SUSTAINABLE PROCESSING OF FOOD SIDE STREAMS AND UNDERUTILIZED LEFTOVERS INTO HIGH-ADDED-VALUE CHEMICALS ASSISTED BY PULSED ELECTRIC FIELDS- AND HIGH-PRESSURE PROCESSING-BASED TECHNOLOGIES

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Sustainable Processing of Food Side Streams and Underutilized Leftovers to Value-Added Chemicals with Pulsed Electric Fields- and High-Pressure Processing-Based Technologies

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Abstract

High-pressure processing (HPP) and pulsed electric fields (PEF) are recognized as non-thermal, intensified technologies to recover high-added-value compounds (HAVCs) through a sustainable strategy, in alignment with some Sustainable Development Goals (SDGs). This review summarizes HPP and PEF principal contributions to sustainably recover HAVCs from food side streams and underutilized leftovers coming from agro-industrial companies, agreeing with a life-cycle assessment for wasted sources. Both HPP and PEF techniques efficiently enable the recovery of valuable, bio-based HAVCs as protein, polyphenols or antioxidant compounds, also noting the concurrent extraction of other frameworks as pectin, or primary metabolites as freely accessible carbohydrates. At this regard, it should be pointed out the environmentally friendly conditions required when they are compared to traditional methods extraction (for instance, the possibility of employing alternative, green solvents or reducing residence times) because of the physicochemical mechanisms that involve these protocols (electroporation, high pressures), resulting in notable yield, and more quality and purity for the recovered extracts. Future trends and industrial outlook for HPP and PEF technologies should encompass the improvement in terms of efficiency and operational conditions, developing a suitable scaling-up approach in biorefineries or food industry that cover the economic, social, and environmental dimension of sustainability.

Keywords: High pressure processing; pulsed electric fields; green extraction; bioactive compounds, biomass valorization; scaling-up

1. Introduction

The concept of sustainability was firstly mentioned in 1713 and has since evolved to the present day, leading to a shift in perspective towards sustainable development throughout the scientific community in 1987. Currently, sustainable development is gaining importance in the industrial sector as new processes are sought with a three-dimensional approach: environmental sustainability, social solidarity, and improvement of economic efficiency [1]. With the growing awareness of the impact on the environment, measures have been proposed to mitigate this impact, considering different fields of action.

The establishment of the Sustainable Development Goals (SDGs; 2015-2030), which are an extension of the Millennium Development Goals (MDGs; 2000-2015), is a universal measure to eradicate poverty, achieve global prosperity, and protect the environment [2]. In this regard, the food industry plays a fundamental role as it is closely related to the achievement of Goal 9, "Build resilient infrastructure, promote sustainable industrialization and foster innovation," which is based on promoting sustainable industrialization through innovation and progress by developing new environmentally friendly methods to increase energy and resource efficiency [3]. Despite significant efforts in food industry as response to UN’s 2030 sustainable development program (SDGs), the conventional food processing presents some lacks in terms of energy efficiency and waste management. In this sense, the application of innovative technologies supposes an eco-friendly alternative to overcome the afore-mentioned issues [4,5]. The physicochemical mechanisms in which these techniques are based on enable a highly efficient processing when evaluating energy saving, atom economy, final yield and total cost. Additionally, they allow to make the most of the initial matrices, thus reducing the waste generation, and also promote a rational use of natural resources as water. On the whole, process intensification technologies are in fully adhesion to the principles of Green Chemistry and encompass the economic, social and environmental factors involved in the dimension of sustainability. Besides, they enable convergence to achieve goals related to industrial sustainability, such as Goal 9 related to infrastructure, Goal 12 related to sustainable production and consumption, and Goal 7 using affordable and clean energy (**Figure 1**). Among them, ultrasounds, microwaves, supercritical fluid- and pressurized liquid extraction, ultra-high-pressure processing, or pulsed electric fields should be noted.

However, it is not only the role of these innovative technologies in industrial sustainability that is noteworthy, but also their role in fulfilling the SDGs related to the purpose of their application. In this context, the development of sustainable innovative technologies has been used for the extraction of bioactive components of nutritional interest from different food matrices and to improve the food safety through the inactivation of enzymes or the reduction of mycotoxins, which is related to SDG 3 "Ensure healthy lives and promote well-being for all at all ages" and SDG 2 "Zero Hunger", respectively.

In light with the above, a sustainable approach at the industrial level enables the conservation of marine and terrestrial ecosystems through action on climate change (Goals 13, 14, 15) [3]. This review summarizes high-pressure processing (HPP) and pulsed electric fields (PEF) principal contributions to sustainable processing regarding the recovery of high-added-value compounds and biomass valorization.

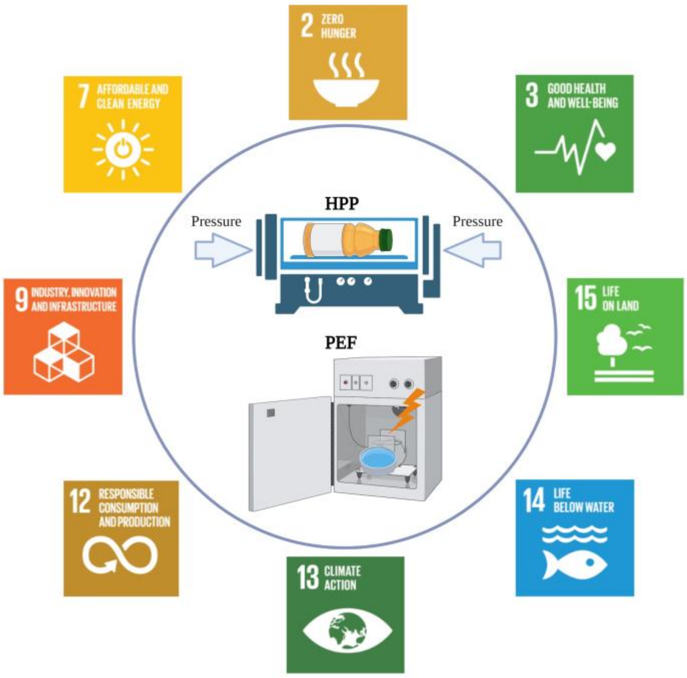

Figure 1. Sustainable Development Goals related to the use of high hydrostatic pressure processing (HPP) and pulsed electric fields (PEF). Created with BioRender.com

2. Physicochemical principles of High Pressure Processing (HPP) and Pulsed Electric Fields (PEF)

2.1 HPP

High Pressure Processing (HPP), also known as High Hydrostatic Pressure (HHP), is a non-thermal technology that uses ultra-high pressure (100–600 MPa) mainly for pasteurization (**Figure 2**). As a mild processing method, this technology can reduce the use of chemical additives and improve the preservation of natural flavors and nutritional values of raw materials [6].

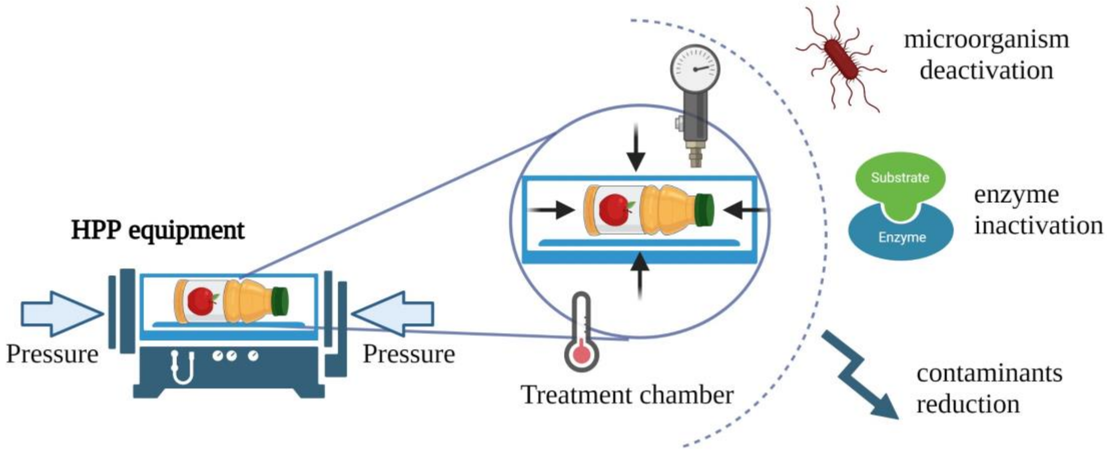

Figure 2. High hydrostatic pressure processing (HPP) principle. Created with BioRender.com

HPP is subject to the Le Chatelier and isostatic principles. Therefore, HPP treatment is independent of product geometry and size and reduces the time required to process large quantities of food. It is used for solid and liquid matrices with high moisture content [7]. The factors that most affect HPP treatment are temperature, pressure, and contact time. Compression heating results in an increase of about 3 °C for a pressure increase of 100 MPa and less than 30 °C for a 600 MPa treatment. Pressure is applied over short periods of time (a few seconds to minutes) in both batch and semi-continuous modes [4,8].

This technology improves the inactivation and inhibition of microorganisms while maintaining the natural state and freshness of food. In general, small molecules such as vitamins, minerals and flavorings are only slightly affected because no covalent bonds are broken. Compared to conventional thermal processing, HPP treatment consumes less energy because it is performed at room temperature. Moreover, the products are packaged to prevent future contamination. Due to these aspects, among others, HPP is considered an environmentally friendly processing. In addition to ensure food safety and quality, HPP treatment has also shown potential applications in obtaining high value-added compounds, improving health attributes by increasing the bioavailability of micronutrients and phytochemicals, reducing food allergenicity, maintaining healthy fats, increasing saltiness perception, reducing the use of salt and food additives, and potentially reducing some food contaminants and preventing their formation or their precursors [9].

However, and always with view to a scaling-up process, HPP encompasses certain economic and processing shortcomings that must be considered. For instance, the acquisition cost of HPP equipment is high, therefore the initial investment can be a financial barrier for companies. In parallel, the energy required to generate the necessary pressure should be considered in these installation [10]. Additionally, the control of the conditions and their adaptation to a matrix is a critical point due to the possible limitations imposed by the shape and characteristics of the container, which must withstand the set pressure without compromising its integrity [11,12].

The temperature limitation should be also considered: regardless being a non-thermal processing technology, certain products may be subject to temperature variations under this HPP-based system. For instance, HPP inactivates microbial spores only when a pressure of 6000 bar is combined with temperatures above 100 °C, which leads to organoleptic and nutritional changes in the food or beverage. Therefore, if the aim is to inactivate these spores, it should be combined with another methodology in order not to avoid alter the functional properties. On the other hand, it should be mentioned that HPP is not an effective technology for dry products, as this process is adequate for products with a water activity > 0.8. In cases where this is not possible, an alternative product should be developed or certain aspects of the product must be modified [12].

Overall, HPP should be adapted to new recipes and formulations to optimize the treatment (mainly in terms of temperature and maximum pressure) and achieve consumer acceptability [13] . For those reasons, the selection of this technology must be preceded by a careful evaluation of the processing target and its characteristics.

2.2 PEF

Pulsed Electric Field (PEF)-based treatment involves the application of short pulses (μs to ms) of electric fields ranging from 100-300 V/cm to 20-80 kV/cm to a product placed between two electrodes. As shown in **Figure 3**, the mechanism of action of PEF involves the permeabilization of biomembranes, the occurrence of electrochemical and electrolytic reactions, the polarization and realignment of molecules, and the reduction of the activation energy of chemical reactions.

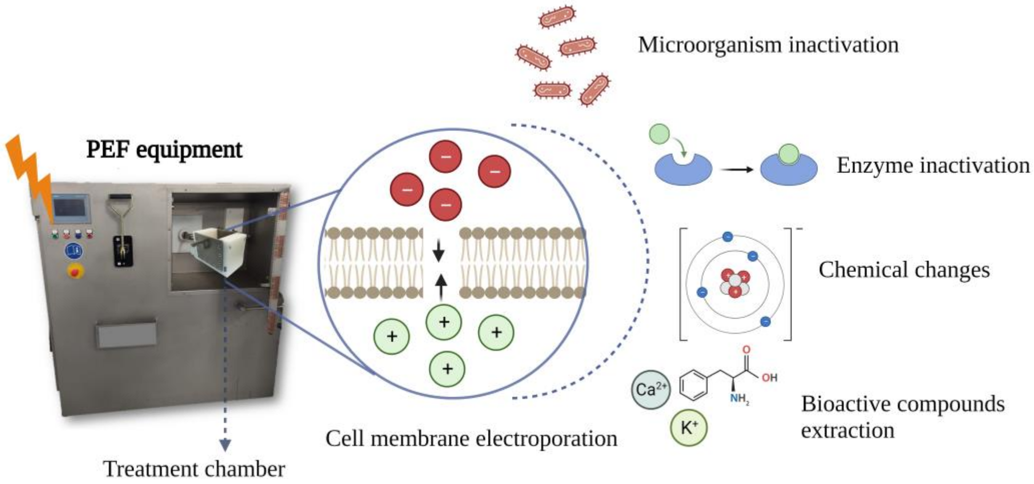

Figure 3. Pulsed electric fields (PEF) principle. Created with BioRender.com

PEF efficiency depends on several factors, such as process parameters (electric field strength, number of pulses, pulse shape, pulse time/length, and output temperature), food product parameters (conductivity, pH, etc.), and processing target characteristics. This technique is considered a non-thermal process that allows thermolabile compounds to be obtained or only slightly modified, with minimal impact on physicochemical properties that are important for food quality and product acceptance [14,15]. As a result, PEF provides products with fresh-like, minimally processed properties and is widely used to process solid and liquid matrices [16] such as vegetables [17–19], milk [20–22], fruit juices [23], and liquid eggs [24]. Compared to thermal treatments, PEF-processed juices retain more biologically active compounds.

In addition, PEF has also been employed in food industry to modify enzymes activities, to extract nutritionally valuable compounds from food side streams and plant tissues, to improve the bioavailability of micronutrients and components, for drying and freezing processes, and to promote some selected properties of food macromolecules and some chemical reactions.

Moreover, PEF also shows promising potential to reduce food processing contaminants and pesticides [25].

As the same as occurs for HPP, the initial economic investment for the equipment is high, and PEF equipment must be specifically designed and adapted for each type of food. Thus, the versatility of the equipment may require additional investment to adapt it to different products in the food industry [26,27]. Moreover, the electric field strength, power, repetition rate and optimization of the overall PEF design must be considered to achieve the industry requirements for treatment uniformity. In addition, most of the limitations are related to the electrochemical reactions that take place between the electrodes and the surface of the starting material when a current charge is applied. These include fouling and corrosion of the electrodes, electrolysis of water, migration of electrode components and chemical changes in the product stream during treatment [28]. In this context, the release of metals in the product of interest must also be considered. For these reasons, the control of PEF conditions is crucial, especially in severe treatments in which these reactions are enhanced.

3. Application of HPP and PEF to food sector and agricultural side streams upgrading

3.1 HPP

3.1.1. Recovery of high-added-value compounds from food side streams

The enormous amount of food waste produced annually represents an environmental problem, making the study of food waste valorization one of the current social necessities [29].

Regardless being an effective strategy for pasteurization in the food sector, HPP has also been proposed as a sustainable and clean method for recovering high-value bioactive compounds from food side streams, as mentioned. This technology is more efficient and economical compared to other more complex processes that require more processing time. HPP promotes solvent penetration into the cells and allows the release of valuable compounds into the solvent. HPP technology has shown good results in the extraction of various valuable compounds (proteins, pectin, phenolic compounds, polyphenols), reducing extraction time and solvent consumption. This technique was applied to different matrices such as grape, lime, persimmon, coffee, olive, and soybean and improved the extraction efficiency compared to conventional techniques. In general, the applied treatments enhanced bioactive compounds recovery at pressure ranged from 200 to 600 MPa with times between 5 and 20 minutes. In addition, the combination of HPP with enzymes resulted in higher yields of bioactive compounds. **Table 1** shows the HPP conditions applied to different food matrices and side streams.

Table 1. Summary of available literature on high pressure processing (HPP) treatment conditions in different food matrices for the extraction of high-added value compounds (HAV).

Matrix	Treatment	Conditions	Optimal conditions	HAV compound	Ref
Grape pomace	HPP + EAE	50,100 and 200 MPa. 0-30 min.	200 MPa, from 5 to 10 min.	Polyphenols: 906.34 mg GAE/100 g	[30]
Grape skin pomace	HPP	300,400 and 500 MPa. 3, 6.5 and 10 min. 22, 26, 30 °C. 30, 50, 70% solvent (methanol and ethanol) concentration.	268.44 MPa, 3.39 min, 29.48 °C, solvent (methanol and ethanol) concentration 70% v/v.	Anthocyanins: 0.96 mg/g dw*min	[31]
Olive pomace	HPP	200 to 600 MPa. 0-40 min.	Polyphenols: 600 MPa, 15 min. Proteins: 200 MPa, 20 min.	Polyphenols: 2.650 mg GAE/L Proteins: 4,323 mg/L	[32]
	HPP	200 and 600 MPa. 10 min. Ethanol 50% (v/v) / Choline chloride-lactic acid (ChLA).	600 MPa. 10 min. Choline chloride-lactic acid (ChLA).	Polyphenols: 25.96 mg GAE/g dw	[33]
Tomato peel	HPP (Pectin) HPP + UAE (Polyphenols)	300 MPa. 10, 20, 30 and 45 min. 80 °C. Nitric acid 0.1 mol/L.	300 MPa. 45 min. 80 °C. Nitric acid 0.1 mol/L.	Pectin: 9.2% yield. Polyphenols: 1625.65 mg/100 g	[34]
Cherry pomace	HPP	400 and 500 MPa. 1, 5 and 10 min. 20 °C. 80% methanol-water (v/v).	500 MPa. 10 min. 20 °C. 80% methanol-water.	Polyphenols: 227.51 mg GAE/100 g	[35]
Açaí pulp	HPP	-	600 MPa. 5 min. 25 °C. Water.	Polyphenols: 250 mg GAE/100 g Anthocyanins: 35 mg C3G/100 g	[36]
Persimmon fruit	HPP	-	200 MPa. 6 min. 25 °C.	Carotenoids: 1.695 mg β-carotene/100 g Tannins: 0.260 g GAE/100 g	[37]

Abbreviations: HPP: High Pressure Processing. EAE: Enzyme-Assisted Extraction. GAE: Gallic Acid Equivalents. C3G: cyanidin-3-glucoside. HAV: High-added-value.

Table 1. Summary of available literature on high pressure processing (HPP) treatment conditions in different food matrices (cont.).

Matrix	Treatment	Conditions	Optimal conditions	HAV compound	Ref
Spent coffee grounds	HPP	300, 400 and 500 MPa. 5, 10 and 15 min. 25 °C.	500 MPa. 15 min. 25 °C.	Polyphenols: 9.5 mg GAE/g	[38]
Jackfruit leaves	HPP	100, 200 and 300 MPa. 10, 15 and 20 min. 0.5 M NaCl, 96% ethanol or absolute methanol.	300 MPa. 20 min. 0.5 M NaCl.	Proteins: 147.3 mg/g	[39]
Soybean Protein Isolate (SPI)	HPP	200 and 400 MPa. 10-30 min. 25 °C. 1:4, 1:8 and 1:12 SPI/water.	281 MPa. 18.92 min. 1:8.33 SPI/water.	Water Holding Capacity: 5.35 g/g Emulsifying Activity Index: 28.11 m^2/g Solubility: 33.7%	[40]
Lime peel	HPP + EAE	100, 200, 300 and 400 MPa. 30 min. 50 °C. Cellulase/xylanase: 50/0, 50/25, 50/50, 25/50, and 0/50 U/g lime peel.	200 MPa. 30 min. 50 °C. 50/50 U/g.	Pectin: 26.5% yield	[41]

Abbreviations: HPP: High Pressure Processing. EAE: Enzyme-Assisted Extraction. GAE: Gallic Acid Equivalents. C3G: cyanidin-3-glucoside.

For instance, the effect of HPP treatment (200 MPa from 5 to 10 min) combined with an enzyme complex provided the highest phenolic compound recovery from grape pomace [30]. In grape skin the best conditions for anthocyanins recovery by HPP (0.96 mg/g d.m.*min) were extraction time of 3.4 min, 29.5 °C, 268.4 MPa and solvent (methanol and ethanol) concentration 70%. The predominant anthocyanins recovered were malvidin [31]. The HPP process (200 to 600 MPa and 0 to 40 min) provided a significant increase of phenolic concentration up to 71.8% when it was applied to olive pomace. Moreover, the HPP-pretreated extracts afforded 88.1% higher protein yield at pressures up to 200 MPa [32]. Also in olive pomace, the combination of natural deep eutectic solvents (NADESs) with innovative extraction-assisted methods resulted to be effective in phenolic compounds extraction. Choline chloride-lactic acid (ChLA) combining with HPP at 600 MPa/10 min showed high phenolic compounds (PC) content (25.96 mg GAE/g dw) and antioxidant activity (15.67 g dw/g DPPH) [33]. In tomato peel waste, HPP was proved for the improvement of pectin and polyphenol recovery. In comparison with conventional extraction, HPP treatment enhanced pectin recovery from 14 to 15% after 30 and 45 min of extraction. The polyphenols extraction was highly influenced by the solvent polarity, being 70% ethanol the most efficient solvent [34]. In cherry pomace, high hydrostatic pressure of 400 and 500 MPa for 1, 5 and 10 min at 20 °C provided better results than conventional extraction method on phenolic compounds contents (227.51 ± 1.2 mg GAE/100 g FW) and antioxidant activity (84.33 ± 0.3%) [35].

In açaí pulp, HPP also provided better results than conventional treatment, since HHP of 600 MPa during 5 min at 25 °C resulted in an increase of 37% in anthocyanin contents, while conventional treatment reduced anthocyanin content by 16.3%. Moreover, HHP leaded to 10.25% increase in phenolic compounds content [36].

In persimmon, HPP processing under conditions of 200 MPa during 6 min at 25 °C, improved the extraction of carotenoids (1.695 mg β-carotene/ 100 g f.w.) and keeps the antioxidant properties (31.154 [Trolox] (μmol/g)) of the fruit in contrast with that was observed with pasteurization treatment. Thus, HPP treatment could improve the extraction of bioactive compounds [37].

In spent coffee grounds, HPP treatment under 300, 400 and 500 MPa at 25 °C for 5, 10 and 15 min parameters was tested in the recovery of phenolic compounds and antioxidant capacity. The results revealed that the amount of phenolic compounds and the antioxidant capacity significantly increased ($p \leq 0.05$) when increasing both pressure and time. Moreover, HPP resulted in more chlorogenic (81.2 mg/kg FW) and caffeic acid (5.4 mg/kg FW) contents than classical solvent extraction, with 24.0 mg/kg FW and 2.2 mg/kg FW, respectively, without affect their chemical structure [38]. Regarding the protein recovery, the employment of an aqueous, eco-friendly system with NaCl 0.5 M produced high yields in jackfruit leaves. In this sense, HPP leaded to 147.3 mg/g protein extraction in jackfruit leaves under optimal conditions of 300 MPa and 20 min [39].

HPP treatment under optimal conditions (281 MPa, 19 min) and in a ratio 1:8.3 Soybean Protein Isolate/water increased the surface hydrophobicity and sulfhydryl groups contents (12.77%) and reduced the relative lipoxygenase (LOX) activity (67.55%). Moreover, water holding capacity and emulsifying activity resulted also improved [40].

In general, HPP in combination with enzymes resulted in an increased bioactive compounds extraction efficiency and enzymatic activity of enzymes such as polygalacturonase, carboxymethylcellulase, and β-glycosidase [42]. In this sense, in lime peel, HPP at 200 MPa in combination with cellulase or xylanase enzymes, provided the highest pectin yields until 26.5%

in comparison to acid and aqueous extraction techniques. Therefore, HPP improve pectin yield without polymer chain degradation [41].

3.1.2 Biomass valorization

In light with a biorefinery-based approach, where the exploitation of renewable and natural sources is the main challenge, the application of innovative and efficient processing plays a crucial role as well, trying to solve the environmental problems and alleviate the gas emissions or waste disposal. With this regard, agricultural leftovers can be rapidly transformed into value-added compound as analogue as traditional companies. Therefore, biomass processing by means of intensified technologies allows to efficiently reduce the recalcitrance lignocellulosic material in a cost-effective and environmental-friendly way, thus becoming crucial as pretreatment step [43]. In this line, this first treatment would facilitate the further development of highly-industrial-applied chemicals, as vanillin, furfural, or levulinic acid, serving in some cases as potential substrates to produce biofuels.

Unfortunately, to the best of our knowledge the literature about the application of HPP to lignocellulosic materials for valorization is still scarce. Nonetheless, some authors reported interesting results. For instance, in sugarcane bagasse, the pretreatment with HPP up to 400–800 MPa in combination with chemicals compounds (sulfuric acid, phosphoric acid, or sodium hydroxide) increased the susceptibility of pretreated sugarcane to enzymatic hydrolysis rising glucose amounts. Therefore, HPP technology can be effective to pretreated lignocellulose biomass, resulting in an increase of glucose yield and favoring subsequent transformations [44]

Further, in Eucalyptus globulus kraft bleached pulp cellulosic fibers, HPP pretreatment (300–400 MPa during 15–45 min) increased the accessibility of xylan throughout enzymatic hydrolysis by xylanase, increasing 5–10-fold the initial hydrolysis rate and leading to gelation of cell wall regions that are accessible to enzymatic attack [45]

In coconut husk, the processing of *Penicillium variabile*, that constitutes a source of cellulases, with HPP treatment (300 MPa and 50 °C) allowed to increase the enzymatic hydrolysis by a factor of 2, improving the efficiency of ethanol production [46].

Overall, a pretreatment by applying high pressure processing not only affords a rapid and efficient recovery of targeted compounds, but also enables the post-remaining solid fraction conversion to fine chemicals in a two-way valorization process. However, further investigations are still required to implement this non-thermal protocol to future biorefineries because of the high cost that this technology involved.

3.2 PEF

3.2.1 High-added-value compounds recovery from food side streams

PEF processing constitutes a substitute to the conventional extraction methods (soxhlet extraction, liquid-liquid extraction, and mechanical shaking), that shows potential to the efficiently extraction of several valuable bioactive compounds from different agro-industrial side streams such as polyphenols and proteins, at the same time that reduce the employment of extraction solvents as the lowest concentration as possible or implementing the use of GRAS solvents, and saving time, energy and as consequence the cost [47]. Numerous studies have reported good recovery yields for polyphenols, proteins and antioxidant compounds employing PEF under electric field strength from 1-20 kv/cm for very short period. In this sense, for instance, when PEF is used as pre-treatment prior to solid-liquid extraction, the recovery of protein was enhanced up to 100%, being even more than 100% in the case of polyphenols. **Table 2** shows the different PEF conditions applied on different food matrices and side streams.

Table 2. Summary of available literature on pulsed electric fields (PEF) treatment conditions in different food matrices.

Matrix	Treatment	Conditions	Optimal conditions	HAV compound	Ref
Tomato peels	PEF	1, 3 and 5 kV/cm. 5 and 10 kJ/kg. 10 Hz. Pulse width 20 µs. 20 °C. Acetone/ethyl lactate.	5 kV/cm. 5 kJ/kg. 10 Hz. Pulse width 20 µs. 20 °C. Acetone.	Lycopene: 17532 mg/kg dw	[48]
	PEF PEF + SB	0.25, 0.5 and 0.75 kV/cm. 1 kJ/kg. 10 Hz. Pulse width 20 µs. 20 °C. Acetone/ethyl lactate.	PEF: 0.75 kV/cm. 1 kJ/kg. 10 Hz. Pulse width 20 µs. 20 °C. Acetone. PEF + SB: 0.50 kV/cm. 1 kJ/kg. 10 Hz. Pulse width 20 µs. 60 °C. Acetone.	PEF -Carotenoids: 27 mg/100 g PEF + SB: 37.9 mg/100 g	[49]

Tomato peels and seeds	PEF	1-5 kV/cm. 0-1500 pulses. 1.1-22.7 kJ/kg. 20 Hz. Pulse width 15 µs. Acetone and ethanol.	Polyphenols: 2 kV/cm. 700 pulses. Lycopene: 1 kV/cm. 500 pulses. Proteins: 5 kV/cm. 200 pulses.	Polyphenols: 56.16 mg GAE/kg Lycopene: 14.31 mg/100 g Proteins: 145.1 mg/100 g	[50]
Rapeseed stems and leaves	PEF	0.2, 0.4, 0.8, 5 and 20 kV/cm. 100-200 pulses. Pulse width 10 µs and 1 ms. Series of pulses 1-20. Total time 2-200 ms.	5 kV/cm (polyphenols purity). 20 kV/cm (protein extraction)	Polyphenols: 91% purity Proteins: 80% yield	[51]
Lemon peel	PEF PEF + pressure	3-9 kV/cm. 0-7.6 kJ/kg. 0-100 pulses. 1 Hz. Pulse width 3 µs. 0, 0.25 and 0.5 MPa.	PEF: 7 kV/cm. 30 pulses. 1 Hz. Pulse width 3 µs. PEF + pressure: 3.5 kV/cm. 0.5 MPa.	Polyphenols (PEF + pressure): 225 mg GAE/100 g	[52]
Olive leaves	PEF	0.7, 0.85 and 1 kV/cm. Pulse period 100, 500 and 1000 µs. Pulse width 1, 2, 5, 10 and 20 µs. 10, 15 and 30 min. 25% ethanol:water (v/v). Rectangular and cylindrical chamber.	0.85 kV/cm. Pulse period 100 µs. Pulse width 2 µs. 15 min. 25 % ethanol:water (v/v). Rectangular chamber.	Polyphenols extractability: ↑38%	[53]
	PEF	1 kV/cm. Pulse width 10 and 100 µs. Pulse period 1000 µs. 30 min. 0-100 % ethanol:water (v/v)	1 kV/cm. Pulse width 10 µs. Pulse period 1000 µs. 30 min. 25 % ethanol:water (v/v).	Polyphenols: 20.75 mg GAE/g dw	[54]
Brewers' spent grain	PEF	0.5, 1.5 and 2.5 kV/cm. 50, 100 and 150 Hz. 5, 10, 15 s. Water.	2.5 kV/cm. 50 Hz. 14.5 s. Water.	Polyphenols: 101 µg/g dw	[55]
Cocoa bean shell	PEF	1.5-3 kV/cm. 500-1000 pulses. Pulse width 5-20 µs. 50 Hz. 30-120 min. 30-70% ethanol:water (v/v).	1.74 kV/cm. 991.28 pulses. Pulse width 11.99 µs. 50 Hz. 118.54 min. 39.15% ethanol:water (v/v)	Polyphenols: 33.05 mg GAE/g	[56]
Coffee silver skin	PEF	1.3-4.4 kV/cm. 500-1000 pulses. Pulse width 5-20 µs. 50 Hz. 30-120 min. 30-	1.37 kV/cm. 1000 pulses. Pulse width 5.45 µs. 50 Hz. 75 min. 62.67%	Polyphenols: 12.12 mg GAE/g	[56]

		70% ethanol:water (v/v).	ethanol:water (v/v)		
Grape pomace	PEF + pressure	0-3 kV/cm. 200-2000 pulses. Pulse width 100 µs. Pulse period 100 ms. Density 0.6-1.3 g/cm^3.	1.2 kV/cm. 18 kJ/kg. Density 1 g/cm^3.	Anthocyanins: 0.648 g/100 g Flavan-3-ols: 90.91 mg/100 g	[57]
Papaya seeds	PEF + SAE	13.3 kV/cm. 1-2000 pulses.	13.3 kV/cm. 300 pulses. SAE: pH 7. 50 °C. 3h.	Yield increase ↑200% (polyphenols, carbohydrates, proteins and isothoicyanates)	[58]
Rainbow trout and Sole head, skin and viscera	PEF	1-3 kV/cm. 123-300 kJ/kg. 15-24h.	-	Protein extract efficiency up to 80%.	[59]

PEF: Pulsed Electric Fields. SB: Steam Blanching. SAE: Supplementary Aqueous Extraction. GAE: Gallic Acid Equivalents.

Regarding the industrial valorization of tomato peels, PEF treatment (5 kV/cm, 5 kJ/kg) prior to solid-liquid extraction with acetone and ethyl lactate enhanced the lycopene yields obtained (12-18%) and the antioxidant power (18.0-18.2%). Comparing between solvents, acetone gave the highest lycopene yield [48]. The same authors also reported that pre-treatment with PEF (0.25-0.75 kV/cm, 1 kJ/kg) promoted the cell permeabilization of tomato peels and improved the carotenoids extraction with acetone (up to 188%) and the antioxidant power (up to 372% for) with respect to untreated tomatoes, being lycopene the mainly carotenoid recovered [49].

In other study, the phenolic compounds extracted under conditions of 2 kV/cm and 700 pulses treatment from tomato waste was reported to be double (56.16 mg gallic acid/kg). Thus, during tomato processing, PEF treatment facilitated the fruits peeling, increased the juice yields obtained and enhanced the recovery of bioactive compounds from tomato waste, increasing the productivity and decreasing the energy consumption. [50]. In stems and leaves from rapeseed, PEF (5-20 kV/cm) increased the extraction yields of polyphenols and proteins. PEF at 20 kV/cm allowed to extract both polyphenols and proteins from rapeseed leaves, while the treatment at 5 kV/cm resulted in the highest polyphenol purity (91.0%) [51]. In lemon peel, PEF treatment at 7 kV/cm improve polyphenol extraction by 300%, giving maximum values of main polyphenols present in lemon (hesperidin and eriocitrin, with contents of 84 mg and 176 mg in 100g FW, respectively [52].

During olive oil production, a large number of wastes and by-products are produced. These side streams constitute a great source of high-added value compounds, such as polyphenols, fatty acids, coloring pigments, tocopherols, phytosterols, squalene, volatile and aromatic compounds, that present good potential to be employed as food additives and/or nutraceuticals [60]. In this sense, PEF treatment has been explored to recover high-added value compound from olive by-products. Regarding polyphenols, PEF showed good results in the extraction form olive leaves. PEF increased the extractability of polyphenols by 38% using the solvent (25% v/v) ethanol:water, pulse duration of 2 μs, electric field strength of 0.85 kV/cm, 100 μs period (tau), and 15 min of duration [53]. Similarity, the same authors also reported that PEF applied at 10 μs pulse duration, 1000 μs pulse period, 1 kV/cm electric field strength, and 30 min increased the total polyphenols extraction up to 31.85% and enhanced major secondary metabolites up to 265.67%. For this, EtOH was employed as the lowest concentration as possible (25%), being possible its substantial reduction [54]. To sum up, the solvent employed, the pulse duration, the structure of the metabolites extracted and their solubility, were the parameters than most contributed to the polyphenol's recoveries from olive leaves.

In brewers' spent grain, an important by-product form beer industry, PEF pretreatment at: 2.5 kV/cm, 50 Hz and 14.5 s increased total free and bound phenolic compounds recoveries a rate of 2.7 and 1.7 times, respectively [55]. In cocoa bean shell and coffee silver skin the optimized PEF treatment enhanced higher recovery yields of polyphenols and methylxanthines (approximately 20%) in comparison with conventional extraction [56].

In grape pomace, PEF treatment was applied on hydro-alcoholic extraction at different temperatures. Under conditions of field strength E = 1.2 kV/·cm; energy input W = 18 kJ/·kg and density ρ = 1.0 g/·cm3) an increasing of total polyphenols contents was obtained in function of temperature. The ratio of total anthocyanins to total flavan-3-ols at 20 °C was higher employing PEF in comparison with the control (9.0 front 7.1) [57]. In papaya seeds, PEF-assisted extraction in combination with a supplementary aqueous extraction at 50 degrees C, pH = 7 during 3 h allowed an important enhancement of valuable compounds, showing yields (+200%) and antioxidant capacities (+20%) [58].

In rainbow trout side streams, (head, skin and viscera), PEF treatment (1-3 kV/cm, 123-300 kJ/kg) allowed the increase of the protein extract efficiency up to 80% and the change in the protein molecular size distribution with high number of bands between 5 and 250 kDa. Oxygen radical absorbance capacity (ORAC) and total antioxidant capacity (ABTS) assays also revealed an increase in the antioxidant capacity [59].

3.2.2 Biomass valorization

PEF technology has been also implemented to facilitate the production of value-added chemicals to meet the high demand of industry due to population growth and to replace fossil fuels with great impact on the environment [61].

As explained, PEF pretreatment facilitates the release of intracellular substances after the disruption of plant cell membranes and the induction of structural changes. At this regard, it could facilitate contact between them and external bacteria for conversion to methane or their extraction for further processing. In addition, this technology also assists the passage of enzymes that enhance sugar production [62]. However, the key process is the improvement in the mass transport rate of different molecules such as carbohydrates, lipids, pigments, and small molecules such as DNA and RNA, as well as the structural changes induced by PEF [63].

As **Figure 4** summarizes, PEF technology is useful at different levels of biomass processing. This technology allows the transformation of plant and algal cells, which is necessary for the genetic modification of this feedstock since the cell wall is a barrier to DNA transfer [64–66]. On the other hand, it enables the energy-efficient performance of processes that require high energy input, such as dehydration of the raw material compared to conventional methods and the pretreatment of the matrix [67,68]. Moreover, PEF technology increases the preservation of constituents with high nutritional value because high temperatures are not required in the extraction process. Therefore, it is useful for both the recovery of components of interest in the feedstock and the reduction of the residues generated after the process [69]. Further, PEF is presented as promising candidate to be applied in biorefinery for lignocellulosic biomass pretreatment, as induces the breakdown of biomass particles inside lignocellulosic biomass, making these regions more accessible [70].

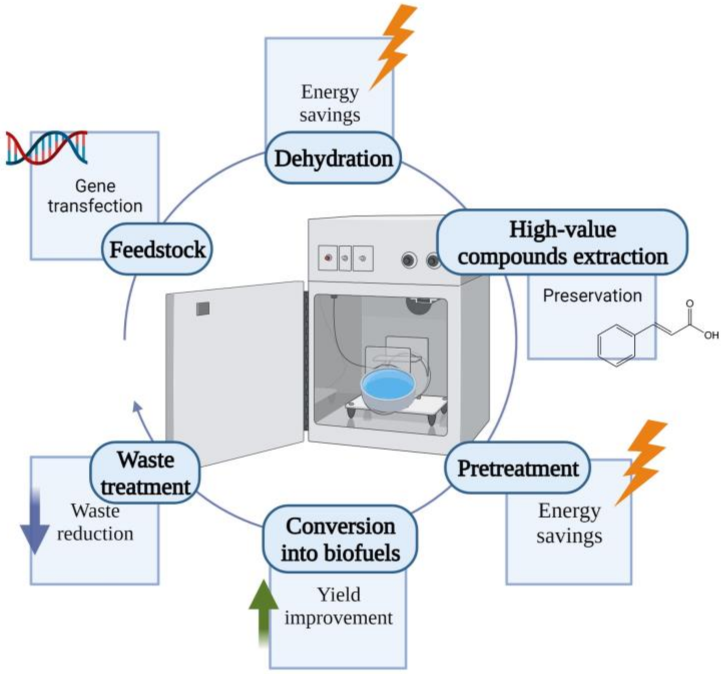

Figure 4. Pulsed electric fields (PEF) applications on biofuels production based on Goldberg et al. [61]. Created with BioRender.com

In this sense, PEF was studied as pretreatment to facilitate microbial decomposition of lignocellulosic structure of grape pomace and methane production. The results obtained revealed that PEF increases the cumulative methane yield and the hydrolysis constant with percentages of 4% and 14%, respectively. However, the highest methane production was achieved after alkaline pretreatment with 10% NaOH w/w dry basis, at 20 °C during 24 h [71]. In other study, the effect of PEF on lignocellulosic biomass for biofuel production was investigated in wood chip and switchgrass samples [72]. Treatments at 10 kV/cm produced an increase in the porosity and permeabilization of both samples, enhancing enzyme hydrolysis rates or acid hydrolysis.

Furthermore, Salgado-Ramos et al. [73] reported the effect of PEF-assisted extraction in the processing of winemaking-derived by-products, namely grape stalk (GS), grape marc (GM), and exhausted grape marc (EGM) [73]. More specifically, for the latter it was reported a boosted to up to 68% in terms of total antioxidants recovery after PEF treatment when comparing to traditional methods, also favoring the further conversion of the remaining post-extraction solid into bioenergy attending to its proximate and ultimate analysis, as well as higher heating value (HHV) [73]. Besides, the multistep combination of PEF (3 kV/cm, 100 kJ/kg, 2 Hz, 100 ms) and supercritical fluid extraction (SFE) with CO_2 (10–20 MPa, 25 mL/min [10% EtOH], 50ºC, 60 min) to the sane matrix favored this recovery to up to 87%, making the lignocellulosic remaining fraction more prone to be further transformed into fine chemicals after recovering of bioactive compounds [74].

Finally, these authors also reported promising results after PEF [75] and PEF+SC-CO_2 [76] processing of almond hull biomass to recover antioxidants, lipids, and carbohydrates. In this line, the application of supercritical fluids as CO2 enhanced the efficiency to up to 77% and 20% for total antioxidants and polyphenols, respectively, compared to the traditional soaking In addition, the high composition in terms of carbohydrates and fibers in the post-extraction recovered solid makes it a valuable feedstock towards fine chemicals, such furfural, levulinic acid or 5-hydroxymethylfurfural[75], whereas distinguished energetic properties by proximate and ultimate analyses of some almond hull-derived fraction after treatment were also reported [76] . Thus, an energetic, chemical two-way valorization was established for this waste in agreement with a life cycle assessment.

Overall, PEF can constitute a useful approach in the pretreatment of lignocellulosic biomass. In this context, it should be highlighted that this protocol enables alternative valorization routes for this agricultural waste, being remarkable the production of value-added chemical acting as biofuel precursors, or the enhanced energetic properties in the post-extraction remaining solid after processing.

4. Industrial outlook: cost processing, and environmental, social and economic sustainability

Regarding the above-described applications for PEF and HPP, both treatments not only contribute to save energy and reduce the environmental impact of compound extraction and further conversion, but also are useful as a pretreatment to improve the efficiency of industrial food production processes. However, with view to a positive industrial executive, some issues should be considered to optimize the process and tackle the total dimension of sustainability.

For instance, to achieve a high-mass transfer flow that allows biomass processing under PEF treatment, large volume treatment chambers and high pulse repetition frequencies are required. In this sense, the use of large volume treatment chambers in turn requires larger distances between electrodes, resulting in high voltage amplitudes. In addition, the voltage and amplitude of the pulses, along with their frequency, are factors that must be considered in sustainable biofuel production [77]. Currently, these factors are considered when evaluating the cost-benefit ratio in the industry, indicating favorable results in the application of these technologies, as mentioned.

Nonetheless, the application of PEF at low intensity (1 kV/cm, 0.2 kJ/kg) as a pretreatment in the production of French fries was implemented in the food sector. In this line, the quality of the product obtained improved by reducing the starch loss during cutting, lowering the lipid content during frying from 7.5 to 6.8%. Therefore, a product with superior health benefits with respect to that obtained by heat treatment was developed, with large energy and cost savings. The reduction in starch and dry matter loss because of the beneficial application of PEF technology even affects the yield of French fries' production, considering daily production capacities to up to several 100 tonnes per day [78].

This reduction of oil uptake by the food surface due to PEF electroporation was reported by Ignat et al. [79], suggesting that the transfer of aqueous and intracellular substances to the food surface creates a barrier that reduces oil uptake. The effect of PEF on matrices such as potatoes was also highlighted by several authors [80–82] and a reduction in acrylamide production during frying process after pretreatment was also observed [83,84].

Thus, as above-mentioned, PEF not only improves economic and energy efficiency, but also bears health benefits and contributes to the transformation of the food industry towards sustainable practices. However, although PEF technologies can be used to improve the drying, freezing, or frying processing, it should be noted that its main application at industrial level is focused on boosting the efficiency of extraction of targeted compounds from different matrices, making efforts in increasing mass transfer and decreasing the degradation of heat-sensitive compounds [85].

Concerning HPP treatment, the energy and production cost come mainly from the pressure pumps and pump energy efficiency [86], as well as the capital investment cost for the equipment installation. HPP industrial implementation stared around 30 years ago, being nowadays the most extended non-thermal technology for preservation. Over the past 30 years, the design, reliability, and productivity of HPP equipment have improved in order to reduce production costs. Nowadays, HPP advance materials and the design improvement allow to apply of a greater number of cycles per hour. One of the most relevant improvements obtained in HPP by equipment manufacturers companies such as Hyperbaric S.A. (Burgos, Spain) is the development of a unit able to process in-bulk large quantities of beverages that can be packed in any kind of package, contributing to a more affordable and sustainable process. In this regard, it is possible to process large amount of food (up to 10,000 L/h) in a fully automated way employing a system with two vessels of 525 L [87].

Comparing the price of HPP processing with traditional pasteurization in orange juice conservation, thermal treatment is more economic than HPP. In this sense, the cost of processing 1 kg of juice with HPP is approximately 1.78 -1.40 times the cost for thermal treatments. However, from an environmental perspective, thermal processing produces higher environmental impact (use of land and mineral resources, stratospheric ozone depletion, and marine eutrophication) maybe due the fact that thermal processing makes use of steam, which is typically obtain from burning methane. Furthermore, HPP contributes to food waste reduction as has been described in this review. Thus, environmental impact should be also considered in the cost cost-benefit analysis [88].

In summary, regardless the high investment and the exhausted technical optimization that should be carried out for the scaling-up approach, the benefits of these intensified technologies at industrial scale are fully guaranteed, covering the total dimension of sustainability. The main factors that support this fact are summarized in **Table 3**.

Table 3. Main benefits of Pulsed Electric Fields (PEF) and High Pressure Processing (HPP) technologies at industrial level in relation to the sustainability. Created with BioRender.com

	Economic	**Social**	**Environmental**
Exploitation of wasted, underutilized natural resources	X	X	X
Physicochemical mechanisms (electroporation for PEF and ultrahigh pressures for HPP): energy efficiency	X		X
Improved purity and quality of the obtained products	X		X
Immediacy for consumers: high availability and market competitiveness	X	X	
Increasing demand of natural, bioactive compounds (food, pharmacy, cosmetics)	X	X	
Distinguished atom economy and energy efficiency (Green Chemistry Performance Metrics)		X	X
GRAS, green solvents (H_2O)			X

5. Current and future trends

High hydrostatic pressure (HPP) processing and pulsed electric fields (PEF) technology are two of the most interesting trends related to the food industry because of their impact on sustainability. Both technologies have applications in improving food safety and extending the shelf life of food products, which is interesting for both reducing the large amount of food waste responsible for part of CO_2 emissions and improving the quality of manufactured products, as they can affect texture and flavor reducing the need to use food additives.

However, it must be also emphasized that the use of these technologies can negatively impact sustainability if used improperly. For instance, the improper use of PEF can damage cell structure, alter food quality, and increase energy requirements whether the appropriate electric field and specific energy conditions are not used, with negative environmental impacts. In this sense, HPP processing can also require large amounts of energy, and its use should be focused on perishable foods with high consumption that require shelf-life extension.

Therefore, future trends PEF and HPP processing technologies should be focused on improving their efficiency and process optimization. For the former, research and development is expected to focus on improving efficiency by optimizing conditions and developing equipment that further reduces the energy required for operation and increases sustainability. In addition, new trends are focused on exploring new applications in wastewater treatment and surface disinfection.

Similarly, new trends in HPP are also aimed at improving efficiency: reducing the time and energy required for application. In addition, new applications are being sought for the preservation of organic foods and the formulation of functional foods.

For both processes, sustainability at economic, social, and environmental levels will continue to be the key factor in the development of these technologies, in order to ensure that the benefits they bring to products do not come at the expense of animal welfare or the environment. The goal for the future, therefore, is to continue to provide sustainable solutions for the industry by finding new applications for existing technologies.

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