Wiley Online Library

ChemBioEng Reviews

Trends, Recent Advances, and Application of Pulsed Electric Field in Food Processing: A Review

Zina T. Alkanan[1], Ammar B. Altemimi[1,2], Mohamed Ibrahim Younis[3], Marwa Rashad Ali[3], Francesco Cacciola[4],*, Tarek Gamal Abedelmaksoud[3],*

Supporting Information available online

Abstract

Generally, thermal inputs dominate the food processing industry for food preservation. Pulsed electric field (PEF) is one of the most promising nonthermal microorganism-killing techniques. The most important factors in PEF processing are electric field strength and treatment duration. At the laboratory level, encouraging results are reported; however, industrialization raises the cost of the command charging power supply and the high-speed electrical switch. In this review, the results of previous experimental studies on PEFs and proposed future research directions in this field are discussed. There is currently no successful PEF processing system for industrial applications. Those who wish to promote the industrial application of the PEF processing system face a significant barrier in the form of the system's high initial cost of installation. Innovative developments in high-voltage pulse technology will reduce the cost of pulse generation and make PEF processing competitive with thermal processing methods.

Keywords: Dairy products, Food processing, Meat products, Pulsed electric field, Vegetable oils

Received: November 29, 2023; *revised:* April 23, 2024; *accepted:* July 11, 2024

DOI: 10.1002/cben.202300078

1 Introduction

For decades, people have been using various methods for preserving foods. Many techniques have been applied to prevent microbial spoilage, which causes economic losses of up to a quarter of the global food supply. These techniques include pasteurization [1], drying [2], smoking [3], packaging [4], irradiation [5], refrigeration [6], freezing [7] and many others. Foods are considered spoiled and not edible when appearance, color, aroma, and texture change. Microorganisms are abundant in the environment (air, water, and soil) and are capable of contaminating food at all stages. They are beginning on the farm and extending to the consumer's table. As a result, food preservation becomes crucial for ensuring safety, preventing spoilage, extending the shelf life of food, preserving quality, preventing poisoning, and reducing economic loss.

In recent years, numerous technologies for the heat treatment of food manufacturing have been developed, including the cold plasma process [8], high pressure [9], irradiation, microwave heating [10], Ohmic heating [11], high hydrostatic pressure [12], high-intensity pulsed light [13], oscillating magnetic field, ultrasound, ultraviolet radiation, and ozone have all been developed to improve, replace, or supplement the primary objective of traditional methods [14].

Pulsed electric field (PEF) treatment is considered one of the most important non-thermal treatment methods [15]. It is distinguished by its ability to preserve liquid food by eliminating

[1] Zina T. Alkanan, Ammar B. Altemimi
https://orcid.org/0000-0001-7750-5988
Food Science Department, College of Agriculture, University of Basrah, Al-Ashar - Corniche Street, Basrah 61004, Iraq.

[2] Ammar B. Altemimi
College of Medicine, University of Warith Al-Anbiyaa, Karbala Road, Karbala, Iraq.

[3] Mohamed Ibrahim Younis, Marwa Rashad Ali, Tarek Gamal Abedelmaksoud (tareekgamal_88@agr.cu.edu.eg)
Food Science Department, Faculty of Agriculture, Cairo University, 1 Gamaa Street, Giza 12613, Egypt.

[4] Francesco Cacciola https://orcid.org/0000-0003-1296-7633 (cacciolaf@unime.it)
Department of Biomedical, Dental, Morphological and Functional Imaging Sciences, University of Messina, Via Consolare Valeria, Messina 98125, Italy.

microorganisms while preserving its nutritional and sensory value [16]. Juices give a product with greater retention of vitamins, ascorbic acid, carotenoids, anthocyanins, lycopene, and organoleptic properties (appearance, flavor, taste, color, and general acceptability) when treated using PEF than thermal treatments [17]. In addition, compared to thermal treatments, non-thermal ones use the least amount of energy resulting in more efficiency [18].

Compared to other thermal treatments in food processing plants, PEF is one of the most successful applications since it drastically reduces harmful changes to food's physical and sensorial properties. Additionally, consumers prefer to purchase processed foods that appear fresh. The application of the PEF as one of the non-thermal manufacturing techniques has become one of the most distinguished and well-known processes due to its high capacity to kill cells and bacterial spores without affecting the functional properties of food materials [19].

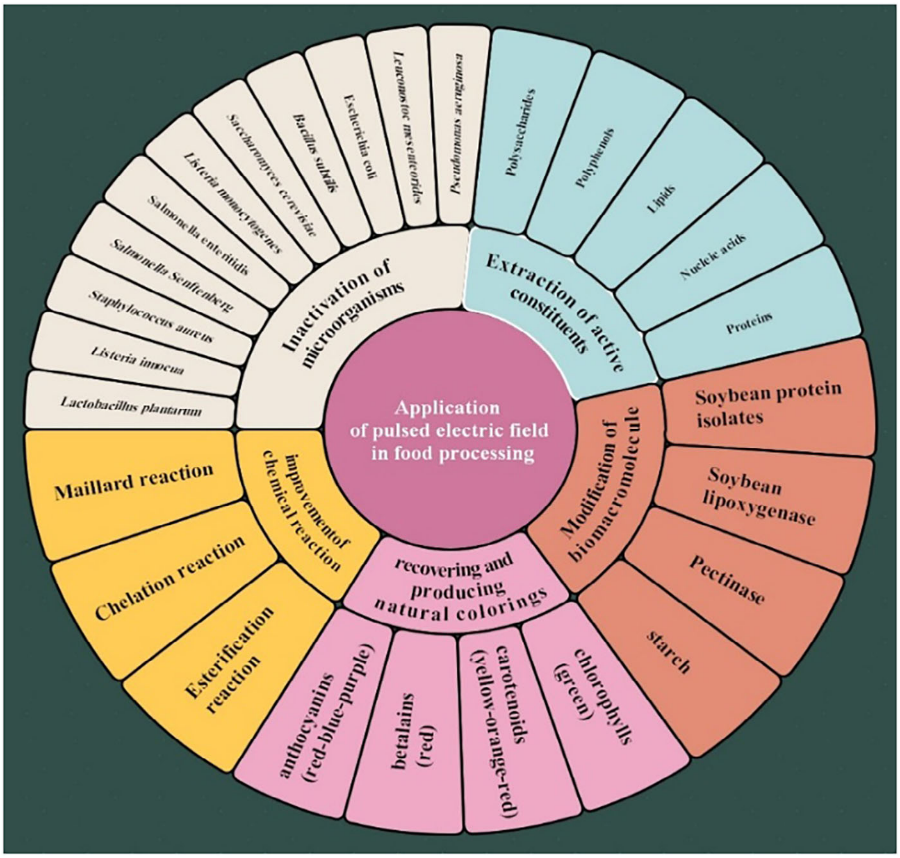

Figure 1. Applications of pulsed electric field (PEF).

PEF could be used for facing food contamination. For example, by using a PEF at >34 kV for 166 μs, it is possible to reduce the number of colon bacteria in apple juice to 4.5 Log10 CFU mL^{-1} [20]. Another study focused on the possibility of increasing the cooperative action of the PEF technique to combine with the thermal treatment; the shelf life of apple juice was thus extended to 67 days when using 35 kV cm^{-1} for 94 μs, while the thermal treatment was performed at 60 °C for 30 s [21]. In addition, previous research has demonstrated that there are no environmental risks associated with the use of modern green technologies in food processing plants, and there is no scientific evidence indicating the occurrence of any toxic effects associated with the use of these techniques in food processing plants [22]. The employment of PEF technology for food processing has resulted in a vast array of industrial applications that are superior at preserving bioactive compounds, e.g., tocopherols, polyphenols, and phytosterols as well as color and flavor [23]. Fig. 1 shows the most striking important applications of the PEF.

PEF technology is based on the application of high-intensity electric pulses with estimated microsecond-long durations [24]. PEF can produce a variety of effects that can be applied to numerous food types [25]. The time (t) required for treatment with the electric field can be calculated mathematically by multiplying the required number of pulses (n_p) by the effective pulse duration (d_p):

$$t = n_p * d_p$$

When food is exposed to an electric field, the electric current flows and moves to every point and location in the liquid via the charged particles in the medium. Under sterile and refrigerated conditions, it is possible to extend its shelf life without changing its physical and chemical properties.

PEF devices consist of a high-voltage pulse generator, a treatment room with a suitable fluid handling system, and control and monitoring devices. Electricity with a nonconductive material prevents electric flow from one object to another. Then, electrical pulses of high voltage and high intensity are applied to the products that have been placed between the electrodes. The first component provides the required shape, duration, and intensity of high-voltage pulses. Depending on the type of processed product, the processing rooms can be divided into batch processing rooms and continuous processing rooms (solid, semi-solid, liquid, and semi-liquid).

When considering the adoption of PEF processing for food preservation and treatment, several important aspects of food items are deemed crucial. The food's electrical conductivity is essential for enabling the spread of electric fields throughout the food structure, which in turn affects the effectiveness of PEF treatment [26]. Foods that have a greater water content are typically more suitable for PEF processing since they have an increased capacity to transmit electricity [27]. Additionally, the electrical conductivity and electrochemical responses of food during PEF treatment can be influenced by its pH. Generally, a

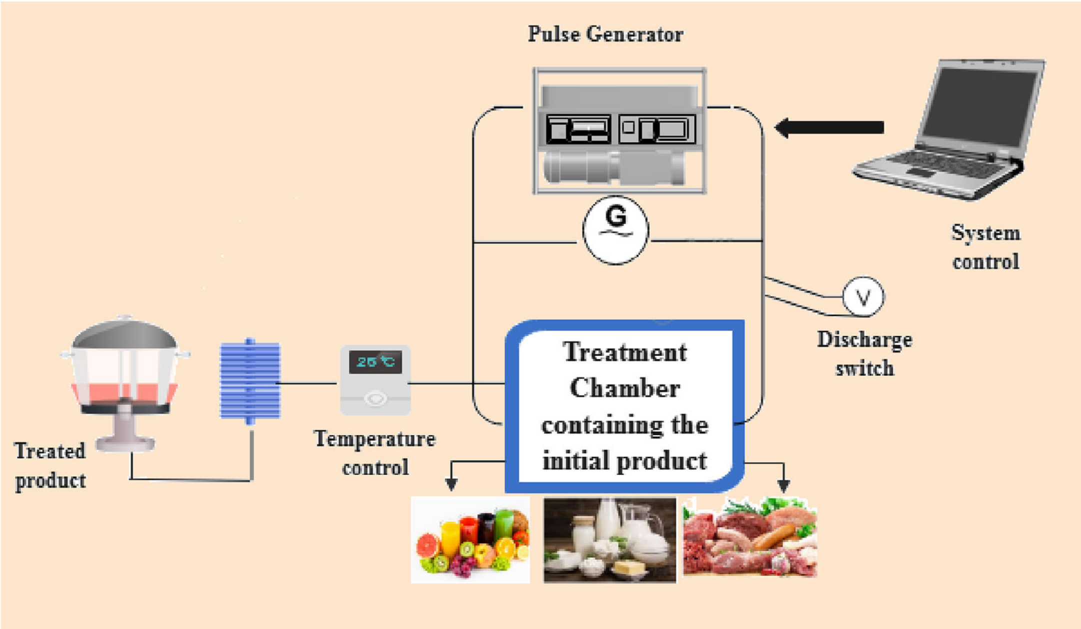

Figure 2. PEF operation process.

pH range that is neutral to slightly acidic is frequently favored [28]. Particle size is an important factor to consider. Smaller particles can help to evenly distribute electric fields throughout the food, but if the particles are too small, it might cause unwanted heating effects [29]. Furthermore, the viscosity of the food might impact its appropriateness for PEF processing, with foods that have lower viscosity generally being more easily processed [30]. Ultimately, the cellular composition of the food plays a crucial role, as PEF is very adept at breaking cell membranes, hence improving the transfer of mass and extraction efficiency [31]. It is crucial to customize the PEF processing settings based on the unique features of the food product and processing objectives in order to maximize its effectiveness and achieve optimal results.

Because semi-liquid and liquid substances are pumped through the chamber of the latter type [32], it is ideally suited for industrial processes. A central computer controls the process by adjusting the transaction, controlling the operation of the pump, and collecting data from sensors placed within the room [33] as illustrated in Fig. 2.

2 Advantages and Disadvantages of the PEF Treatment

Previous studies have demonstrated that PEF treatment does present many advantages that indicate its significance, such as its low cost and environmental friendliness [34], as well as its energy efficiency and minimal manufacturing requirements. Its capacity to kill cells utilizes processes and mechanisms that do not alter the protein composition [35]. The electric field de-emulsification process has practical advantages such as reduced chemical addition [36, 37] and the use of simple equipment, as well as the capacity to achieve physical separation of the oil–water mixture and recovery of oily substances to a certain extent without polluting the environment. Pre-treatment with PEF permits greater extraction with less energy [38]. It is suggested to use the PEF as a pre-treatment to support the great effects of green extraction methods of medicinal plants such as supercritical carbon dioxide [39]. As a consequence, it is an alternative food preservation method that can enhance food's functionality and nutritional value and its constituents [40]. It has been demonstrated that treatment with PEF increases the permeability of plant and animal tissues, thereby enhancing the transfer of water and active compounds from biological tissues and their drying efficiency [41]. Due to its capacity to pasteurize numerous types of meat and meat products, it is a suitable method for producing heat-sensitive foods and is applied to many solid and liquid foods [42].

Low pH solutions result in a higher concentration of metals on the electrodes identified by Gad and Jayaram [43] as one of the most significant disadvantages. In addition, its industrial application increases the price of electrical energy consumption [44]. Additionally, the investigations demonstrated that the application of the PEF to inhibit bacteria is limited to foods with low conductivity and no air bubbles [19]. Unexpected occurrences, such as heat accumulation, electric field disruptions, particle deposition, and the creation of gas bubbles, are among its downsides [45].

PEF processing offers several advantages over conventional pasteurization methods, making it an attractive option for food preservation and treatment. First, in terms of energy savings, PEF typically requires lower energy inputs, compared to conventional pasteurization techniques such as thermal processing. While conventional methods involve heating foods to high temperatures, PEF relies on short pulses of electrical energy, resulting in reduced energy consumption and operational costs. Furthermore, PEF can lead to lower overall costs, compared to traditional pasteurization methods. Although the initial investment in PEF equipment may be higher, the reduced energy requirements and shorter processing times can result in long-term cost savings. Additionally, PEF systems are often more compact and require less infrastructure, compared to large-scale thermal processing equipment, further contributing to cost efficiencies [46].

In terms of water consumption, PEF offers significant advantages over conventional methods. Unlike thermal pasteurization, which often requires large volumes of water for heating and cooling processes, PEF processing is typically a dry or low-moisture process, leading to minimal water usage and reduced wastewater generation [47].

PEF also excels in nutrient retention and the preservation of physicochemical and antioxidant properties of foods, unlike thermal processing, which can lead to the degradation of heat-sensitive nutrients and changes in texture, flavor, and color. Several studies concluded that PEF treatment can better preserve the nutritional quality, sensory attributes, and antioxidant properties of foods due to its non-thermal nature [48, 49].

Moreover, PEF is highly effective in inactivating pathogens and extending the shelf life of foods. The intense electric fields generated during PEF treatment disrupt microbial cell membranes, leading to microbial inactivation without significant heating. This allows for the preservation of fresh-like quality and the extension of shelf life while ensuring food safety [50, 51].

Overall, PEF processing offers numerous advantages over conventional pasteurization methods, including energy savings, lower costs, reduced water consumption, better retention of nutrients and physicochemical properties, effective pathogen inactivation, and prolonged shelf life. These advantages make PEF a promising technology for enhancing food safety and quality while meeting the demands of sustainable food processing.

3 The Effect of the PEF on Microorganisms

Food manufacturers and sellers are concerned about food safety in terms of microorganisms [52] due to the considerable growth in the number of persons with foodborne infections, which is a serious public health concern [53]. Many food processing industries worldwide have depended on considerable research to improve their safety [54]. In addition to preserving the nutritional and sensory value of food, appropriate procedures and diverse distribution networks are employed to prevent or limit undesirable biological and fungal decomposition [55]. Studies have demonstrated that PEF has an antimicrobial impact not only as a result of the rupture of the cell membrane but also as a result of the creation of several chemical processes that produce reactive molecules, such as free oxygen, hydrogen, hydroxyl, and hydroperoxyl radicals [56]. PEF treatment can reduce spoilage and pathogens caused by microorganisms in food using low temperatures (10–55 °C) and in a short time (590 ns–1206 μs) [57]. The sensitivity of microorganisms to PEF treatment depends on the size and shape of the cell, the type of microorganism, and its stage of development [58]. The electric perforation process takes place in three stages, the first is the increase in membrane expansion and swelling, the second stage is the formation of pores, and in the third stage, there is a development in the number and size of the pores, and the membrane may recover when the treatment with PEF stops and returns to its natural state, and this depends on the extent of the effect of the electric field. If the membrane is deeply perforated, it will lead to cell death and non-recovery of the membrane [59]. Additionally, the efficacy of pathogens inactivation by PEF is influenced by parameters such as pH, water activity (Aw), and electrical conductivity [60].

Gram-positive bacteria are covered with several thick layers of peptidoglycan, which confers more resistance to PEF than gram-negative ones [61] as shown in Fig. 3. Tab. S1 represents a number of studies of some different foods to observe the effect of the PEF in inhibiting microorganisms.

4 Effect of PEF on Various Fruit Juices

Fruit juices represent a part of a balanced diet, providing some essential nutrients [60]. Due to the comparatively large levels of active substances such as anthocyanins [20], vitamin C, flavor compounds [61], flavonoids, and phenolic acids [62] found in fruit juices, researchers have focused extensively on their production [63]. The way how juice is handled and extracted can impact its active and flavor ingredients [64]. It was discovered that juices require stringent conditions to maintain quality. Therefore, a non-thermal technique was applied, which is the treatment with PEF without causing changes in flavor, taste, or nutritional value, and as a good way to preserve the qualities of juices [16] similar to those of natural juice by effectively inhibiting enzymes and bacteria that work on the structural change of α-helix and altering the active site of enzymes [65]. In addition, the use of PEF in the production of juices enhances the amount of juice extracted from fruits and vege [66], lengthens the shelf life and hence stability throughout the storage period, thus promoting the expansion of trade and distribution of the product to vast areas [65].

Interestingly, treating juices with a PEF improves the clarity and look of juice while reducing turbidity [67]. The effect of PEF treatment on the physical and chemical properties of fresh citrus juices (lemon, grapefruit, tangerine, and orange) and the impact of PEF technology on pH, Brix°, electrical conductivity, viscosity, and non-enzymatic browning index was investigated [68].

Tab. S2 presents numerous studies proving the influence of the PEF on various fruit and vegetable juices.

5 Effect of PEF on Dairy Products

Milk and fresh dairy products are vital dietary components, but they have a very limited shelf life, making their distribution to local markets challenging due to their microbial growth-friendly makeup. Therefore, pasteurization increases the

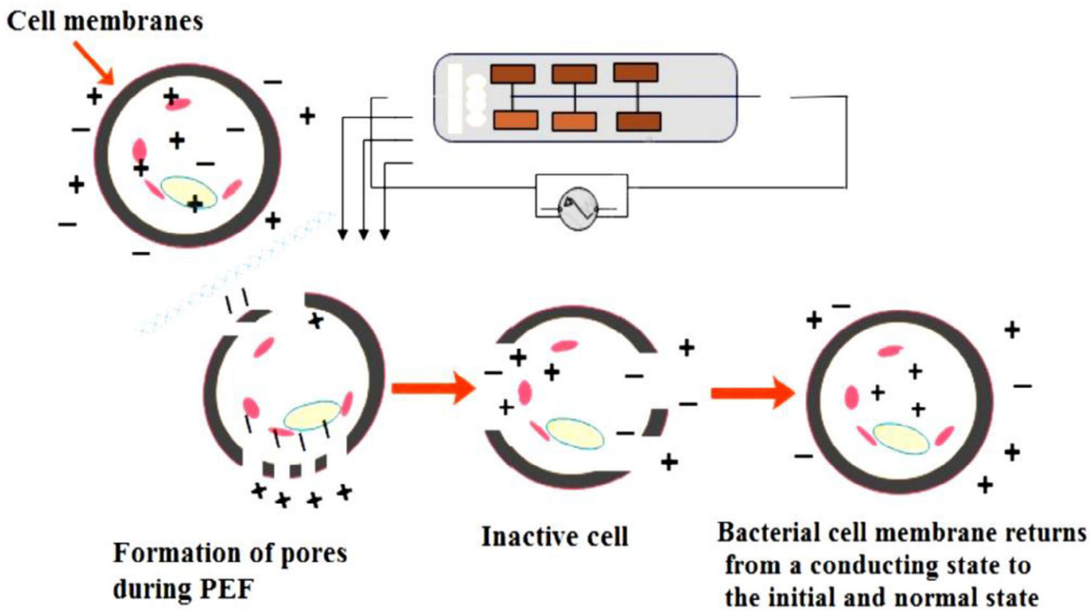

Figure 3. Effect of PEF on gram-positive bacteria.

microbiological safety of dairy products, but this heat can lead to undesired chemical, biological, and nutritional changes that can impair the final dairy products' color, flavor, and taste [69]. People who have adopted diets that restrict or eliminate meat have increased demand for dairy products in recent years [70]. As customer demand for these items expanded, it became vital to develop treatments that allow dairy products to be produced with higher quality and greater stability while reducing energy losses without compromising product and treatment safety [71]. Therefore, numerous studies have demonstrated the effect of PEF technology on dairy products and the extent to which the structural and functional properties of proteins can be improved [72]. Tab. S3 demonstrates a number of research examining the effect of PEF treatment on various dairy products.

6 Effect of PEF on Meat Products

PEF technology has been used to treat meat due to its effectiveness in increasing the permeability of the cell membrane or in creating pores in muscle cells. This approach improves the efficiency and effectiveness of meat products, making the structural effects of PEF on meat of enormous commercial worth [73]. Such an interesting study also showed that the moderate intensity PEF (MIPEF) works to prevent or inhibit microorganisms in muscle foods when using indirect application at 2.5, 4.67, and 7 kV cm^{-1}; this was applied to chicken breast meat inoculated with pure cultures of *Pseudomonas aeruginosa, Listeria monocytogenes, Salmonella enteritidis, Escherichia coli, Staphylococcus aureus*, and *Campylobacter jejuni* and stored at 4 °C; both *E. coli* and *C. jejuni* showed an extraordinary resistance to MIPEF at the electric field of 4.67 and 7 kV cm^{-1}, respectively [74]. Bhat et al. [75] studied the effect of the PEF on reducing sodium in processed meat using different samples of salt concentrations from beef jerky, a control sample with a concentration of 2 % of NaCl, a sample not treated with PEF, a salt concentration of 1.2 %, and a sample treated with PEF with a salt concentration of 1.2 %. The PEF-treated samples gave significantly less sodium content ($p < 0.05$) than the control samples, and the results of the sensory evaluation showed no significant differences ($p > 0.05$), compared to the control sample; more than 84 % of the arbitrators preferred the sample with a concentration of 1.2 % and the treatment with the PEF technique. The other treatment with the same salt concentration and not treated with PEF demonstrated the potential for PEF technology to improve the taste of salinity through its work on the ease of diffusion and penetration of sodium into the muscle pores, resulting in a greater sensitivity to taste or flavor when chewing; consequently, it was concluded that the technique of using PEF to produce healthy, low-sodium meat products is effective [75]. According to Ghosh et al. [76], by using an electric field with short high-voltage pulses followed by long low-voltage pulses with mechanical pressure to extract the active compounds from chicken breast muscles, the PEF treatment helped to extract about 12 ± 2 % of chicken waste; a protein content of 78 ± 8 mg mL^{-1} was reached and 2,2-Diphenyl-1-picrylhydrazyl (DPPH) and 2,2′-azinobis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS) tests showed interesting antioxidant properties, thus bringing additional income to farmers and meat processors and encouraging the reduction of waste and environmental pollution. Zhang et al. [77] demonstrated that PEF has an effect in reducing the duration of seasoning for beef, which is attributed to the disintegration of cells and the increase in gaps or pores, thus facilitating the permeability of seasoning materials between muscle cells; in addition, the tenderness of the meat was increased by 22.9 % when using a specific energy of 12.50 kJ kg^{-1}, 125 pulses, and an electric field of 2.0 kV cm^{-1}. Furthermore, in a study conducted by Kantono et al. [78] on chilled and frozen lamb chops treated with PEF and stored for 7 days, the results showed that lamb chops retained the volatile compounds (2-nonanone, 2-pentylfuran, pyrrole, methyl pyrazine, 2-ethyl-3-methyl pyrazine, and thiophene), which had a significantly positive effect on the flavor associated with the meat as well as the juiciness of lamb chops, which were associated with the presence of fatty acids; the appearance of brown color on the treated pieces of meat, was attributed to the presence of amino acids (threonine, phenylalanine, isoleucine, tyrosine, and methionine) and some volatile compounds (heptanal, 2-ethylfuran, pyridine, dimethyl disulfide), dimethyl trisulphide, and 3,5-diethyl-2-methyl pyrazine.

7 The Effect of the PEF on Yield and Quality of Vegetable Oils

Environmental, health, and safety risks are associated with traditional oil extraction methods that use organic solvents microwave-assisted enzymatic extraction, ultrasound-assisted extraction, and supercritical fluid technology-assisted extraction. PEF-assisted extraction is a new non-thermal approach used to boost the efficiency of extracting vegetable oil from diverse oilseeds. The process includes the discharge of direct electric pulses into the oleaginous material at high voltages of up to 50 kV for a short period (microseconds to milliseconds) [79].

The new physical technology enhances mass transfer procedures. Furthermore, PEF pre-treatment of crushed oilseeds boosts oil output and bioactive component recovery. By using this method, the malaxation temperature may be lowered while still maintaining the yield and sensory quality of the product. In addition, PFE is an effective de-emulsification technique because it facilitates the coalescence of oil molecules in an oil-in-water emulsion. Therefore, two techniques are used to increase the yield; electroporation from tissues and oil recovery from the emulsion [80].

Fig. 4 demonstrates PEF technology's application in commercial olive oil production. After the two oil-production phases of crushing and malaxation, PEF is used to produce olive oil. The first step was to enhance the following oil during malaxation after crushing. The second objective was to accelerate oil demulsification during malaxation and enhance mass transfer during the subsequent centrifugation [81]. In addition, a PEF can promote cell membrane permeability and breakage, improving oil extractability and quality, particularly concerning the components accountable for the extra virgin olive oil's beneficial health and sensory attributes. The studies reported in Tab. S4 demonstrate the impact of PEF on the yield and quality of vegetable oils.

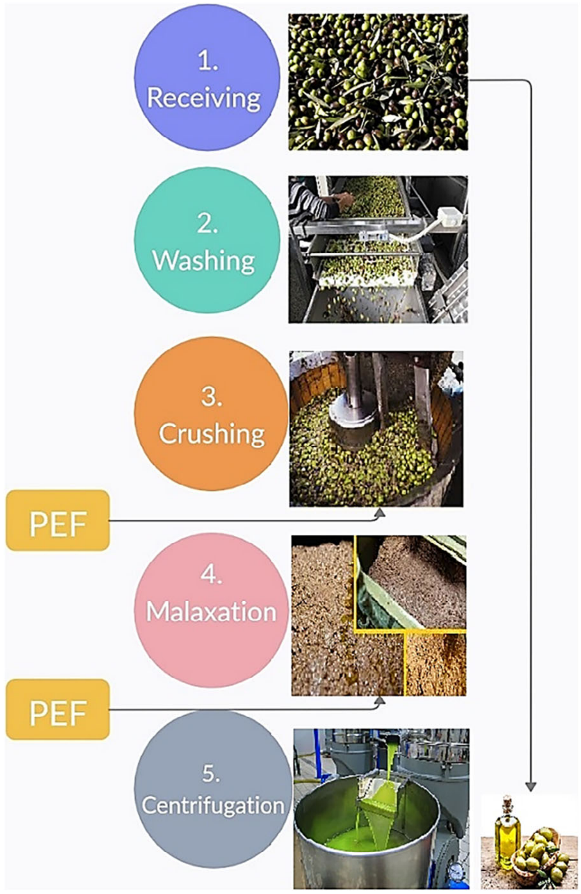

Figure 4. Utilization of PEF technology in industrial olive oil production.

8 The Effect of the PEF on Fried Products

Frying is an extremely complicated process involving many physical and chemical interactions and simultaneous heat, mass, and momentum transference. During frying, the compounds of plant tissue, such as amino acids, reducing sugars, starch, and water, interact, causing chemical changes (Maillard reaction) that alter the final product's characteristics. In addition, the mass transfer from the oil to the food results in physical events, such as water evaporation and oil absorption, that modify the structure of the final product [82]. Potato chips, French fries, and fried chicken are just a few examples of the numerous food products with a significant market appeal that are produced using the widely used process of frying [83]. Food fried has distinct flavors and textures [84]; however, the high fat and calorie content of fried foods may increase the risk of obesity, diabetes, hypertension, and cancer. It has therefore been a major topic in producing low-fat products to reduce fat consumption from fried food while keeping their attractive sensory characteristics. Therefore, it is crucial to modify the proper pre-treatment method and boost the quality of fried foods. Food processing has recently researched numerous non-thermal methods that promise to save energy costs and avoid material degradation. Among them, PEF has received much attention, and prior research has shown that PEF may be used effectively in frying quality, as shown in Tab. S5.

In PEF's treatment chamber, food is repeatedly subjected to high-voltage pulses while positioned between two electrodes [85]. When plant tissues are exposed to PEF, proteins and the lipid bilayer in the cell membrane degrade because the charging process increases the transmembrane potential. The cell membrane is penetrated and pores form when the transmembrane potential is higher than cells can tolerate. The extent of PEF treatment affects the number and size of pores. By using this technique, food preserves its nutrients, essential color, and flavor [86–88] with a favorable effect on frying quality. However, when newly cut slices are exposed to PEF, electroporation alters cell permeability, hence affecting tissue shape and mass transfer procedure. Also, several studies reported a decrease in the reduced sugar level in samples investigated, treated with PEF, with a lowered Maillard process and acrylamide formation. Additionally, following PEF treatment, the oil content of fried products declined due to the improved mass transfer ability [84, 89, 90].

9 Conclusion

PEF technology is a highly efficient way for preserving and processing a wide variety of food products without significantly affecting their quality attributes. However, research on PEF as a non-thermal approach should focus not only on microbial inactivation but also on the slowing of many spoilage-inducing chemical and enzymatic reactions and the retention of functioning food components during and after treatment. Even though the literature contains information on the efficacy of PEF processing on enzyme inactivation, enhancement of proteolysis in protein-enriched foods, and its effects on certain food quality characteristics, more research is necessary to investigate the mechanisms underlying these functionalities. PEF uses brief bursts of electrical energy to reduce the negative effects of heat and oxidation, therefore maintaining the beneficial qualities of antioxidants. Moreover, the absence of heat in PEF treatment preserves the structural integrity and functionality of antioxidant components, guaranteeing their effectiveness in eliminating free radicals and enhancing the overall health advantages of processed foods. In addition, the largest impediment to the industrial adoption of this approach is the high initial cost of creating a PEF processing plant. However, PEF systems are attractive because of their lower running costs and the high-quality, little-processed products they provide. There is currently no continuous PEF processing technology appropriate for industrial application. It is challenging for food and electrical engineers to create a continuous treatment chamber and a pulse generator that fulfills industry standards.

Supporting Information

Supporting information for this article can be found under DOI: https://doi.org/10.1002/cben.202300078.

Conflicts of Interest

The authors declare no conflict of interest.

Zina T. Alkanan specializes in food processing and preservation, holding a Ph.D. from the University of Basrah. Her research is focused in Ohmic heating technology and its application in the production of juices and other food products.

Ammar B. Altemimi is a renowned professor at the University of Basrah's College of Agriculture and holds a Ph.D. from the USA, underscoring his deep commitment to academic excellence. Specializing in food sciences, he focuses on nonthermal processes and food safety.

Mohamed Ibrahim Younis is a Food Science professional who earned his master's degree in 2023 from Jiangsu University, Jiangsu, China. His research interest concern the employment of modern extraction tecniques and freeze-drying processes.

Marwa Rashad Ali is an associate professor of Food Science, Faculty of Agriculture, Cairo University, Giza, Egypt. She holds a Ph.D. from Cairo University, Egypt and her research interests are food preservation methods, food packaging, production and evaluation of innovative edible films.

Francesco Cacciola is an associate professor of Food Chemistry at the University of Messina, Italy. He holds a Ph.D. in Food Chemistry and Safety. His research focuses on the application of innovative analytical techniques for the characterization of bioactive molecules in food and natural products.

Tarek Gamal Abedelmaksoud is an associate professor of Food Science at the Faculty of Agriculture, Cairo University, Giza, Egypt. He holds a Ph.D. from Cairo University, Egypt, in cooperation with DTU Denmark. He specializes in fruits and vegetables processing as well as enzyme technology.

Acknowledgments

Open access publishing facilitated by Universita degli Studi di Messina, as part of the Wiley - CRUI-CARE agreement.

References

[1] A. E. Alcántara-Zavala, J. D. Figueroa-Cárdenas, *Int. J. Gastron. Food Sci.* **2022**, *28*, 100497.
[2] M. I. H. Khan, S. S. Sablani, M. U. H. Joardder, M. A. Karim, *Dry Technol.* **2022**, *40*, 1051–1067.
[3] L. Zhang, Q. Chen, Q. Liu, X. Xia, Y. Wang, B. Kong, *Food Chem.* **2022**, *367*, 130680.
[4] S. D. Alam, R. Raja, V. Shirsath, A. K. Jain, S. A. Khan, I. Ali, in *Biomaterials in Food Packagaging* (Eds: S. D. Alam, R. Raja, V. Shirsath, A. K. Jain, S. A. Khan, I. Ali), Jenny Stanford Publishing, Singapore **2022**, 121–135.
[5] W. Jia, X. Wang, R. Zhang, Q. Shi, L. Shi, *Food Rev. Int.* **2023**, *39*, 4442–4464.
[6] A. Rawat, P. Benyathiar, F. Ozadali, D. K. Mishra, *LWT–Food Sci. Technol.* **2022**, *165*, 113752.
[7] P. K. Jha, A. Le-Bail, S. Jun, in *Food Engineering Innovations Across the Food Supply Chain* (Eds: P. Juliano, K. Knoerzer, J. Sellahewa, M. H. Nguyen, R. Buckow), Academic Press, London **2022**, 187–206.
[8] R. Kaavya, R. Pandiselvam, M. Gavahian, R. Tamanna, S. Jain, et al., *Crit. Rev. Food Sci. Nutr.* **2023**, *63*, 11370–11384.
[9] W. Balasooriya, C. Clute, B. Schrittesser, G. Pinter, *Polym. Rev.* **2022**, *62*, 175–209.
[10] R. Yang, J. Chen, *Foods* **2021**, *10*, 2029.
[11] Z. T. Alkanan, A. B. Altemimi, A. R. Al-Hilphy, F. Cacciola, S. A. Ibrahim, *Foods* **2021**, *10*, 2920.
[12] K. Aganovic, C. Hertel, R. F. Vogel, R. Johne, O. Schlüter, U. Schwarzenbolz, V. Heinz, *Compr. Rev. Food Sci. Food Saf.* **2021**, *20*, 3225–3266.
[13] R. Mandal, A. Wiktor, X. Mohammadi, A. Pratap-Singh, *Food Bioprocess. Technol.* **2022**, *15*, 92–104.
[14] V. Chiozzi, S. Agriopoulou, T. Varzakas, *Appl. Sci.* **2022**, *12*, 1–40.
[15] S. El Kantar, M. Koubaa, *Res. Agric. Eng.* **2022**, *68*, 80–92.
[16] S. Kumar, N. Agarwal, P. K. Raghav, *Int. J. Eng. Res. Mod. Educ.* **2016**, *1*, 111–118.
[17] F. Salehi, *Int. J. Food Prop.* **2020**, *23*, 1036–1050.
[18] B. Surano, G. Leiva, G. Marshall, F. Maglietti, C. Schebor, *J. Food Eng.* **2022**, *317*, 110864.
[19] W. Zhao, R. Yang, X. Shen, S. Zhang, X. Chen, *Food Control* **2013**, *32*, 6–12.
[20] S. Min, G. A. Evrendilek, H. Q. Zhang. *IEEE Trans. Plasma Sci.* **2007**, *35*, 59–73.
[21] W. Katiyo, R. Yang, W. Zhao, *J. Food Saf.* **2017**, *37*, e12369.
[22] M. Guderjan, P. Elez-Martínez, D. Knorr, *Innov. Food Sci. Emerg. Technol.* **2017**, *8*, 55–62.
[23] I. Oey, S. Giteru, S. Y. Leong, *Emerg. Food Process. Technol.* **2022**, 1–29.
[24] F. Zeng, Q. Y. Gao, Z. Han, X. A. Zeng, S. Y. Yu, *Food Chem.* **2016**, *194*, 1313–1319.
[25] X. Yu, O. Bals, N. Grimi, E. Vorobiev, *Ind. Crop Prod.* **2015**, *74*, 309–318.
[26] M. M. A. Ranjha, R. Kanwal, B. Shafique, R. N. Arshad, S. Irfan, M. Kieliszek, R. M. Aadil, *Molecules* **2021**, *26*, 4893.
[27] R. N. Arshad, Z. Abdul-Malek, U. Roobab, M. A. Munir, A. Naderipour, M. I. Qureshi, R. M. Aadil, *Trend Food Sci. Techonl.* **2021**, *111*, 43–54.
[28] R. Wang, L. H. Wang, Q. H. Wen, F. He, F. Y. Xu, B. Chen, X. A. Zeng, *Food Hydrocoll.* **2023**, *134*, 108049.
[29] M. F. Manzoor, N. Ahmad, R. M. Aadil, A. Rahaman, Z. Ahmed, A. Rehman, A. Manzoor, *J. Food Process. Eng.* **2019**, *42* (8), e13299.
[30] X. Wu, C. Wang, Y. Guo, *J. Food Eng.* **2020**, *274*, 109837.
[31] S. Jeyamkondan, D. S. Jayas, R. A. Holley, *J. Food Protect.* **1999**, *62*, 1088–1096.
[32] K. Nowosad, M. Sujka, U. Pankiewicz, R. Kowalski, *J. Food Sci. Technol.* **2021**, *58*, 397–411.
[33] *Novel Food Processing Technologies* (Eds: G. V. Barbosa-Cánovas, M. S. Tapia, M. P. Cano). CRC Press, Boca Raton **2004**.
[34] P. Geada, R. Rodrigues, L. Loureiro, R. Pereira, B. Fernandes, J. A. Teixeira, A. A. Vicente, *Renew. Sust. Energ. Rev.* **2018**, *94*, 656–668.
[35] A. Verma, S. J. Asivatham, T. Deneke, Q. Castellvi, R. E. Neal, *Circ. Arrhythm. Electrophysiol.* **2021**, *14*, e010086.
[36] K. J. Ptasinski, P. J. A. M. Kerkhof, *Sep. Sci. Technol.* **1992**, *27*, 995–1021.
[37] M. Mousavichoubeh, M. Ghadiri, M. Shariaty-Niassar, *Chem. Eng. Process.: Process Intensif.* **2011**, *50*, 338–344.
[38] J. M. Martínez, C. Delso, I. Álvarez, J. Raso, *Compr. Rev. Food Sci. Food Saf.* **2020**, *19*, 530–552.
[39] M. I. Younis, X. Ren, A. K. Alzubaidi, K. F. Mahmoud, A. B. Altemimi, F. Cacciola, T. G. Abedelmaksoud, *Molecules* **2022**, *27*, 4329.

[40] S. Yang, G. Liu, Z. Qin, D. Munk, J. Otte, L. Ahrné, in *Effect of Emerging Processing Methods on the Food Quality* (Eds: S. Roohinejad, M. Koubaa, R. Greiner, K. Mallikarjunan), Springer International Publishing, Cham **2019**, 27–67.
[41] F. Donsì, G. Ferrari, G. Pataro, *Food Eng. Rev.* **2010**, *2*, 109–130.
[42] B. Gómez, P. E. Munekata, M. Gavahian, F. J. Barba, F. J. Martí-Quijal, T. Bolumar, P. C. B. Campagnol, I. Tomasevic, J. M. Lorenzo, *Food Res. Int.* **2019**, *123*, 95–105.
[43] A. Gad, S. H. Jayaram, *Proc. IEEE Conf. on Electrical Insulation and Dielectric*, Montreal, Canada October **2012**, 170–173.
[44] S. Jeyamkondan, D. S. Jayas, R. A. Holley, *J. Food Prot.* **1999**, *62*, 1088–1096.
[45] F. Sampedro, A. McAloon, W. Yee, X. Fan, H. Q. Zhang, D. J. Geveke, *Inn. Food Sci. Emerg. Tech.* **2013**, *17*, 72–78.
[46] E. Pino-Hernández, P. Valério, S. Dias, M. B. Evangelista, M. Alves, *Int. Conf. on Water Energy Food and Sustainability* (Eds: J. R. D. C. S. Galvão, P. Brito, F. D. S. Neves, H. D. A. Almeida, S. D. J. M. Mourato, C. Nobre), Springer, Cham **2023**.
[47] I. P. C. Brito, E. K. Silva, *Food Res. Inter.* **2024**, *184*, 114207.
[48] I. Souli, N. Chaira, M. Jemni, S. Tlahig, A. Ferchichi, J. L. Lanoisellé, *Processes* **2023**, *11*, 884.
[49] C. Kantala, S. Supasin, P. Intra, P. Rattanadecho, *Foods* **2022**, *11*, 1102.
[50] T. Z. Jin, H. Q. Zhang, *Food Saf. Eng.* **2020**, 553–577.
[51] S. He, X. Shi, *Foodborne Pathog. Dis.* **2021**, *18*, 510–518.
[52] R. Pandiselvam, S. Subhashini, E. P. Banuu Priya, A. Kothakota, S. V. Ramesh, S. Shahir, *Ozone Sci. Eng.* **2019**, *41*, 17–34.
[53] M. Compton, S. Willis, B. Rezaie, K. Humes, *Innov. Food Sci. Emerg. Technol.* **2018**, *47*, 371–383.
[54] A. A. De Souza Machado, W. Kloas, C. Zarfl, S. Hempel, M. C. Rillig, *Glob. Chang. Biol.* **2018**, *24*, 1405–1416.
[55] W. D. C. Martins Antunes de Melo, R. Celiešiūtė-Germanienė, P. Šimonis, A. Stirkė, *Virulence* **2021**, *12*, 2247–2272.
[56] R. N. Arshad, Z. Abdul-Malek, U. Roobab, M. A. Munir, A. Naderipour, M. I. Qureshi, A. El-Din Bekhit, Z.-W. Liu, R. M. Aadil, *Trends Food Sci. Technol.* **2021**, *111*, 43–54.
[57] S. Q. Abbas, *J. Nutr. Health Food Eng.* **2017**, *6*, 168–172.
[58] K. Yogesh, *J Food Sci. Technol.* **2016**, *53*, 934–945.
[59] F. Pillet, C. Formosa-Dague, H. Baaziz, E. Dague, M. P. Rols, *Sci. Rep.* **2016**, *6*, 19778.
[60] J. Li, J. Shi, X. Huang, T. Wang, X. Zou, Z. Li, D. Zhang, W. Zhang, Y. Xu, *LWT–Food Sci. Technol.* **2020**, *132*, 109873.
[61] P. Sourri, C. C. Tassou, G. J. E. Nychas, E. Z. Panagou, *Foods* **2022**, *11*, 747.
[62] Q. Quan, W. Liu, J. Guo, M. Ye, J. Zhang, *Foods* **2022**, *11*, 1920.
[63] D. Mihaylova, I. Desseva, M. Stoyanova, N. Petkova, M. Terzyiska, A. Lante, *Molecules* **2021**, *26*, 1187.
[64] X. Pan, J. Wu, W. Zhang, J. Liu, X. Yang, X. Liao, F. Lao, *Food Chem* **2021**, *338*, 128117.
[65] U. Roobab, A. Abida, J. S. Chacha, A. Athar, G. M. Madni, M. M. A. N. Ranjha, M. Trif, *Molecules* **2022**, *27* (*13*), 4031.
[66] J. Ben Ammar, J. L. Lanoisellé, N. I. Lebovka, E. Van Hecke, E. Vorobiev, *Food Biophys.* **2010**, *5*, 247–254.
[67] N. Grimi, F. Mamouni, N. Lebovka, E. Vorobiev, J. Vaxelaire, *J. Food Eng.* **2011**, *103*, 52–61.
[68] Z. Cserhalmi, A. Sass-Kiss, M. Tóth-Markus, N. Lechner, *Innov. Food Sci. Emerg. Technol.* **2006**, *7*, 49–54.
[69] V. Lacivita, A. Conte, M. A. Del Nobile, in *Biotechnical Processing in the Food Industry: New Methods, Techniques, and Applications* (Eds: D. K. Verma, A. R. Patel, K. S. Sandhu, A. Baldi, S. Garcia), Apple Academic Press, Palm Bay **2021**, 3–33.
[70] M. Mefleh, A. Pasqualone, F. Caponio, M. Faccia, *J. Sci. Food Agric.* **2022**, *102*, 8–18.
[71] R. Buckow, P. S. Chandry, S. Y. Ng, C. M. McAuley, B. G. Swanson, *Int. Dairy J.* **2014**, *34*, 199–212.
[72] A. Taha, F. Casanova, P. Šimonis, V. Stankevič, M. A. Gomaa, A. Stirkė, *Foods* **2022**, *11*, 1556.
[73] R. Karki, I. Oey, P. Bremer, S. Y. Leong, P. Silcock, *Innov. Food Sci. Emerg. Technol.* **2023**, *89*, 103485.
[74] E. Aşık-Canbaz, S. Çömlekçi, A. Can Seydim, *Br. Poult. Sci.* **2022**, *63*, 641–649.
[75] Z. F. Bhat, J. D. Morton, S. Mason, A. E. D. A. Bekhit, *Food Chem.* **2020**, *306*, 125622.
[76] S. Ghosh, A. Gillis, J. Sheviryov, K. Levkov, A. Golberg, *J. Clean. Prod.* **2019**, *208*, 220–231.
[77] Y. Zhang, R. Wang, Q. H. Wen, A. Rahaman, X. A. Zeng, *Innov. Food Sci. Emerg. Technol.* **2022**, *80*, 103061.
[78] K. Kantono, N. Hamid, D. Chadha, Q. Ma, I. Oey, M. M. Farouk, *Foods* **2021**, *10*, 1148.
[79] E. Bozinou, I. Karageorgou, G. Batra, V. G. Dourtoglou, S. I. Lalas, *Beverages* **2019**, *5*, 8–20.
[80] X. A. Zeng, Z. Zhang, *Adv. Food Process. Technol.* **2019**, *121*, 125–135.
[81] M. Abenoza, M. Benito, G. Saldaña, I. Alvarez, J. Raso, A. C. Sanchez-Gimeno, *Food Bioprocess. Technol.* **2013**, *6*, 1367–1373.
[82] Z. Xu, S. Y. Leong, M. Farid, P. Silcock, P. Bremer, I. Oey, *Foods* **2020**, *17*, 949.
[83] L. Li, R. Yang, W. Zhao, *Foods* **2021**, *10*, 2606.
[84] C. Zhang, J. Ye, X. Lyu, W. Zhao, J. Mao, R. Yang, *Food Chem.* **2022**, *369*, 130516.
[85] J. M. Martínez, F. Schottroff, K. Haas, T. Fauster, M. Sajfrtová, I. Álvarez, H. Jaeger, *Food Chem.* **2020**, *323*, 126824.
[86] K. A. Shiekh, S. Benjakul, *Food Chem.* **2020**, *309*, 125516.
[87] D. Niu, X.-A. Zeng, E.-F. Ren, F.-Y. Xu, J. Li, M.-S. Wang, R. Wang, *Food Res. Int.* **2020**, *137*, 109715.
[88] L. Putnik, Kresoja Ž, T. Bosiljkov, A. Režek, F.J. Barba Jambrak, J. M. Lorenzo, *Food Chem.* **2019**, *279*, 150–161.
[89] M. A. Schouten, J. Genovese, S. Tappi, A. Di, E. Baraldi Francesco, M. Cortese, S. Romani, *Innov. Food Sci. Emerg. Technol.* **2020**, *64*, 102397.
[90] R. Ostermeier, K. Hill, A. Dingis, S. Töpfl, H. Jäger, *Innov. Food Sci. Emerg. Technol.* **2020**, *67*, 102553.