

Engineering Development of a Pulsed Electric Field System for Heavy Metal Reduction in Blood Clams (*Anadara Granosa*)

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ABSTRACT

Blood clams (*Anadara granosa*) are valuable seafood prone to heavy metal contamination, particularly iron (Fe) and lead (Pb). This study developed and evaluated a Pulsed Electric Field (PEF) system integrated

with an automatic conveyor as a non-thermal method to reduce heavy metals through electroporation. PEF treatment was applied at 10.5 kV/cm for 30, 60, and 90 s, and metal levels were analyzed using atomic absorption spectrophotometry. The 90-second treatment reduced Fe and Pb by 49.41% and 49.40%, respectively, without significantly affecting protein content ($p > 0.05$). Scanning Electron Microscopy (SEM) revealed electroporation with visible membrane pores. Phase-Resolved Partial Discharge (PRPD) analysis confirmed corona discharge within safe limits. The conveyor-based PEF prototype showed stable electrical and mechanical performance, minimal temperature rise, and efficient load handling. Overall, this solid-state cascade PEF system offers an energy-efficient and safe approach for reducing heavy metals in seafood while maintaining nutritional quality.

Keywords-Pulsed Electric Field (PEF); blood clams; electroporation; heavy metal; food

I. INTRODUCTION

Blood clams (*Anadara granosa*) are a valuable and affordable source of marine protein abundant in Indonesian waters. However, blood clams are highly susceptible to accumulating heavy metals such as iron (Fe) and lead (Pb) due to water pollution [1]. This accumulation of heavy metals not only reduces product quality and causes rejection in international trade but also poses serious long-term health risks, including neurological disorders, kidney damage, and cancer [2]. Various processing methods, such as depuration [3], bioremediation [4], chemical washing [5], and heat treatment [6], have been tested to reduce metal levels. However, these methods have shortcomings, such as altering physicochemical properties, and their application is still limited because they are inefficient, expensive, and challenging to adapt, especially for Small and Medium Industries (SMIs) [7].

Pulsed Electric Field (PEF) has emerged as one of the innovative non-thermal technologies that has the potential to address this issue. PEF works by delivering high-voltage electrical pulses over a short duration, which increases cell membrane permeability through electroporation. This mechanism has been applied to various food products for microorganism inactivation and salting [8], based on the principle of opening cell pores, which causes cell leakage. Therefore, electroporation provides a mechanism for reducing the metal content in blood clam meat. Generally, PEF systems operate at high currents (10–20 A) and an electric field >10 kV/cm [9]. However, high current poses safety risks, especially when applied in SMIs in Indonesia. The use of low currents, such as 2 A, also has the same potential benefits as shown in previous microbial reduction studies [10].

This study aims to design a simulation-based PEF system with a current strength of 2 A that is adapted to the actual conditions of the seafood processing industry, particularly blood clams. A conveyor system with a moving box-shaped chamber is applied to prevent the reabsorption of metals released from the shellfish tissue during the PEF treatment process. Evaluations are conducted on the performance of PEF with the conveyor system, the effectiveness of metal content reduction, protein level changes, and microstructure observations of the shellfish tissue resulting from the electroporation effect of PEF treatment.

II. RESEARCH METHOD

A. Materials and Equipment

The research materials consisted of fresh blood clams (average weight of 20–30 g/clam), obtained from Tegal Port, heavy metal standard solutions (Fe and Pb; Oxoid) for AAS calibration, phosphate buffer (pH 7; Oxoid), deionized water, and analytical reagents (concentrated HNO_3 , HCl, H_2O_2 ; Bratachem).

The generator was developed according to the circuit configuration proposed in [11]. The experimental setup also included conveyor design equipment, an atomic absorption spectrophotometer (AAS; Thermo Fisher), a UV-Vis spectrophotometer (Thermo Fisher), a histology microscope (Thermo Fisher), an analytical balance, a homogenizer, a pH meter, and centrifuge tubes, among others.

B. Research Design

This experiment consisted of two stages: (1) evaluating the effectiveness of PEF treatment in reducing the concentrations of Fe and Pb in blood clam tissue and assessing its effect on the protein content and microstructure of the tissue; and (2) designing a simulation-based PEF system with a treatment chamber integrated with a conveyor to simulate small-scale industrial processing conditions.

The PEF treatment was performed at an electric field strength of 10.5 kV/cm with exposure times of 30, 60, and 90 seconds.

1. Testing the Effect of PEF on Blood Clams

The first stage involved testing metal content reduction in blood clams using PEF. The metal content was determined by crushing ± 9 g of blood clam meat samples (3 clams without shells) into 350 mL of distilled water. The samples were then destroyed using HNO_3 , H_2O_2 , or HCl. The prepared samples were injected into an AAS to determine the Fe and Pb content. The total protein content of blood clams was determined using the Kjeldahl method in accordance with AOAC procedures [12]. Scanning Electron Microscope (SEM) images were taken based on a previous study with modifications [13]. Blood clam samples (1×1 cm) were taken from each treatment. The sections were placed in a Quorum E3100 drying cabinet at 45°C for 12 hours. Next, the samples were coated with 90% Au and 10% Pd using a Cressington Sputter Coater 108 Auto.

2. Designing PEF Conveyor Systems

The second stage began with the design of the PEF system, which included a conveyor system tailored to the needs of the

shellfish processing industry. The conveyor system design series is shown in Figure 1. Following the design phase, corona discharge and Phase-Resolved Partial Discharge (PRPD) at the electrodes were observed to assess potential temperature rises in the treatment chamber, supported by thermodynamic-based calculations [14].

$$\Delta T = \frac{Q}{m \cdot C_p} \quad (1)$$

where ΔT is the estimated temperature increase due to energy from electric current, Q is the total energy, m is the mass of the solution, and C_p is the specific heat capacity of salt solution.

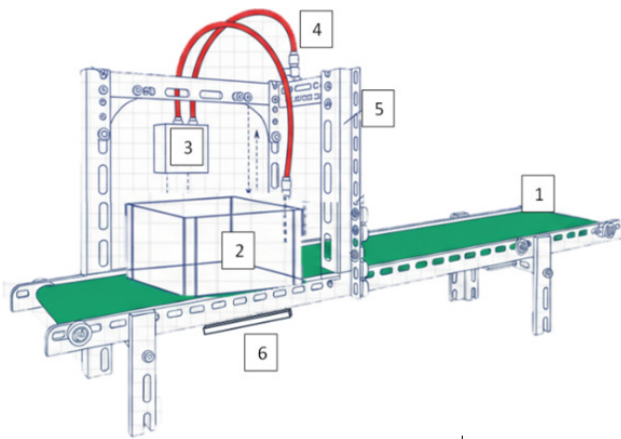


Fig. 1. Conveyor-based PEF system design showing its main components: (1) conveyor, (2) chamber, (3) proximity sensor, (4) cable electrode, (5) support frame, and (6) DC motor.

The mechanical performance of the proximity sensor-based conveyor system in the PEF unit was evaluated by testing its resistance to varying loads and by monitoring motor current, speed stability, temperature, and slippage during continuous operation. Tests were conducted using a single-factor design with load levels of 0%, 25%, 50%, 75%, and 100% of maximum capacity, each operated for 60 minutes at a constant conveyor speed of 0.3 m/s.

3. Statistical Analysis

The data were analyzed using SPSS software version 22. One-way analysis of variance (ANOVA) with a significance level of 95% ($\alpha = 0.05$) was used to evaluate the effect of electric field strength and treatment time on heavy metal reduction. Meanwhile, in the mechanical performance test, ANOVA was also used to analyze the effect of load level on each observed parameter.

III. RESULTS AND DISCUSSION

A. Evaluation of the Effect of PEF on Heavy Metal Reduction in Blood Clams

PEF treatment significantly reduced Fe and Pb levels in blood clams. The control sample contained 7.03 ± 0.7 ppm of Fe and 3.5 ± 0.3 ppm of Pb, while PEF treatment at 10.5 kV/cm for 30–90 seconds reduced the levels by 49.41% and 49.40%, respectively ($p < 0.05$). The metal reduction data are shown in Table I. In Tables I and II, the control sample

(without PEF treatment) is marked with an asterisk (*) and the difference in superscript numbers indicates a significant value.

Reduction efficiency increases with exposure duration, indicating a positive correlation between exposure time and the total electrical energy the tissue receives. The primary mechanism of metal reduction is associated with electroporation, in which high-voltage electrical pulses form temporary or permanent pores in the cell membrane, allowing Fe and Pb ions to diffuse out of the tissue. These results are consistent with the findings in [14], where the authors reported an increase in metal detoxification with increasing pulse duration. Overall, PEF at 10.5 kV/cm for 90 seconds has been proven effective as a low-energy green processing technology for heavy metal detoxification in fishery products.

TABLE I. REDUCTION OF METAL CONTENT IN BLOOD CLAMS

sample and treatment	metal content (ppm) per ± 9 grams of blood clams			
	iron (Fe)	decrease (%)	lead (Pb)	decrease (%)
Control*	7.03 ± 0.7^a	–	3.5 ± 0.3^a	–
PEF 10.5 kV/cm (30 second)	4.05 ± 0.6^b	42.46	2.014 ± 0.1^b	42.45
PEF 10.5 kV/cm (60 second)	3.8 ± 0.3^{bc}	45.93	1.89 ± 0.05^{bc}	45.90
PEF 10.5 kV/cm (90 second)	3.56 ± 0.1^c	49.41	1.77 ± 0.03^c	49.40

B. The Effect of PEF on Total Protein in Blood Clams

The protein content of blood clams after PEF treatment showed relatively stable values, ranging from 1.26 to 1.28 g per 9 g sample, similar to the control. The data show no significant difference ($p > 0.05$). This phenomenon aligns with the basic principle of PEF technology as a non-thermal method that aims to avoid protein denaturation due to heat. The effect of PEF on total protein content is shown in Table II.

TABLE II. EFFECT OF PEF ON TOTAL PROTEIN IN BLOOD CLAMS

Treatment	Protein Content (per ± 9 g)
Control*	1.281 ± 0.35^a
PEF 10.5 kV/cm (30 s)	1.277 ± 0.3^a
PEF 10.5 kV/cm (60 s)	1.26 ± 0.01^a
PEF 10.5 kV/cm (90 s)	1.26 ± 0.2^a

During the PEF process, a high-intensity electric field (kV/cm) creates an electroporation effect on cell membranes, releasing intracellular components without generating excessive heat. Since the process temperature is relatively low (usually $< 40^\circ\text{C}$), the tertiary and quaternary structures of proteins generally remain stable [15]. Similar results on fish meat [15] and shrimp [16] reported that PEF treatment up to 15 kV/cm did not cause significant changes in crude protein content. However, a slight decrease in average protein content in the 60- and 90-second PEF treatments may be attributed to the release of a portion of water-soluble (sarcoplasmic) protein fractions into the medium due to increased cell membrane

permeability. Nevertheless, these differences were not statistically significant and were still within the natural range of fluctuation in biological protein composition. These results confirm that PEF can be applied to blood clams without reducing protein content.

C. PEF Observation of Blood Clam Structure

SEM observations of blood clam tissue were conducted on control samples and samples treated with PEF for 90 seconds, as their protein levels did not show significant changes. The results are presented in Figure 2.

The SEM micrographs revealed apparent morphological differences between the control and PEF-treated samples. In the control (Figure 2(a)), the tissue surface appeared dense, homogeneous, and tightly closed micro-pores. This microstructure indicates the integrity of myofibrillar proteins and lipids without structural degradation, consistent with previous findings [16]. In contrast, the PEF treatment (Figure 2(b)) resulted in microcracks and voids, indicating electroporation and partial protein disruption due to high-intensity electric fields. This mechanism causes membrane charge redistribution, leading to the formation of temporary pores that increase cell permeability. A similar alteration in surface topography linked to partial protein denaturation due to PEF was reported in fish muscle [17]. Overall, while PEF treatment successfully reduced metal levels, it did not affect the protein content (Table II). Furthermore, it did not result in physical changes commonly observed in other bioremediation technologies [4] or acid-based treatments [5].

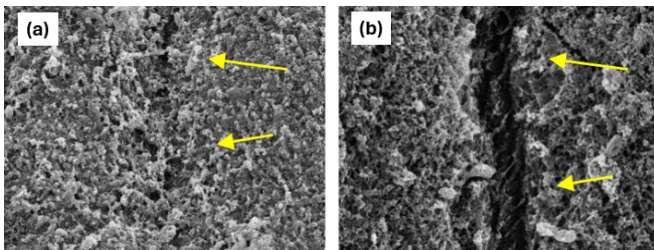


Fig. 2. Effect of PEF on shellfish meat structure: (a) control sample without treatment and (b) sample treated with PEF 10.5 kV/cm for 90 seconds.

D. Development of Conveyor-Based PEF Design

The PEF system comprises an electrical circuit and an automated conveyor to generate high-voltage pulses [18] and precisely control both the electric field and sample movement (Figure 3). The system operates on a 220 V AC electrical power supply (1). The AC voltage is stepped down via the CT transformer and rectified to 12 VDC by the rectifier module (2). This voltage is then stepped down to 5 VDC using a step-down DC-DC converter (3) to supply power to the frequency generator IC (4). The pulse frequency is set by a potentiometer (5), which affects the IC output signal. This signal is sent to the MOSFET driver (6), acting as a high-speed electronic switch. Activation of the MOSFET generates a high-voltage pulse in the inductor coil (7), which is fed to the treatment electrode. The distance between electrodes is adjusted using a slider motor (10) controlled by up (8) and down switches (9). The

system has a conveyor (12) and a proximity sensor (11) that stops sample movement during PEF exposure. The integration of the electrical system, frequency control, and automatic sensors enables efficient, safe, and uniform PEF operation for processing blood clams. The circuit design (components 1–12) facilitates integration into laboratory- or small-scale industrial systems and can be modified as needed.

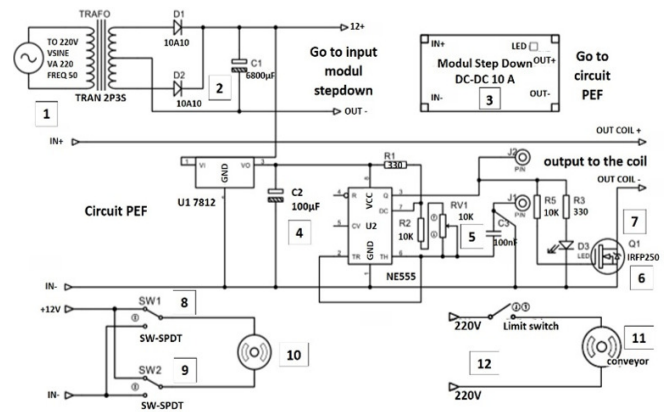


Fig. 3. Electrical circuit design of the conveyor system PEF. Key components are: (1) 220 V AC power supply, (2) AC-DC rectifier module, (3) 5 V step-down DC-DC converter, (4) frequency generator IC, (5) pulse frequency adjustment potentiometer, (6) MOSFET driver, (7) inductor coil, (8) up switch, (9) down switch, (10) slider motor for adjusting electrode distance, (11) proximity sensor, and (12) sample conveyor system.

E. Temperature Measurement and Corona Discharge of PEF Electrodes

Corona discharge observations were conducted to assess temperature rise in the treatment chamber, with results and thermodynamic comparisons shown in Figure 4. Differences between theoretical and experimental results arise from external factors like room temperature and electrode density, which are not included in the thermodynamic model. However, the temperature increase had no effect on PEF performance. Corona discharge tests also measured PRPD from the electrodes, as shown in Figure 5.

The PRPD data from the PEF electrodes showed point distributions in two main phase regions (60–120° and 240–300°), indicating corona discharge characterized by low charge amplitude (<100 °C) and repetitive patterns near voltage peaks. This phenomenon arises from air ionization at electrode edges with high electric field gradients, causing partial energy loss before reaching the food medium and potentially leading to electrode erosion, ozone generation, and insulation degradation [19]. The PRPD pattern indicates uneven electric fields from sharp or irregular electrodes. Despite low intensity, corona discharge must be controlled to ensure pulse stability and electrode longevity. Optimizing electrode design and using smooth conductors are essential, with PRPD analysis aiding in monitoring insulation and maintaining stable PEF performance.

F. Load Test Evaluation on the Conveyor System PEF

Increased load significantly impacts microcontroller-based conveyor performance, particularly motor current consumption, as shown in Table III. Different superscript letters in the same column indicate significant differences ($p < 0.05$). The current

increases linearly from 1.02 ± 0.09 A at 0% load to 5.17 ± 0.14 A at 100%, indicating a proportional relationship between torque and DC motor current [20, 21]. The conveyor speed decreased by only 4.7% from 0.300 ± 0.0047 m/s to 0.286 ± 0.0057 m/s, which is still within the mechanical system's operating tolerance [21]. The absence of slip indicates high power transmission efficiency and stable PWM control performance. The motor temperature increased moderately from 28.31 ± 2.60 °C to 40.89 ± 2.45 °C due to electrical power loss and internal friction, but it was still within the safe operating limits of the DC motor [22]. In summary, the system demonstrates good mechanical and thermal stability, supporting its integration into PEF units to ensure uniformity of electric field treatment and efficiency of food processing.

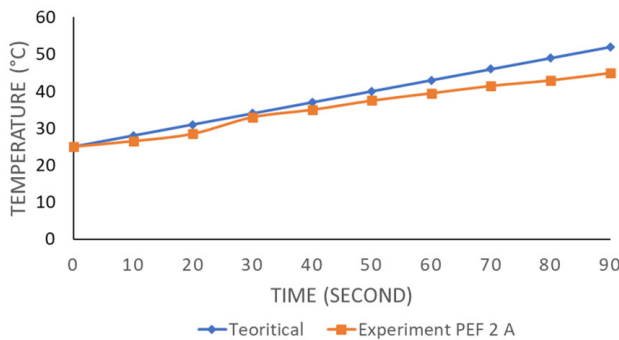


Fig. 4. Observation and calculation of temperature increase.

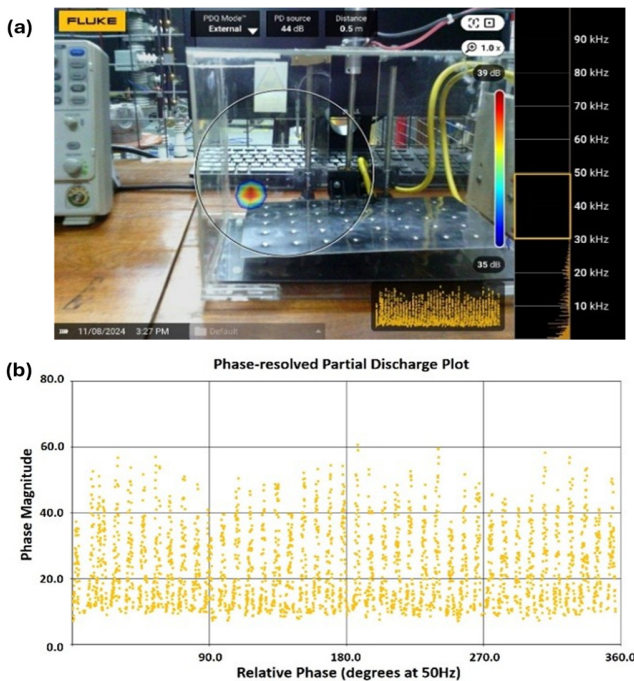


Fig. 5. (a) The appearance of the corona discharge phenomenon and (b) the PRPD pattern.

TABLE III. LOAD AND TORQUE TEST RESULTS OF CONVEYOR SYSTEM

Load (%)	Motor current (A)	Speed (m/s)	Motor temperature (°C)	Slip occurred
0	1.02 ± 0.09^c	0.300 ± 0.0047^a	28.31 ± 2.6^c	No
25	2.09 ± 0.12^d	0.297 ± 0.0052^a	31.45 ± 1.32^d	No
50	3.12 ± 0.13^c	0.293 ± 0.0041^{ab}	34.61 ± 0.15^c	No
75	4.17 ± 0.13^b	0.290 ± 0.0068^{bc}	37.83 ± 1.20^b	No
100	5.17 ± 0.14^a	0.286 ± 0.0057^c	40.89 ± 2.45^a	No

G. Cycle Time Production PEF Conveyor Prototype

The total cycle time of the PEF process using a prototype conveyor system for industrial simulation was recorded at 201 seconds (± 3.35 minutes), which includes the product preparation stage, automatic detection, electric field treatment of 10.5 kV/cm, washing and cold storage. PEF cycle time data are shown in Table IV.

The longest time was spent in the PEF application stage (100 seconds), indicating that the duration of electrical exposure is a significant factor of the process cycle. Integrating an automatic conveyor system with product detection sensors and electrode synchronization proved capable of minimizing the pause time between stages (transition only 2–5 seconds), increasing efficiency and continuity of operation. Thus, this conveyor-based PEF prototype demonstrated performance similar to industrial systems in terms of continuous flow, while also serving as an effective model for future production-scale testing.

TABLE IV. DATA CYCLE TIME PEF CONVEYOR PROTOTYPE

Process stage	Description of activity	Duration (second)
Product Preparation	Blood clam products placed in the chamber of the conveyor line.	60
Approach to PEF treatment room Zone	The product moves to the treatment chamber containing the lowered electrodes into the chamber.	5
Product Detection & Synchronization	Sensors detect the presence of product to lower the electrodes and trigger an electric field.	2
PEF Application (Treatment Zone)	The electric field is given an intensity of 10.5 kV/cm.	100
Exit the PEF Zone	Finished products after treatment	4
Washing, packaging process and cold storage entry	The products are collected, washed, and packed for cold storage	30

H. Specifications and Limitations of the PEF Conveyor Prototype

After completing all testing stages, the final design of the PEF prototype, with its specifications and components presented in Figure 6.

This solid-state cascade PEF system is compact and efficient, supporting its integration with an automatic conveyor for blood clam processing, and has the following specifications. This topology enables gradual voltage increases through semiconductor stages, improving efficiency, reducing switch voltage stress, and preventing reverse currents. The microcontroller-based conveyor allows continuous treatment of solid samples without significant temperature rise, which

enhances electric field uniformity and accelerates heavy metal reduction through electroporation. The system demonstrates greater stability and energy efficiency than transformer-based or Marx bank topologies [18]. Operating at 2 A, it provides a safe and effective non-thermal process for reducing metal contaminants in blood clam products.

However, the system still has limitations related to electrode durability under prolonged operation, potential corona discharge at high humidity, and the need for further optimization to scale up pulse uniformity and energy efficiency at larger industrial capacities.

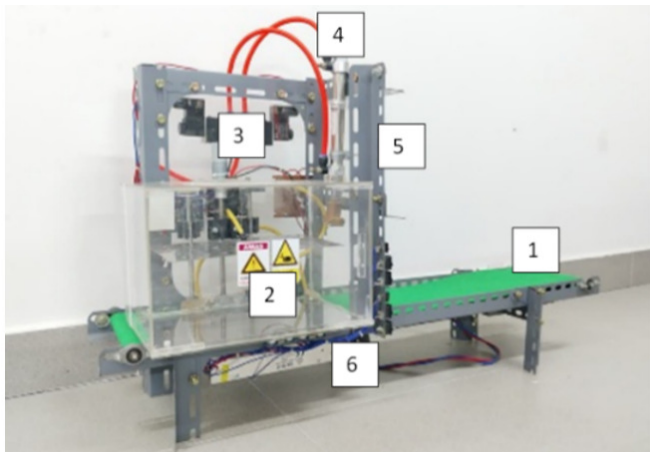


Fig. 6. PEF system conveyor prototype design showing its components: (1) conveyor, (2) chamber, (3) proximity sensor, (4) cable electrode, (5) support frame, and (6) DC motor.

TABLE V. COMPONENTS AND SPECIFICATIONS OF THE PEF SYSTEM CONVEYOR

Component	Specification
Conveyor Belt	Material: PVC; Thickness: 2.5 mm; Width: 100 mm; Hardness: Shore A80; Color: Green; Surface: Smooth/Glossy; Bottom Layer: Fabric; Tension for 1% Elongation: 8 N/mm; Temperature Range: -10°C to 80°C (maximum)
Electrode Chamber	Chamber Material: Clear acrylic, 4 mm thick Electrode Plate Material: Stainless steel Plate Type: Perforated plate Dimensions (L x W): 22×15 cm
Slider Motor	Voltage: 12 V DC; Speed: 35 RPM
Chamber Support	Material: Stainless steel
Electrode Separator	Material: Perforated gray angle bar, 1.15 mm thick
Power supply	Output Voltage: 12 V; Current: 10 A

IV. CONCLUSIONS

This study successfully developed and evaluated a Pulsed Electric Field (PEF) system integrated with an automatic conveyor for reducing heavy metals in blood clams (*Anadara granosa*). The PEF treatment at 10.5 kV/cm for 90 seconds effectively decreased Fe and Pb levels by 49.41% and 49.40%, respectively, without significantly affecting protein content ($p > 0.05$). Scanning Electron Microscopy (SEM) confirmed electroporation through visible microcracks and pore formation on cell membranes, facilitating metal ion release. Phase-Resolved Partial Discharge (PRPD) analysis revealed corona

discharge activity in two main phase regions, indicating uneven field distribution but within a safe operational range. The conveyor-based PEF prototype demonstrated stable electrical and mechanical performance, with minimal temperature rise, consistent torque, and speed stability under varying loads. These findings confirm that the designed solid-state cascade PEF system is safe, and adaptable for small and medium-scale seafood industries. In summary, this system offers a promising non-thermal technology for improving food safety by reducing heavy metal contamination while preserving the nutritional integrity of marine products.

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