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The Impact of Pulsed Electric Field Technology on Enzymes, Microbial and Nutritional Quality in Milk Processing - A Comprehensive Review

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Abstract A pulsed electric field is a non-thermal technology used in the processing of foods, especially liquid foods such as milk, fruit juices, etc. The objective of this review is to provide an understanding of pulsed electric field technology and its application in milk processing, particularly in whole milk, skim milk, and UHT milk. This technology can be used as an alternative to traditional heat treatments such as pasteurizing, hot filling, blanching, and sterilization. In this technology, short high-intensity electric field is used at moderate temperatures. A pulsed electric field is an effective technology to inactivate microorganisms and enzymes with minimum changes in nutritional, functional, and organoleptic qualities compared to heat treatments. Pathogenic and spoilage bacteria can be reduced effectively when using pulsed electric field technology. However, there are variations between studies. As a recent advance, the pulsed electric field is used with mild heating. This shows a significant reduction in microbial count with less detrimental effects on the physico-chemical and organoleptic properties of food. It also has minimal impact on nutrients present in the milk such as proteins, milk fat globules, and vitamins. In this review, we describe in detail the introduction, the principle of pulsed electric field, the impact of pulsed electric field on microorganisms, enzymes, and nutrients, and the advantages and disadvantages of using PEF technology. Further studies can be conducted to investigate the combined approach of the pulsed electric field with mild heating treatment methods including pasteurization and sterilization.

Keywords: Microbial inactivation, Milk processing, Non-heat treatment, Preservation, Pulsed electric field.

Introduction

Based on the World Health Organization's estimation, 31 foodborne illnesses result in 600 million cases of illness globally each year, or nearly one out of every ten people on the planet falling ill. Of the 31 foodborne illnesses, ingesting milk and milk products is linked to 4% of all foodborne zoonotic illnesses worldwide, and mostly low- and middle-income nations are affected (Kapoor et al., 2023).

Milk is widely consumed worldwide due to its high nutrition, pleasant aroma, and slightly sweet taste. Milk is a highly nutritious medium that facilitates the growth of many spoilage and pathogenic microorganisms as it is rich in carbohydrates, fat, protein, vitamins, and minerals. Hence, milk has a very limited shelf life. A comparatively wide variety of microorganisms, including yeasts, moulds, bacterium spores, and both positive and negative bacteria, are found in raw milk (Shamsi et al., 2008). Bacteria are the main cause of the common spoilage of milk (Lu & Wang, 2017). The organisms that cause milk spoilage most frequently are called psychrotrops, such as *Pseudomonas* spp. (Ercolini et al., 2009). Milk that has been improperly pasteurized or raw is extremely perishable and may contain pathogenic microbes and spoilage (Sarkar, 2016). Drinking raw milk has been linked to several food-borne infections brought on by pathogens, including *Listeria* spp. and *Escherichia coli* O157:H7 (Colaco, 2011). These lead to quality and safety issues including food poisoning and food allergies. Proper processing and storage conditions are important for controlling issues related to milk, ultimately resulting in an extended shelf life (Fernandez-Molina et al., 2005).

Heat treatment is employed to extend the shelf-life by destroying microorganisms and improving microbial quality. However, the treatment affects the nutritional and organoleptic properties of milk (Melini et al., 2017). Due to heat treatment, milk fat globule membrane changes, and protein gets denatured. Furthermore, heat treatment induces protein denaturation and protein-protein interaction during sterilizing milk (Xiang et al., 2011). Consumer demand is high when there are fewer changes in nutritional and organoleptic properties and when the shelf life is extended. Therefore, in recent years, the non-thermal processing of milk has become very popular. Non-thermal processing methods use less heat or no heat, thereby reducing the energy required (Halpin et al., 2013). Pulsed electric field (PEF) technology is one of the non-thermal processing methods. Short bursts of high voltage are given to the food when the food is pumped through a chamber. The most common acceptable mechanism is reversible or irreversible pore formation in the cell membrane. It avoids the negative effects caused by heat treatments such as colour alteration, nutrient losses, and flavour damage (Shamsi et al., 2008). According to many research findings it is claimed that PEF has the potential to successfully extend the shelf life of milk by inactivating microorganisms (Craven et al., 2008; Guerrero-Beltrán et al., 2010; Halpin et al., 2013). It is also highly applicable to liquids and has minimal effects on the flavour, nutritional, and functional characteristics of milk (Craven et al., 2008). In addition, chemical changes will not occur in food due to PEF application (Fernandez-Molina et al., 2005). The use of PEF is mainly used in liquid foods such as milk, dairy products, and fruit juices (Roobab et al., 2022; Soltanzadeh et al., 2022). Additionally, it is used in different sectors including meat, fish, seafood, fruits, and vegetables (Kempkes & Munderville, 2017; Bhat et al., 2019; Gómez et al., 2019).

The study conducted by Mohamad et al., (2021) shows that the level of microbial and enzyme inactivation is highly dependent on the intensity of the electric field, pulse parameter, processing time, and inlet-outlet temperature enzyme inactivation needs more severe PEF than inactivation of microorganisms. Increasing electric field intensity and temperature leads to a more significant inactivation of enzymes (Shamsi et al., 2008). PEF processing of low-pH foods shows better results than the neutral pH foods. Furthermore, foods with low conductivity show higher levels of inactivation than foods with high conductivity (Noci et al., 2009).

PEF technology can be used alone or combined with other techniques. Mild pre-heating is an extra hurdle to inactivate microorganisms (Noci et al., 2009). Mild thermal processing with PEF helps to retain the physical, chemical, and nutritional characteristics of milk (Fernandez-Molina et al., 2005). High-intensity PEF (HIPEF) contains high voltage and short time electric pulses. This review aims to discuss many of the advances in the application of PEF technology in milk processing, particularly the effect of PEF on microorganisms, milk nutrients, and enzymes.

Principle of PEF Technology

PEF technology involves the delivery of brief yet potent electric pulses to cells and materials. These pulses create a strong electric field capable of affecting cell membranes, a phenomenon known as electroporation (Saulis, 2010). Electroporation temporarily forms nanoscale pores in the lipid bilayer of the cell membrane, allowing the passage of molecules and ions that would not typically be able to cross (Miklavcic *et al*, 2006). According to the theory, when cells are subjected to strong electric fields, their membrane permeability rises and results in electroporation. When a critical transmembrane voltage is applied for a long enough period, a non-reversible pore with a specific width form on the cell membrane, which ultimately causes cell death (Sampedro et al., 2005).

Electroporation occurs when electric pulses disturb the balance of charge in cellular membranes, leading to the creation of a localized electric field. If the intensity of these pulses exceeds a certain threshold, it causes the formation of nanopores in the lipid bilayers of cells. These nanopores allow disruptive molecular transfer, compromising normal physiological processes. The degree of electroporation varies based on pulse characteristics like magnitude and duration. Milder pulses can restore function, while more intense pulses may trigger apoptosis. Adjusting factors such as voltage and pulse duration offers a means to control medical outcomes manually (Gusbeth et al, 2004). The extent of electroporation is influenced by critical pulse attributes, such as duration, strength, and the inherent properties of the cells or materials being targeted. The samples should be prepared before

PEF treatment. As a preparation method, the samples are suspended in a suitable carrier medium to ensure uniform exposure to the electric pulse. PEF system consists of two electrodes arranged opposite to each other. The sample is placed in between them. The parameters of the PEF system such as intensity, duration, pulse frequency, and total number of pulses are adjusted.

Power Supply Requirements for PEF Systems

The PEF system needs a power supply. Power supply specification depends on the application, desired results, and the characteristics of the target materials or cells. The aspects of power supply are voltage and current, pulse duration, pulse frequency, number of pulses, control and monitoring, safety features, energy efficiency, and scalability. Pulse intensity is the strength of the electric field. High voltage power supply is used ranging from 20,000 to 100,000 volts. The delivery of current may depend on the intended application (Knoerzer et al., 2012). Pulse duration is the time the electric pulse is applied. Pulse duration varies from microseconds to milliseconds. This is customized according to the properties of the sample or target materials. Pulse frequency is the number of pulses administered per unit of time. Pulse frequency is determined by the requirements of the application and the designated treatment protocol. Number of pulses is the total count delivered during the treatment. The power supply should be capable of generating the required number of pulses for optimal results. Some applications demand a sequence or pattern of pulses. Real-time controlling and monitoring are essential when operating PEF technology. Parameters such as intensity, duration, frequency, and number of pulses are precisely controlled and monitored. Safety features are considered to mitigate electrical hazards which include safety interlocks, insulation, and grounding. These are followed to prevent unintended exposure to high voltage. Energy efficiency is also one of the main considerations regarding the application of PEF. To ensure cost-effectiveness, minimal power consumption and heat generation are considered. The power supply of PEF should be scalable and be able to accommodate various sample sizes and throughput requirements (Zhu et al., 2022). The outcome of the PEF process is carefully controlled. For that, fine-tuning of the pulse parameters can be done by adjusting the number of pulses while minimizing potential side effects.

Combined heat/PEF technology

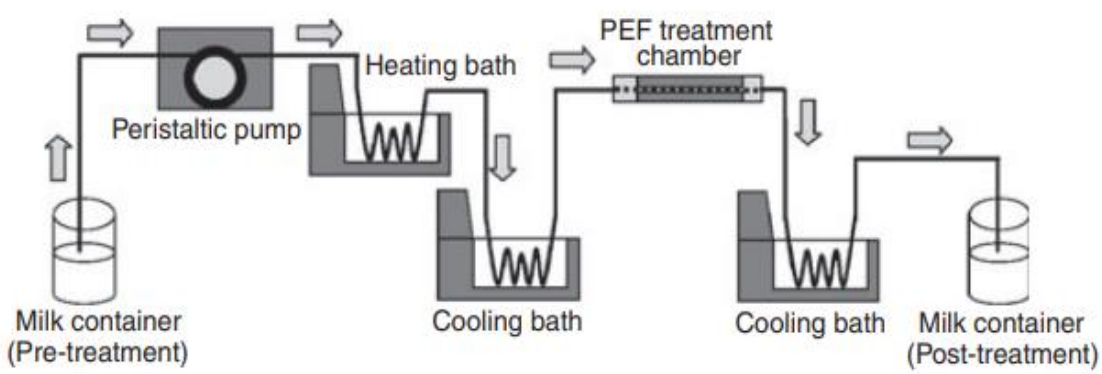

Figure 1: Schematic drawing of the equipment used for milk processing combining moderate heat and PEF. Adopted from Walkling-Ribeiro et al. (2009).

A PEF processing system contains a treatment chamber, a cooling system, a current measuring device, a control unit, and a data acquisition system (Datir et al., 2019). As a recent advance, PEF is used with mild heating. Figure 1 shows the combined heat/PEF approach. Milk is heated initially in the heating bath at 30 ºC, 40 ºC, or 50 ºC for 60 s and, cooled in a cooling bath at 10 ºC for 120 s. Subsequently, milk is treated with a PEF processing system. The electrode length, total electrode area, constant flow rate, and residence time vary with the design used. The maximum temperature increase is up to 55 ºC. Finally, it is cooled to 10ºC in 120 s (Walkling-Ribeiro et al., 2009).

PEF with other processing technologies

A study carried out by Halpin et al. (2013) to examine the microbiological quality of post-processing of each of the milk samples to assess the efficacy of two non-thermal technologies (manothermosonication; MTS, and PEF) in comparison to thermal pasteurization. At two temperatures (37 °C or 55 °C), homogenized milk was subjected to MTS (amplitude: 27.9 m, pressure: 225 kPa), and then was immediately treated with PEF (electric field strength: 32 kV/cm, pulse width: 10 µs, frequency: 320 Hz). As a control treatment, thermal pasteurization (72 °C, 20 s) was applied to homogenized milk. Over the course of 21 days, the microbial composition of every milk sample was observed. It was found that milk treated with MTS/PEF at 37 °C and 55 °C had lower microbial levels, but after 14 days, milk that had been pasteurized by conventional methods contained significantly ($P<0.05$) fewer microorganisms than raw milk. The results of this study demonstrated that milk treated with MTS/PEF can prevent microbial growth without using high heat such as that used in thermal pasteurization. While thermal pasteurization seems to be the best way to extend the shelf life of milk, the outcomes of MTS/PEF treatment for microbial inactivation was promising. Additional processing condition optimisation would be necessary to raise the quality of milk treated with MTS/PEF's microbiological quality to a level comparable to that of thermally pasteurized milk (Halpin et al., 2013). According to the study carried out by Noci et al. (2009), thermosonication (TS) for 80 s combined with PEF (40 kV cm^{-1}) on pre-heated milk showed higher microbial inactivation (6.9 log_{10} cfu ml^{-1}) than thermal pasteurization particularly inactivating *Listeria innocua*.

Effect of PEF on microbial quality

Studies conducted over the past years on PEF treatment of milk have demonstrated that PEF is highly successful in inactivating bacterial cells, yeasts, and vegetative moulds (Bendicho et al., 2002). Gram-positive bacteria are typically more resistant to PEF treatment than gram-negative bacteria. Because of their bigger size, yeasts are more susceptible to the strength of an electric field than bacteria (Toepfl et al., 2014). The product's composition and electrical conductivity influence the level of microbial inactivation (Müller et al., 2020).

Whole milk

In the study conducted by Sharma et al. (2014), PEF processing, which involved preheating the milk and stepwise intermediate cooling, was compared for their ability to inactivate both gram-positive and gram-negative bacteria in whole milk with thermal pasteurization. Milk was exposed to varying electric field strengths (18–28 kV cm^{-1}) for a duration of 17–235 µs at various temperatures. Although PEF treatment at 4 ºC did not lower the number of bacteria, it became more effective as the temperature rose (Moonesan & Jayaram, 2013). PEF treatments at 22–28 kV cm^{-1} for 17–101 µs at 50 ºC resulted in a 5–6 log reduction below the detection limit for *Pseudomonas aeruginosa*, while *Escherichia coli*, *Staphylococcus aureus,* and *Listeria innocua* were reduced to below the detection limit at 55 ºC. Compared to gram-positive bacteria, gram-negative bacteria showed lower resistance to PEF.

PEF of high intensity can also be used, and it can inactivate *Staphylococcus aureus*, a significant pathogen associated with milk (Kajiwara et al., 2015). Using a response surface methodology, the inactivation of *Staph. aureus* suspended in milk by a high-intensity pulsed electric field (HIPEF) was investigated. The controlled variables included the milk's fat content, electric field intensity, pulse number, width, and polarity. It was discovered that the microbial inactivation of *Staph. aureus* was not considerably impacted by the fat content of milk. 150 bipolar pulses of 8 µs duration at 35 kV/cm were applied to achieve a maximum reduction of 4.5 logarithmic units. The application of bipolar pulses proved to be more efficacious than monopolar ones. The survival fraction of *Staph. aureus* dropped due to an increase in electric field intensity, pulse number, or pulse width. Similar patterns were seen in the combined action of pulse number and electric field intensity, suggesting that various combinations of the variables can achieve the same fraction of microbial death (Sobrino-Lopez et al., 2006).

Raw skim milk and ultra-heat treatment (UHT) milk

PEF treatment was used to process raw skim milk, UHT skim milk, and skim milk infused with *Pseudomonas fluorescens*, *Lactococcus lactis*, and *Bacillus cereus*. According to results of the study conducted by Alvarez et al. (2003), PEF treatment resulted in a 0.3 to 3.0 log reduction of total microorganisms in raw milk and of *P. fluorescens, L. lactis, and B. cereus* in UHT milk. The results of the study conducted by Fernández-Molina et al. (2006) showed that PEF treated milk at 40 kV/cm and 30 pulses of 2 µs duration show 6.2 log cfu/ml reduction in total aerobic count after 14 days of storage at 4ºC. The shelf life of the thermal/PEF-processed skim milk was more than 22 days. Short-term application of pulsed electric field energy proved effective in inactivating *Pseudomonas fluorescens* and *Listeria innocua* which had been inoculated into 0.2% skim milk. For *L. innocua*, which corresponded to input voltages of 30, 35, and 40 kV, the energy densities needed to achieve three log reductions of the microorganisms were 120, 212, and 270 kJ/L; for *P. fluorescens*, under the same input conditions, the corresponding energy densities were 88, 105, and 128 kJ/L. The chosen treatment times were 145 µs and 290 µs, respectively, and the wave pulses had an exponential decaying duration of 3 µs. The study conducted by Craven et al., (2008) showed that the majoring spoilage bacteria *Pseudomonas* species has been reduced to at least 5 logs due to the application of combined PEF treatment 31 kV cm^{-1} and a mild heat treatment (55 ºC). The inactivation of total plate count (TPC), *Pseudomonas*, and *Enterobacteriaceae* counts in raw skim milk were studied by Shamsi et al., (2008) in response to PEF treatments at field intensities of 25–37 kV cm^{-1} and 15 °C and 60 °C of final PEF treatment temperatures. The TPC and *Pseudomonas* counts decreased by 1 log at 15 °C with PEF treatments of 28 to 37 kV cm^{-1}, while the *Enterobacteriacea*e count decreased by at least 2.1 log units to below the detection limit of 1 CFU mL^{-1}. PEF treatments at 25 to 35 kV cm^{-1} at 60 °C resulted in TPC inactivation of up to 2.4 log reduction, while *Pseudomonas* and *Enterobacteriaceae* counts were reduced to below the detection limit of 1 CFU mL^{-1} by at least 5.9 and 2.1 logs, respectively. The study found that for inactivating TPC, *Pseudomonas*, and *Enterobacteriaceae*, among other natural microflora in raw skim milk, PEF treatment at 35 kV cm^{-1} and 60 °C was equally effective as thermal pasteurization (Shamsi et al., 2008).

Effect of heat and PEF on Milk Nutrients

Lipids, protein, lactose, vitamins, and minerals are the nutrients present in milk (Ahmad et al., 2013). Fats or lipids influence the cost, nutrition, functional, and sensory attributes of milk and dairy products. Polar lipids, cholesterol, proteins, glycoproteins, and enzymes are present within the milk fat globule membrane (MFGM). The unique composition and structure of milk fat globules (MFG) and MFGM lead to structural changes (Mohamad et al., 2021). Protein is present as lipoprotein in MFGM.

Lipid

Fat and fatty acids are prone to oxidation in the presence of heat (Hashemi et al., 2019). The products of lipid oxidation may contain mutagenic, carcinogenic, and cytotoxic properties which cause risks to human health (Guerrero-Beltrán et al., 2010). Temperature affects the colloidal structure, stability, chemical reactivity, etc. Although PEF is a non-thermal processing method, ohmic heating causes an increase in temperature (Arora, 2021). Ohmic heating is a process in which foods are heated when an electric current passes through them. When an electric current passes through the sample, ions and other molecules, such as proteins and lipids, take on charges, which leads to ohmic or Joule heating (Arora, 2021).

Protein

There are two types of proteins present in milk, namely casein and whey. In the milk proteins, 80% is casein and 20% is whey. Casein proteins are classified as αs1, αs2, β, and κ-casein. Whey proteins are classified as α-lactalbumin (α-La) and β-lactoglobulin (β-Lg) (Mann et al., 2018). Protein structure is highly affected by the PEF treatment. In particular, secondary and tertiary structures are prone to denaturation. The functional properties such as solubility, gelation, and coagulation are also affected by PEF treatment (Sampedro & Rodrigo, 2015). Amino acids and proteins that are primarily associated with weaker bonds such as hydrogen bonds, hydrophobic bonds, and disulfide bonds are affected by PEF treatment (Riener et al., 2009). Protein aggregates mainly occur due to the breakage of disulfide bonds (Visschers & De Jongh, 2005). Proteins are susceptible to denaturation when subjected to heat processing. PEF treatment on milk has little impact on the tertiary structure of whey protein. Furthermore, PEF could enhance protein augmentation through disulfide and hydrophobic reaction aggregation. This changes the protein's thermal stability and enzymatic digestibility. Some chemical bonds such as peptides and non-covalent bonds as well as hydrophobic, electrostatic, and Van der Waals interactions, counterbalance the protein structure (Gouse Masthan et al., 2017).

Some studies suggest that the PEF application can modify the polarity and microenvironment of amino acid residues by discharging native molecular structures including whey proteins (Mohamad et al., 2021). According to some studies, PEF treatment (40 kV/cm; 30 kV/cm) at mild temperatures (40-60 ºC) can cause the denaturation of milk proteins. This occurs due to the unfolding of protein molecules or their positioning towards an applied PEF (Mohamad et al., 2021). These results were also found by Arora (2021), who found significant changes in the concentration of natively folded lactoferrin, aggregated protein, and surface hydrophobicity of whey protein isolate after PEF treatment (30-35 kV/cm, 19.2 and 211 µs; 760 mL/min; 60-70 ºC). The effects of PEF on proteins are less pronounced than thermal pasteurization. Cooling systems can be installed between two treatment chambers to minimize the thermal effects (Sharma et al., 2014).

Vitamin

Water-soluble vitamins are more sensitive to heat treatments compared to fat-soluble vitamins (Hashemi et al., 2019). Among these, riboflavin is the most resistant to heat, with only 10% of it destroyed during milk sterilization (Riener et al., 2009). Thiamine, on the other hand, may decrease by 25-50% after in-bottle sterilization. The most vulnerable vitamin to heat is ascorbic acid. Reports indicate a loss of 40-60% of ascorbic acid in milk after in-bottle sterilization and around 20-40% after UHT treatments (Gouse Masthan et al., 2017). After pasteurization treatment, a drop of 15% and a reduction of 25% have been observed. Fat-soluble vitamins, in general, are heat-resistant. No losses of cholecalciferol have been observed after pasteurization or sterilization treatment of milk. Tocopherols are also heat-stable but are susceptible to aggressive forms of oxygen. Their oxidation is accelerated at high temperatures (Bendicho et al., 2002).

PEF treatment had a minimal effect on the vitamin content of milk (Bendicho et al., 2002). Some studies suggest that prolonged PEF treatment times and foods with high electric field intensities lead to decreased vitamin retention values. However, in the case of fresh bovine raw milk, PEF treatment (15–35 kV/cm; 12.5–75 s; 30 ºC) did not significantly affect ($p > 0.05$) the levels of thiamin, riboflavin, retinol, and a-tocopherol (Bendicho et al., 2002). There were no significant changes ($p > 0.05$) in both classes of vitamins, except for ascorbic acid. However, the decrease in ascorbic acid was found to be dependent on the electric field strength, treatment time, and temperature (Mercali et al., 2014).

Effect of PEF on enzymes alkaline phosphate, Lactoperoxidase, and other dairy enzymes

Enzyme inactivation is important because it assists in milk preservation and exhibits antimicrobial activity. According to the study conducted by Arora (2021), the effects of PEF treatment on the activities of various milk enzymes including alkaline phosphatase (ALP), lipases, Lactoperoxidase (LPO), and proteases commonly present in milk or simulated milk ultrafiltrate (SMUF) have been reported. In this study, a reduced activity of enzymes plasmin (12%) and xanthine oxidase (32%) on PEF treatment of 26.1 kV/cm for 34 µs in combination with preheating at 55 ºC for 24 s have been reported. Bermúdez-Aguirre et al. (2012) found a reduction in the activity of lipase, alkaline phosphatase, and protease of fresh bovine milk by 14%, 29%, and 37%, respectively on the application of 35 kV/cm for 75 µs. Enzyme inactivation requires a more severe PEF treatment than that needed for inactivating microorganisms (D'Incecco et al., 2021). The higher the electric field intensity and temperature, the greater reduction in enzyme activity is achievable related to unfolding, denaturation, breakdown of covalent bonds, and oxidation-reduction reactions in the protein structure to enzyme inactivity (Gouse Masthan et al., 2017). ALP is a natural milk enzyme responsible for removing phosphate groups from protein molecules (Datir et al., 2019). Due to its heat stability, which is greater than that of any vegetative pathogens in milk, the ALP test is widely used to validate the thermal pasteurization (Barbosa-Cánovas & Bermúdez-Aguirre, 2010; Clawin-Rädecker et al., 2021) process of milk and to check for the possible addition of raw milk to pasteurized milk. Although PEF treatment of milk has been reported to have varying success in inactivating ALP (Buckow et al., 2014). For instance, a PEF treatment of milk at 20 kV/cm² for 400 MS can cause noticeable activity loss of ALP, and even prolonged treatments at 21.5 kV/cm² or short treatments at 34 kV/cm² at temperatures below 50 ⁰C can inactivate only up to 10% of the enzyme (Shamsi et al., 2008). However, when the outlet temperature is increased to 60 °C, inactivation of ALP increases to 67% at 37 kV/cm². Therefore, PEF can be used to effectively inactivate ALP in raw milk, and the mild heat can further enhance its efficiency (Pereira & Vicente, 2016). LPO is a natural enzyme found in milk and is a crucial component of the LPO-thiocyanate-hydrogen peroxide antimicrobial system. The antimicrobial properties of LPO have been studied in terms of its ability to control microorganisms in raw milk and extend its shelf life when refrigerated (Buckow et al., 2014). LPO is sensitive to heat treatments above 70 ⁰C, the temperature range used for pasteurizing milk products. There are some studies on the inactivation of LPO in dairy systems through PEF processing. However, LPO inactivation in raw milk was insignificant during PEF treatment at 19 or 35 kV/cm² and relatively long treatment times (up to 500 ms), as long as the treatment temperature was kept below its thermal inactivation temperature (Buckow et al., 2014). Conversely, some studies reported up to 25% LPO inactivation in raw whole milk when PEF processing at 21.5 kV/cm² and temperature of approximately 50 ⁰C (da Cruz et al., 2010). Higher inactivation levels of LPO in milk and SMUF were found at 38-40 kV/cm² when the treatment temperature was allowed to increase to temperatures of 60 ⁰C (Sobrino-Lopez et al., 2006). These studies concluded that enzyme inactivation is largely due to thermal effects, but approximately 5-12% of the inactivation of LPO is related to the non-thermal effects of the PEF treatment at these temperatures. Although studies on the inactivation of bovine LPO by PEF are not conclusive and thermal effects have not been substantiated, there is some evidence that the enzyme is more PEF-resistant than other enzymes in milk (Gouse Masthan et al., 2017).

Advantages of PEF

PEF is a new non-thermal food processing technology that can be used alone or in conjunction with other techniques to alter biological macromolecules, enhance chemical reactions, and hasten the aging of fermented foods (Lasekan et al.,2017 and Niu et al., 2020). It is used as a supplement or to replace the traditional techniques in the food manufacturing process. PEF processing can effectively inactivate dangerous bacteria (*Pseudomonas* species) with at least 5 log reduction and inactivate enzymes without significantly reducing the product's quality attributes, making it a viable alternative to heat treatment for pasteurizing milk (Craven et al., 2008). PEF preserves liquid foods by preserving their sensory qualities (Lasekan et al., 2017). PEF treatment extends the shelf life up to 8 days at 4 ⁰C and limits the loss of milk's qualitative features associated with heat treatments (Craven et al., 2008).

Disadvantages of PEF

Although there are many advantages, some factors restrict the usage of this technology widely. Recognizing the efficient PEF system is the key barrier to commercial adoption (Arshad et al., 2021). Other than this constraint, high initial investment costs (Góngora-Nieto et al., 2002), dielectric breakdown due to bubble formation and dissolved gases, employing conductive materials, and insufficient economic and engineering evaluations are also contributing to the limitation of this technology commercially. The specific internal energy efficiency for various food applications is still uncertain. Treating milk with PEF affects both the biological and quality characteristics of milk. It is well understood that the specific parameters employed in the PEF process, as well as the inherent characteristics of the end product, play a critical role in determining the extent of microbial inactivation. In addition, the effect of PEF particular variables related to the product's sensory and physical attributes as well as its ability to extend shelf life are significant factors affecting the viability and usefulness of using PEF as a preservation technique in industrial settings.

Future trends

There is limited research on the effects of PEF on food proteins, and several facets demand future investigation. The impact of various electric field strengths on the structure and techno-functional properties of proteins must be studied to determine the ideal PEF conditions. A fundamental challenge in PEF applications lies in both internal PEF device characteristics and external variables such as pH, conductivity, and solution concentration, which affect the outcome of the treatments. More effective PEF devices can be constructed with controlled treatment conditions. Further studies can be done to investigate the combined approach of PEF with other mild heating treatment methods. Many scientific studies have been performed using small sample volumes on a laboratory scale. This technology is currently applied to process fruit juices to extend their shelf life. The cost of applying PEF for milk processing is slightly higher due to the high electrical conductivity of dairy systems. Soluble salt fraction is the reason for having high electrical conductivity in milk. The additional cost of PEF over conventional thermal processing is offset by premium-priced products. The application of PEF requires further systematic research on the safety, quality, and health-promoting aspects of PEF processed milk to assure regulatory food safety approval.

Conclusion

PEF is a good alternative method to treat various food products by inactivating microorganisms and enzymes while having minimal effect on nutrients and flavour. PEF stands out as a nonthermal method of considerable interest due to its capacity to mitigate alterations in the sensory attributes of liquid foods while ensuring their microbiological safety, particularly in the context of the food and dairy industry including milk processing. PEF with mild heating supports the inactivation of microorganisms and prevents the direct effect of pasteurization of milk. Low processing temperature and microsecond residence times promote the retention of nutrients and quality of milk. Furthermore, it is essential to evaluate potential shortcomings and critical factors in the handling and treatment of milk because the conditions used vary for different liquid foods. In practical terms, the prospect of integrating PEF with traditional heat treatment s including pasteurization and thermal sterilization or emerging techniques should not be dismissed, as this may offer a synergistic approach to significantly prolong the shelf life of milk. Consequently, PEF emerges as a promising non-thermal technique with the potential to transform the milk industry. It enhances the marketability of fresh milk products such as whole milk, skim milk, and UHT milk.

Conflicts of Interest

The authors declare that they have no conflict of interest.

Author Contribution

M.S.Christopher involved in finding the review topic, data gathering, writing, editing, finalizing the review article
W.A.M.B.W. Adhipathu gave contribution in planning, data gathering, writing, and editing the review article
M.M.M.T. Marasinghe was involved in data gathering and writing the review article
T.A.S.V. Thunmuduna was involved in data gathering and writing the review article
M.H.S. Udayanga was involved in data gathering and writing the review article

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