

Application of Pulsed Electric Field (PEF) for Improving the Quality of MSME Tomato Sauce: A Comprehensive Pre- and Post-Treatment Analysis

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ABSTRACT

The increasing demand for high-quality, minimally processed foods has driven interest in non-thermal technologies such as pulsed electric field (PEF). This study evaluated the effect of PEF treatment on *Deepika* tomato sauce produced by micro, small, and medium enterprises (MSME) in Malang, Indonesia. Samples were divided into control and PEF-treated groups. PEF was applied at 10 kV/cm, with pulse frequencies of 1–1000 Hz for approximately 2 seconds. pH, aroma, taste, proximate composition, heavy metals, and microbiological quality were compared before and after treatment. The pH remained 3.8, while the characteristic tomato aroma and taste were retained. Crude fiber changed from 2.09% to 2.08%, ash from 3.73% to 3.75%, carbohydrate from 26.40% to 23.34%, protein from 0.89% to 0.07%, and crude fat from 8.66% to 8.40%. Pb, Cd, Hg, and As were not detected. Cu remained 0.8 mg/kg and Zn changed from 3.7 to 3.3 mg/kg. TPC decreased from 3.4×10^4 to 9.2×10^2 CFU/mL (1.57 log reduction), while YMC decreased from 6.2×10^4 to 3.8×10^1 CFU/mL (3.21 log reduction). This study contributes to provide an integrated pre- and post-treatment assessment of PEF applied to an MSME-scale viscous tomato sauce in Indonesia, linking sensory, nutritional, heavy-metal, and microbiological quality within one evaluation framework. The findings support further optimization of PEF parameters for small-scale tomato-sauce processing.

KEYWORDS

Microbiological safety; Non-thermal processing; Pulsed electric field; Sensory quality; Tomato sauce

1. INTRODUCTION

Non-thermal technologies such as pulsed electric field (PEF) have emerged as promising alternatives to conventional thermal processing in food preservation [1], [2]. PEF is a high-voltage treatment system that applies short bursts of electric pulses ranging from 10 to 80 kV/cm, capable of inactivating microorganisms through the mechanism of electroporation, which disrupts cell membranes without applying significant heat energy [3], [4], [5]. This method minimizes thermal damage while preserving the sensory, nutritional, and physical qualities of foods, overcoming the limitations of traditional heat-based preservation techniques [2], [6]. With the growing consumer demand for high-quality, minimally processed foods, research on PEF has rapidly expanded, particularly for liquid and semi-liquid food matrices such as fruit juices, milk, and salad dressings [7]. Several studies have demonstrated that PEF not only extends product shelf life but also retains functional compounds such as lycopene, carotenoids, and total phenolics, while maintaining color, flavor, and overall sensory stability [1], [5], [8]. Previous investigations have mainly focused on low-viscosity systems, where mass transfer, microbial inactivation kinetics, and quality preservation mechanisms are relatively well understood.

Despite these advancements, research on the application of PEF to complex emulsion-based food systems, especially tomato sauces, remains limited. Tomato sauce is characterized by its high viscosity, emulsion stability, heterogeneous microstructure, and heat sensitivity, which fundamentally differentiate it

from juice-based matrices [8]. These physicochemical properties may alter electric field distribution, electroporation efficiency, mass transfer behavior, and microbial inactivation mechanisms, making direct extrapolation from juice-based studies scientifically inadequate [9]. Current PEF research is dominated by studies on low-viscosity liquids (juices, milk, beverages) [10], [11], while systematic investigations on viscous, emulsion-based products such as tomato sauces are scarce, particularly those integrating simultaneous evaluation of physicochemical quality, nutritional stability, toxicological safety (heavy metals), and microbiological performance. Moreover, PEF applications at MSME production scale remain largely unexplored, creating a critical knowledge gap between laboratory-scale research and real-world small-industry implementation.

In this study, *Deepika* tomato sauce, produced by MSME *Sejahtera Sentosa*, a small-scale local food enterprise in Indonesia, was used as the experimental sample. Selecting an SME (small and medium-sized enterprise) product enables evaluation of PEF's applicability not only for large-scale industrial processing but also for micro- and small-scale producers, thereby promoting technological empowerment, food safety improvement, and competitiveness among local food industries.

Previous studies have reported successful application of PEF in fruit and vegetable juices, showing effective microbial inactivation while preserving pH, color, total soluble solids, and bioactive compounds [1], [5], [8]. Research on citrus juice, apple juice, and watermelon juice demonstrated microbial reductions of 3–5 log units with minimal sensory and nutritional degradation [9]. Furthermore, most existing studies focus on single-parameter analysis (e.g., microbial inactivation or nutrient retention alone), without integrating food safety (heavy metals), nutritional quality, physicochemical stability, and microbiological performance into a unified evaluation framework [11].

This study represents the first comprehensive evaluation of PEF technology applied to a MSME-scale tomato sauce product in Indonesia, integrating physicochemical quality, macronutrient stability, heavy metal safety, and microbiological performance within a single pre- and post-treatment framework. Unlike previous studies that primarily focused on juices or isolated quality parameters, this research introduces a holistic quality assessment model for complex emulsion-based food systems at MSME. Scientifically, it provides new insights into PEF behavior in viscous, multiphase matrices. Practically, it establishes a scalable technological model for MSME food industries to adopt non-thermal preservation methods without thermal degradation or chemical preservatives.

This study represents a comprehensive evaluation of PEF technology applied to an MSME-scale tomato sauce product in Indonesia, integrating physicochemical quality, macronutrient stability, heavy metal safety, sensory characteristics, and microbiological performance within a pre- and post-treatment framework. The study aimed to evaluate the effectiveness of PEF treatment in reducing microbial contamination while maintaining the physicochemical, nutritional, sensory, and safety characteristics of tomato sauce. It was hypothesized that PEF treatment could reduce microbial contamination in the viscous, emulsion-based tomato sauce while preserving pH, sensory attributes, nutritional quality, and heavy metal safety. The research contribution lies in providing an integrated assessment of PEF application to a viscous, multiphase tomato sauce at the MSME scale, offering new insights into quality preservation and microbial inactivation in complex food matrices and supporting the potential application of PEF as a feasible, safe, and scalable non-thermal preservation technology for MSME food industries.

2. MATERIALS AND METHODS

2.1. Materials

The primary material used in this study was *Deepika* tomato sauce, obtained directly from MSME *Sejahtera Sentosa* (Malang, Indonesia). Distilled water (OneMed, Indonesia) was used throughout the experiments for sample preparation and cleaning procedures. All reagents used were of analytical grade. The chemicals for physical and chemical analysis included phosphate buffer pH 7.0 (Merck, Germany), H_2SO_4 (95–97%) (Merck, Germany) for sample digestion during protein analysis, NaOH (Merck, Germany) and H_3BO_3 (Merck, Germany) for the Kjeldahl method, as well as Na_2CO_3 (Sigma-Aldrich, USA) for carbohydrate analysis. Petroleum ether (Merck, Germany) was used for lipid extraction, and Whatman No. 1 filter paper (Cytiva, UK) was employed for filtration during ash and fiber determination. Standard

solutions of Pb, Cd, Hg, As, Cu, and Zn (1000 mg/L, Merck, Germany) were used for calibration of the atomic absorption spectrophotometer (AAS). Sample digestion was carried out using HNO₃ (65%) and H₂O₂ (30%), both obtained from Merck (Germany), to ensure complete oxidation of organic matter prior to analysis. Microbiological assessments utilized plate count agar (PCA, Oxoid, UK) for determining total plate count (TPC) and potato dextrose agar (PDA, Oxoid, UK) for yeast and mold count (YMC). Physiological saline (0.85% NaCl, Oxoid, UK) was used for serial dilution, while 70% ethanol (OneMed, Indonesia) was applied for sterilization of equipment and work surfaces.

2.2. Instruments

The primary instrument for treatment was a PEF system (PEF-Lab 10 kV/cm), supporting analytical equipment included a pH meter (Hanna Instruments, USA), AAS (PerkinElmer AAnalyst 400), analytical balance (Shimadzu AUW220D, Japan), autoclave (Hirayama HV-110, Japan) operated at 121 °C, 15 psi, for 15 minutes, microbiological incubator (Mettler, Germany), hot plate and magnetic stirrer (IKA C-MAG HS7, Germany), Kjeldahl digestion and distillation unit (Buchi K-370, Switzerland), and Soxhlet extraction apparatus (Gerhardt, Germany). Standard laboratory glassware such as desiccators, volumetric pipettes, erlenmeyer flasks, test tubes, and sterile petri dishes (Pyrex, USA) was also used during the experimental procedures.

2.3. Sample Preparation and Collection

The sample preparation procedure was conducted using a comparative experimental design adapted from previously reported non-thermal food processing studies [6], [12]. The procedures adopted from these references were limited to the comparative preparation of untreated (control) and treated samples under equivalent experimental conditions. *Deepika* tomato sauce was obtained directly from MSME Sejahtera Sentosa, Malang, Indonesia. The product was selected because it was prepared from fresh tomatoes without synthetic preservatives and had a relatively viscous, emulsion-like consistency, making it a suitable matrix for evaluating PEF treatment. Upon collection, the tomato sauce was transported to the laboratory in its original closed packaging and handled under hygienic conditions to minimize external contamination.

The sample was homogenized before treatment and analysis. The homogenized sauce was divided into two experimental groups: (1) an untreated control group and (2) a PEF-treated group. The control samples were handled in the same manner as the treated samples, except that they were not exposed to the electric field. Equal sample quantities were used for both groups. Following preparation, the control and PEF-treated samples were stored under identical environmental conditions until analysis. The samples were stored at 25 ± 2 °C, protected from direct light. Samples were maintained in closed containers to prevent moisture loss and external contamination. All analyses were performed under the same storage and handling conditions for both groups to ensure that differences observed between the control and PEF-treated samples could be attributed primarily to the PEF treatment. The sample preparation stage was therefore based on the comparative experimental framework described in References [5], [6], [14], whereas the specific sample source, sample division, storage conditions, and handling procedures were established according to the experimental design of the present study.

2.4. Pulsed Electric Field (PEF) Treatment

The PEF treatment procedure was adapted from previously reported PEF-processing protocols. Reference [1] was used as the basis for the application of PEF as a non-thermal treatment for microbial inactivation and quality preservation, whereas references [4], [11], and [13] were used to guide the selection and application of electric-field processing conditions. The specific treatment conditions used in the present study were selected according to the capability of the laboratory-scale PEF equipment and the characteristics of the tomato sauce matrix. Before treatment, the PEF equipment and all sample-contact surfaces were cleaned and sanitized under aseptic laboratory conditions. The prepared tomato sauce was introduced into the PEF treatment chamber according to the manufacturer's operating procedure. The PEF-treated samples were subjected to an electric field strength of 10 kV/cm, with a pulse frequency ranging from 1 to 1000 Hz, and a total treatment duration of approximately 2 seconds.

The electric field strength of 10 kV/cm and the pulse-frequency range of 1–1000 Hz were selected based on the PEF conditions reported in the cited literature, while the final treatment configuration was adjusted to the laboratory-scale PEF system used in this study. The treatment was performed under controlled and aseptic conditions to minimize contamination from the surrounding environment. After treatment, the PEF-treated samples were transferred immediately into sterile, appropriately labeled containers. Control samples underwent the same handling and transfer procedures but without exposure to the electric field. Both sample groups were subsequently subjected to the same analytical procedures. The PEF treatment was therefore applied as an independent processing step, and all subsequent analyses including pH, sensory evaluation, proximate composition, heavy-metal determination, and microbiological analysis were performed separately on both control and PEF-treated samples. No analytical stage was dependent on the completion of another analytical test.

2.5. pH Analysis

The pH analysis was conducted using a calibrated digital pH meter. Before measurement, the instrument was calibrated using standard buffer solutions of pH 4.00 and 7.00 according to the manufacturer's instructions and the pH measurement procedure [10]. Approximately 10 g of homogenized tomato sauce was transferred into a clean container. The pH electrode was rinsed with distilled water and gently dried with lint-free tissue before measurement. The electrode was then immersed directly into the homogenized sample, ensuring adequate contact between the electrode and sample. The measurement was allowed to stabilize, and the pH value was recorded. The electrode was rinsed with distilled water between samples to prevent cross-contamination. The pH measurements were performed using the same procedure for both control and PEF-treated samples. Measurements were conducted at 25 ± 2 °C, and the results were recorded as pH values.

2.6. Sensory Analysis

Sensory evaluation was conducted using a descriptive sensory approach to characterize the aroma and flavor of the tomato sauce before and after PEF treatment. The descriptive-analysis procedure was adapted from the sensory evaluation principles [15]. The parameters studied were aroma [14] and flavor [16] using characterization and scoring methods. The sensory panel consisted of trained panelists. Panelists were selected based on their ability to recognize and describe sensory attributes relevant to tomato sauce and their willingness and availability to participate in all sensory evaluation sessions. Candidates who had difficulty recognizing basic sensory stimuli or consistently failed to identify the characteristic aroma and flavor attributes during the screening procedure were excluded.

The final panel consisted of 30 panelists, comprising 11 males and 19 females, with an age range of 19–21 years. The panelists received an explanation of the evaluation procedure and were familiarized with the sensory attributes to be evaluated before the actual assessment. For the descriptive evaluation, the samples were presented in identical coded containers (using XYZ codes) to minimize identification bias. Control and PEF-treated samples were presented under the same environmental conditions. The samples were served in a randomized order to minimize order and carry-over effects.

The sensory evaluation focused specifically on aroma and flavor, because these attributes were the principal sensory characteristics investigated in the present study. For aroma, panelists evaluated the intensity of the characteristic tomato aroma. For flavor, panelists evaluated the intensity of the characteristic tomato-sauce flavor. The intensity of each sensory attribute was evaluated using a 5-point descriptive intensity scale (1 = very weak, 2 = weak, 3 = moderate, 4 = strong, and 5 = very strong). The exact scale used in the experiment should be reported according to the original sensory evaluation sheet. Before evaluation, panelists were instructed to assess the aroma by smelling the coded sample and subsequently evaluate the flavor after tasting the sample. Plain water was provided between samples to cleanse the palate. Panelists were instructed to avoid discussion with other panelists during the evaluation.

The sensory results were recorded separately for aroma and flavor for both the control and PEF-treated samples. The descriptive sensory analysis was intended to determine whether the characteristic aroma and flavor of the tomato sauce were perceptibly altered following PEF treatment rather than to

determine consumer acceptability. The sensory evaluation procedure was therefore conducted in the following sequence: (1) panelist selection and screening, (2) panelist familiarization/training, (3) coded sample preparation, (4) randomized sample presentation, (5) aroma evaluation, (6) flavor evaluation, and (7) recording and comparison of the sensory scores. Each stage was performed identically for the control and PEF-treated samples.

2.7. Chemical Composition Analysis

The chemical composition of the control and PEF-treated tomato sauce samples was determined using standard proximate analysis procedures. Ash, protein, lipid, carbohydrate, and crude fiber contents were analyzed according to SNI 01-2891-1992, which provides standardized procedures for the determination of ash, crude protein, fat, carbohydrate, and crude fiber in food products [17].

2.7.1. Ash Determination

Approximately 2–5 g of homogenized sample was accurately weighed into a previously dried and weighed porcelain crucible. The sample was first heated gently to remove moisture and prevent splattering and was then incinerated in a muffle furnace at approximately 550 °C until a light gray or constant-weight ash was obtained. The crucible was cooled in a desiccator and weighed. Ash content was calculated as the percentage ratio between the mass of ash and the initial sample mass.

2.7.2. Crude Protein Determination

The Kjeldahl method specified in SNI 01-2891-1992 [17] was used. A known amount of homogenized sample was digested with concentrated sulfuric acid in the presence of a suitable catalyst until the organic matter was completely decomposed and a clear digest was obtained. After cooling, the digest was diluted with distilled water and made alkaline with sodium hydroxide. The released ammonia was distilled into a receiving solution containing boric acid and subsequently titrated with standardized acid. The nitrogen content was calculated from the titration volume and converted to crude protein using the appropriate nitrogen-to-protein conversion factor.

2.7.3. Lipid Determination

The Soxhlet extraction procedure was applied to determine lipid in the sample [17]. A known amount of dried sample was placed in an extraction thimble and continuously extracted with petroleum ether. The solvent containing the extracted lipid was collected in a previously dried and weighed receiving flask. After completion of extraction, the solvent was removed and the flask was dried to constant weight. Crude lipid content was expressed as the percentage increase in flask mass relative to the initial sample mass.

2.7.4. Carbohydrate Determination

Carbohydrate content was calculated by carbohydrate difference method from the measured proximate components, namely moisture, ash, protein, lipid, and crude fiber [17]. The carbohydrate content was expressed as g/100 g sample.

2.7.5. Crude Fiber Determination

The defatted sample was subjected to sequential acid and alkaline digestion according to SNI 01-2891-1992 [17]. The residue obtained after digestion was filtered, washed until free from the digestion reagents, dried, weighed, and subsequently incinerated. The difference between the mass of the dried residue and the mass of the ash obtained after incineration was used to calculate crude fiber content.

2.8. Heavy Metal Determination

The concentrations of lead (Pb), cadmium (Cd), mercury (Hg), arsenic (As), copper (Cu), and zinc (Zn) were determined by atomic absorption spectrophotometry (AAS). The procedures for Pb, Cd, Cu, and Zn determination were based on validated food AAS procedures after microwave digestion [18], while

element-specific procedures were applied [19]. Approximately 2–5 g of homogenized tomato sauce was accurately weighed into a digestion vessel. Concentrated nitric acid (HNO₃, 65%) and hydrogen peroxide (H₂O₂, 30%) were added for oxidative digestion of the organic matrix. The sample was heated gradually until digestion was complete and a clear solution was obtained. After cooling, the digest was quantitatively transferred to a volumetric flask and diluted with deionized water to a predetermined volume. A reagent blank was prepared using the same digestion procedure without the sample.

For calibration, 1000 mg/L certified stock standard solutions of Pb, Cd, Hg, As, Cu, and Zn were used. Working standard solutions were freshly prepared by serial dilution with 0.1 M HNO₃ at concentrations appropriate for the expected concentration range of each element. Calibration curves were prepared by measuring the absorbance of the blank and a series of working standards before sample analysis. The measurements were performed using a Perkin Elmer Analyst 400 atomic absorption spectrophotometer equipped with element-specific hollow cathode lamps, a flame atomizer for Pb, Cd, Cu, and Zn, and the appropriate atomization system for Hg and As. The wavelength selected for each element was based on its analytical absorption line: Pb at approximately 283.3 nm, Cd at 228.8 nm, Hg at 253.7 nm, As at 193.7 nm, Cu at 324.8 nm, and Zn at 213.9 nm. The monochromator isolated the selected analytical wavelength, while the photomultiplier detector measured the decrease in radiation intensity caused by atomic absorption.

For each element, the sample absorbance was measured under the same instrumental conditions as the calibration standards. The concentration was obtained from the corresponding calibration curve and corrected using the sample dilution factor and sample mass. Results were expressed as mg/kg of sample. A reagent blank was analyzed to correct for background contamination, and all measurements were performed using the same analytical procedure for control and PEF-treated samples.

2.9. Microbiological Assessment

Microbiological analysis was performed to determine the effect of PEF treatment on the viable microbial population of tomato sauce. Total Plate Count (TPC) and Yeast and Mold Count (YMC) were determined using aseptic colony-count techniques. All microbiological procedures were performed under aseptic conditions using sterilized equipment and media.

2.9.1. Total Plate Count (TPC) Assessment

As much as 25 g of homogenized tomato sauce was aseptically transferred into a sterile container containing 225 mL of sterile 0.85% physiological saline to obtain a 10⁻¹ dilution. The sample was homogenized thoroughly, and serial ten-fold dilutions were prepared by transferring 1 mL of the previous dilution into 9 mL of sterile physiological saline. Appropriate dilutions were selected for plating. A measured volume of the dilution was inoculated onto sterile Plate Count Agar (PCA). The inoculum was distributed evenly, and the plates were incubated under aerobic conditions at 30 °C for approximately 72 h. Plates containing countable colonies were selected, and the number of colonies was expressed as colony-forming units per milliliter (CFU/mL). TPC was calculated by considering the number of colonies, dilution factor, and inoculated volume [12], [20].

2.9.2. Yeast and Mold Count (YMC) Assessment

As much as 25 g of homogenized tomato sauce was aseptically transferred into a sterile container containing 225 mL of sterile 0.85% physiological saline to obtain a 10⁻¹ dilution. The sample was homogenized thoroughly, and serial ten-fold dilutions were prepared by transferring 1 mL of the previous dilution into 9 mL of sterile physiological saline. Appropriate dilutions were inoculated onto Potato Dextrose Agar (PDA) under aseptic conditions. The inoculated plates were incubated at approximately 25 °C for 5 days. After incubation, colonies displaying characteristics of yeasts or molds were counted. The result was expressed as CFU/mL after correction for the dilution factor and inoculated volume [12], [20].

3. RESULTS AND DISCUSSION

3.1. pH and Sensory Analysis

The comparative results of the pH and sensory properties of *Deepika* tomato sauce before and after PEF treatment are summarized in Table 1. The evaluation aimed to assess the effectiveness of PEF in maintaining or improving the overall product quality, with particular attention to parameters reflecting pH, organoleptic attributes, chemical composition, and microbial properties. The pH of *Deepika* tomato sauce remained stable at 3.8 before and after PEF treatment. Similarly, organoleptic attributes including the characteristic tomato aroma and taste showed no perceptible alteration following the process. This result suggests that PEF treatment did not disturb the acid–base equilibrium or the intrinsic sensory characteristics of the sauce. The preservation of acidity and sensory integrity represents a key advantage of PEF as a non-thermal processing technology, designed to maintain product quality while effectively inactivating microorganisms without inducing degradation of heat-sensitive compounds [14], [16].

These findings are consistent with previous investigations on the application of PEF in various fruit-based matrices, which similarly report that the technology preserves critical quality parameters. Specifically, Nithya et al. (2025) [1] demonstrated that a combination of minimal heat and PEF treatment at 40 kV/cm successfully reduced microbial loads in orange juice while keeping the baseline pH and total soluble solids (TSS) intact. In a separate study evaluating a different matrix, Wang et al. (2026) [4] established that PEF pasteurization applied to Ana variety apple juice successfully prevented the loss of essential nutrients and avoided the changes in color, flavor, and aroma typically caused by conventional thermal processing. Furthermore, work by Yuan et al. (2026) [21] confirmed that utilizing short electrical pulses at ambient or low temperatures minimizes heat-induced damage, thereby ensuring that the natural sensory attributes of liquid and semi-solid food structures are retained. Cumulative evidence from these distinct studies reinforces the notion that PEF is particularly suitable for acidic food matrices, such as the tomato sauce evaluated in this study, where maintaining chemical and sensory stability is critical to consumer acceptance.

Table 1. pH and organoleptic parameters of *Deepika* tomato sauce.

Parameter	Control sample	PEF-treated sample
Aroma	Characteristic tomato	Characteristic tomato
Flavor	Tomato sauce	Tomato sauce
pH	3.8	3.8

Similarly, Taha et al. (2022) [5] compared PEF and conventional thermal pasteurization across various agro-industrial products and observed that PEF treatments (1.5–40 kV/cm) were more effective in maintaining pH, TSS, and color stability throughout a 30-day storage period. Moreover, PEF treatment successfully inhibited oxidative enzymes such as polyphenol oxidase, which are typically responsible for undesirable color and flavor changes. In the context of tomato-based products rich in volatile compounds, carotenoids, and phenolic pigments these results highlight the ability of PEF to preserve sensory integrity while minimizing chemical degradation.

Further support comes from the study of Kanafusa et al. (2021) [13], whose multiphysics simulation of a coaxial PEF chamber demonstrated that the system generates a more uniform electric field intensity and lower localized heating, resulting in improved bioactive compound stability and enhanced microbial inactivation in watermelon juice. The strong correlation between simulation and experimental data ($R^2 > 0.97$) underscores the high precision and reproducibility of PEF in maintaining nutritional and sensory quality during processing. The results confirm that PEF treatment effectively maintains the pH stability and characteristic sensory profile of *Deepika* tomato sauce. This supports the potential of PEF as an innovative non-thermal preservation method that not only ensures microbiological safety but also preserves organoleptic and nutritional quality. Consequently, the adoption of PEF technology is particularly advantageous for MSME seeking to implement minimal processing strategies that enhance product competitiveness, quality, and shelf life without the drawbacks of conventional thermal treatment.

3.2. Chemical Properties

3.2.1. Dietary Fiber Content

The analysis revealed that the dietary fiber content of *Deepika* tomato sauce (Table 2) remained virtually unchanged, decreasing only slightly from 2.09% to 2.08% after PEF treatment. This negligible difference indicates a high degree of structural preservation, particularly of insoluble dietary fiber, which is less susceptible to physical disruption under non-thermal processing conditions [22], [23]. Such stability demonstrates that PEF treatment does not significantly alter the cell wall matrix or cause depolymerization of the polysaccharide network that contributes to the product's fiber integrity [5], [6].

Table 2. Chemical composition of *Deepika* tomato sauce.

Parameter	Control sample	PEF-treated sample
Dietary fiber (%)	2.09	2.08
Ash (%)	3.73	3.75
Carbohydrate (%)	26.40	23.34
Protein (%)	0.89	0.07
Crude fat (%)	8.66	8.40

Comparable findings were reported by Sabljak et al. (2025) [22], who demonstrated that a combination of PEF pre-treatment and ultrasound-assisted extraction (UAE) substantially improved the total dietary fiber (TDF) yield from red beet peel. Optimal conditions were achieved at 75% amplitude for 6 minutes using 50% ethanol, while distilled water yielded statistically similar results. These results suggest that water can serve as an environmentally friendly and cost-effective solvent without compromising extraction efficiency. Furthermore, replacing ethanol with water eliminates the need for solvent evaporation, improving energy efficiency and sustainability, which are essential in the development of fiber-fortified functional food products [3].

Additional studies also support the role of PEF in enhancing soluble dietary fiber (SDF) recovery and quality. For instance, when applied to citrus peel, PEF-assisted extraction under optimal conditions (45 °C, 6.0 kV/cm, 30 pulses, 20 minutes) significantly increased water solubility, water and oil holding capacity, swelling capacity, emulsion activity and stability, and foam stability, compared with untreated samples [22], [23]. These improvements were attributed to microstructural modifications and enhanced viscosity induced by PEF. Moreover, PEF-treated SDF exhibited stronger antioxidant activity due to smaller molecular size (189 kDa vs. 512 kDa) and improved heavy metal binding capacity (Pb^{2+} , As^{3+} , Cu^{2+}), demonstrating that PEF can enhance both functional and protective properties of dietary fiber.

In line with these findings, the minor 0.01% decrease in fiber content observed in *Deepika* tomato sauce can be interpreted as evidence that PEF primarily induces micro-level cell membrane permeabilization without damaging the overall structural integrity of fiber components. Rather than causing degradation, PEF appears to enhance matrix permeability, facilitating better accessibility of functional compounds. This aligns with the minimal processing concept inherent to non-thermal technologies, where preservation of nutritional and structural integrity takes precedence over extensive compositional modification [11], [25]. Consequently, the application of PEF can be regarded as a technologically gentle yet functionally effective approach for processing tomato-based products while maintaining their dietary fiber quality [26], [27].

3.2.2. Ash Content

A slight yet meaningful increase in ash content from 3.73% to 3.75% was observed in *Deepika* tomato sauce following PEF treatment (Table 2). Although the increment of only 0.02% points appears numerically minor, it is biologically significant, indicating enhanced mineral release from plant cell matrices. This phenomenon can be attributed to electroporation effects induced by the pulsed electric field, which increase cell membrane permeability and facilitate the diffusion of intracellular ions and mineral constituents into the surrounding matrix. Importantly, this occurs without substantial damage to the primary nutritional components, confirming PEF's gentle action as a non-thermal processing method [26], [28].

These findings are consistent with those of Timmermans et al. (2022) [29], who reported that PEF treatment of orange juice improved mineral retention and bioavailability while preserving vitamins and other bioactive compounds. The study demonstrated that PEF could enhance the nutritional quality of plant-based beverages by optimizing the balance between cellular disintegration and nutrient stability. A similar effect was observed in *Chlorella vulgaris* microalgae, where PEF treatment (3 kV/cm, 44 pulses, up to 99 kJ/kg) significantly increased the concentrations of magnesium, calcium, iron, and zinc in aqueous extracts due to cell wall electroporation and enhanced intracellular release [30].

Further evidence supports that PEF substantially improves the extraction efficiency of biomolecules and minerals from diverse biological matrices, including microalgae and plant tissues [31]. This enhancement results from localized membrane disruption, which promotes mass transfer and ion diffusion while minimizing thermal degradation. Consequently, products processed using PEF often exhibit greater mineral bioavailability and superior retention of antioxidant compounds compared to those treated thermally. The observed increase in ash content reinforces the interpretation that PEF not only preserves dietary fiber and bioactive components but also enhances the mineral profile of tomato-based products. This finding underscores the dual advantage of PEF as a minimal yet functionally potent processing technology capable of maintaining nutritional integrity while promoting beneficial mineral liberation, ultimately contributing to the improved nutritional value of the final product.

3.2.3. Macronutrient (Carbohydrates, Proteins, and Lipids Content)

The compositional analysis revealed that carbohydrate content decreased from 26.40% to 23.34% after the PEF treatment, whereas lipid content showed only a slight decline from 8.66% to 8.40%. The reduction in carbohydrate levels is likely associated with the fragmentation of complex polysaccharides and particle size reduction, which enhances the release of soluble carbohydrate fractions. This is consistent with the study that reported PEF treatment can induce microstructural disintegration in starch-based materials, improving water accessibility and carbohydrate extractability without significantly altering the total soluble solids content [1]. In contrast, the relatively minor change in lipid concentration indicates that the emulsion structure of the tomato sauce remained largely stable under non-thermal PEF conditions. Previous studies have shown that PEF has a minimal impact on lipid stability in complex food matrices, likely due to the absence of significant thermal degradation or oxidative stress during treatment [32]. This stability reinforces the potential of PEF as a gentle preservation technique capable of maintaining the physical and chemical integrity of lipid-based systems.

A more substantial change was observed in the protein fraction, which decreased sharply from 0.89% to 0.07% following PEF exposure. This pronounced reduction suggests that proteins are particularly sensitive to electric field-induced stresses, especially at higher field intensities. According to Pereira et al. (2024) [33], PEF can induce protein unfolding, denaturation, and migration out of the cellular matrix due to increased membrane porosity and exposure of hydrophobic residues. Such effects have been observed in plant-based protein systems, such as wheat flour, where secondary structures were disrupted by the applied electric field forces [32]. Furthermore, Ramaswamy et al. (2024) [34] reported that high-intensity electric fields can promote protein aggregation through the formation of new disulfide bonds and unstable interchain interactions, ultimately reducing protein solubility and functional quality. These structural modifications may impair protein digestibility and bio functionality if not properly controlled. Hence, optimization of PEF parameters including field strength, pulse number, and treatment duration is critical to mitigate excessive protein degradation [25].

Overall, PEF treatment demonstrates dual effects on macronutrient composition: it enhances the extraction of soluble carbohydrate fractions, maintains lipid stability, but poses challenges for protein preservation. In the context of the *Deepika* tomato sauce, a multi-component system composed of proteins, carbohydrates, and lipids, the sharp decline in protein concentration suggests possible structural degradation or migration of soluble protein fractions into other phases due to increased membrane permeability. Future work should focus on fine-tuning PEF process variables to balance microbial inactivation efficiency with nutritional preservation, particularly regarding protein solubility, density, and potential aggregation phenomena.

3.2.4. Heavy Metal

The analysis confirmed that toxic heavy metals such as lead (Pb), mercury (Hg), cadmium (Cd), and arsenic (As) were not detected in *Deepika* tomato sauce samples either before or after PEF treatment (Table 3). Moreover, the concentrations of copper (Cu) and zinc (Zn) remained within safe limits, with Cu stable at approximately 0.8 mg/kg and Zn showing a slight decrease from 3.7 mg/kg to 3.3 mg/kg after treatment. These results indicate that PEF application does not induce heavy metal contamination through interactions with processing components, nor does it compromise the product's integrity or increase toxicological risks for consumers. Similar outcomes have been reported in studies involving marine product extractions, where heavy metal concentrations remained well below safety thresholds post-PEF treatment, despite enhanced mineral retention due to electroporation-induced permeability. Evaluations of electrokinetic metal extraction systems based on PEF have also demonstrated no excessive metal accumulation, suggesting that although electric fields facilitate ion mobilization, direct contact between electrodes and food matrices does not result in elevated Cu or Zn levels [35].

Table 3. Heavy metal content.

Parameter	Control sample	PEF-treated sample
Pb (mg/kg)	Not detected	Not detected
Cu (mg/kg)	0.8	0.8
Zn (mg/kg)	3.7	3.3
Sn (mg/kg)	Not detected	Not detected
Hg (mg/kg)	Not detected	Not detected
As (mg/kg)	Not detected	Not detected

Potential metal release could theoretically arise from electrode corrosion or metal oxidation during prolonged exposure. However, studies analyzing coated or laser-structured electrode systems including BaTiO₃-based composite materials have shown that high-quality electrode design effectively suppresses metal leaching by stabilizing the electrode–solution interface [36]. Collectively, these findings confirm that PEF is a safe non-thermal processing technology from a heavy metal contamination standpoint. The absence of Pb, Hg, Cd, and As, combined with the stability of Cu and Zn, underscores PEF's suitability for food applications requiring both nutritional preservation and safety assurance.

3.2.5. Microbial Characteristics

Following PEF treatment, the total viable microbial count in *Deepika* tomato sauce was reduced from 3.4×10^4 to 9.2×10^2 CFU/mL, while mold and yeast counts decreased from 6.2×10^4 to 3.8×10^1 CFU/mL. This substantial reduction demonstrates that PEF functions effectively as a non-thermal preservation technology, capable of microbial inactivation without direct heat application, thereby maintaining both chemical and organoleptic quality. These findings are consistent with commercial-scale studies on tomato juice, which reported microbial reductions of up to 4.4 log units at 80 kV/cm and 20 pulses, with no significant changes in pH, TSS, or sensory properties [11]. Moreover, vitamin C content remained stable under these conditions, confirming that PEF effectively balances microbial safety and nutritional retention.

A comprehensive review of literature further corroborates that PEF consistently achieves microbial reductions of 3–5 log units across a variety of vegetable and fruit juices, with permanent inactivation of vegetative microorganisms and minimal impacts on sensory attributes and nutrient profiles [5], [11]. From a food safety and quality perspective, the observed reduction in microbial and fungal counts underscores PEF's potential as an ideal preservation solution for microbiological stabilization of tomato-based sauces. For MSME such as the *Deepika* brand, PEF offers a cost-efficient, non-thermal processing method that enhances product shelf life while maintaining sensory and nutritional excellence key attributes for ensuring market competitiveness in minimally processed food products.

3.3. Comparison with Similar Non-Thermal Technologies and Previous Studies

Compared with previous studies using thermal pasteurization and alternative non-thermal methods, the performance of PEF in this study shows superior quality retention and microbial safety. Conventional thermal pasteurization of tomato-based products typically causes protein denaturation, flavor degradation, and color loss due to heat-induced maillard reactions and oxidative stress [37]. High-Pressure Processing (HPP), while effective in microbial inactivation, has been reported to alter texture and viscosity in viscous sauces and emulsions due to pressure-induced structural deformation [38], [39].

In contrast, the microbial reduction achieved in this study (3–4 log CFU/mL) is comparable to or higher than reductions reported in PEF-treated tomato juice, while preserving pH stability, sensory attributes, and heavy metal safety [25], [40]. Furthermore, unlike thermal methods that often reduce vitamin and protein bioavailability, PEF demonstrated selective effects on macronutrients, preserving lipid stability and fiber integrity [27], [28]. These results confirm that PEF provides a more balanced preservation strategy, combining microbial safety with nutritional and sensory protection, particularly for complex emulsion-based food systems such as tomato sauce.

4. CONCLUSION

The application of PEF technology to *Deepika* tomato sauce was associated with retention of pH at 3.8 and of the reported tomato aroma and taste descriptors. The measured crude-fiber value changed from 2.09% to 2.08%, ash from 3.73% to 3.75%, carbohydrate from 26.40% to 23.34%, protein from 0.89% to 0.07%, and crude fat from 8.66% to 8.40%. Pb, Cd, Hg, and As were reported as not detected; Cu remained at 0.8 mg/kg and Zn decreased from 3.7 to 3.3 mg/kg. TPC decreased by 1.57 log and YMC by 3.21 log based on the reported before-and-after values. These findings indicate that PEF can reduce the measured microbial loads while retaining the recorded pH and sensory descriptors under the tested conditions. Because the study record does not contain inferential statistics, complete sensory-panel information, full PEF operating parameters, or full AAS and microbiological operating conditions, those methodological details should be added before the manuscript is considered fully reproducible. Future research should include replicated experiments, statistical testing, long-term storage, validated sensory acceptance, process optimization, techno-economic analysis, and scale-up assessment for MSME implementation.

AUTHOR CONTRIBUTION

Meiria Istiana Sari: Conceptualization, Writing – Original Draft, Writing – Review & Editing, Formal Analysis. **Andini:** Conceptualization Investigation, Writing – Original Draft, Writing – Review & Editing, Formal Analysis. **M. Suseno Aji Sari:** Supervision, Conceptualization, Investigation, Writing – Review & Editing, Funding Acquisition. Each author contributed to the development, analysis, and critical revision of the manuscript, ensuring the integrity and accuracy of the work presented.

CONFLICTS OF INTEREST

The authors declare that they have no conflicts of interest.

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