



Pulsed electric field-assisted extraction of bioactive compounds from fruits: Principles, recent advances and industrial perspective

Jeevita J Pujari¹, Dr. Viswanatha Angadi², Sangeetha L¹, Shreya N Biradar¹, Shwetha S M¹

¹ College of Agriculture Karekere, Hassan. University of Agricultural Sciences, Mandya, Karnataka, India

² Associate Professor and Head, Department of Food Science and Technology, College of Agriculture Karekere, Hassan. University of Agricultural Sciences, Mandya, Karnataka, India

Abstract

Interest in naturally derived functional ingredients has encouraged researchers to seek extraction strategies that protect fragile plant-derived functional molecules during recovery. Fruits supply numerous compounds of interest, including polyphenolic substances, flavonoid groups, anthocyanin pigments, carotenoid molecules and vitamins, many of which are associated with antioxidant, inflammation-modulating, antimicrobial and cardiovascular-supporting functions. Conventional recovery operations can consume substantial solvent, time and heat, conditions that may lower yield or damage temperature-sensitive constituents. Pulsed electric field (PEF) processing offers a non-thermal route in which electrical treatment temporarily alters cellular barriers, promoting movement of within-cell compounds into an extraction phase while limiting heat exposure. Progress in equipment engineering, operating-condition process refinement and combined processing has broadened the recovery of valuable plant-derived functional molecules from whole fruits and processing residues. This review examines the operating basis of PEF-assisted recovery, variables governing performance, uses involving fruit-derived compounds and movement toward commercial operation. Particular attention is given to scale-up, process uniformity, economics, standardization and incorporation into circular biorefinery models. Overall, PEF provides a potentially resource-efficient route for obtaining high-value natural ingredients for food and related industries.

Keywords: Pulsed electric field (PEF), electroporation, bioactive compounds, fruit processing, green extraction, sustainable processing, phytochemicals, non-thermal processing approach

Introduction

Growing preference for foods associated with benefits beyond nutrient supply has strengthened research interest in compounds originating from fruits. Fruit tissues contain diverse plant-derived functional molecule families, such as polyphenols, flavonoids, anthocyanins, carotenoids, phenolic acids and vitamins. (Kusmann *et al.*, 2023) [13].

Their documented biological functions include antioxidant action, modulation of inflammatory processes, antimicrobial effects and cardiovascular protection. Associations between these constituents and lower incidence of several chronic disorders have encouraged their incorporation or investigation in functional foods, nutraceutical preparations, pharmaceutical products and cosmetic formulations (Patra *et al.*, 2023) [18].

Obtaining these constituents efficiently is difficult because many are located inside cells where plant-wall structures and membrane barriers restrict contact with the extraction liquid. Anthocyanins, carotenoids and ascorbic acid are also vulnerable to oxidation or heat-related deterioration. (Weaver and Chizmadzhev, 1996) [24] Thus, the selected recovery operation influences not only the quantity obtained but also the quality and stability of the resulting extract (Donsi *et al.*, 2010) [6] Yan *et al.*, 2017) [27]

Established strategies such as soaking-based extraction, solvent treatment, Soxhlet operation, hydrodistillation and mechanical pressing remain in use owing to their established procedures and comparatively straightforward. Their drawbacks include lengthy operation, substantial energy requirements and frequent dependence on organic solvents. (Azmi *et al.*, 2013) [1] Exposure to elevated temperatures can additionally compromise heat-labile

constituents, while solvent-intensive processing creates ecological concerns. These disadvantages have encouraged investigation of extraction strategies that use fewer resources without sacrificing recovery (Barba *et al.*, 2015) [2].

Within the group of non-thermal strategies, PEF has attracted substantial research interest for releasing within-cell plant-derived functional molecules. Brief high-voltage pulses alter the permeability of plant-cellular membranes through electroporation, making internal metabolites more accessible to the surrounding extraction medium without relying on severe heating. Reported benefits include greater recovery, abbreviated treatment periods, reduced solvent demand, better retention of sensitive constituents and suitability for continuous processing (Barba *et al.*, 2015) [2], Yan *et al.*, 2017) [27], Ranjha *et al.*, 2021) [20].

The expanding PEF literature contains substantial evidence of technical effectiveness, yet findings concerning operating-condition process refinement, scale-up, combined processing strategies and commercial deployment are distributed across many studies. Bringing these developments together is necessary for understanding the present technological position and identifying unresolved research needs.

Accordingly, this review brings together information on the physical basis of PEF-assisted extraction, the variables that determine treatment performance, uses involving different fruit materials and progress toward industrial utilization. It also considers emerging strategies, practical constraints and subsequent investigations needs in relation to sustainable food processing and circular bioeconomy development.

Bioactive Compounds in fruits and Extraction Challenges

Fruit tissues constitute important reservoirs of compounds that can contribute to both food quality and biological functionality. Their chemical repertoire includes polyphenols, flavonoids, anthocyanins, carotenoids, phenolic acids, vitamins, tannins and other secondary metabolites. (Azmir *et al.*, 2013) ^[1] These substances have attracted attention because of described antioxidant, inflammation-modulating, antimicrobial, cardiovascular and anticancer activities, creating opportunities for their use in functional foods, nutraceuticals, medicines and personal-care products (Ranjha *et al.*, 2021) ^[19].

The abundance and profile of these molecules are not fixed. They are affected by fruit species and cultivar, stage of ripening, growing environment and handling after harvest. For example, berries commonly provide substantial anthocyanin concentrations; citrus materials supply flavanones and vitamin C; grapes contain resveratrol and phenolic acids; and mango, papaya and tomato tissues are important sources of carotenoid pigments such as β -carotene and lycopene. Such diversity makes both edible material and processing residues attractive feedstocks for producing higher-value ingredients (Barba *et al.*, 2015) ^[2], Ranjha *et al.*, 2021) ^[19].

Polyphenolic compounds have received extensive scientific attention because they can interact with reactive oxygen species and biological signalling pathways associated with chronic disorders. Flavonoid subclasses, including flavanols, flavanones, flavones and anthocyanins, contribute strongly to the antioxidant potential of many fruits and have been investigated in relation to cardiovascular and metabolic health. Carotenoid pigments such as β -carotene, lycopene, lutein and zeaxanthin also possess antioxidant functions and are relevant to visual, immune and cellular protection. (Ranjha *et al.*, 2021) ^[19]. Vitamin C is another important water-soluble antioxidant and participates in immune regulation and collagen formation (Vallverdú-Queralt *et al.*, 2012) ^[23].

Recovering these molecules without compromising them presents a processing challenge. Many plant-derived functional molecules occupy vacuoles or other within-cell locations enclosed by firm cell walls and selective membranes, which limits movement of extraction liquids into the tissue. Oxidative reactions, enzymatic activity and heat can further alter susceptible compounds during processing. Consequently, extraction design strongly influences both recovery and stability. The need for cleaner production and high-quality natural ingredients has therefore stimulated interest in methods that increase accessibility while limiting chemical deterioration and environmental load (Weaver and Chizmadzhev, 1996) ^[24], Donsì *et al.*, 2010) ^[8], Yan *et al.*, 2017) ^[27].

Extraction Technologies for Bioactive Compounds in Fruits

Successful plant-derived functional molecule recovery requires an operation capable of overcoming the physical barriers of plant tissue while maintaining the integrity of the desired molecules. (Azmir *et al.*, 2023) ^[1]. Traditional procedures such as maceration, solvent-based extraction, Soxhlet extraction, hydrodistillation and cold pressing are well established, but their use can involve lengthy contact periods, heating and substantial solvent requirement. These

conditions may be unfavorable for thermolabile compounds (Katekar *et al.*, 2023) ^[11].

Environmental considerations and consumer demand for minimally processed ingredients have encouraged alternatives that lower solvent use, energy input and processing duration. Ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), supercritical fluid extraction (SFE), high hydrostatic pressure (HHP) and PEF are among the strategies investigated for recovering fruit plant-derived functional molecules. (Barba *et al.*, 2015) ^[2]. Rather than depending only on molecular diffusion through a solvent, these methods use acoustic, thermal, enzymatic, pressure-driven or electrical effects to promote tissue disruption and movement of solutes (Ranjha *et al.*, 2021) ^[19].

The usefulness of each alternative depends on the material and the molecules being targeted. Acoustic cavitation generated during UAE can promote tissue disruption; MAE uses dielectric heating to accelerate solvent movement; EAE employs enzymes to weaken cell-wall structures; and SFE uses supercritical carbon dioxide for selective recovery of suitable non-polar constituents. HHP can increase cellular permeability under pressure while limiting extensive heat exposure. Because fruit matrices and plant-derived functional molecules differ widely, no single approach can be regarded as universally optimal (Barba *et al.*, 2015) ^[2], Ranjha *et al.*, 2021) ^[19].

PEF is distinctive because its principal disruptive action is electrical rather than thermal. Electrical treatment can create transient or persistent membrane porosity, reducing resistance to mass movement and enabling within-cell material to become accessible with limited temperature rise. (Donsì *et al.*, 2010) ^[8] In suitable uses this can be accompanied by reduced solvent demand, shorter operation and lower energy use. Yan *et al.*, 2017) ^[27] Combining PEF with ultrasound, enzymes or supercritical-fluid processing has also been explored to exploit complementary mechanisms and develop integrated extraction schemes (Ranjha *et al.*, 2021) ^[19].

Pulsed Electric Field Technology: Principles and Mechanisms

PEF is a non-thermal processing approach in which externally applied electrical pulses increase the permeability of biological membranes. Although the processing approach was initially investigated largely for microbial control and preservation of liquid foods, its use has broadened to include extraction, drying-related uses, dehydration and recovery of valuable material from biomass. (Toepfl *et al.*, 2006) ^[21] Because electrical treatment can promote movement of solutes without extensive heating, it is relevant to fruit matrices containing temperature-sensitive plant-derived functional molecules (Barba *et al.*, 2015) ^[2].

During treatment, biological material is placed within an electric field and exposed to pulses lasting from microseconds to milliseconds. The applied field creates a voltage difference across the phospholipid membrane. Once the induced transmembrane potential reaches a critical level, generally around 0.5–1.0 V, the membrane becomes electrically destabilized and microscopic water-filled openings can form. This phenomenon, termed electroporation, raises permeability and allows extraction liquids to interact more readily with within-cell metabolites, promoting their transfer while limiting thermal deterioration

(Zimmermann, 1986)^[29], Weaver and Chizmadzhev, 1996)^[24].

The resulting membrane alteration may either disappear after treatment or remain permanent, depending on the electrical dose. Mild conditions can produce reversible electroporation, with membrane structures recovering after the field is removed. (Weaver and Chizmadzhev, 1996)^[24] Stronger fields or longer exposure can produce irreversible electroporation, in which membrane disruption persists and promotes release of within-cell material. Extraction uses commonly seek sufficient irreversible permeabilization for effective release while avoiding unnecessary tissue destruction and excessive heat generation (Demir *et al.*, 2023)^[7].

The principal contribution of PEF to extraction is an increase in mass-transfer rate rather than deliberate chemical alteration of the recovered molecules. Lower membrane resistance allows the extraction liquid to reach within-cell regions more readily and assists movement of compounds such as polyphenols, anthocyanins, carotenoids and flavonoids into the external phase. Consequently, suitable PEF treatments have been associated with promoted recovery, reduced processing duration, lower solvent use and retention of antioxidant characteristics relative to conventional operations (Donsi *et al.*, 2010)^[8], Yan *et al.*, 2017)^[27].

More recent work has paired PEF with other low-impact extraction methods, including ultrasound, enzymatic treatment and supercritical-fluid processing. Such combinations apply different forms of tissue disruption or mass-transfer promotement in sequence or simultaneously and can provide complementary effects. These developments broaden the potential role of PEF within advanced food-processing and biorefinery configurations.

Equipment Configuration and Process Parameters governing PEF-assisted Extraction

A practical PEF installation normally contains a high-voltage pulse source, an energy-storage section, a switching mechanism, a treatment chamber containing electrodes and an automated control arrangement. (Tzima *et al.*, 2021)^[22] Stored electrical energy is released through the sample as controlled pulses. The resulting field interacts with the biological material, alters membrane porosity and supports movement of within-cell constituents into the extraction phase (Ntourtoglou *et al.*, 2022)^[16].

Extraction performance is not determined by the electrical system alone. Electrical settings interact with moisture level, conductivity, tissue structure and the chemical attributes of the feedstock. Careful adjustment is therefore necessary to obtain adequate permeabilization while controlling energy use and unwanted temperature rise (Toepfl *et al.*, 2006)^[21], Barba *et al.*, 2015)^[2], Knoerzer *et al.*, 2012)^[12].

Electric Field Strength

Field intensity strongly affects the extent of membrane permeabilization. Raising the electric field generally raises membrane disruption and promotes recovery until a material-specific optimum is reached. (Donsi *et al.*, 2010)^[8] Beyond that region, additional electrical input can increase Joule heating and may accelerate deterioration of temperature-sensitive molecules. The suitable range therefore depends on tissue architecture, electrical conductivity and the compounds being recovered (Zhou *et al.*, 2015)^[28].

Pulse Duration and Pulse Number

Pulse length affects the time available for membrane charging and pore development, while the number of pulses determines how much cumulative treatment the sample receives. Increasing either variable can intensify permeabilization and thereby promote recovery, but an excessive dose may favor oxidation or structural damage of susceptible constituents. These two factors should consequently be considered together during process refinement rather than treated as unrelated settings (Wiktor *et al.*, 2015)^[26], Donsi *et al.*, 2010)^[8].

Pulse Frequency and Specific Energy

Pulse repetition rate affects both residence time and the opportunity for heat dissipation. Rapid pulsing can shorten the overall treatment period, but closely spaced pulses may increase Joule heating because less cooling occurs between events. Specific energy, which combines the principal electrical treatment variables into an overall intensity measure, is therefore useful for comparing processes. In many cases an intermediate energy input provides a practical compromise between promoted recovery and protection of sensitive plant-derived functional molecules (Barba *et al.*, 2015)^[2], Comuzzo *et al.*, 2020)^[5].

Material characteristics such as cellular dimensions, water content, conductivity, ripening stage and tissue organization influence the response to PEF. Softer tissues with relatively large vacuolated cells may undergo permeabilization more readily than highly lignified structures.

The extraction liquid also matters: electrical treatment raises membrane access but does not remove the intrinsic selectivity of the solvent. Matching solvent attributes with the target molecules is therefore important for achieving high recovery (Donsi *et al.*, 2010)^[8], Yan *et al.*, 2017)^[27].

The response of vegetative tissues to PEF is strongly influenced by their structural and physicochemical characteristics, including cell size, moisture content, electrical conductivity, maturity stage and tissue architecture. Soft fruit matrices containing large vacuolated cells generally respond more effectively than lignified materials. (Donsi *et al.*, 2010)^[8] Solvent polarity also remains an major determinant of recovery performance because electroporation promotes membrane porosity but does not alter solvent selectivity. Consequently, combining refined solvent systems with PEF treatment often produces superior extraction performance. (Yan *et al.*, 2017)^[27]

Optimization studies increasingly use response surface methodology, artificial neural networks, machine-learning strategies and mathematical simulation to locate suitable combinations of operating variables. (Zhou *et al.*, 2015)^[28] These tools permit several factors to be evaluated together and can generate predictive relationships for individual fruit matrices. Better prediction may promote reproducibility, lower unnecessary operating expenditure and support movement from laboratory trials toward larger processing systems (Frontuto *et al.*, 2019)^[10], Carpentieri *et al.*, 2023)^[4].

Recent studies increasingly employ advanced process refinement tools such as response surface methodology (RSM), artificial neural networks (ANN), machine learning and computational modelling to identify optimal treatment conditions for different fruit matrices. These strategies enable simultaneous evaluation of multiple process variables and promote the development of predictive models

that promote process reproducibility, reduce operational costs and accelerate large-scale industrial implementation. (Zhou *et al.*, 2015)^[28], Frontuto *et al.*, 2019)^[10], Carpentieri *et al.* 2023)^[4]

During the last two decades, PEF has increasingly been investigated as a pretreatment for recovering valuable compounds from fruits and materials left after processing of fruit materials. Electrical permeabilization promotes access to within-cell regions and promotes movement into the extraction phase. (Barba *et al.*, 2015)^[2]. The magnitude of the benefit depends on tissue structure, plant-derived functional molecule composition and the selected electrical conditions, so treatment settings must generally be tailored to the particular matrix (Ranjha *et al.*, 2021)^[19].

Applications of Pulsed Electric Field in the Recovery of Fruit Bioactive Compounds

Phenolic substances constitute a major research focus because of their biological relevance and commercial value. Grapes, apples, berries, pomegranates and citrus materials contain phenolic acids, flavonoids, tannins and related molecules that may be located inside cellular compartments (Delsart *et al.*, 2012)^[6], Luengo *et al.*, 2013)^[14], El Kantar *et al.*, 2018)^[9].

PEF pretreatment can increase access to these constituents by modifying membrane porosity and easing movement of the extraction liquid through the tissue. Investigations have described elevated phenolic recovery and shorter downstream extraction periods relative to conventional solvent procedures. The principal role of the electrical step is to promote transport kinetics rather than intentionally change the molecular identity of the phenolics, which is advantageous where both throughput and extract quality matter (Delsart *et al.*, 2012)^[6], Luengo *et al.*, 2013)^[14], El Kantar *et al.*, 2018)^[9].

Phenolic compounds are the most extensively studied plant-derived functional molecules in PEF-assisted extraction because of their broad biological activities and commercial importance. Fruits such as grapes, apples, berries, pomegranates and citrus contain abundant phenolic acids, flavonoids, tannins and related compounds that are often confined within within-cell compartments. (Delsart *et al.*, 2012)^[6], Luengo *et al.*, 2013)^[14], El Kantar *et al.*, 2018)^[9].

Anthocyanins are commercially important pigments because they can supply natural coloration while also contributing functional characteristics. Their stability is strongly affected by temperature, oxygen exposure and pH, making harsh extraction conditions undesirable (Zhou *et al.*, 2015)^[28], Delsart *et al.*, 2012)^[6].

PEF offers a low-heat route for opening membrane barriers around anthocyanin-containing cellular compartments. Work with grapes, blueberries, strawberries and blackberries has indicated promoted pigment recovery and, under suitable conditions, better colour retention and antioxidant performance. These attributes support investigation of PEF for naturally coloured beverages, functional formulations and nutraceutical products (Pataro *et al.*, 2020)^[17].

Anthocyanins are valuable natural pigments increasingly used as functional ingredients and natural food colorants. Because these compounds are highly sensitive to temperature, oxygen and pH, conventional extraction often results in pigment degradation and loss of antioxidant activity. (Zhou *et al.*, 2015)^[28], Delsart *et al.*, 2012)^[6]

Carotenoids such as β -carotene, lycopene, lutein and zeaxanthin are fat-soluble pigments associated with chromoplast structures and membrane systems that can hinder conventional solvent access. PEF-induced permeabilization can reduce these physical barriers, supporting solvent movement and recovery while avoiding extensive heat exposure. Reported work on tomato lycopene and β -carotene from mango and papaya indicates potential for obtaining sensitive lipophilic ingredients for functional foods and supplement uses (Pataro *et al.*, 2020)^[17].

Recovery of Carotenoids

Fruit peels, pomace, seeds and pulp remaining after industrial processing are increasingly viewed as feedstocks rather than simply discard material. Such fractions may retain appreciable levels of plant-derived functional molecules and dietary fibre, sometimes at concentrations comparable with or exceeding those found in edible portions (Ranjha *et al.*, 2021)^[19].

PEF-based recovery has been examined for residues such as apple pomace, grape marc, citrus peel and pomegranate material. By increasing access to phenolics, flavonoids, anthocyanins and fibre, the treatment can support production of value-added ingredients while reducing solvent demand. (Luengo *et al.*, 2013)^[14]. This creates simultaneous opportunities for waste minimization, resource recovery and more resource-conscious processing (El Kantar *et al.*, 2018)^[9].

Valorisation of Fruit Processing By-products

Combining PEF with another extraction technique has become an active area of investigation. Pairing electrical permeabilization with ultrasound, enzymes, microwave treatment or supercritical fluids brings together different mechanisms for disrupting tissue and promoting movement of target compounds (Tzima *et al.*, 2021)^[22], Ntourtoglou *et al.*, 2022)^[16].

Studies of these combined configurations have frequently shown improvements in recovery and reductions in treatment time or solvent demand compared with individual operations. Nevertheless, many integrated systems have so far been examined mainly at laboratory or pilot scale. Their further development will depend on demonstrating reliable performance, economic viability and practical compatibility at industrial throughput.

Hybrid Extraction Strategies

Movement of PEF from experimental studies toward food-industry use has been supported by progress in high-voltage electronics, treatment-chamber engineering and automated control. Commercial installations are used in areas such as juice processing, wine production, drying-related operations, microbial inactivation and recovery of valuable compounds (Barba *et al.*, 2015)^[2], Toepfl *et al.*, 2006)^[21].

Fruit-juice processing is among the established industrial uses. Electrical pretreatment can increase cellular permeability, helping release liquid and naturally occurring antioxidants, pigments and aroma constituents. Because the process can operate with limited thermal exposure, retention of compounds such as vitamin C and anthocyanins may be promoted relative to more heat-intensive treatment (Barba *et al.*, 2015)^[2], Toepfl *et al.*, 2006)^[21].

In winemaking, PEF has been investigated for accelerating grape tissue breakdown and promoting transfer of

anthocyanins and tannins during maceration. Shorter processing can be accompanied by desirable colour development and maintenance of sensory attributes. Recovery of valuable constituents from fruit residues is another industrial opportunity, linking PEF with functional ingredients, nutraceutical uses and circular use of processing streams (Delsart *et al.*, 2012)^[6], Comuzzo *et al.*, 2020)^[5].

Continuous-flow chambers make it possible to expose larger quantities of material to controlled electrical treatment. Current systems can monitor variables such as applied voltage, current, temperature and conductivity, helping maintain repeatable operation and manage energy use. At larger scale, however, chamber dimensions, electrode arrangement, cooling capacity and flow distribution must be carefully designed to prevent hot spots and uneven treatment (Knoerzer *et al.*, 2012)^[12], Barba *et al.*, 2015)^[2].

The purchase price of industrial PEF equipment can be substantial. Even so, lower solvent demand, shorter processing periods, promoted recovery and preservation of product value may contribute to favorable long-term economics. Reduced energy demand and the conversion of processing residues into useful ingredients can further strengthen the environmental case for integrating PEF into biorefinery operations (Barba *et al.*, 2015)^[2], Ranjha *et al.*, 2021)^[19].

Similarly, the wine industry has adopted PEF to accelerate grape maceration and promote extraction of anthocyanins and tannins, reducing treatment duration while maintaining color intensity and sensory quality. Increasing interest has also been directed toward recovering biologically active constituents from fruit-processing residues for use in functional foods, nutraceuticals and cosmetic formulations, supporting waste valorisation and circular bioeconomy initiatives. (Delsart *et al.*, 2012)^[6], Comuzzo *et al.*, 2020)^[5]

Although substantial progress has been made, broader industrial adoption still faces scientific, engineering and financial barriers. Results obtained in laboratory and pilot experiments do not automatically translate into commercial performance. Issues involving standardized procedures, chamber engineering, energy management and regulatory requirements need further resolution (Ranjha *et al.*, 2021)^[19], Naliyadhara *et al.*, 2022)^[15].

Variation among fruit materials is a major source of uncertainty. Differences in cellular organization, moisture, electrical conductivity, maturity and plant-derived functional molecule profile can alter the response to the same electrical treatment. Consequently, a condition developed for one fruit cannot necessarily be transferred unchanged to another. Matrix-specific models and standardized characterization procedures are needed to promote transferability (Donsì *et al.*, 2010)^[8], Yan *et al.*, 2017)^[27].

Scale-up creates another engineering difficulty. A uniform field is easier to establish in a small treatment chamber than in a continuous unit carrying high product flow. Poor electrode geometry, unsuitable flow patterns or inadequate chamber design can generate uneven permeabilization and localized heating, which may reduce process consistency. Future engineering work should therefore address chamber geometry, hydrodynamics, cooling and online control as an integrated problem (Knoerzer *et al.*, 2012)^[12], Barba *et al.*, 2015)^[2].

Financial feasibility also deserves systematic assessment. Although PEF may decrease solvent use, energy demand

and extraction time, the initial investment associated with high-voltage equipment can be difficult for smaller enterprises. Techno-economic studies should jointly examine capital expenditure, operating performance, value of recovered products and environmental gains before commercial decisions are made (Barba *et al.*, 2015)^[2], Naliyadhara *et al.*, 2022)^[15].

Regulatory alignment remains another requirement for wider acceptance. Internationally consistent guidance for PEF-assisted recovery is still developing. Clearly defined operating procedures, specifications for finished extracts and safety-evaluation methods would help industries demonstrate reproducibility and product quality. Cooperation among researchers, equipment developers, processors and regulatory bodies can support this process.

Digital methods are creating additional possibilities for process control. Artificial intelligence, machine learning, digital-twin concepts and computational-fluid-dynamics modelling are being explored for predicting treatment behavior and selecting treatment conditions. When coupled with online sensors, such tools could support adaptive control, promote batch-to-batch consistency and limit unnecessary energy expenditure.

Integrated extraction schemes remain an important research pathway. Electrical permeabilization can be coupled with ultrasound, enzymatic hydrolysis, microwave treatment, high-pressure processing or supercritical-fluid extraction, allowing different mechanisms to operate together. Future investigations should compare these combinations not only on recovery but also on energy use, environmental burden, cost and feasibility at production scale (Tzima *et al.*, 2021)^[22], Ntourtoglouet *et al.*, 2022)^[16].

The circular-bioeconomy concept provides another route for expanding PEF uses. Peels, pomace and seeds generated during processing of fruit materials frequently retain useful plant-derived functional molecules yet are discarded or used in low-value uses. Recovering these constituents through PEF-supported biorefinery schemes could reduce disposal, promote resource efficiency and generate functional ingredients. Such integration is consistent with broader efforts toward lower-waste food manufacturing (Brianceau *et al.*, 2015)^[3], Rajha *et al.*, 2019)^[19].

Future investigations should therefore extend beyond demonstrating recovered quantity. Greater emphasis is required on integrated process design, life-cycle assessment, techno-economic evaluation, regulatory consistency and validation under industrial treatment conditions. Resolving these issues will determine how effectively PEF-assisted extraction can contribute to food, nutraceutical, pharmaceutical and cosmetic manufacturing.

Hybrid processing strategies also represent an important research direction for subsequent investigations. Combining PEF with ultrasound-assisted extraction, enzyme-assisted extraction, microwave-assisted extraction, high-pressure processing or supercritical fluid extraction may exploit complementary mechanisms of cell disruption and movement of solutes, resulting in greater recovery performance than any single processing approach alone. Future studies should emphasize refinement of these integrated processes while evaluating their environmental, economic and industrial sustainability. (Tzima *et al.*, 2021)^[22], Ntourtoglouet *et al.*, 2022)^[16]

PEF-assisted recovery has developed into an important non-thermal option for obtaining valuable plant-derived

functional molecules from fruits and their processing residues. Electrical permeabilization reduces barriers to within-cell mass movement and can promote compound release without the extensive heating associated with some conventional operations. Depending on the matrix and treatment conditions, the process can reduce solvent demand and processing duration while supporting retention of temperature-sensitive constituents.

The literature reviewed here covers the physical basis of electroporation, the principal operating variables and uses involving phenolics, flavonoids, anthocyanins, carotenoids and related fruit plant-derived functional molecules. Evidence across different matrices indicates that appropriate PEF treatment can promote recovery and maintain desirable product attributes. Industrial examples involving juice processing, wine operations and utilization of processing residues further illustrate the processing approach's practical relevance.

Several barriers nevertheless need attention before broad commercial deployment can be expected. Reproducible operating protocols, well-designed treatment chambers, credible techno-economic evidence and compatible regulatory frameworks are important requirements. At the same time, digital process refinement, sensor-based monitoring and combined extraction systems offer avenues for promoting process control and scale-up.

Integration with circular biorefinery systems may allow PEF to contribute simultaneously to resource recovery and waste reduction. Continued collaboration across food engineering, modelling, materials science and industrial bioprocessing approach will be important for establishing reliable large-scale operation. As these areas develop, PEF-assisted extraction may become an increasingly useful platform for manufacturing natural high-value ingredients for food, nutraceutical, pharmaceutical and cosmetic uses.

This review has highlighted the fundamental principles of electroporation, the influence of critical process parameters and recent advances in the extraction of phenolics, flavonoids, anthocyanins, carotenoids and other biologically active constituents from diverse fruit matrices. The growing body of evidence demonstrates that PEF can significantly promote both recovered quantity and product quality while supporting resource-conscious processing practices. Moreover, the successful application of PEF in fruit juice production, wine processing and by-product valorisation illustrates its expanding industrial relevance.

Despite these advances, several challenges remain before PEF can achieve widespread commercial implementation. Standardized processing protocols, refined equipment design, techno-economic validation and harmonized regulatory frameworks are still required to ensure consistent industrial performance. In parallel, emerging processing strategies- including AI-assisted process refinement, digital process monitoring and hybrid extraction systems-offer new opportunities to promote process efficiency and promote industrial scale-up.

Looking forward, the integration of PEF into sustainable biorefinery concepts and circular bioeconomy strategies is expected to play an increasingly increasing relevance in maximizing the value of fruit resources while minimizing ecological burden. Continued interdisciplinary research combining food engineering, process modelling, materials science and industrial bioprocessing approach will further strengthen the commercial viability of PEF-assisted extraction. As technological innovations continue to mature, PEF is well positioned to become a key enabling processing approach for the resource-efficient production of high-value natural ingredients in the global food, nutraceutical, pharmaceutical and cosmetic industries.

Comparison of conventional and resource-efficient extraction strategies

Technology	Principle	Advantages	Limitations
Solvent extraction	Solvent diffusion	Simple, versatile	High solvent use, long extraction time
Soxhlet extraction	Continuous solvent reflux	High recovery performance	Thermal degradation, high energy demand
Cold pressing	Mechanical expression	Solvent-free, preserves flavor	Low recovery of within-cell compounds
UAE	Acoustic cavitation	Rapid extraction, reduced solvent	Localized heating, equipment erosion
MAE	Dielectric heating	Fast processing, high efficiency	Possible degradation of thermolabile compounds
EAE	Enzymatic hydrolysis	Mild conditions, promoted recovery	High enzyme cost, longer treatment duration
SFE	Supercritical CO ₂	High-purity extracts, solvent-free	High capital cost, limited efficiency for polar compounds
HHP	Pressure-induced permeabilization	Minimal thermal damage	Expensive equipment
PEF	Electroporation	High recovery performance, low solvent use, short treatment duration, preservation of thermolabile compounds	Scale-up process refinement and equipment cost

Critical process parameters influencing PEF-assisted extraction

Parameter	Influence on extraction
Electric field strength	Determines the extent of membrane opening
Pulse duration	Affects pore development and electrical dose
Pulse number	Sets cumulative membrane disturbance and recovery
Pulse frequency	Changes residence time and heat generation
Specific energy input	Provides an integrated measure of electrical dose
Electrical conductivity	Changes field distribution and electrical current
Temperature	Can affect stability of thermolabile molecules
Solvent composition	Controls solubility and release of selected compounds
Tissue attributes	Influence ease of membrane permeabilization and compound movement

Representative uses of PEF-assisted extraction in fruits

Fruit matrix	Major biologically active constituents	Principal outcome of PEF treatment	Potential application
Grapes	Anthocyanins, flavonoids, tannins	Greater phenolic release with a shorter maceration period	Wine production
Apples	Chlorogenic acid, catechins	More efficient recovery of phenolics from residue	Waste valorisation
Blueberries	Anthocyanins	Better pigment preservation with stronger antioxidant performance	Functional beverages
Strawberries	Anthocyanins, flavonoids	Greater recovery with limited heat-related loss	Natural food colorants
Citrus fruits	Flavanones, vitamin C	Improved recovery alongside retention of antioxidant quality	Nutraceutical ingredients
Tomatoes	Lycopene	Greater release of carotenoid pigments	Functional food ingredients
Mango/Papaya	β -Carotene, phenolics	Higher carotenoid release	Nutraceutical production
Pomegranate peel	Ellagitannins, anthocyanins	Effective utilization of residual fruit material	Circular bioeconomy

Current industrial uses of PEF processing approach

Industrial sector	Major application	Principal benefit
Fruit juice industry	Juice extraction and preservation	Greater juice recovery with promoted retention of nutrients
Wine industry	Grape maceration	Accelerated phenolic release and favourable colour development
Nutraceutical industry	Recovery of plant-derived functional molecules	Improved compound recovery and extract quality
Functional food industry	Production of natural ingredients	Better preservation of antioxidant constituents
Fruit processing industry	Valorisation of processing by-products	Lower residue burden and promoted material use
Food ingredient manufacturing	Natural pigments and antioxidants	Resource-efficient recovery requiring less solvent

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