

REVIEW ARTICLE

Advances and Opportunities of Pulsed Electric Field Technology for Preservation of Fruit Juices and Beverages: A Comprehensive Review

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ABSTRACT

Pulsed Electric Field (PEF) technology is a promising non-thermal processing method that effectively inactivates microorganisms and enzymes while preserving fruit juices and beverages' freshness, nutritional value, and sensory characteristics. This review explores the mechanism of microbial and enzyme inactivation by PEF, highlighting its effectiveness in maintaining product quality. Advances in PEF systems, including electroporators and treatment chamber designs, have enhanced their efficiency and application. Studies on various fruit juices, including apple, orange, strawberry, tomato, watermelon, Opuntia dillenii cactus juice, and pomegranate fermented beverages, demonstrate PEF's ability to extend shelf life, retain bioactive compounds, and minimize thermal degradation. Additionally, PEF has been successfully applied to milk-date beverages and beer as a non-thermal alternative to conventional pasteurization. Economic and environmental considerations, including energy efficiency and cost-effectiveness, suggest that PEF is a viable alternative for industrial-scale beverage processing. However, further optimization and integration with complementary techniques, such as mild heat treatments, are needed to ensure complete enzyme inactivation and microbial safety while maximizing economic benefits.

Keywords: Fruit juice preservation, Environmental Sustainability, Industrial-scale processing, Non-thermal processing, Pulsed Electric Field (PEF).

INTRODUCTION

Sustainable food production is becoming increasingly important as the global food industry seeks to reduce waste, conserve resources, and implement eco-friendly processing methods. One of the key challenges in food processing is the high consumption of water and energy, which often leads to environmental concerns such as water contamination, greenhouse gas emissions, and increased operational

costs. As a result, the industry is shifting towards energy-efficient and sustainable technologies to improve food preservation while minimizing its environmental footprint (Arshad et al., 2022). Non-thermal processing technologies, such as pulsed electric fields (PEF), ultrasound, and high hydrostatic pressure, have emerged as viable alternatives to conventional thermal methods. PEF, in particular,

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has gained significant attention due to its ability to inactivate microorganisms and enzymes while preserving food products' freshness, nutritional value, and sensory properties. Its application in fruit juices and beverages has demonstrated promising results in extending shelf life, retaining bioactive compounds, and reducing thermal degradation. Moreover, advancements in PEF systems, including optimized electroporators and treatment chamber designs, have improved their efficiency and industrial feasibility.

This review explores the potential of PEF technology as a sustainable alternative for food and beverage processing. It examines the mechanisms of microbial and enzyme inactivation, the benefits of PEF-assisted pasteurization, and its integration with other non-thermal techniques to enhance food quality and safety. Economic and environmental considerations are also discussed to assess PEF's viability for large-scale commercial applications. Finally, future research directions and challenges in optimizing PEF technology for widespread adoption are highlighted.

Mechanism of microbial and enzyme inactivation by PEF

Pulsed Electric Field (PEF) treatment involves applying short, high-voltage pulses (<50 kV/cm) to food placed between electrodes, leading to electroporation, which disrupts microbial cell membranes. This process enhances microbial inactivation, bioactive compound extraction, and juice yield by increasing cell permeability. Larger cells, such as plant and animal cells, require lower field strength (0.5–2 kV/cm) than microbial cells (10–14 kV/cm). Pore formation can be temporary or permanent, depending on the intensity of the treatment. PEF is particularly effective in foods with low electrical conductivity, as differences in conductivity between food and microbial cells enhance ion flow, weakening microbial membranes. Factors like pH, water activity, and soluble solids in fruit and vegetable juices influence the effectiveness of PEF, which can be further improved by natural antimicrobials (Koubaa *et al.*, 2018; Salehi, 2020; Arshad *et al.*, 2021).

Enzyme inactivation is essential in the fruit juice industry to prevent degradation and maintain quality. While thermal treatments have traditionally been used, PEF technology has emerged as an effective non-thermal alternative. According to Roobab *et al.* (2022), PEF efficiently inactivates enzymes and bacteria while preserving the juice's fresh-like

properties. This process alters enzyme structures, leading to energy savings, reduced waste, and new product opportunities. However, some enzymatic activity may recover during storage due to incomplete inactivation or resistant isozymes. To address this, combining PEF with mild heat or other non-thermal methods provides a cleaner alternative to conventional heat treatments. Additionally, integrating PEF with traditional pasteurization improves juice preservation, offering economic benefits such as longer shelf life, better stability, and more efficient production.

Advances in PEF systems

PEF technology is a developing food processing method, with research focusing on improving chamber designs for even electric field distribution in large-scale systems. Pilot-scale units can handle 400–2,000 L/h, while commercial units process 400–6,000 L/h. The U.S. juice industry adopted PEF, with Genesis Juice Cooperative using it before switching to high-pressure processing (HPP) for unknown reasons. PEF processing costs depend on equipment investment and energy use (Sampedro *et al.*, 2013).

PEF pasteurization helps maintain the freshness and nutritional value of liquid foods compared to traditional thermal methods, but its industrial use remains limited due to system inefficiencies. Arshad *et al.*, (2022) aimed to enhance the electroporator by addressing uneven electric field distribution, which leads to temperature inconsistencies. A coaxial treatment chamber with sieves and a double-exponential (DE) waveform was introduced to improve uniformity and prevent hotspots. Computational modeling confirmed improved flow properties, and a three-stage Marx generator was developed to generate the DE waveform. Microbial and chemical analyses of PEF-treated, thermally processed, and untreated orange juice stored at 4°C for nine days revealed lower microbial growth in PEF and thermally treated samples. However, PEF-treated juice retained a brighter color than thermally processed juice, highlighting its potential for effective microbial inactivation while preserving product quality.

Advances in PEF-assisted pasteurization of fruit juices and fruit-based beverages

Apple juice

Saldana *et al.* (2011) examined the impact of temperature and N α -lauroyl ethyl ester (LAE) on *E. coli*

O157:H7 inactivation in apple juice using PEF treatment. α -lauroyl ethyl ester (LAE) is an antimicrobial agent effective against bacteria, yeasts, and molds. Recognized as safe (GRAS) in the US since 2005 (up to 200 ppm), it has also been evaluated by EFSA for use in fruit-based drinks, energy drinks, and meat products. The goal was to establish industrial-scale conditions ensuring safety comparable to thermal processing. Inactivation ranged from 0.4 to 3.6 Log₁₀ cycles in untreated juice and 0.9 to 6.7 Log₁₀ cycles with 50 ppm LAE. A mathematical model estimated treatment conditions for a 5 Log₁₀ reduction in *E. coli*, validated with *Listeria monocytogenes*, *Staphylococcus aureus*, and *Salmonella enterica*. At 25 kV/cm for 63 μ s (65 °C, 125 kJ/kg), over 5 Log₁₀ reductions were achieved. With LAE, required treatment time decreased to 38.4 μ s, outlet temperature to 55 °C, and energy input to 83.2 kJ/kg, enhancing efficiency.

Katiyo *et al.* (2014) explored the effects of combining PEF with mild heat treatment on the enzyme activity of Polyphenol Oxidase (PPO) and Peroxidase (POD) in red apple juice. Researchers used response surface methodology to optimize pasteurization conditions and assess color changes, comparing results with thermal and unpasteurized juices. The study found that enzyme inactivation was influenced by electric field strength, treatment duration, and post-treatment temperature. While PPO and POD were affected, POD was more resistant to this treatment. The most effective conditions for reducing enzyme activity were 30 kV/cm, 1000 μ s, and 60 °C, achieving similar enzyme inactivation levels as conventional thermal pasteurization while preserving the juice's natural color. These findings highlighted the potential of combining PEF with mild heat as an alternative to traditional pasteurization. This method-maintained juice quality while reducing enzyme activity, offering a promising solution for producing natural, nutritious, and functional red apple juice.

Apple juice is the second most consumed juice worldwide after orange juice, but is prone to enzymatic browning due to polyphenoloxidase. Sulaiman *et al.* (2017) assessed the effects of thermosonication (TS: 1.3 W/mL, 58 °C, 10 min), pulsed electric field (PEF: 24.8 kV/cm, 60 pulses, 169 μ s, 53.8 °C), and heat treatment (75 °C, 20 min) on Royal Gala apple juice stored at 3 °C and 20 °C for 30 days. Sensory evaluations indicated that TS- and PEF-treated juices had distinct flavors than heat-treated juice. Except for PEF juice kept at room temperature, all samples

remained stable, with unchanged pH and soluble solids and no signs of fermentation. Polyphenoloxidase did not reactivate during storage, though antioxidant activity declined while color changes increased slightly. TS boosted antioxidant activity from 86% to 103%, PEF preserved it, and heat processing reduced it to 67%. After storage, the processing methods had no major significant color differences. TS and PEF may serve as effective alternatives to thermal treatment, with refrigeration advised for PEF-treated juice.

Dziadek *et al.* (2019) investigated the effects of PEF treatment on apple juice's shelf life and nutritional properties. The juice was processed in a chamber between electrodes, with each cycle consisting of 50 pulses delivered every 30 seconds. It underwent 4, 6, or 8 cycles, totaling 200, 300, and 400 pulses, using an electric field strength of 30 kV/cm. To prevent the loss of vitamin C and polyphenols, samples were cooled at 4 °C for 15 minutes after each cycle. Researchers assessed vitamin C, polyphenol content, antioxidant activity, and microbial presence immediately after treatment and after 24, 48, and 72 hours of refrigerated storage. The findings indicated that PEF did not affect bioactive compound levels, as vitamin C and polyphenols remained stable. Additionally, PEF effectively eliminated spoilage microorganisms, including bacteria, fungi, and yeast. The effectiveness of microbial inactivation depended on the number of pulses—400 pulses ensured stability for 72 hours, while 300 pulses-maintained preservation for 48 hours. In summary, PEF is an effective technique for prolonging shelf life while maintaining apple juice's freshness and nutritional value, making it a promising method for juice preservation.

Mango juice

Salinas-Roca *et al.* (2017) examined the impact of High-Intensity Pulsed Electric Fields (HIPEF) on the microbial safety, enzyme activity, and quality of mango juice to determine the best treatment duration. Mango juice treated with HIPEF (35 kV/cm, 1800 μ s) was compared with thermally treated (90 °C, 60 s) and untreated samples over 75 days of refrigerated storage. HIPEF treatment for 800 μ s effectively reduced *Listeria innocua* by 5 log cycles, while a longer treatment of 1800 μ s significantly lowered enzyme activities (PPO by 70%, LOX by 53%, and POD by 44%). The treated juice maintained its fresh-like color, sensory properties, and microbial stability for

up to two months. Additionally, the phenolic content increased from 333 to 683 µg GAE/mL over storage, while antioxidant and carotenoid levels gradually declined in all samples. However, bioactive compounds were better preserved in HIPEF-treated juice than in thermally processed juice. Overall, HIPEF proved to be an effective method for ensuring microbial safety, retaining nutritional properties, and extending the shelf life of mango juice.

***Opuntia dillenii* cactus juice**

Opuntia dillenii cactus juice has valuable physicochemical properties and bioactivity. Moussa-Ayoub et al. (2017) compared PEF, high hydrostatic pressure (HHP), and thermal pasteurization (TP) for microbial inactivation and quality retention. All methods reduced microbes from 10^3 to below 10 cfu/mL while maintaining the juice's flow behavior. PEF and HHP preserved more ascorbic acid and antioxidant activity than TP, which caused a 22% loss and slight changes in isorhamnetin glycosides. *O. dillenii* juice shows promise for improving low-viscosity foods like processed strawberries. PEF and HHP matched TP in microbial inactivation over 15 days while preserving bioactive compounds and juice quality better.

Tomato and watermelon juice

Aganovic et al., (2017) assessed energy consumption for preserving tomato and watermelon juice at a production capacity of 120 L/h. The study indicated that high-pressure processing (HPP) exhibited the highest energy requirement, followed by PEF and thermal processing. Despite the higher energy demands of PEF and HPP, these technologies offer improved product quality compared to thermal processing. The efficiency of PEF can be enhanced by increasing inlet temperatures to optimize heat recovery. At the same time, HPP can achieve greater energy efficiency by reducing pressure, shortening holding time, and improving filling efficiency, provided that safety standards are maintained. From a life cycle assessment perspective, the environmental impact of all three methods was comparable, with HPP exhibiting a slightly higher impact. However, PET bottle production accounted for approximately 85% of the total environmental footprint. In the "farm to gate" analysis, raw material production contributed significantly to environmental impact—64% for tomato juice and 20% for watermelon juice—while processing accounted for 30% and 50%, respectively. Strategies to mitigate environmental impact include optimizing

raw material use, reducing waste, and selecting HDPE packaging over PET. Energy consumption and environmental outcomes may vary as production scales up, highlighting the need for further large-scale studies.

Orange juice

Vervoort et al. (2011) evaluated the impact of thermal, high-pressure (HP), and PEF processing on the mild pasteurization of orange juice, ensuring equivalent microbial inactivation. Thermal pasteurization was carried out at 72 °C for 20 seconds, HP treatment was applied at 600 MPa for 1 minute with an initial juice temperature of 5 °C, and PEF processing involved monopolar pulses of 2 µs at 23 kV/cm and 90 Hz in continuous flow at a rate of 130 L/h, with inlet and outlet temperatures of 38 °C and 58 °C, respectively. The findings indicated that while most chemical and biochemical quality parameters remained unchanged, residual enzyme activities varied among treatments. Pectin methylesterase was not completely inactivated by any method, though heat and HP processing were the most effective in reducing its activity. Peroxidase was entirely inactivated by thermal pasteurization but was more resistant to HP and PEF treatments. Other quality factors, such as sugar and organic acid content, bitterness, vitamin C concentration, carotenoids, and the formation of certain degradation compounds, showed no significant differences among the three pasteurization techniques.

Sampedro et al. (2013) evaluated the cost of PEF pasteurization for orange juice, ensuring it met US FDA safety standards and commercial shelf-life requirements. PEF treatment at 30 kV/cm and 60 °C effectively reduced *E. coli*, *Salmonella Typhimurium*, and *Lactobacillus* spp. by more than 5 log, extending the juice's shelf-life to two months at 4 °C. The estimated cost of pasteurization was 3.7¢ per liter, with capital expenses comprising 54%, labor 35%, and utilities 11%. Compared to conventional thermal pasteurization, PEF was 2.2¢/L more expensive. Although PEF pasteurization enhances juice quality, its adoption in the industry has been slow, likely due to limited cost analysis. A large-scale PEF system was developed to assess expenses, using bacterial strains resistant to acidic conditions and PEF treatment. *Lactobacillus* showed the highest resistance, followed by *Salmonella* and *E. coli*. The chosen processing

conditions (30 kV/cm, 60 °C) ensured a sufficient safety margin and microbial reduction. This research gave companies a clearer understanding of PEF technology's costs and benefits, helping them decide whether to adopt this nonthermal pasteurization method.

Timmermans *et al.* (2022) explored the effects of moderate-intensity PEF processing on the quality of freshly squeezed orange juice, comparing it to conventional thermal pasteurization. PEF treatments were applied at electric field strengths of 0.9 and 2.7 kV/cm with a long pulse duration of 1000 µs, and the impact was assessed at different maximum temperatures. Results showed no significant changes in pH or soluble solids across treatments, while minor variations were observed in color and vitamin C content, particularly at higher temperatures. PEF treatment at temperatures of 78°C or above effectively reduced pectinmethylesterase (PME) activity to levels ensuring cloud stability, while better preserving key volatile compounds linked to fresh juice flavor than thermal processing. Additionally, microbial inactivation was higher at 2.7 kV/cm than at 0.9 kV/cm, and moderate-intensity PEF combined with heating between 65–90°C achieved greater microbial and enzymatic inactivation than high-intensity PEF with lower temperatures. These findings suggest that PEF at moderate intensity with a maximum temperature of 78°C is a promising alternative to thermal pasteurization, retaining the juice's freshness and quality while meeting safety requirements.

Arshad *et al.* (2022) developed a cost-effective, portable electroporator for liquid food pasteurization using PEF technology. Electroporation, which uses electric fields to break cell membranes, is helpful in food processing but is often expensive and specialized. The new system includes a coaxial treatment chamber with static mixers and a flexible high-voltage generator. Tests on orange juice showed a 5.4 log reduction in microbes and extended shelf life to nine days at 4 °C without affecting quality factors like color, vitamin C, or sweetness. Compared to traditional thermal pasteurization (65 °C for 30 minutes), PEF achieved similar microbial inactivation while using nearly half the energy. This research highlights PEF as a sustainable way to preserve fruit juices, with potential for industrial use. Further improvements are needed to enhance efficiency and expand its applications.

Kantala *et al.* (2022) explored its impact on microbial inactivation and quality in Thai orange juice (TOJ). The findings showed that PEF and conventional thermal pasteurization (CTP) successfully removed *Staphylococcus aureus* and *Escherichia coli* from TOJ. Using PEF at 30 kV/cm for 10 pulses resulted in a 5-log microbial reduction, mainly due to electroporation rather than heat. PEF had less impact on juice quality than CTP, preserving pH, color, viscosity, and total soluble solids (TSS). It also retained more vitamin C, sugars (sucrose, glucose, fructose), and minerals (sodium, lithium, potassium, magnesium, calcium). The study confirmed that PEF at 30 kV/cm for 10 pulses effectively reduced microbes while maintaining juice quality. Additionally, PEF required less energy and generated less heat than CTP. Although both methods led to some nutrient loss, PEF better preserved essential nutrients. The study recommended using PEF under these conditions for microbial safety and quality retention in TOJ, with future research focusing on cooling systems for industrial applications.

Wibowo *et al.* (2022) subjected the orange juice from the Siam cultivar to pasteurization using PEF technology to evaluate its impact on nutritional, physical, chemical characteristics and microbial content. The study tested PEF treatment durations of 5, 10, and 15 minutes. Various parameters were examined, including Vitamin C levels, density, pH, total soluble solids, and microbial count. Findings indicated that PEF pasteurization did not significantly alter these properties compared to untreated juice. The optimal treatment duration was 10 minutes (2 cycles), effectively preserving juice quality while ensuring microbial safety.

Evelyn *et al.* (2024) explored ways to reduce *Paecilomyces variotii* spores in orange juice using PEF and ultrasound, both non-thermal preservation methods. PEF (65 kV/cm) and thermosonication (ultrasound with heat at 75°C) were compared to ultrasound. The effect of juice soluble solids on PEF efficiency was also examined, along with a comparison between PEF combined with heat and traditional thermal pasteurization. Results showed PEF was more effective than ultrasound and thermosonication, reducing spores by up to three logs. Higher soluble solids made spore reduction less effective. The best results came from PEF, followed by heat treatment (144 s at 52, 72, and 92°C for 10 min), which lowered

spore levels by more than two logs. Microscopy showed significant spore damage when PEF and heat were combined. This method improved juice safety and reduced spoilage, making it a promising alternative for fruit juice preservation.

Landi *et al.* (2024) examined the potential of pulsed electric field technology for pasteurizing orange juice with heat recovery as a sustainable alternative to the conventional high-temperature short-time method. Their study assessed energy efficiency, cost-effectiveness, and environmental impact. Although the initial investment was higher, the electric method demonstrated significant utility savings and greater sustainability. The most efficient and eco-friendly scenario involved preheating to 40 °C with 20% thermal recovery, reducing water consumption and emissions. The findings suggest that this approach is a viable and environmentally friendly solution for orange juice pasteurization, promoting sustainable food processing.

Strawberry juice

Geveke *et al.* (2015) used a pilot-scale PEF system to pasteurize strawberry purée. Both buffered peptone water (BPW) and strawberry purée (pH 2.4) were processed at field strengths of 24.0–33.6 kV/cm and 45.0–57.5 °C. *E. coli* was reduced by 6.5 log in BPW at 30 kV/cm and 57.5 °C and by 7.3 log in purée at 24 kV/cm and 52.5 °C. A storage study showed that the resulting strawberry beverage maintained its bright red color and fresh taste for three months with minimal flavor loss. A cost-effective data acquisition system was developed to record and analyze over 1.4 million pulses per hour, providing a reliable validation method to support FDA approval of PEF processing

Yildiz *et al.* (2021) examined high pressure (HP), ultrasound (US), and PEF as alternative methods to preserve the quality and antioxidant properties of strawberry juice (SJ) compared to thermal pasteurization (72 °C, 15 s). HP (300 MPa for 1 min), US (55 °C for 3 min, 517.1 mW/mL), and PEF (35 kV/cm, 27 µs) achieved similar *E. coli* reductions of at least 5-log. All treatments lowered bacteria, yeast, and mold counts below 2 log CFU/mL. There were no significant changes in total soluble solids (7.83–8.00 °Brix), titratable acidity (0.79–0.84 g/100 mL), or pH (3.45–3.50), except for slight pH variations in US-treated juice. HPP and PEF retained higher levels of total phenolic content (TPC) and radical scavenging activity (RSA) than thermal pasteurization. These

methods also increased total anthocyanin content (TAC) compared to untreated juice. TPC rose by 4–5%, RSA by 18–19%, and TAC by 15–17%. Multivariate data analysis, including principal component analysis (PCA) and hierarchical cluster analysis (HCA), effectively classified juice samples based on their physicochemical and phytochemical characteristics. HPP and PEF showed better quality retention than US, thermal pasteurization, and unprocessed juice. This research suggested that nonthermal processing methods can maintain or even enhance juice quality, making them viable alternatives for fruit juice production.

Sour cherry juice

Akdemir Evrendilek *et al.* (2021) examined how PEF affects the properties of sour cherry juice (SCJ), including its nutrients and the formation of unwanted compounds like furfural and hydroxymethylfurfural (HMF). The results show that key factors such as pH, acidity, color, and total soluble solids (TSS) remained unchanged at energy levels up to 0.0341 J/L. PEF treatments increased the juice's antioxidant capacity (TAC) without significantly breaking down essential acids and phenolic compounds. No furfural or HMF was detected. The study also found that frequency had a more substantial impact than electric field strength (EFS) on acidity, color, and specific compounds. The best processing conditions were identified as 350.9 µs, 6.78 kV/cm, and 98 Hz.

Pomegranate fermented beverage

Rios-Corripio *et al.* (2022) assessed the effects of PEF and pasteurization methods on the microbial, physicochemical, bioactive, and sensory properties of a fermented pomegranate beverage (PFB) stored at 4 °C. The treatments included PEF at 11.7 and 18 kV/cm, batch (VAT) and high-temperature short-time (HTST) pasteurization. Microbial analysis indicated that applying 6 ms of bipolar PEF at 18 kV/cm with a 200 Hz repetition frequency significantly reduced microbial levels by approximately 4-log cycles, leaving fewer than 10 CFU/mL of bacteria and yeasts/molds. PEF had little effect on total soluble solids, pH, ethanol content, total acidity, and color, while all processed samples showed a slight decline in bioactive compounds over time. Sensory evaluation found that VAT pasteurization had the lowest acceptability score, which was still considered acceptable.

Milk-date beverage

Younis *et al.* (2023) investigated the optimal pulsed electric field processing conditions to maintain a milk-date beverage's microbiological safety and quality. The PEF treatment was conducted at 40 kV/cm electric field strength. Using response surface methodology, the effects of pulse off time (20–40 μ s), number of pulses (20–80), date powder concentration (10–25% w/w), storage duration (2–6 days), and storage temperature (5–25 °C) were analyzed. The findings revealed these factors significantly impacted microbial load, pH, color, and total soluble solids. The most effective conditions—40 μ s pulse off time, 80 pulses, and storage at 5 °C—successfully minimized microbial growth and preserved beverage stability for up to six days. The study concluded that PEF is a reliable technique for extending the shelf life of milk-date beverages while maintaining their quality at low temperatures.

Beer

Milani *et al.* (2015) PEF as a non-thermal alternative to pasteurizing beer while maintaining its sensory quality. Beer samples with 0–7% alcohol were treated at 45 kV/cm, 46 pulses, and 70 μ s, with temperatures below 43 °C. Yeast inactivation increased with alcohol content, showing a 2.2 log reduction in 7% alcohol beer. Combining PEF with mild heat at 53 °C further improved microbial reduction. Compared to traditional thermal pasteurization, PEF preserved beer's aroma and flavor more effectively, making it a promising method for beer preservation.

Combination of PEF with other non-thermal technologies

Thermosonication and PEF

Walkling-Ribeiro *et al.* (2009) examined the impact of thermosonication (TS) and PEF on orange juice's shelf life and sensory characteristics. The juice underwent TS at 55 °C for 10 minutes, followed by PEF treatment at 40 kV/cm for 150 μ s, and was compared to high-temperature short-time (HTST) pasteurization (94 °C for 26 seconds). A panel of 37 participants evaluated sensory attributes, finding no significant differences between the two treatments. Physical properties remained stable over 168 days at 25 °C, though microbial counts were slightly higher in TS/PEF-treated juice than in HTST-treated samples. Colour differences were notable, indicating the need for further refinement to improve juice quality.

Aadil *et al.* (2015) examined the effects of combining sonication and PEF on the quality of grapefruit juice. The treatment did not significantly impact pH, acidity, °Brix, or electrical conductivity. However, viscosity decreased, and cloud value increased after processing. The results suggest that this combined method can enhance juice quality and could be effectively used in commercial grapefruit juice processing. Notably, the treatment improved cloud value and reduced enzymatic browning, making it a promising technique for improving fruit juice properties

High power ultrasound and PEF

Bebek Markovinović *et al.* (2024) explored the impact of combining high-power ultrasound (HPU) and PEF treatments on bioactive compounds and antioxidant activity in strawberry juice stored at 4 °C for seven days. HPU was applied at 25% amplitude with a 50% pulse for 2.5, 5.0, and 7.5 minutes, while PEF was used at 30 kV/cm and 100 Hz for 1.5, 3, and 4.5 minutes. Results showed that the order of treatments influenced bioactive compounds preservation, with HPU followed by PEF being more effective than the reverse. Shorter treatment times maintained higher levels of bioactive compounds, with 2.5 minutes of HPU yielding the best retention of phenolic compounds, flavonols, and antioxidant capacity. Longer HPU or PEF treatments led to greater losses. Antioxidant activity declined over seven days, regardless of treatment sequence. While shorter HPU treatments preserved bioactive compounds better, some antioxidant properties, like DPPH and HCA, required slightly longer treatments. The authors suggested that using HPU and PEF together is a promising method for preserving the quality of functional strawberry juice and has potential for industrial use.

Membrane-assisted pulsed electric field (M-PEF) technology

Market trends show a growing demand for bottled fresh sugarcane juice due to its high nutritional and therapeutic value. However, its short shelf life is affected by active enzymes like peroxidase, polyphenol oxidase, and microbial activity. Atchaya *et al.* (2024) used membrane-assisted pulsed electric field (M-PEF) technology, combining a 10 kDa ultra-filter membrane at 1 bar pressure as a pretreatment before PEF processing. The juice was treated at field strengths of 20, 30, and 40 kV/cm with pulse widths of 100, 150, and 200 μ s. At 30 kV/cm and

150 μ s, polyphenol oxidase and peroxidase activity were reduced by 92% and 80% while maintaining juice quality. Due to pore size exclusion, membrane filtration led to an 85–95% reduction in protein and polysaccharides. Ascorbic acid was retained, and antioxidant capacity increased. PEF treatment also achieved a 3-log reduction in total plate count, demonstrating its potential as an effective method for fresh juice preservation.

CONCLUSIONS

PEF-assisted pasteurization has become an effective alternative to conventional thermal processing for fruit juices and beverages. It offers significant advantages, including microbial and enzymatic inactivation, improved retention of sensory and nutritional qualities, and reduced energy consumption. Advances in PEF technology, such as optimized treatment chambers and cost-effective electroporators, have improved its industrial feasibility. Studies indicate that PEF-treated juices maintain superior quality compared to thermally processed counterparts, with better preservation of antioxidants, vitamins, and volatile compounds. While PEF alone may not completely inactivate certain enzymes, combining it with mild heat treatments or natural antimicrobials enhances its efficacy. Despite the higher initial investment, PEF processing demonstrates long-term benefits regarding product quality, shelf-life extension, and sustainability. The combination of PEF with other non-thermal technologies presents a promising approach to improving the quality, safety, and shelf life of fruit juices while minimizing the drawbacks of traditional thermal processing. Studies have demonstrated that integrating PEF with thermosonication, high-power ultrasound, or membrane-assisted filtration can enhance juice stability, preserve bioactive compounds, and improve sensory characteristics. While some challenges remain, such as optimizing treatment parameters to balance microbial inactivation with nutrient retention, these hybrid techniques show significant potential for commercial juice processing. Further research and industrial-scale implementation could refine these methods, making them viable alternatives to conventional pasteurization while meeting consumer demand for minimally processed, high-quality beverages. Future research should focus on large-scale implementation, cost reduction strategies, and integrating PEF with other emerging food preservation technologies to enhance its commercial adoption.

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