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# Review on Pulsed Electric Fields: A New Horizon in Food Processing Health Techniques

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**Abstract:** Pulsed electric fields (PEF) are a novel, non-thermal, promising, and energy-efficient method of food preservation that utilizes short electrical pulses for microbial inactivation by causing minimal impacts on the quality attributes of food. In the PEF method, high-voltage pulses are generated between two electrodes immersed in fluid or paste-like foods to sterilize them by passing electricity through the food. PEF technology is predominantly applied in processing dairy, eggs, meat, fish, and liquid foods like juices and milk to inhibit microbial growth. As a non-thermal food preservation technique, PEF effectively manages biological hazards. Current research extends beyond microbial inactivation, demonstrating PEF's capability to enhance juice extraction from plant materials and to improve the efficiency of food drying and dehydration processes. Moreover, this technique targets the cytoplasmic membrane to enhance the selective release of intracellular compounds without the adverse effects of heat on extract quality and characteristics. Its low-energy pretreatment process also facilitates high yields in extraction. In addition, this process can improve the antioxidant activity, immunomodulatory activity, and inhibitory activity of ACE and can degrade pesticide residue as well. While much research focuses on PEF's microbial reduction, fewer studies examine its effects on the quality and consumer acceptance of treated foods. However, recent studies are highlighting the potential of PEF technology in achieving higher yields and preserving the quality of nutrients in food products.

**Keywords:** Pulsed Electric Field (PEF); Food Health Processing; Food Preservation; Non-Thermal Technique; Microbial Inactivation; Electroporation of Food Products; Inhibit Microbial Growth; Angiotensin-I-Converting Enzyme (ACE).

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## 1. Introduction

Food production is essential for human survival and health. Consequently, technologies ensuring safety and quality in food production have emerged as a critical priority in the global food industry [7]. Food becomes unsafe for consumers due to physical, chemical, and biological hazards, with natural hazards, primarily food-borne pathogens, posing a significant challenge in food preservation [8]. Pulsed electric field (PEF) technology stands out in preserving food quality aspects compared to traditional thermal processing methods. It effectively prevents or significantly minimizes alterations in foods' sensory and physical properties, aiming to provide consumers with high-quality food products [9].

PEF represents a non-thermal processing method proven to be an adequate substitute for traditional thermal processing techniques [10]. This technology applies short electrical pulses, ranging from milliseconds to microseconds, with pulse

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strengths between 100-300 V/cm to 10-80 kV/cm. At high electric fields (>20 kV/cm) [11]-[13], PEF serves as an alternative to conventional thermal processing. It effectively inactivates spoilage-causing and pathogenic microorganisms and enzymes related to quality degradation while maintaining or minimally altering liquid food products' sensory, nutritional, and health-promoting properties [10].

Food preservation methods primarily focus on stopping or reducing microbial growth. These methods work by altering conditions like temperature, water activity, preservatives, pH, and the atmosphere around the food. This approach doesn't necessarily kill the microbes, but it stops their activity. They can become active again if conditions become favourable. This is crucial because even a small number of harmful microbes can cause infection without multiplying in the food. For a new preservation technology to be considered a viable alternative, it must significantly enhance food quality while keeping costs reasonable [3]. Recently, several new technologies have emerged that can deactivate microbes at lower temperatures compared to traditional heating methods. These advancements offer promising alternatives for food preservation, and PEF is one of the best technologies among them [14].

Furthermore, the use of PEF significantly improved the extraction of intracellular compounds. It was shown that this enhancement in lipid extraction was attributable to electroporation rather than any temperature-related effects. The feasibility of integrating PEF treatment as an initial step in the extraction process, followed by the use of solvents in a subsequent step, was also established. In a comparative study, various cell disruption techniques, including PEF, High Voltage Electrical Discharge (HVED), Sonication (S), and High-Pressure Homogenization (HPH), were applied for extracting intracellular components from the microalgae Nannochloropsis sp [15].

This review systematically explains the successes of PEF technology in food processing, explores the underlying principles relevant to food processing, and addresses the obstacles faced in applying PEF on a large industrial scale. Additionally, the review proposes future perspectives of research in this field.

## 2. Research Overview

The realm of PEF has been a focus of research activity in recent times, with significant strides made in various applications. This section aims to encapsulate the essence of these research efforts, drawing upon studies and experiments conducted in previous years to shed light on the future potential of PEF.

Over the span of 2020, Abu et al. [4] demonstrated that their research revealed the most effective reduction of microbial activity in pineapple juice processed with PEF, which occurred at a field strength of 13 kV/cm. However, as this level of field intensity did not achieve the critical transmembrane potential, a certain number of bacteria either survived or experienced reversible pore formation, leading to their proliferation post-treatment. The phytochemicals examined in this study exhibited minor alterations due to PEF processing and deteriorated at a similar rate to the untreated juice over time, with the exception of total phenolics and β-carotene.

Moreover, they illustrated that in untreated juice, the decline in total phenolic content (TPC) and β-carotene was more rapid compared to the PEF-treated juice, which corresponded with a decrease in antioxidant capacity. Therefore, phenolics and β-carotene seem to play a significant role in enhancing the antioxidant properties of pineapple juice. Notably, the PEF treatment did not cause any noticeable change in the juice's temperature.

PEF treatment was recognised as an excellent potential as a fundamental step in the aqueous extraction of algae components by Parniakov et al. [15]. They stated that this technique, combined with pH-assisted extraction methods, has enabled the selective extraction of unique proteins distinct from those obtained through traditional extraction methods. This innovative approach leverages the synergistic effects of PEF pretreatment in a neutral medium (pH = 8.5) and subsequent extraction in a basic medium (pH = 11). This method has proven effective for the targeted extraction of various intracellular components, demonstrating the benefits of integrating PEF with specific pH conditions for selective extraction processes [15].

PEF treatment stands as a highly favored non-thermal technology, increasingly viewed as a viable supplement or alternative to conventional thermal methods. This preference stems from its distinct benefits, including remarkably brief processing times and reduced energy usage.

Furthermore, PEF is mentioned for its ability to maintain certain beneficial physiochemical properties in food. In recent times, the application of PEF technology has expanded, particularly in enhancing the efficacy of antioxidant peptides found in various food products. Egg whites are extensively utilized in the food industry for their high content of protein and functional peptides. These components offer several biological benefits, including antifungal, antiviral, antihypertensive, and antioxidant properties.

Specifically, egg-white protein peptides, when hydrolyzed by the enzyme alcalde, exhibit potent reducing abilities and significant antioxidant activities.

In-depth research has been conducted on the impact of PEF on these antioxidant peptides, particularly focusing on peptides with varying molecular weights derived from egg white protein. Corn gluten meal, commonly utilized as animal feed, has limited nutritional value for human consumption due to its lack of essential amino acids, water insolubility, and distinct odour.

Nevertheless, when broken down enzymatically into corn peptides, these derivatives show promising bioactivities. These include enhancing alcohol metabolism, potential anti-breast cancer properties, and improved antioxidative capabilities, along with better solubility than the original corn gluten. In a related context, the impact of PEF technology on augmenting the antioxidant activity of corn peptides has been explored, particularly by assessing their ability to inhibit DPPH [17].

**3. Fundamentals and working principle of PEF**

The technique involves delivering pulsed electrical currents to a food product between electrodes, with the space between these electrodes known as the PEF chamber's treatment gap. This high voltage generates an electric field, leading to microbial inactivation. The electric field can be applied as exponentially decaying, square wave, bipolar, or oscillatory pulses, typically at ambient or near-ambient temperatures.

Post-treatment, the food is aseptically packaged and refrigerated. As food generally possesses electrical conductivity due to various ions, the applied electric field causes an electrical current to flow through the liquid food, evenly distributing due to the charged molecules present [8];[9].

A PEF system features several key components: treatment chambers are specific containers used to carry food samples during exposure to PEF [2];[3], High-voltage pulse generator used to generate high-voltage direct current (DC) at a specific intensity by power supply and to discharge high voltage in the form of pulses with specific shapes and widths through a pulse-forming network (PFN) [6] which are revealed in Figure 1.

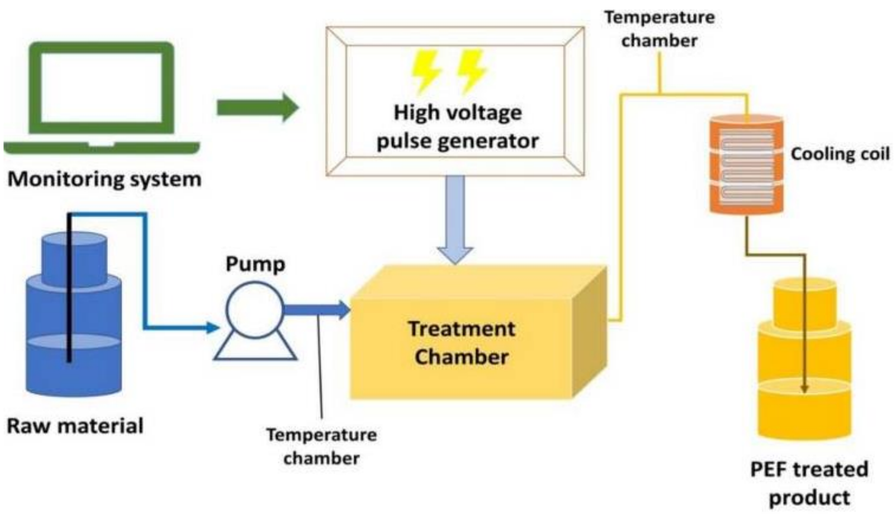


**Figure 1:** Schematic diagram of pulsed electric field (PEF) processing apparatus [2]

It also includes resistors to delay the current flow and impose a voltage reduction [18], capacitors for energy storage [19], switchers to connect or disconnect the electric current and control the discharge of the stored energy [20] and a cooling system to balance the temperature-rise during treatment [21].

**4. Mechanism of action of PEF**

PEF is believed to create an electroporation effect on microbial cell membranes. Applying a high-intensity electric pulse leads to pore formation in these membranes, increasing cell permeability and facilitating the expulsion of molecules and ions. The impact of electroporation by PEF can either cause temporary cell membrane discharge, which is reversible, or permanent cell membrane rupture, known as lysis, depending on the electric field's strength [14];[22];[23]. Figure 2 depicts the action mechanism of PEF processing. Pallares et al. [24] observed a 43 to 70% reduction in mycotoxins in juices and smoothies; however, the effect was less marked in water.

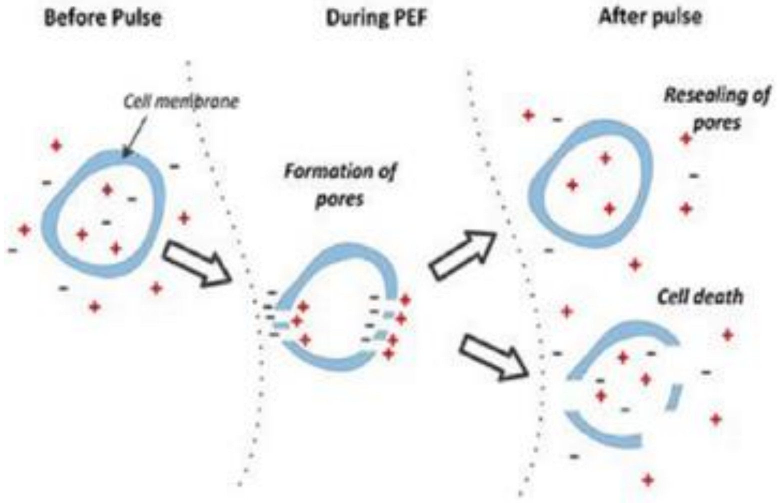


**Figure 2:** Mechanism of action of pulsed electric field on cell [1]

Figure 2 illustrates the impact of pulsed electric fields (PEF) on cell membranes, depicting the stages before, during, and after the application of the PEF. Before the pulse, the cell membrane remains intact, acting as a natural barrier that separates the cell's internal environment from the external surroundings. This membrane maintains impermeability to certain ions, represented by the red plus symbols, effectively protecting the cell's internal structures and functions.

During the PEF treatment, the electric field causes temporary destabilization of the cell membrane, resulting in the formation of pores. This process, known as electroporation, increases the membrane's permeability, allowing ions and other molecules to pass through. The formation of these pores disrupts the membrane's structural integrity, making the cell vulnerable to external factors. After the pulse, two potential outcomes occur. In some cases, the pores in the membrane may reseal, allowing the cell to recover and return to its normal state. This resealing process is crucial for cells that need to survive after PEF exposure. However, if the PEF treatment is intense or prolonged, the membrane may not fully recover, leading to irreversible damage and, ultimately, cell death. The failure to close the pores results in the leakage of cell contents, causing the cell to lose its viability. This mechanism is significant for applications such as microbial inactivation in food processing, where the goal is to disrupt the membranes of microorganisms, ensuring their inactivation and enhancing food safety and preservation.

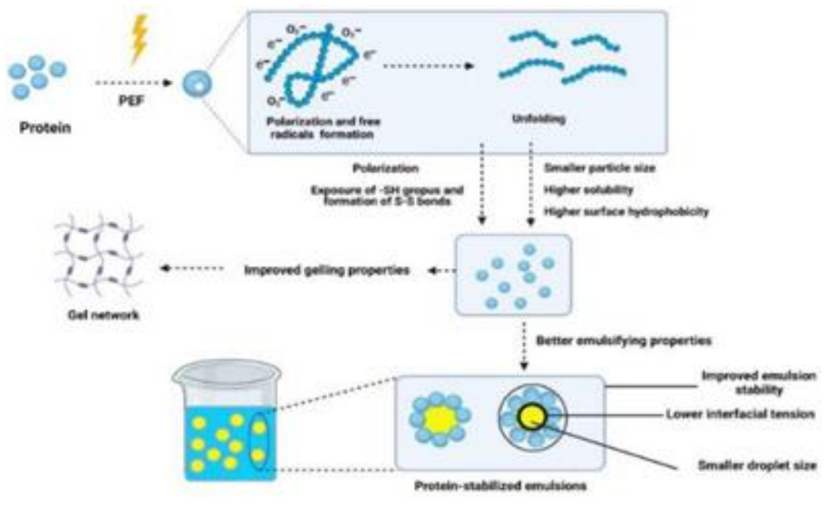


**Figure 3:** Proposed mechanism of PEF effects on the emulsifying and gelling properties of proteins [5]

The main mechanism behind the effects of electric fields on proteins remains unclear. However, it's suggested by some scientists that during PEF treatments, the polar groups in proteins absorb energy, leading to the creation of free radicals (Figures 3 and 4). These free radicals can then impact the internal interactions within the protein molecules, such as hydrophobic and electrostatic interactions, disulfide bridges, hydrogen bonds, salt bridges, and Van der Waals forces [25]. Furthermore, PEF treatments might modify the apparent charge of proteins by altering their ionic interactions. As a result, both the structure and function of proteins may undergo significant changes [26];[27].

**5. Application of PEF**

PEF technology is a cutting-edge technique used in various fields, ranging from food processing to medical treatments. PEF's ability to alter cell permeability without significant damage to the cells makes it a valuable tool in different areas. Below are descriptions of some of them:

- Extending the shelf life of fruits, vegetables, milk, and its products without affecting it’s organoleptic attributes is one of the most prominent applications of PEF, as delineated by Poojitha et al. [28].
- Alahakoon et al. [29] demonstrated that this technique could improve the thermostability of the connective tissues of the pectoralis muscle from beef. Additionally, it can enhance the quality of meat using less concentration of additives in less treatment time.
- PEF treatment enhanced foaming capacity by 48% and emulsifying capacity by 26%, surpassing heat treatment results [30].
- This process can enhance the utilization of by-products from fish processing industries. It also aids in extracting calcium from fish bones [28].
- The PEF effect on the extraction of bioactive compounds from beetroots [31] *Moringa oleifera* dry leaves [32]. The techniques were also applied to extract chitosan from inulin from chicory tissues [33], anthocyanins from red cabbage [34], and anthocyanins and antioxidants from blueberry juice [35].
- Wang et al. [36] delineated that PEF can improve biological activities, such as antioxidant (in egg white [36], corn gluten meal [37], soybean [38], pine nut [39]), immunomodulatory activity (in pine nut [40]) and Angiotensin-I-converting enzyme (ACE) inhibitory activity (in orange juice and milk mixed beverage fortified [41]).
- This method can activate, limit, and inactivate or cause no change to the enzyme activity. Ho et al. [42] explained the inactivation of lipase in wheat germ dissolved in distilled water under specific treatment conditions.
- Pesticide residue degradation is another aspect of PEF, as stated by Zhang et al. [17].

**6. Case studies of PEF**

In 2023, Abu et al. [2] illustrated the microbial inactivation in PEF-treated pineapple juice and compared it with the untreated one. The researchers observed the samples for ten days in storage at -20ºC, contrasting them with an untreated juice sample. By employing a PEF device, they applied electric field strengths of 9 kV/cm, 11 kV/cm, and 13 kV/cm at a frequency of 100 Hz. The most significant microbial inactivation occurred at the 13 kV/cm field intensity, which was the highest field strength attainable by the PEF system [4].

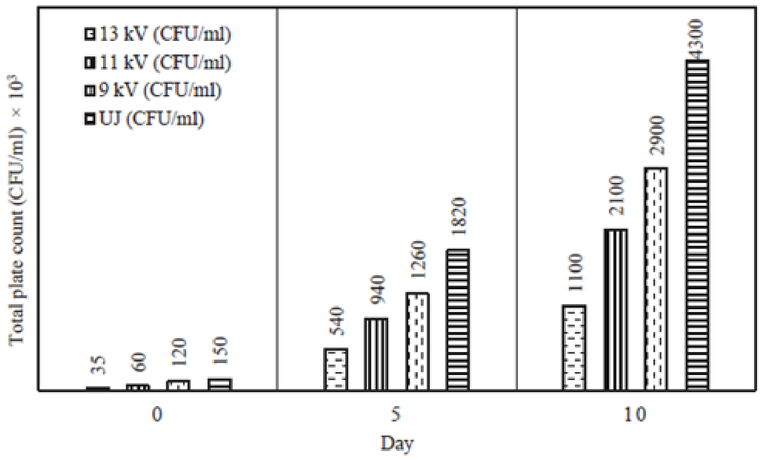


**Figure 4:** Total plate count of PEF treated (at 9 kV/cm, 11 kV/cm, and 13 kV/cm) and untreated juice [46]

Figure 4 illustrates the total plate count (CFU/ml) over time (Day 0, Day 5, and Day 10) for samples treated with different pulsed electric field (PEF) intensities: 13 kV/cm, 11 kV/cm, 9 kV/cm, and untreated juice (UJ), measured in CFU/ml × $10^3$. At Day 0, the microbial counts for all PEF-treated samples (13 kV, 11 kV, and 9 kV) and untreated juice (UJ) are relatively low, with the highest count observed in untreated juice at 150 CFU/ml × $10^3$. The 13 kV sample shows the lowest microbial count at 35 CFU/ml × $10^3$, indicating that the higher voltage effectively reduces the initial microbial load. By Day 5, there is a notable increase in microbial growth across all samples. However, the untreated juice (UJ) shows the highest microbial count of 1820 CFU/ml × $10^3$, followed by the 9 kV sample at 1260 CFU/ml × $10^3$. The 13 kV sample exhibits the lowest count at 540 CFU/ml × $10^3$, suggesting that higher PEF intensities are more effective in suppressing microbial growth.

On Day 10, microbial growth has further accelerated. The untreated juice (UJ) has reached 4300 CFU/ml × $10^3$, significantly higher than the PEF-treated samples. The 13 kV sample shows the slowest growth at 1100 CFU/ml × $10^3$, while the 11 kV and 9 kV samples have counts of 2100 and 2900 CFU/ml × $10^3$, respectively. Overall, the graph demonstrates that higher PEF intensities (13 kV and 11 kV) are more effective at controlling microbial growth over time compared to lower intensities (9 kV) and untreated juice, with the 13 kV sample showing the best performance in suppressing microbial growth throughout the 10-day period.

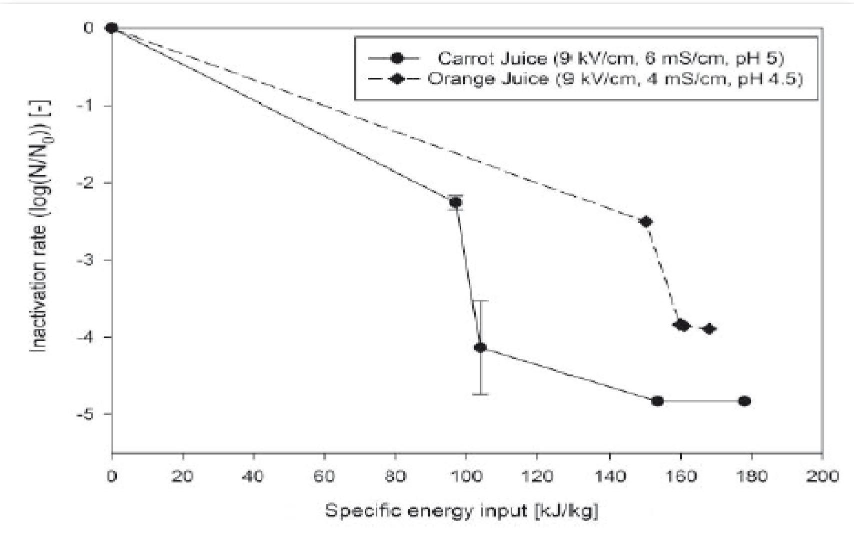


**Figure 5:** Inactivation of *Alicyclobacillus acidoterrestris* spores in orange juice and carrot juice by using PEF [2]

Several log levels of Alicyclobacillus acidoterrestris in orange juice and carrot juice can be achieved in dependence on the specific energy, as represented by Siemer and Töpfl, [16]. In both cases, the detection limit can be achieved with an energy input of 160 kJ/kg. Figure 4 depicts the inactivation rate of microorganisms in carrot juice and orange juice as a function of specific energy input during pulsed electric field (PEF) processing.  The x-axis represents the specific energy input in kilojoules per kilogram (kJ/kg), which measures the energy delivered during PEF treatment.

The data for carrot juice, represented by solid circles, and orange juice, depicted by diamonds, are shown for different conductivity and pH conditions. Carrot juice was treated at 9 kV/cm, 6 mS/cm, and pH 5, while orange juice underwent treatment at 9 kV/cm, 4 mS/cm, and pH 4.5. As the specific energy input increases, the inactivation rate of microorganisms in both juices increases, indicating that higher energy inputs lead to more effective microbial inactivation. Notably, carrot juice shows a sharper inactivation rate decrease, particularly around 120 kJ/kg, reaching an inactivation rate of approximately -5 log(N/N0), indicating a 99.999% reduction in microbial count. Orange juice follows a less steep trajectory, reaching around -3 log(N/N0), signifying a less pronounced inactivation rate at similar energy inputs.

This comparison highlights how PEF treatment's effectiveness varies depending on the juice type, electrical conductivity, and pH. The results suggest that carrot juice requires less energy input than orange juice to achieve the same level of microbial inactivation, possibly due to differences in conductivity and pH, which affect the PEF process's efficiency. In particular, thermoacidophile bacteria, e.g. A. acidoterrestris, which can also form spores, are especially important for the fruit juice industry. Furthermore, Siemer and Töpfl [16] reported the inactivation of A. acidoterrestris spores in orange juice and carrot juice by using PEF, and they stated PEF as a practical approach not only for the spores but also for the vegetative germs.

## 7. Advantages and disadvantages of PEF

Pulsed Electric Fields (PEF) technology offers numerous advantages, making it a highly attractive method for food processing and other industries, but it also comes with certain drawbacks that need to be addressed for optimal utilization. This table outlines the compensations (advantages) and drawbacks associated with PEF.

### 7.1. Advantages of PEF

One of the key benefits of PEF is its energetic efficiency and environmentally friendly nature. As it consumes low energy, PEF provides an alternative to traditional methods that may require significantly more resources and energy. This not only leads to reduced operational costs but also minimizes the environmental impact of the processing industry.

PEF also boasts short processing times, which is critical for industries looking to enhance throughput while maintaining product quality. This time efficiency, paired with the waste-free nature of the process, helps companies reduce operational delays and eliminate by-products that could otherwise require disposal.

In addition to low energy consumption, PEF technology is relatively low-cost to operate, making it accessible for small-scale businesses. Its non-destructive nature ensures that the structural and nutritional integrity of the product remains intact, which is crucial for food processing applications where the quality of food matters.

One of the standout features of PEF is its high selectivity, allowing for precise targeting of certain microorganisms or cells without affecting other components. This makes PEF a versatile tool across various industries, particularly where selective cell disruption is essential. Additionally, PEF does not generate thermal effects, and there is no evidence of toxicity, making it safe for use in food processing without altering the product's taste or nutritional value.

The technology is also easy to scale up, making it a feasible option for larger operations seeking to increase production. Furthermore, PEF enhances the retention of nutrients, flavors, and colors, which is vital for maintaining the organoleptic qualities of food products. Its suitability for processing heat-sensitive foods is another major advantage, as it provides a method for treating foods that cannot withstand high temperatures without compromising their quality.

### 7.2. Drawbacks of PEF

Despite its many benefits, PEF technology does have some limitations. One of the major drawbacks is its dependence on medium composition. The effectiveness of the process can vary significantly based on the nature of the medium being treated, which can present challenges for consistent results across different products.

Another disadvantage is the high cost of equipment. Although the operational costs are low, the initial investment in PEF machinery can be prohibitive for some businesses, especially small and medium-sized enterprises.

Additionally, PEF is only suitable for liquids, limiting its application to certain types of food and beverages. It is also more effective when combined with heat, which may negate some of the benefits of being a non-thermal process in certain applications.

PEF is ineffective against gram-positive bacteria, yeasts, and spores, which limits its application in situations where these microorganisms pose a threat. In such cases, other methods may be required to complement the PEF treatment.

The use of high-intensity PEF can lead to the destruction of cell membranes, which, while useful in certain applications, can be detrimental in others where cell integrity must be preserved.

The presence of bubbles during the PEF process can lead to non-uniform treatment and operational challenges, reducing the effectiveness of the process. Additionally, there is a lack of extensive economic and engineering studies for upscaled continuous processes, which limits the widespread industrial adoption of PEF.

PEF technology presents a promising method for food processing, with numerous advantages such as energy efficiency, rapid processing, and the retention of product quality. However, its application is currently limited by the high cost of equipment, its ineffectiveness against certain microorganisms, and challenges in scaling up for continuous operations. Addressing these drawbacks through further research and technological advancements could expand the use of PEF across various industries, offering a sustainable and efficient alternative to traditional processing methods.

## 8. Conclusion and Future Perspectives of PEF

Food preservation methods aim to deactivate microorganisms upon detection to prevent food spoilage. PEF stands out as a promising green technology offering an alternative to traditional thermal processing in food preservation because of maintaining the quality of food products' sensory, physicochemical, and nutritional properties. The use of this method in food preservation, particularly for developing the quality of the end product, has progressed from small-scale laboratory and pilot applications to full-scale industrial implementation, especially in liquid foods. By increasing shelf life, PEF simplifies production planning and allows for a broader range of products. To date, there is only a limited number of studies on using PEF in processing cereals, pulses, spices, and condiments. The efficiency of PEF in terms of shorter processing times and lower energy consumption suggests its potential applicability to a broader range of agricultural commodities, pending successful trials. Additionally, PEF could be used in cereals and pulses to address drought resistance and germination defects. In summary, there is significant scope for establishing the PEF technique more broadly in the market to enhance product quality.

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