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The science behind physical field technologies for improved extraction of juices with enhanced quality attributes

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ABSTRACT

Consumer demand for high-quality, nutritious juice products is steadily increasing. Ongoing research and innovation in juice extraction technologies will likely further shape the landscape of the juice industry. The expanding market for healthy and natural juices has led to the development and adoption of novel technologies and practices in the juice industry. These advancements have the potential to not only revolutionize juice extraction and processing but also address sustainability concerns and meet the evolving needs of health-conscious consumers. This review provides a critical discussion about recent advances in physical field technologies such as pulsed electric field, high hydrostatic pressure, ultrasound, and microwave. Their mechanisms and modes of application on cellular structures are analyzed, and the main drawbacks and limitations of their industrial-scale use are discussed. Physical field technologies represent a promising group of innovative methods that can be employed in the food industry to address various processing challenges, including improved juice extraction with enhanced quality attributes. The demand for improved juice extraction methods stems from various factors, including the desire to enhance juice quality, increase extraction efficiency, and promote sustainability. As the juice market continues to expand, the development and adoption of advanced juice extraction technologies will be crucial for ensuring the long-term success and sustainability of the industry.

1. Introduction

The global juice market has witnessed significant growth in recent years, driven by increasing consumer demand for healthy and natural beverages [1]. Consumers are increasingly health-conscious and are seeking products with minimal additives and preservatives [2]. Modern consumers understand the link between consuming bioactive compounds from fruits and vegetables and the associated health benefits and overall well-being [3]. In fact, the global juice market is projected to reach a value of $189.9 billion by

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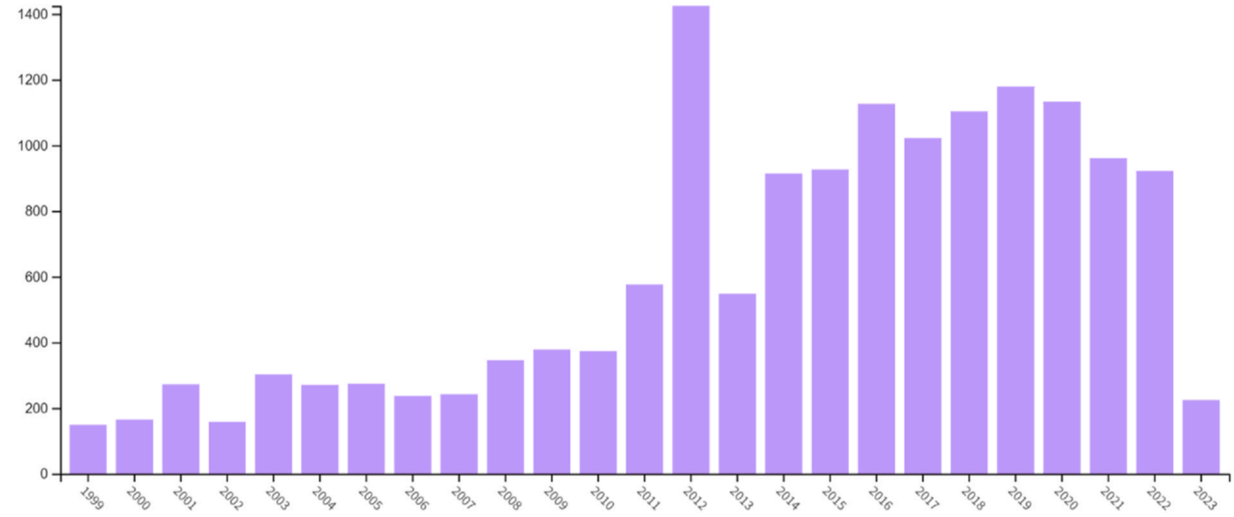

Fig. 1. Number of publications on juice extraction. A bibliometric analysis using the search term "juice extraction" in Web of Science showed that the number of publications related to juice extraction has increased significantly in the past decade.

2028, with a compound annual growth rate (CAGR) of 4.52% between 2023 and 2028 [4]. This rapid expansion can be attributed to the growing awareness of the health benefits of consuming fruits and vegetables, coupled with the increased availability of a wide range of juice products. As a result, there has been a steady rise in demand for juices made from fresh fruits and vegetables, with minimal processing and no added sugars [5]. Research indicates that consuming such juices is associated with numerous health benefits, including a reduced risk of chronic diseases, improved immune function, and enhanced digestion. Furthermore, juices rich in antioxidants, such as those made from berries and dark-colored fruits, have been linked to reduced inflammation and improved cardiovascular health [6]. Fig. 1 illustrates the significance of research related to juice extraction in the literature.

Furthermore, the functional beverage market, which includes juices fortified with vitamins, minerals, and other health-promoting ingredients, has experienced significant growth [7]. Functional beverages are formulated to deliver specific health advantages beyond basic nutrition, such as energy enhancement, immune support, or cognitive improvement. The global functional beverage market reached a value of $145.2 billion in 2022 and is anticipated to expand at a CAGR of 5.60% from 2023 to 2030 [7]. This trend can be attributed to the increasing consumer demand for products offering health benefits beyond mere nutrition, coupled with the growing availability of functional beverages in various formats, such as ready-to-drink (RTD) juices, smoothies, and shots.

Moreover, sustainability concerns have spurred consumers to seek more eco-friendly production methods for their juice products. This trend has prompted companies to explore innovative and environmentally friendly technologies to fulfill these expectations, including efforts to minimize environmental footprints, initiatives to reduce waste, and the integration of renewable energy sources into production processes. Additionally, certain juice companies have adopted practices such as sourcing locally grown produce and establishing fair trade partnerships to promote sustainability and social responsibility [8].

The growing market for healthy and natural juices has spurred research and development efforts in the area of novel juice extraction technologies. These innovations aim to optimize the extraction process, reduce energy consumption, and minimize the impact on the nutritional and sensory attributes of the final product. For example, physical field technologies, such as pulsed electric field (PEF), high hydrostatic pressure (HHP), and ultrasound, have garnered increasing attention in the juice industry due to their potential to improve extraction efficiency, enhance juice quality, and extend shelf life [9–12]. Physical field technologies have emerged as promising alternatives to traditional juice extraction methods, offering several advantages, such as increased efficiency, better preservation of quality attributes, and reduced energy consumption [11]. This review article aims to elucidate the science behind ultrasound, PEF, HHP, and microwave-assisted extraction methods and their impact on juice extraction and quality. We delve into the mechanisms and applications of these technologies at the cellular level, while also exploring potential opportunities and limitations in their adoption.

2. The science of physical field technologies

2.1. Historical overview of juice extraction methods

The history of juice extraction dates back thousands of years, with evidence of fruit and vegetable juicing present in various ancient civilizations. Over time, numerous methods have been developed and refined to extract juice from fruits and vegetables more effectively, with a keen emphasis on optimizing juice yield, quality, and nutritional value. The historical overview outlines the evolution of juice extraction methods, from traditional techniques to modern advancements [13].

Hand pressing is the earliest known traditional method of juice extraction, which involves the manual pressing of fruits and vegetables to release their juices. This technique has been utilized by various ancient cultures, such as the Greeks, Romans, and

Egyptians, who consumed fresh fruit juices for their perceived health benefits and as an essential part of their diets. As civilizations advanced, stone presses were developed to extract juice more efficiently. Stone presses typically involved a large, flat stone surface and a heavy stone wheel, which was rolled over the fruits or vegetables to crush them and release their juices [14]. Wooden screw presses emerged in the Middle Ages as a more sophisticated means of juice extraction. These devices typically comprised a wooden screw mechanism that exerted pressure on a perforated wooden barrel filled with fruits or vegetables. This pressure forced the juice to flow through the holes and into a collection container [14].

The Industrial Revolution led to significant advancements in juice extraction technologies. In the early 19th century, hydraulic presses were introduced, which utilized water pressure to apply force to a pressing plate, crushing fruits and vegetables to extract their juice more efficiently. This technology greatly improved juice yield and facilitated large-scale juice production. In the early 20th century, centrifugal juicers were developed, allowing for faster and more efficient juice extraction. These devices use a rapidly spinning mesh basket to shred fruits and vegetables, and the centrifugal force generated by the spinning motion separates the juice from the pulp [15].

Cold pressing, also known as slow juicing or masticating juicing, has become popular in recent decades due to its ability to preserve the nutritional content and flavor of juices better than other methods. Cold press juicers use a slow, grinding auger to crush fruits and vegetables, extracting juice with minimal heat generation and oxidation [16]. In recent years, novel juice extraction technologies, such as PEF, HHP, ultrasound, and microwave-assisted extraction, have emerged. These methods are designed to enhance juice yield, quality, and nutritional value, while also aiming to reduce energy consumption and environmental impact [11].

2.2. The need for improved juice extraction methods

Traditional juice extraction methods, though sufficient for juice production, have limitations in terms of yield, quality, nutritional value, and sustainability. This has led to a growing need for improved juice extraction methods that can address these challenges and meet the evolving preferences of health-conscious consumers.

Traditional juice extraction methods have drawbacks such as generating heat and introducing oxygen, which can lead to the degradation of heat-sensitive nutrients, such as vitamins and antioxidants. Improved extraction methods, such as novel physical field technologies used alone or in combination with cold pressing, offer better preservation of the nutritional content of juice, thereby making it more appealing to health-conscious consumers [17–19]. Similarly, the taste and aroma of juice are critical factors influencing consumer preferences. Traditional extraction methods can sometimes cause alterations in taste and aroma compounds, diminishing the overall sensory quality of the juice [20]. The flavor of fruit juices is primarily determined by sugars (sweetness) and organic acids (sourness), as well as volatile compounds, including alcohols, ketones, aldehydes, ethers, and esters [21]. Traditional thermal treatment (95 °C, 22 mL/min, 43 s) has been reported to reduce the concentration of flavor contributors (β-myrcene and β-linalool) in orange juice [22]. Advanced juice extraction methods aim to preserve the natural taste and aroma profiles of fruits and vegetables, resulting in a more enjoyable and authentic tasting experience for consumers [11]. The shelf life of juice products is a significant concern for both consumers and manufacturers. Conventional extraction methods can introduce spoilage microorganisms and promote enzymatic browning, leading to a shortened shelf life for the juice. Improved juice extraction methods can reduce the risk of microbial contamination and enzymatic browning, thereby extending the shelf life (PEF, by 28 days at 4 °C) of juice products without compromising their quality or safety [20,23].

Maximizing juice yield is essential for the economic viability of juice production, as it directly impacts the profitability of the process. Traditional extraction methods may not fully exploit the juice potential of fruits and vegetables, resulting in lower juice yields. Improved juice extraction methods, such as those involving physical field technologies, can increase juice yield by effectively disrupting cell structures and releasing more juice from the fruit or vegetable matrix [24]. Reducing energy consumption is crucial for the juice industry, as it helps minimize production costs and the industry's overall environmental impact. Traditional extraction methods, particularly those involving heat, can be energy-intensive. Improved juice extraction methods, such as cold pressing and novel physical field technologies, can offer energy-efficient alternatives by minimizing heat generation and utilizing more targeted energy inputs [20].

Fruit juice contains several bioactive compounds, such as flavonoids, phenolics, ascorbic acid, and carotenoids. Conventional thermal treatments can preserve juices, but they can lead to unwanted physicochemical changes and the loss of heat-sensitive bioactive components [25]. In this sense, advanced juice extraction technologies not only extend the storage period but also preserve the nutritional, organoleptic, and phytochemical characteristics of the juices [26]. Thermal treatment (85–145 °C) has been reported to degrade nutrients such as β-carotene and vitamin C in apricot nectar [27]. However, nonthermal treatment (PEF, 14 kV/cm) has been reported to retain heat-sensitive bioactive constituents [28].

Juice production generates significant amounts of waste, such as fruit and vegetable pomace, which can have negative environmental consequences if not managed appropriately. Improved juice extraction methods can reduce waste generation by more effectively extracting juice from fruits and vegetables, leaving behind less residual pulp [29]. In addition, novel extraction technologies can facilitate the recovery of valuable compounds from waste byproducts, promoting a more circular economy within the juice industry. Similarly, water is a critical resource in the juice industry and is used extensively in various stages of production, such as washing, peeling, and processing. The increasing global demand for water resources has made it essential for the juice industry to adopt more sustainable water management practices. Improved juice extraction methods can contribute to more efficient water use by minimizing water consumption during processing and incorporating water recycling technologies. Nowadays, the juice industry faces growing pressure to reduce its environmental footprint and adopt more sustainable production practices. Improved juice extraction methods can help address this challenge by reducing energy consumption, waste generation, and water use, leading to a lower environmental impact overall. Moreover, novel extraction technologies can facilitate the integration of renewable energy sources and promote cleaner production practices within the juice industry [30].

2.3. Overview of physical field technologies

Physical field technologies are a group of innovative methods that employ various physical forces, such as electrical, magnetic, ultrasonic, and pressure fields, to process food materials. These technologies have gained significant attention in the food industry due to their ability to improve processing efficiency, enhance product quality, and minimize environmental impact. Physical field technologies operate by applying controlled and targeted physical forces to food materials, thereby modifying their properties and structures to achieve the desired processing outcomes. These forces often disrupt cell walls and membranes, facilitating the release of intracellular contents such as juice, while preserving the nutritional value and sensory characteristics of the products. Physical field technologies can also influence mass transfer processes, enzymatic reactions, and microbial inactivation, offering versatile solutions for various food processing challenges [31].

3. Pulsed electric field (PEF) technology

3.1. Explanation of PEF technology and how it works

PEF technology is an innovative nonthermal processing method that has attracted considerable interest in the food industry, particularly for juice extraction. This technology utilizes short, high-voltage electric pulses to induce changes in cell membrane permeability, leading to improved extraction efficiency and enhanced product quality [9]. PEF technology offers several advantages over conventional juice extraction methods. First, PEF is a nonthermal process, which means that it does not involve the application of heat. This is beneficial for preserving heat-sensitive nutrients, such as vitamins and antioxidants, and for maintaining the natural taste and aroma profiles of fruits and vegetables [32]. In addition, PEF can inactivate spoilage microorganisms (by damaging cellular walls) and enzymes (by conformational changes in structure) [33,34], thereby extending the shelf life of juice products without compromising their safety or quality. Moreover, PEF technology has been reported to improve the extraction efficiency of various fruits and vegetables, such as apples, oranges, grapes, and tomatoes, resulting in higher juice yields compared to traditional methods. This increased efficiency can contribute to more cost-effective and profitable juice production processes, making PEF an attractive option for the juice industry [35].

A PEF apparatus is an intricate system composed of a high-voltage pulse generator, a treatment chamber incorporating a fluid management assembly, and a regulatory and monitoring subsystem. It also includes a charger responsible for converting alternating current (AC) to direct current (DC) and an energy storage component within the generator. The system operates by toggling a high-voltage circuit on and off, resulting in the generation of electric pulses. This process becomes complex due to the high-energy discharge, which is characterized by high-voltage and short-duration pulses. The system ensures continuous monitoring of the capacitor, and it is stepped up when a voltage interruption occurs. Within the treatment chamber, two discrete electrodes are present: one is connected to the high-voltage generator, while the other is grounded. These electrodes enclose a gap filled with the target food product. The disparity in electric potential across the membrane induces an electric field. The strength of this electric field is contingent on factors such as the type of electrodes, the distance separating them, and the nature of the sample. Further considerations include the pulse profile, the configuration of the treatment chamber, and the conductivity inherent to the product. For example, in the context of enhancing polyphenol extraction, PEF treatment parameters based on empirical observations are grouped into three categories: high ($E > 1$ kV/cm), medium ($E \approx 0.1$–1 kV/cm), and low ($E < 0.1$ kV/cm) electric fields. The PEF extraction operation can generally be divided into two primary categories: a batch processing system or a continuous extraction system [9].

Ongoing research efforts are focused on improving the design and performance of PEF equipment, optimizing processing conditions, and developing innovative applications of PEF in the food industry [36]. Furthermore, combining PEF with other physical field technologies, such as ultrasound or high-pressure processing, may offer synergistic effects and enhance the overall efficacy of juice extraction. Overall, PEF technology represents a promising avenue for juice extraction, offering numerous benefits and potential applications in the food industry. With ongoing research and development, PEF has the potential to revolutionize the juice industry and contribute to the production of high-quality, nutritious, and sustainable juice products.

3.2. Mechanisms of action and effects on cell membranes

Several hypotheses exist regarding the mechanisms through which sudden exposure to an electric field disrupts the cellular membrane. The theory of electrical breakdown, based on the concept of transmembrane potential (TMP), is broadly accepted. This hypothesis perceives the cell membrane as a capacitor housing dielectric compounds [37]. In contrast to the membrane, the cell's cytoplasm exhibits a significantly higher dielectric constant, around 6–8 times greater. This is paralleled by the liquid food encapsulating the cell. The resulting disparity in dielectric constants on either side of the membrane engenders a TMP, which approximates 10 mV ($1\ \text{mV} = 10^{-3}$ V) [38]. TMP represents a combination of the induced potential difference traversing the cell membrane and the resting membrane potential. TMP occurs via the accumulation of free charges at the inner and outer surfaces of the cell membrane. Under typical conditions, ions that bear charges migrate from regions of higher concentrations to those with lower concentrations. Simultaneously, they tend to move away from similar charges and toward opposing ones. Nevertheless, the introduction of an external electric field instigates the movement of ions, both inside and outside the cell, along the field lines until they meet resistance and begin to accumulate at the membrane, thereby augmenting the TMP. Oppositely charged ions (+ and −) on either side of the membrane experience attraction, which compresses the membrane and reduces its thickness. As the strength of the electrical field escalates beyond the critical threshold value of the TMP, pore formation occurs [38]. This critical TMP value is approximately 1 V [39]. The pore formation may be either reversible or irreversible, contingent upon the intensity of the treatment. If PEF intensity is such that the energy imparted on the membrane does not induce substantial Joule heating, the cell can often recover from the inflicted membrane damage. Conversely, when the membrane surface begins to harbor numerous and/or extensive pores, irreversible membrane breakdown ensues. This culminates in the mechanical destruction of the membrane, leading to eventual cellular death [38].

The magnitude of the external electric field required to incite pore formation in the cellular membrane is dependent on a variety of factors, including cell size and morphology, the cell's orientation within the electric field, the dielectric attributes of the liquid food, cytoplasm, membrane, and ambient temperature. The permeabilization process of a cell membrane comprises five distinct phases: induction (or triggering) (μm), expansion (ms), stabilization (ms), resealing (s), and memory (h) [40]. When PEF is applied to the cell, it results in the creation of an induced transmembrane voltage (ΔVi), which is inherently tied to the local dielectric properties of the plasma membrane.

The induced transmembrane voltage could be explained by the following Laplace differential equation:

$$\Delta Vi(M, E, t) = -fg(\lambda) r_{cell} E_e \cos\theta(M)\left(1 - \exp\left(-\frac{t}{\tau m}\right)\right)$$

In this equation, M represents a specific point on the cell under consideration, while t corresponds to the duration of the electric field application. The factor f depends on the cell's geometric characteristics, and r_{cell} denotes the radius of the cell. E_e signifies the strength of the electric field, and $\cos\theta(M)$ corresponds to the angle between the cell surface and the field direction. The function $g(\lambda)$ pertains to differing conductivities [37].

$$g(\lambda) = \frac{2\lambda e\left[2\lambda m + \lambda i + (\lambda m - \lambda i)\left(r_{cell} - \frac{d}{r_{cell}}\right)^3 - 3\lambda m\left(r_{cell} - \frac{d}{r_{cell}}\right)\right]}{\left[(2\lambda e + \lambda m)(2\lambda m + \lambda i) + 2\left(r_{cell} - \frac{d}{r_{cell}}\right)^3(\lambda i - \lambda m)(\lambda m - \lambda e)\right]}$$

where λm symbolizes the conductivity of the membrane, while λi and λe represent the conductivities of the cytoplasm and the external medium, respectively. The variable d stands for the thickness of the membrane, measured in nanometers. The characteristic time constant associated with membrane charging, denoted as τm, can be determined using a specific mathematical equation.

$$\tau m = \frac{rCm(2\lambda e + \lambda i)}{(2\lambda e \lambda i)}$$

In this equation, Cm (0.5–1.0 μF/cm^2) represents the specific membrane capacitance.

Electroporation is established as long as the electrical field maintains a critical value, a phase referred to as the expansion step. Fig. 2 visually presents the impact of PEF on plant cells. Previous research highlights that, even though cell membrane permeability begins at the onset of the pulse, the structural reconfiguration of the membrane occurs over a significantly prolonged timescale [41]. The stabilization phase is a crucial aspect of cellular membrane electroporation; it is imperative that the pores remain stable enough to facilitate interactions between the intra- and extracellular mediums [42]. Gabriel and Teissie [43] noted that once the field strength becomes subcritical, a sharp decline in the flow of polar molecules is detected despite the membrane's ongoing permeability to such compounds. Following the stabilization phase, the cell membrane gradually reseals, a process that may span seconds to minutes, and recovers its semi-permeability. Concurrently, during this resealing stage, reactive oxygen species production has been observed in the permeabilized segment of the cell surface [41]. Lastly, a memory effect has been noticed, signifying that some alterations in membrane properties persist over several hours, although eventually, cellular behavior reverts to its typical state. In general, pinpointing cellular tissue electroporation is a challenging task, primarily due to the short-lived nature of pore formation (sub-microseconds) and the minimal area covered by the pores, which typically constitutes just 0.1% of the total membrane surface [40].

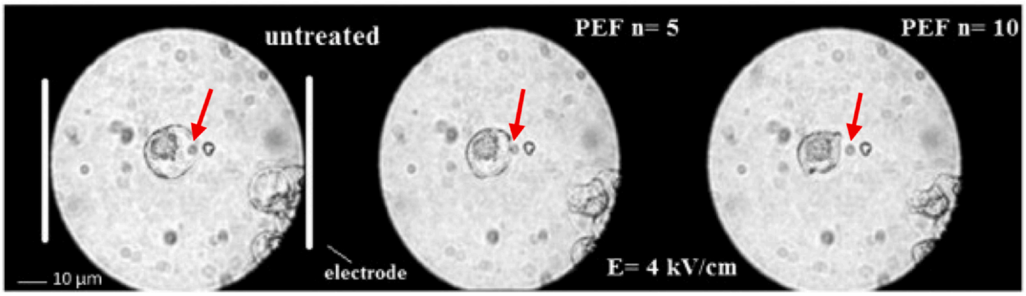

Fig. 2. Protoplast (highlighted with red arrow) serves as a model system for visualizing the impact of PEF-induced (4 kV/cm) membrane rupture and cell shrinking at n = 5 and n = 10 pulses [44].

3.3. Recent literature related to PEF technology in the juice extraction industry

Literature published from 2019:

Dziadek *et al.* [45] investigated the effects of PEF treatment (E = 30 kV/cm, 35 °C) on the nutritional properties and shelf life of 100% apple juice across various cycles: 4, 6, and 8 (where 1 cycle equals 50 pulses). Each pulse was followed by a 30-s pause, and after each cycle, the sample was refrigerated for 15 min to thwart the degradation of vitamin C and polyphenols. The authors reported that PEF treatment did not alter the concentration of bioactive compounds. Neither the amount of vitamin C nor the total polyphenols in the PEF-treated juice showed changes during 72 h of storage under refrigeration conditions at 4 °C. Furthermore, PEF treatment effectively deactivated a broad spectrum of the most prevalent food spoilage microorganisms, including mesophilic bacteria, yeast, and fungi. The researchers concluded that PEF treatment is an effective method to extend the shelf life (72 h) and maintain the nutritional integrity of apple juice during storage. In a study conducted by Rahaman *et al.* [28], the influence of PEF treatment on the nutritional and physicochemical attributes of apricot (*Prunus armeniaca* L.) juice was assessed. PEF treatment parameters (14 kV/cm, 1 kHz, 500 µs, 40 mL/min, 25 °C) did not cause significant alterations in the pH, °Brix, or color of apricot juice relative to the untreated variant. However, the researchers highlighted a marked escalation in flavonoids (from 307.91 to 564.47 µg/g), phenolic compounds (from 57.93 to 63.14 µg/g), cloud value (from 0.06 to 0.09), and antioxidants (from 38.99% to 47.12%). A decrease was reported in the browning index when compared to the untreated sample (from 0.41 to 0.34). Moreover, Fourier transform infrared spectroscopy (FTIR) analysis indicated alterations in the functional groups of the biological compounds. Therefore, it was concluded that PEF treatment can significantly augment the nutritional and sensory properties of apricot juice.

Beetroot is a rich source of betalains, a red pigment with numerous health benefits, and is frequently employed as a colorant in food and nutraceutical products. Visockis *et al.* [46] demonstrated that PEF pretreatment (parameters: 2.0 kV/cm, 2.53 kJ/kg, 3 pulses, 100 µs pulse duration, 1 Hz pulse repetition, 22 °C) substantially increased the aqueous extraction rate of betalains by up to 70% within an hour. In a separate study focusing on PEF treatment (parameters: 4.38 kV/cm, 4.10 kJ/kg, 20 pulses) of beetroot, researchers observed an increase of 329% and 244% in the yield of betanin and vulgaxanthin, respectively, compared to control studies [47]. Carrots, another globally popular root vegetable, are rich in carotenoids, such as α-carotene, β-carotene, and lutein. According to a study by López-Gámez *et al.* [48], PEF treatment (parameters: E ≥ 2 kV/cm, 1.19 kJ/kg, 5, 12, 30 pulses) favorably affected the quality of carrot juices by enhancing carotenoid contents without significantly altering the color, pH, or TSS for at least 24 h. Following PEF treatments, total carotenoids increased by 39.3–81.3%, phytoene by 45.5–95.4%, and β-carotene by 36–91.2%, whereas lutein decreased by 15.1–96.4%. The study also found significant correlations between the energy input applied and the content of lutein and phytoene. It was concluded that PEF pretreatment offers a potential method for producing derivatives like juices or purees with an elevated antioxidant content [48].

The consumption of fresh fruits and their derivatives has been associated with a decreased risk of numerous degenerative diseases. Specifically, strawberries have been linked to enhanced human health due to their ability to detoxify free radicals, bolster antioxidant defense mechanisms, and mitigate DNA damage [23]. Studies indicate that the application of PEF treatment to strawberry juice has a pronounced impact on both its quality and shelf life. In a study by Yildiz *et al.* [23], PEF treatment (parameters: 35 kV/cm, 27 µs) achieved a 5-log cfu/mL inactivation of *E. coli* over 28 days of storage at 4 °C, as compared to conventional thermal pasteurization (parameters: 72 °C for 15 s). Moreover, unlike thermal pasteurization, PEF treatment was able to retain the juice's bioactive components and antioxidant activity throughout the storage period. Although the acidity and pH of the samples varied, no significant changes were observed in the total soluble solids content. Similarly, PEF treatment, varying in parameters such as 0.5–2.5 kV/cm electric field intensity, 3.5–575 kJ/kg specific energy, 0–4000 pulses, and a 15-µs pulse width, has also been successfully applied to chopped tomatoes and the residues of tomatoes after the initial juicing process. Researchers have reported a 20% enhancement in the juice yield from chopped tomatoes using PEF, culminating in an overall yield of up to 90.2% when combining both juices. In addition, the post-processing residues from PEF exhibited a notable augmentation in bioactive compounds. These include carotenoids (increased by 56.4%), lycopene (ranging from 9.84 to 14.31 mg/100 g), and total phenolic compounds (increased by 56.16 mg gallic acid/kg). The conclusion drawn from this study was that PEF treatment reduces environmental impact while allowing for high extraction yields without sacrificing extract functionality [49]. Furthermore, the application of PEF technology has been associated with the improved extraction of bioactive compounds in black currant juice. Optimal pretreatment conditions (parameters: 1.3 kV/cm, 30 kJ/kg, 315 pulses, 22 °C) yielded a 45% increase in antioxidant activity, along with a 19% and 6% increase in total phenolic content and total anthocyanins, respectively. Given the high concentration of anthocyanins, these juices can be consumed fresh, incorporated as functional food ingredients, or used as food colorants [50]. Table 1 presents an overview of the application of PEF technology in the juice industry.

4. High hydrostatic pressure (HHP) technology

4.1. Explanation of HHP technology and how it works

HHP technology, also known as high-pressure processing (HPP), is a nonthermal food preservation method that utilizes high pressure to inactivate microorganisms and enzymes in food products, including fruit juices. By applying pressures between 100 and 800 MPa (1000–8000 bars), HHP technology disrupts the cellular structures of microorganisms, leading to their inactivation without the need for high-temperature treatments. This process not only ensures the safety of juice products but also preserves their nutritional and sensory properties, which can be negatively affected by traditional thermal processing methods [56]. In the juice industry, HHP technology has been recognized for its ability to maintain the fresh-like characteristics of fruit juices, such as color, flavor, and

Table 1
Effect of PEF technology on juice properties.

Sample	Treatment parameters	Compared with	Results	Reference
Beetroot	2 kV/cm (2.53 kJ/kg) 1 Hz, 22 °C, 3 pulses (100 µs each)	Different PEF strengths 0.8, 2.0, and 4.0 kJ/kg	70% increase in total betalains	[46]
Sugarcane juice added with lemon and ginger	20 kV/cm, 150 pulses, 4 °C	Untreated sugarcane juice	14 days of shelf life increase at 4 °C, microbial stability, below 10^6 cfu/mL	[51]
Apple	400 V/cm, 10 pulses, each pulse duration 100 µs, $\Delta T \leqslant 5$ °C	Untreated apple juice	Increased juice yield (64 g/100 g), antioxidant activity and phenolic content	[52]
Blueberry (*Vaccinium myrtillus* L.)	1 kV/cm, 10 kJ/kg, 10 Hz, 20 µs, 23 °C	Untreated blueberry juice	+ 28% juice yield, + 43% polyphenols, + 60% total anthocyanins, + 31% antioxidant activity	[53]
Apple juice	30 kV/cm, 35 °C, 4–8 cycles (each cycle = 50 pulses)	Untreated apple juice	Stability of vitamin C and polyphenols increased, inactivation of spoilage microbes	[45]
Beetroot	4.38 kV/cm, 20 pulses, 9.2 °C, 10 µs pulses in monopolar mode	Untreated beetroot sample	244% and 329% increase in vulgaxanthin and betanin, respectively	[47]
Strawberry juice	35 kV/cm (27 µs), using 2 µs monopolar square pulses	Thermal pasteurization (72 °C, 15 s)	5-log reduction of inoculated *E. coli*, TSS unaffected, + 5% TPC, + 19% RSA	[54]
Broccoli juice	15 kV/cm, 500 µs, 35 °C, 4 µs pulse width and 100 Hz frequency, monopolar mode	Thermal treatment (90 °C/60 s)	154.4% histidine and 125.2% lysine retention, minerals (Fe, Mn, and Zn) increase 114%	[55]
Blackcurrant	1.3 kV/cm, 30 kJ/kg, 315 pulses, 22 °C	Untreated blackcurrant juice	19% and 45% increase in anthocyanins and antioxidant activity, respectively	[50]

nutritional content. The high-pressure treatment also extends the shelf life of juices (blackcurrants 7 days at 4 °C) by inactivating spoilage microorganisms and enzymes that can cause quality deterioration over time [57].

HHP technology has been successfully applied to various fruit juices, such as orange, apple, grape, and pomegranate juices, demonstrating improved quality attributes and an extended shelf life. In addition, HHP technology can be combined with other mild preservation techniques, such as natural antimicrobials and modified atmosphere packaging, to enhance the overall preservation effect and further extend the shelf life of fruit juices [58].

HHP equipment is designed to apply uniform and instantaneous pressure to food products, ensuring the effective inactivation of microorganisms and enzymes without the need for high temperatures. The main components of HHP equipment include a high-pressure vessel, a pressure-generating system, and a temperature control system. The high-pressure vessel is a thick-walled, cylindrical chamber made of high-strength materials, such as stainless steel, which can withstand extreme pressure levels. The vessel contains a flexible, pressure-transmitting medium, usually water or a water-based solution, which evenly transmits pressure to food products. Food products, such as fruit juices, are packaged in flexible, hermetically sealed containers or pouches that can withstand high pressure without rupturing. These containers are then placed in a high-pressure vessel, fully submerged in the pressure-transmitting medium. The pressure-generating system typically consists of an intensifier pump, which is driven by either hydraulics or pneumatics. This pump compresses the pressure-transmitting medium, which in turn applies pressure to the food products in the high-pressure vessel. The pressure gradually increased to the desired level, ranging from 100 to 800 MPa [56]. Once the target pressure is reached, it is maintained for a specific period, typically ranging from a few seconds to several minutes, depending on the food product and the desired effect. During this holding time, the pressure effectively inactivates microorganisms and enzymes in the food products. After the holding time has elapsed, the pressure is gradually released, allowing the food products to return to atmospheric pressure. Pressure release can be either slow or rapid, depending on the specific requirements of the food product [59]. Although HHP is a nonthermal process, the application of pressure can generate some heat, known as adiabatic heating. To ensure that the temperature remains within a specific range, the HHP equipment is equipped with a temperature control system that can either heat or cool the pressure-transmitting medium as required. The treated food products are removed from the high-pressure vessel and can be stored or distributed. Due to the effective inactivation of microorganisms and enzymes, HHP-treated food products exhibit an extended shelf life and improved quality attributes [59].

4.2. Mechanisms of action and effects on cell membranes and cell walls

HHP technology has gained popularity in the food industry due to its ability to maintain the nutritional and sensory quality of food products while ensuring safety and an extended shelf life. HHP technology exerts its effects on biological systems through the application of pressure, typically ranging from 100 to 800 MPa. The pressure disrupts the cell membrane and cell wall of plant tissues, leading to the release of intracellular contents, such as water, sugars, acids, and other bioactive compounds. This disruption occurs due to the compressive forces generated by HHP, which affect the lipid bilayers and proteins in the cell membranes and the polysaccharides in the cell walls [57]. The pressure-induced inactivation of microorganisms occurs due to the denaturation of proteins, alterations in membrane permeability, and damage to genetic material. The inactivation of enzymes is primarily due to the pressure-induced denaturation and aggregation of proteins, resulting in the loss of their catalytic activity [56]. Moreover, HHP technology induces changes in the food matrix, which may affect the texture, color, flavor, and nutritional properties of the extracted juice. The pressure can cause protein denaturation, starch gelatinization, and the modification of pectin and other polysaccharides, leading to changes in the rheological properties and stability of juice. Moreover, the pressure can influence chemical reactions, such as oxidation, hydrolysis, and Maillard reactions, by altering the equilibrium constants and reaction rates [60].

4.3. Recent literature related to HHP technology in the juice extraction industry

Literature published from 2019:

High-pressure processing (HPP) serves as a terminal barrier technology within a series of microbial inhibition techniques. It is executed post-packaging and plays a significant role in reducing microbial hazards, thereby extending the shelf life of stored food products. In tandem with cold chain systems, HPP also aids in the preservation of the inherent colors and flavors of food ingredients. In addition, HPP offers promising potential for developing food products tailored for the elderly or foods with reduced additive concentrations. This aligns with the requirements for “clean label” food production procedures, which advocate for minimalistic and transparent ingredient lists [61].

The global appreciation for Açaí juice has grown significantly due to its health-beneficial bioactive compounds. However, conventional preservation methods, such as thermal pasteurization, can degrade these compounds and impair the beneficial bioactivities of Açaí juice. HPP at 500 MPa for 5 min at 20 °C has proven to be more efficient in retaining anthocyanins and significantly boosts the extractability of non-anthocyanin phenolic compounds, compared to thermal treatments. Furthermore, the antioxidant properties toward biologically relevant reactive species are either equivalent or superior to those offered by thermal processing. Both HPP and thermal treatments demonstrate stability in the presence of tocopherols and vitamin E. Therefore, HPP stands out as a promising alternative preservation technique, capable of delivering Açaí juice with superior functional quality [62].

Aroma is an important factor in determining the quality and acceptability of fruit juices. To improve juice quality, studies on the characterization of volatile chemicals in fruits have been conducted. Numerous volatile chemicals, primarily esters, aldehydes, and alcohols, have been discovered in fruits to date. However, not all volatile chemicals contribute to the aromatic quality of fruits, and only a small percentage of volatiles (referred to as aroma-active compounds) play a significant role in sensory perception and add to

Table 2
Effects of HHP technology on juice properties.

Sample	Treatment parameters	Compared with	Results	Reference
Sugarcane (*Saccharum officinarum*) juice	600 MPa, 60 °C, 25 min	Untreated sugarcane juice	Microbial stability and enzymes (PPO and POD) activity was inhibited and browning reduced by 22%	[67]
Grapefruit juice	600 MPa, 10 °C, 5 min	Thermal pasteurization (85 °C, 45 s)	Naringinase activity maintained at 92%, better retention of sensory properties	[68]
Pêra-Rio orange juice	520 MPa, 60 °C, 360 s (90 days storage)	Thermal pasteurization (95 °C, 30 s)	Microbial stability decreases, 13% decrease in PME, and vitamin C content during storage	[69]
Keitt mango juice	400 MPa, 15 min	Thermal pasteurization (80 °C, 30 min)	Better preservation of aromatic compounds (*E*)-β-ocimene, (*E*)-2-nonenal, (*E*, *Z*)-3,6-nonadien-1-ol and ethyl butyrate	[63]
Jabuticaba (*Myrciaria jaboticaba*) juice	500 MPa, 5–10 min	Untreated jaboticaba juice	+ 38% phenolic compounds, + 46% antioxidant activity, sensory properties unaffected	[70]
Strawberry–apple–lemon juice blend	500 MPa, 15 min, 20 °C	Heat treatment (86 °C, 1 min)	+ 18% polyphenols, $< 2 \log_{10}$ CFU/mL aerobic bacteria, better preservation of anthocyanins and sensory properties	[66]
Kiwifruit juice	500 MPa, 10 min	Thermal pasteurization (80 °C, 20 min)	Better retention of aromatic compounds (*E*)-2-hexenal and 1-hexanol	[10]
Pomegranate (*Punica granatum L.*) beverage	600 MPa, 5 min	Thermal pasteurization (63 °C, 30 min)	Better retention of polyphenols and antioxidant activity, microbial stability decreases	[65]
Carrot juice	600 MPa, 5 min, 22 °C	Untreated carrot juice	New polyphenols detected oleuropein, 4-vinylsyringol, isocoumarin, and 4-hydroxybenzaldehyde, 57% PPO and 31% POD reduction	[71]

the overall aroma. HHP technology has been associated with better retention of aromatic compounds in kiwifruit juice and mango (cultivar Keitt) juice when compared to thermal treatments [10,63,64]. In another study, HHP treatment (600 MPa, 5 min) of fermented pomegranate (*Punica granatum* L.) beverages showed microbiological stability for a storage period of 42 days, similar to thermal treatment. The physicochemical parameters were not affected by storage duration and HHP and thermal treatment. However, HHP processing better retained the sensory attributes of the sample when compared to thermal treatment [65]. Similar results were reported in another study, where HHP treatment (500 MPa, 15 min, 20 °C) significantly reduced the log value of aerobic bacteria and yeast and mold count in strawberry–apple–lemon juice blend during 10 days of refrigerated storage. Anthocyanins were retained and phenolic compounds were increased by 18% after HHP treatment; associated antioxidant activity also increased [66]. Table 2 illustrates the use of HHP technology in the juice industry.

5. Ultrasound technology

5.1. Explanation of ultrasound technology and how it works

Ultrasound technology is a nonthermal food processing method that utilizes high-frequency sound waves to induce various physical and chemical changes in food matrices. This technique has gained attention in the food industry due to its potential to improve the extraction, quality, safety, and shelf life of food products, including juices [11]. Ultrasound technology facilitates the release of intracellular contents from plant tissues, enhances the mass transfer of solutes, and inactivates microorganisms and enzymes. Ultrasound is a mechanical wave with a frequency above the human hearing range (> 16 kHz), typically between 20 kHz and 500 MHz. Ultrasound technology operates in two main modes: low-intensity, high-frequency (LIHF) ultrasound (100 kHz–1 MHz), and high-intensity, low-frequency (HILF) ultrasound (16–100 kHz). LIHF ultrasound is primarily used for analytical and diagnostic purposes, while HILF ultrasound is employed for food processing applications, with frequencies typically ranging from 20 kHz to 100 kHz. Ultrasound waves propagate through a medium by causing the particles to oscillate in the direction of wave propagation, generating compressions (high-pressure zones) and rarefactions (low-pressure zones). The alternating pressure cycles create mechanical stresses in the medium, leading to cavitation, microstreaming, and other physical phenomena that can affect the structure and properties [72] of food materials [72].

Ultrasound equipment used in food processing, including juice extraction, typically consists of four main components: a power supply, a signal generator, a transducer, and a reaction chamber or vessel. The power supply provides the necessary electrical energy to operate the ultrasound equipment. It is responsible for converting the input voltage from the mains supply to the required output voltage and current levels needed for the signal generator and transducer to function properly. The signal generator, also known as a function generator, is responsible for producing the electrical signals that drive the transducer. It generates high-frequency electrical signals, usually sinusoidal, with frequencies typically ranging from 20 kHz to 100 kHz for food processing applications. The signal generator is also responsible for controlling the amplitude, frequency, and waveform of the electrical signals to achieve the desired ultrasound parameters. The transducer is the key component that converts electrical energy into mechanical energy in the form of ultrasound waves. It is typically made of piezoelectric materials, such as lead zirconate titanate (PZT) or quartz, which can change their shape when subjected to an electric field. When electrical signals from the signal generator are applied to the transducer, it oscillates at the same frequency, generating mechanical vibrations that propagate as ultrasound waves into the medium. Transducers can be designed in various shapes and sizes, tailored to meet specific application needs and requirements [73]. The reaction chamber or vessel is where the food material, such as fruit or vegetable tissues, is exposed to ultrasound waves. The design of the chamber can vary depending on the specific application, but it generally consists of a container made from a material that can transmit ultrasound waves, such as stainless steel or glass. In some cases, the transducer can be directly immersed in the liquid medium (known as an immersion or probe-type system), while in other cases, the transducer is attached to the chamber wall or at the bottom (known as a contact or plate-type system). The reaction chamber should be designed to ensure uniform distribution of ultrasound waves and to minimize energy losses due to reflections and absorption [73].

5.2. Mechanisms of action and effects on cell structures

Ultrasounds affect the cellular structures by the cavitation and microstreaming phenomenon. Cavitation is the formation, growth, and collapse of microscopic bubbles or cavities in a liquid medium due to pressure fluctuations induced by ultrasound waves. When cavities collapse, they release a high amount of energy, resulting in local temperature and pressure spike[s], shock waves, and microjets. These events cause physical disruption of the plant tissues, facilitating the release of intracellular contents, such as water, sugars, acids, and other bioactive compounds. Microstreaming is the fluid motion generated around oscillating bubbles or solid particles in the medium due to ultrasound-induced pressure gradients. This phenomenon enhances the mass transfer of solutes between plant tissues and the surrounding liquid, promoting the extraction of juice components and improving the yield and quality of the extracted juice [74]. Ultrasound technology also exhibits antimicrobial and enzyme-inactivating effects, contributing to improved safety and shelf life (orange; 28 days at 5 °C) of the extracted juice. The inactivation of microorganisms and enzymes is primarily attributed to mechanical stresses, shear forces, and temperature and pressure spikes associated with cavitation and microstreaming [75]. Ultrasound technology can induce changes in the food matrix that may affect the texture, color, flavor, and nutritional properties of the extracted juice. Ultrasound waves can cause protein denaturation, starch gelatinization, and the modification of pectin and other polysaccharides, leading to changes in the rheological properties and stability of juice. Moreover, ultrasound can influence chemical reactions, such as oxidation, hydrolysis, and Maillard reactions, by altering the reaction rates, mass transfer, and formation of reactive species [76].

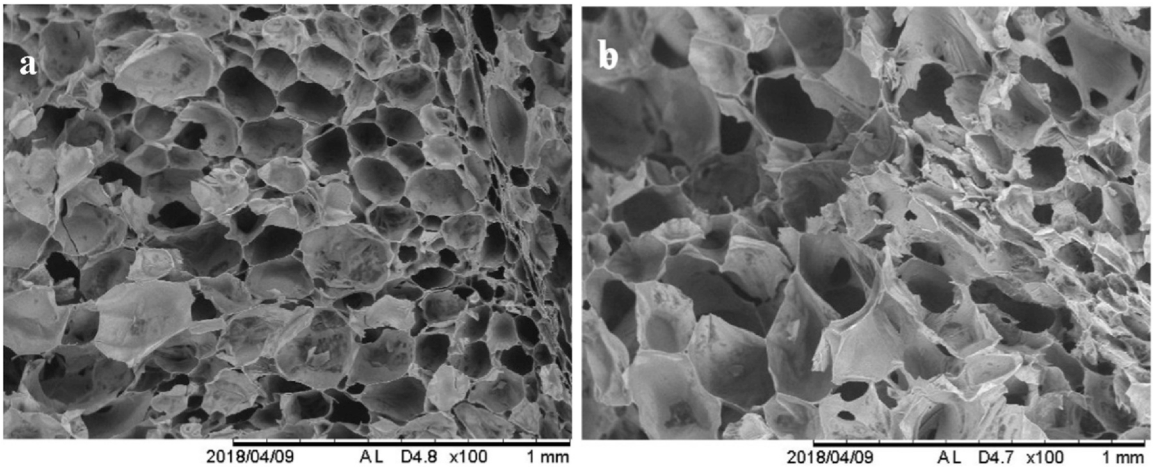

Fig. 3. Photomicrographs of strawberry cells after ultrasound treatment (b: 20 kHz, 400 W, 16 min) show bigger pore sizes as compared to the control (a) [12].

5.3. Recent literature related to ultrasound technology in the juice extraction industry

Literature published from 2019:

Sohiong, a bird cherry species indigenous to the eastern Himalayan foothills, including Nepal, Myanmar, China, and India, is an underutilized fruit with an abundant source of micronutrients like polyphenols, vitamins, minerals, and anthocyanin. This fruit showcases its impressive antioxidant properties and promising radical scavenging potential. Vivek *et al.* [77] investigated the synergistic impact of ultrasound and enzymatic treatment on sohiong (*Prunus nepalensis*) fruit juice extraction. Optimum juice recovery and quality were observed under conditions of 90% ultrasound amplitude, 9.95 min of treatment time, 0.03% w/w enzyme concentration, and 57.44 min of incubation duration. Utilizing ultrasound as a pretreatment strategy not only amplified the juice yield by 20% but also escalated total soluble solids (TSS), anthocyanins, antioxidant activity, and total phenolic compounds by 24%, 25%, 4.4%, and 8%, respectively. Simultaneously, incorporating pectinase enzyme treatment significantly reduced the extraction time by 22 min. The application of ultrasound technology has been reported to confer multiple advantages for the processing of fruit juices. These benefits encompass improved microbial stability, better preservation of bioactive compounds, and ascorbic acid retention. One such application was on red grape juice, where ultrasound treatment, performed at 70% intensity for 5 or 10 min at a frequency of 20 kHz, exhibited superior preservation characteristics when compared to traditional thermal pasteurization at 80 °C for 2 min [78]. Similar findings were observed in the application of ultrasound technology to kiwifruit juice and strawberry juice [79]. Moreover, it has been observed that the degree of cellular disruption via ultrasound is directly related to the processing time. For instance, a 16-min ultrasound treatment resulted in the formation of a significant number of microscopic channels or pores within the intercellular spaces (Fig. 3), thus promoting the efficient extraction of bioactive compounds [79].

Dragon fruit (*Hylocereus polyrhizus*) is known to be rich in various bioactive compounds that offer potential health benefits. One predominant group is betacyanin, which is primarily responsible for the fruit's red pigments. This compound plays an integral role in antioxidant activity; its free-radical scavenging capabilities stem from the presence of betalamic acid and acyclic amine groups in its molecular structure. Ultrasound combined with enzymatic treatments has been leveraged to optimize the extraction of phenolic compounds and betacyanin in dragon fruit juice. It was found that such combined treatment notably boosted the release of betacyanin content (ranging between 144.41 and 154.86 mg/L), total phenolic content (TPC, ranging between 190.7 and 212.12 mg GAE/L), and free radical scavenging activity (ranging between 6.12% and 7.48%) in the juice [80]. Similar findings were also documented in a separate study involving plum (*Prunus salicina* L.) juice [81]. Table 3 highlights the potential applications of ultrasound technology within the juice industry.

6. Microwave technology

6.1. Explanation of microwave technology and how it works

Microwave technology in juice extraction involves the use of electromagnetic radiation to generate heat within fruit and vegetable tissues. This heat causes the cell walls to rupture, releasing juice from the intracellular compartments. The microwave-assisted extraction process typically results in improved juice extraction efficiency, higher yield, and reduced processing time compared to conventional methods. Microwave technology can also be advantageous in preserving the nutritional and sensory properties of the extracted juice. The rapid and selective heating can help retain the vitamins, minerals, and antioxidants in the juice while minimizing the negative effects on flavor, color, and texture [90]. However, there are potential drawbacks to consider when using microwave technology for juice extraction. Overheating may occur, which could result in the degradation of heat-sensitive nutrients and the formation of unwanted compounds. Moreover, the penetration depth of microwaves may limit their effectiveness for certain fruits and vegetables, requiring optimization of the process parameters [90].

Table 3
Some applications of ultrasound in the juice industry.

Application	Product	Comments	References
Extraction	Blackberry juice, Sohiong (*Prunus nepalensis*) juice	• Increase the juice yield and the quality of the extract • Optimization is required for each food matrix to achieve the optimum gain	[77,82]
Microbial decontamination	Tomato juice, cranberry juice, blueberry juice, strawberry juice, guava juice	• Reduce microbial activity in juices and delay the recovery of yeasts and molds during the course of storage • Ultrasound may assist in the disaggregation of microbes in fruit juices	[12,83,84]
Sterilization and pasteurization	Apple juice, peach juice, pomegranate juice	• Cavitation phenomenon induced by ultrasounds affects the stability of enzyme systems and thus prevents enzymatic browning • The same phenomenon has the capacity to break molecules, thus generating free radicals in the water sonolysis (H^+ and OH^-), which leads to microbial inactivation	[31,85,86]
Polyphenols and sensory properties	Bilberry juice, plum juice, apple juice, guava juice, strawberry juice	• Ultrasounds at optimum processing conditions can rupture the tissue of the fruit matrix and form microcavities that facilitate the release of bioactive compounds in the juice. This activity can be exploited commercially to attract customers and gain nutritional advantages. • Cavitation phenomena reduce the particle size in juices, which increases the cloudiness	[12,81,87–89]

Microwave-assisted extraction (MAE) equipment works by generating electromagnetic waves that penetrate the fruit or vegetable tissue. These waves induce vibrations in the water molecules within the cells, generating heat through molecular friction. This heat leads to the rupture of cell walls and the release of juice [91].

The main components of MAE equipment include a microwave generator, a waveguide, an extraction chamber, a control system, and a collection system. The microwave generator is the source of microwaves, typically a magnetron converting electrical energy into electromagnetic waves at a specific frequency, usually 2.45 GHz for industrial applications. The waveguide directs these microwaves from the generator to the extraction chamber, ensuring uniform and efficient transmission. The extraction chamber is where the fruit or vegetable material is placed for extraction. It is often designed to accommodate specific volumes or shapes and may contain a rotating mechanism for uniform heating. The control system is essential for monitoring and regulating the temperature and pressure within the extraction chamber to optimize the extraction process and prevent overheating or over-pressurization. Finally, the collection system allows the released juice to be collected after microwave treatment. This is typically done through a filtration system that separates the juice from the solid residue. The juice can then be further processed or packaged as desired [92,93].

6.2. Mechanisms of action and effects on cell walls

Microwave radiation consists of electromagnetic waves, most commonly at a frequency of 2.45 GHz for industrial applications. When these waves interact with plant tissues, the polar water molecules within the cells oscillate in response to the alternating electromagnetic field. This oscillation generates heat through molecular friction, resulting in a rapid increase in temperature within the cells. The heating effect of microwaves is selective and volumetric, which means that the energy is absorbed directly by the water molecules within the cells, rather than being transferred through the tissue via conduction. As a result, the cells heat up more quickly and uniformly compared to traditional heating methods [94]. The rapid heating caused by microwave radiation leads to various effects on the cell walls of fruits and vegetables, which contribute to the enhanced extraction of juice. The quick rise in temperature causes the water molecules within the cells to expand, exerting pressure on the cell walls. This pressure can cause the cell walls to rupture, releasing the intracellular contents, including the juice, into the surrounding medium [94].

The cell walls of fruits and vegetables are primarily composed of cellulose, hemicellulose, and pectin. Microwaves can cause the breakdown of cellular components: cellulose, hemicellulose, and, particularly, pectin, which serves as a cementing substance between cells. The disruption of pectin weakens the cell wall structure [95], making it easier for the juice to be extracted. The rapid heating of plant tissues by microwaves can improve the mass transfer of juice from the cells to the extraction medium. The increase in temperature accelerates the diffusion of solutes and reduces the viscosity of the juice, allowing it to flow more easily through the disrupted cell walls [91].

These effects on the cell walls collectively contribute to the improved efficiency and yield of juice extraction using microwave technology. However, it is crucial to optimize the process parameters, such as microwave power and extraction time, to ensure that the cell walls are disrupted effectively without causing excessive damage to the quality attributes of the extracted juice. It is important to note that there are potential drawbacks associated with the use of microwave technology for juice extraction. Overheating can occur if the process parameters are not optimized, leading to the degradation of heat-sensitive nutrients and the formation of undesirable compounds. Moreover, the penetration depth of microwaves may limit their effectiveness for certain fruits and vegetables, requiring careful optimization of the process parameters for each specific case [96].

6.3. Recent literature related to microwave technology in the juice extraction industry

Literature published from 2019:

Microwave technology is not associated with direct juice extraction. It has been extensively reported, however, in the extraction of bioactive compounds from various matrixes, such as pomegranate external peels [97], pomegranate solid waste [98], grape juice byproducts [99], kiwi juice pomace [100], orange juice waste [101], and grape pomace [102].

Pradhan *et al.* [103] studied the impact of microwave treatment for 3 min on sugarcane juice and reported that it can efficiently improve microbiological stability for 21 days at ambient temperature and 56 days at refrigeration temperatures. Thus, microwave treatments can be utilized in the production of sugarcane juice-based beverages. Microwave treatment has been applied to improve the pasteurization process of cloudy apple juice in comparison with conventional thermal treatments. Results revealed that the volatile profile of the microwave pasteurized sample was similar to the non-pasteurized sample when compared to conventional pasteurization. However, phenolic content was independent of the processing technology utilized. Nevertheless, microwave technology was recommended based on better flavor retention ability and shorter processing time [104].

7. Mechanical force

7.1. Explanation of mechanical force and its role in juice extraction

Mechanical force in juice extraction generally refers to the application of physical pressure or force on fruits and vegetables to disrupt their cellular structure and to release the juice contained within the cells. This force can be applied in various ways, depending on the type of fruit or vegetable and the desired characteristics of the final product. The role of mechanical force in juice extraction is to break down the cell walls and membranes, which are the primary barriers preventing the release of juice from plant tissues. By applying sufficient mechanical force, the cell walls can be ruptured, allowing the juice to flow out and be collected. This process is essential for obtaining juice from fruits and vegetables in a practical and efficient manner [105]. The effectiveness of mechanical force in juice extraction depends on several factors, including the characteristics of the plant material, such as its texture, moisture content, and cell wall composition, as well as the type and intensity of the force applied. It is important to optimize these factors to maximize the extraction yield while maintaining the quality and nutritional value of the extracted juice. In addition to its role in liberating juice from plant tissues, the mechanical force can also impact the quality attributes of the final product. For example, the application of mechanical force can lead to the release of enzymes, such as polyphenol oxidase, which can cause browning and other undesirable changes in the juice. In addition, the extraction process can result in the inclusion of cell debris, which may affect the juice's clarity and texture. These factors must be considered when designing juice extraction processes and equipment that rely on mechanical force [106].

7.2. Mechanisms of action and effects on cell structures

Mechanical force applies compressive stress to the plant tissues, which directly acts upon the cell walls and membranes. The pressure exerted by these compressive forces is often sufficient to cause the cells to rupture, releasing their contents, including the juice. When plant tissues are subjected to mechanical force, they also experience shear forces, which act parallel to the surface of the cells. These forces can cause cells to deform, stretch, and eventually rupture, contributing to the release of juice from the cells [107]. Along with the cell walls, mechanical force can also disrupt the cell membranes, which are the semipermeable barriers that separate the intracellular contents from the extracellular environment. The rupture of cell membranes facilitates the release of juice and other intracellular components. Mechanical forces can also lead to the release of enzymes from plant cells, which may impact the quality of the extracted juice. For example, the release of polyphenol oxidase can cause browning and other undesirable changes in the juice due to the enzymatic oxidation of phenolic compounds. The breakdown of cell structures can result in the presence of cell debris in the extracted juice. This debris may affect the clarity, texture, and overall quality of the juice, necessitating additional processing steps, such as filtration, to obtain a clear and smooth product [108].

8. Quality and safety aspects of juice extracted using physical field technologies

Physical field technologies can have a significant impact on the sensory attributes of juice products, including taste, aroma, color, and texture. PEF and HHP treatments are known to have minimal impact on taste and aroma compounds, as they do not rely on high temperatures for juice extraction [109]. This can result in juice products with fresher and more natural tastes and aromas compared to those obtained through traditional thermal methods. Ultrasound- and microwave-assisted extraction may have a more significant impact on the sensory attributes of juice products due to the localized heating effects associated with these technologies. However, careful optimization of process parameters can help minimize any adverse effects on taste, aroma, and color [110]. In terms of texture, physical field technologies can enhance the homogeneity and smoothness of juice products by facilitating the more efficient extraction and release of cellular components. For example, high-pressure homogenization can improve the texture of juice by reducing particle size and creating a more uniform product [111].

Physical field technologies are also associated with the preservation of various nutrients, such as vitamins, minerals, and bioactive compounds. PEF and HHP technologies are known to better preserve heat-sensitive nutrients, such as vitamins C and E, compared to conventional thermal methods [45]. This can result in juice products with higher nutritional value. Similarly, ultrasound- and microwave-assisted extraction may have varying effects on the nutritional content of juice products, depending on the process parameters and the specific nutrients involved. Localized heating effects can potentially degrade some heat-sensitive nutrients, but optimized extraction conditions can help minimize these losses. Furthermore, physical field technologies can enhance the extraction of bioactive compounds, such as polyphenols and carotenoids, which contribute to the antioxidant and health-promoting properties of juice products. For example, ultrasound-assisted extraction has been shown to improve the recovery of phenolic compounds from grape pomace, resulting in juice products with higher antioxidant activity [112].

9. Overview of the potential risks and challenges associated with physical field technologies

While physical field technologies offer several benefits in juice extraction, it is essential to recognize the potential risks and challenges associated with their use. These technologies can cause alterations in flavor and color, which may impact the overall acceptability of juice products. PEF and HHP generally have a minimal impact on taste and aroma compounds, preserving the fresh and natural characteristics of juice products. However, under certain conditions, these treatments can cause changes in volatile compounds or promote enzymatic reactions, potentially affecting the taste and aroma profiles of the products [65].

Ultrasound- and microwave-assisted extraction can lead to more significant changes, such as the formation of Maillard reaction products or the degradation of color pigments, such as carotenoids and anthocyanins. This can result in undesirable changes in the sensory properties of juice products [76]. Careful optimization of process parameters is necessary to minimize these effects. Similarly, excessive processing of high-pressure homogenization can cause the rupture of cellular structures, leading to the release of pectin, which may increase the viscosity of the juice and negatively affect its mouthfeel. HHP is extensively reported in the literature due to its propensity to release pectin from various food matrixes [113]. This issue is also associated with ultrasound- and microwave-assisted extraction. Therefore, optimization of the processing parameters is crucial to achieving the desired texture characteristics, while minimizing any adverse effects on the product quality.

The cell structure and composition of fruits and vegetables can significantly impact the efficiency of juice extraction technologies. Fruits and vegetables with a more robust or fibrous cell structure may require more intensive treatment, such as higher electric field strengths in PEF or higher-pressure levels in HHP, to achieve optimal juice extraction. Understanding the unique characteristics of each fruit and vegetable is crucial for selecting the appropriate technology and optimizing the process parameters [24]. The heat sensitivity of the target juice product is an important factor when choosing a physical field technology. For juice products containing heat-sensitive nutrients or volatile flavor compounds, nonthermal technologies, such as PEF or HHP, are more suitable for maintaining the nutritional quality and sensory properties of the juice [20].

The adoption of physical field technologies in juice extraction may face challenges related to energy consumption and costs. Some of these technologies, such as PEF and HHP, require significant capital investment in equipment and infrastructure, which can be a barrier for small- and medium-sized enterprises. Furthermore, the energy consumption associated with these technologies can impact their overall feasibility and sustainability, especially when considering large-scale operations. Ultrasound- and microwave-assisted extraction may have lower initial capital costs, but their energy consumption can be relatively high depending on the process parameters and the scale of the operation. The application of these technologies may face challenges related to regulatory requirements and consumer acceptance. As novel processing methods, these technologies need to comply with food safety regulations, and in some cases, they may require specific approval from regulatory agencies, such as the U.S. Food and Drug Administration (FDA) or the European Food Safety Authority (EFSA) [114]. Consumer acceptance of juice products obtained using physical field technologies can also be a challenge, as consumers may have concerns regarding the safety and quality of the products. It is essential to communicate the benefits and safety aspects of these technologies effectively and transparently to gain consumer trust and acceptance.

10. Conclusion and future perspectives

Juice extraction methods have undergone significant evolution throughout history, progressing from primitive hand-pressing techniques to advanced technologies designed to preserve the nutritional content and quality of juices. Physical field technologies, in particular, have emerged as key players in enhancing the quality and safety of juice products, encompassing improvements in sensory attributes, nutritional content, and shelf life. Among these technologies, PEF stands out as the superior choice for juice extraction due to its high efficiency in improving juice yield, superior preservation of sensory properties and nutrients, lower energy consumption, and excellent scalability and adaptability. Although other physical field technologies, such as HHP, ultrasound, and microwave-assisted extraction, offer certain advantages, the combination of benefits offered by PEF renders it the most appealing option for revolutionizing the juice extraction industry. By leveraging the unique properties of physical forces, these technologies collectively contribute to achieving more efficient, sustainable, and high-quality food processing outcomes.

It is essential for industry stakeholders, researchers, and regulators to continue working collaboratively to overcome the challenges associated with scaling up these technologies, ensuring the safety and quality of juice products, and raising consumer awareness about the benefits of healthy and natural juices. Future research efforts should prioritize exploring the synergistic effects achieved through combining these technologies with other methods. Moreover, optimizing equipment and operational parameters is necessary to maintain control over the final product. The future of juice extraction lies in the continuous development and optimization of physical field technologies, enabling the industry to meet the increasing demand for high-quality, sustainable, and nutritious juice products.

Ethics approval statement

Not applicable.

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CRediT authorship contribution statement

Xin-An Zeng: Resources, Funding acquisition, Conceptualization. **Wei Zhao:** Writing – review & editing. **Songyi Lin:** Writing – review & editing. **Mengwai Woo:** Writing – review & editing. **Zhong Han:** Writing – review & editing, Supervision, Resources, Funding acquisition, Conceptualization. **Muhammad Talha Afraz:** Writing – original draft, Investigation, Conceptualization. **Xindong Xu:** Writing – review & editing, Resources.

Conflict of Interest

Xin-An Zeng and Songyi Lin are Associate Editors and Wei Zhao is an editorial board member for Food Physics, all of them were not involved in the editorial review or the decision to publish this article. All other authors declare that there are no competing interests.

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