines under the Effects of Air Pressure, Temperature, Humidity and Improvement Measures. *Electr. Power Syst. Res.* **2024**, *234*, 110574. [\[CrossRef\]](#)
52. Hu, Q.; Shu, L.; Jiang, X.; Sun, C.; Qiu, Z.; Lin, R. Influence of Air Pressure and Humidity on Positive Direct Current Corona Discharge Performances of the Conductor in a Corona Cage. *Int. Trans. Electr. Energy Syst.* **2014**, *24*, 723–735. [\[CrossRef\]](#)
53. Liu, H.; Wang, L.; Liao, R.; Zhao, X.; Hao, J.; He, G. Effect of Relative Humidity on the Surface Electric Field Intensity Characteristics under DC Voltage in a Corona Cage. *IEEE Trans. Dielectr. Electr. Insul.* **2021**, *28*, 888–896. [\[CrossRef\]](#)
54. Shen, N.; Su, Z.; Zhang, Y.; Lu, T. The Influence of Charge Characteristics of Suspension Droplets on the Ion Flow Field in Different Temperatures and Humidity. *Plasma Sci. Technol.* **2022**, *24*, 044004. [\[CrossRef\]](#)
55. Li, H.; Zhu, J.; Yang, W.; Zhang, X.; Wang, D.; Zhu, J.; Bian, X. Humidity Effects on the Ground-Level Resultant Electric Field of Positive DC Conductors. *Plasma Sci. Technol.* **2019**, *21*, 074001. [\[CrossRef\]](#)
56. Wang, X.; You, C. Effect of Humidity on Negative Corona Discharge of Electrostatic Precipitators. *IEEE Trans. Dielectr. Electr. Insul.* **2013**, *20*, 1720–1726. [\[CrossRef\]](#)
57. Aronsson, K.; Rönnér, U. Influence of pH, Water Activity and Temperature on the Inactivation of *Escherichia Coli* and *Saccharomyces Cerevisiae* by Pulsed Electric Fields. *Innov. Food Sci. Emerg. Technol.* **2001**, *2*, 105–112. [\[CrossRef\]](#)
58. Palou, E.; López-Malo, A.; Barbosa-Cánovas, G.V.; Welte-Chanes, J.; Swanson, B.G. High Hydrostatic Pressure as a Hurdle for *Zygosaccharomyces Bailii* Inactivation. *J. Food Sci.* **1997**, *62*, 855–857. [\[CrossRef\]](#)

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.