

Review

Recent Advances and Applications of Pulsed Electric Fields (PEF) to Improve Polyphenol Extraction and Color Release during Red Winemaking

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Abstract: Pulsed electric fields (PEF) technology is an innovative food processing system and it has been introduced in relatively recent times as a pre-treatment of liquid and semi-solid food. Low cost-equipment and short processing time, coupled to the effectiveness in assisting the extraction of valuable compounds from vegetable tissues, makes PEF a challenging solution for the industrial red winemaking; a tailored PEF-assisted maceration was demonstrated to promote an increase in wine color quality and an improvement in the polyphenolic profile. Despite the application of PEF has been studied and the positive effects in selected wine varieties were demonstrated on batch and pilot-scale systems, there is a need for a more detailed characterization of the impact in different grapes, and for a better understanding of potential undesirable side-effects. This review aims to summarize the state of the art in view of a detailed feasibility study, to promote the introduction of PEF technology in the oenological industry.

Keywords: pulsed electric field; polyphenolic extraction; red winemaking; color intensity

1. Introduction

The implementation of food products in terms of nutritional value and shelf-durability and the optimization of the production processes (with a consequent reduction of the production costs) have been the main challenges faced by the food industry in recent decades. Based on these premises, innovative technologies with potential application on an industrial scale have been investigated with the aim of enhancing food quality, increasing competitiveness in the food market and matching customer's expectation [1–3].

Thermal processing is traditionally used for the biological stabilization, by subjecting the food to a temperature range from 60 to above 100 °C for variable periods, and involving a massive energy transfer from the heat source to the treated matrix [4]. Although the energy obtained is effective in destroying or inhibiting undesirable microorganisms, many unwanted secondary reactions leading to the loss of nutritional and sensorial quality of food have been highlighted in recent studies [5,6]. Mild thermal treatments are also applied to enhance mass transfer phenomena, obtaining the removal of water from food and the release of nutraceutical compounds; despite the temperature supply is limited compared to the pasteurization treatment, the use of heat in fresh food matrices potentially results in the deterioration of sensory properties [7–9].

Non-thermal food processing involving ambient temperatures constitute a concrete alternative to thermal technologies, improving food safety while maintaining product quality and economic feasibility; several non-thermal technologies were proposed for preserving the nutritional constituents of food including vitamins, minerals, and essential flavors. High hydrostatic pressures, oscillating

magnetic fields, intense light pulses, irradiation, the use of chemicals and biochemicals, high-intensity pulsed electric fields were all recognized as emerging solutions in the early 2000s [10,11]. Among them, pulsed electric field (PEF) represents a promising emerging solution for the food industry, being effective on the process scale and competitive in terms of cost. The use of pulsed electric field was introduced in the food industry in the early 90ies, and it is based on the application of high-frequencies electric pulses with intense field strengths, which are able to modulate the activity of biological membranes. The use of high-voltage pulsed treatments was initially hypothesized for inactivation of microorganisms and pasteurization of liquid foods [12]; afterwards, the improved understanding on the mechanisms involved, and the development of efficient pilot-scale equipment with reduced processing time and continuous flow applicability have extended the application fields in the food industry [13–15].

The “dielectric breakdown” theory provides a reliable mechanistic description of the impact of electric pulses in the modification of biological membranes. Accordingly, the membrane of a cell is modeled as a capacitor filled with a low-dielectric constant fluid; after being exposed to a strong electric field, ions migrate along the fluid and toward the membrane walls, thus forming free charges of opposite sign which accumulate at both membrane sides. Due to the attractive interaction of charges, the cell wall undergoes a compression which reduces the membrane thickness; the mechanism proceeds until the electric field strength gains a critical value, usually around 1V potential, at which micropores are formed on the membrane, increasing permeability (electroporation). The electroporated membrane may be damaged owing to the direct rupture, as a consequence of Joule overheating of the membrane surface, or following the chemical imbalances caused by the enhanced transmembrane transport throughout the membrane pores.

In a typical PEF treatment microsecond, intense electric pulses are applied to a conductive material (whether it is liquid or solid) which is located between two working electrodes; the external electric field induces a reversible or irreversible permeabilization of biological cells membranes in organic food matrices, supporting step production processes like tissues soaking, peels removal or the extraction of bioactive compounds [12,16–18].

The mechanism of alteration of transmembrane permeability has also gained specific interest for the oenological industry, having a potential application for improving the maceration stage in red vinification. As the majority of the compounds responsible for the quality and stability of wine color (polyphenolic compounds, colour precursors, tannins) are located in the grape skin vacuoles of the grape berries, the mass transfer is a critical mechanism for achieving their efficient extraction, and the winemaking techniques aim to increase the permeability of cytoplasmic membranes to facilitate their release; however, an effective extraction of such compounds strongly impacts the industrial process in terms of duration and cost. Different techniques have been developed to enhance the extraction of polyphenols and pigmented compounds improving the performances of the static maceration: thermovinification, grape freezing, the use of maceration enzyme, among others, have been tested on pilot and industrial scales [19–21]. To date, many of these approaches require a significant amount of energy and cause losses of valuable nutraceuticals: conducting alcoholic fermentation at high temperatures can cause fermentation failures and loss of volatile compounds, freezing grapes was demonstrated to affect the wine quality on different extents, and commercial formulations of maceration enzymes provide different levels of purity and potential contamination of detrimental species like β -glucosidases [22–24].

Treating red grapes with pulsed fields is a challenging opportunity to enhance the mass transfer phenomenon reducing the duration of the extraction process, thus limiting the economic impact and potential side effects of maceration. The bulk of research on the oenological field has evolved over the years 2007–2012, with few advances in the following years; during this period, along with the efficacy of the treatment, attention was paid to the potential undesirable effects, which have inhibited the application of PEF on an industrial scale so far [25].

The aim of this review is a critical evaluation of the state of art, to overcome actual limitations and promote the application of PEF technology in the wine industry. The manuscript is structured

in the following sections: (i) generic overview on the PEF technology; (ii) a brief description of the PEF-assisted mass transfer of valuable compounds from vegetable tissues; (iii) presentation of the main scientific contributions to the use of the PEF technology in winemaking, considering the decade 2007–2017, and also highlighting limitations and potential challenges.

2. An Overview on PEF Technology: Equipment and Processes

PEF involves the direct application of very short current voltage pulses to the food matrices; the time duration of the pulses cycling is variable (ranging micro to milliseconds) during which the material placed between two electrodes is treated with high voltages; the specific intensity of the treatment could be modulated on the basis of the geometry and distance of the working electrodes, the voltage delivered, the conductivity of the material treated. There is no strict definition regulating such intensity: on the basis of empirical experience, treatment ranges required to increase polyphenols and color extraction have been defined as high ($E > 1 \text{ kV cm}^{-1}$) medium ($E \approx 0.1\text{--}1 \text{ kV cm}^{-1}$) and low-intensity ($E < 0.1 \text{ kV cm}^{-1}$) electric fields [26].

The basic components of a typical PEF apparatus for producing exponentially decay pulses are schematically represented in Figure 1: regardless the settings required for specific industrial processes, the bulk of the equipment is constituted by a generator of electric pulses and a treatment chamber. In the generator, a charger converts the AC to DC current supplying an energy storage device, and a switch shortly turn on and off the high voltage circuit to generate electric pulses; the discharge of electrical energy is a critical step due to high voltages and short timing involved, and the capacitor is continuously monitored and stepped up if voltage collapse [27]. For square pulses, the electric scheme is more complex involving several LRC circuits (electrical circuits consisting of a resistor (R), an inductor (L), and a capacitor (C)) associated. The treatment chamber is composed by two electrodes separated by isolating materials and a gap to be filled with the food to be treated; the distance between electrodes, the voltage applied and the geometry of the chamber affect the treatment by defining the strength of the electric field, and modulating the energy supplied per unit of area. The food industry treatments frequently take place under continuous flow, thus making difficult modelling and predicting the distribution of the electric field along the treated material; most preliminary studies have provided static models were the electrodes have coaxial, co-linear (non-uniform electric field distribution) or parallel flat (uniform electric field distribution) electrodes, and the scale-up provides laminar flow at constant rates to optimize the treatment's efficiency [28].

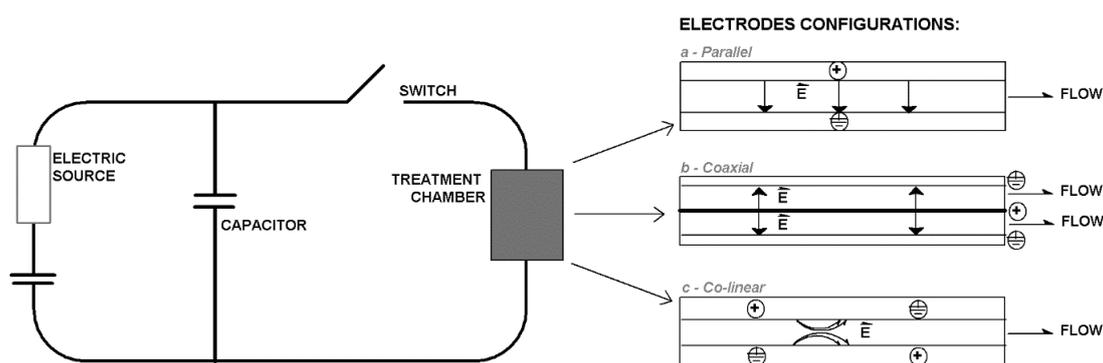


Figure 1. Schematic representation of a pulsed electric fields (PEF) circuit system for producing exponentially decay pulses, including the structure of the most exploited treatment chambers.

After modulating the set-up of the apparatus, the following process parameters must be defined: (i) electric field strength; (ii) pulse shape; (iii) pulse width; (iv) number of pulses; (v) pulse specific energy, (vi) pulse frequency [27]. The electric field strength is also related to the uniformity of electric field, which is dependent on the specific set-up of the apparatus as previously mentioned: in the parallel configuration of electrodes the treatment is uniform along the treated matrix, while in collinear

and co-axial set-ups intensity gradients of the electric field are formed within the treatment chamber (Figure 1). The commonly used pulse shapes are exponential decays and square waveform, the latter being the most suitable to maximize the effect of a PEF treatment: in square waveform any power decay occurs and the intensity remains constant for the whole duration pulse width, increasing efficiency compared to the pulses sent per unit of time. The specific energy delivered during the treatment is a function of the voltage applied, duration of the treatment, resistance and conductivity of the material treated, and temperature variation induced by electric field in the material, and it constitute a process parameter that can be modulated based on preliminary trials; the parameters described are also used to evaluate the PEF treatment efficiency and economic impact in prevision of scale-up [29].

3. Enhancement of Mass Transfer from Vegetable Tissues by PEF

Electroporation is a physical mechanism to induce permeabilization of cell membranes through the application of external intense electric pulses, and it can be exploited in the food processing [30]. In more detail, the application of a PEF treatment in plant cell could assist the extraction of valuable compounds such as pigments, antioxidants, flavors, contained in membranes and vacuoles of plant tissues. In eukaryote plant cells permeabilization of the membrane is easier to obtain if compared with bacterial cell, resulting in lower electric intensities required and subsequent lower energy consumption; for this reason, PEF treatment is considered competitive in term of cost/effectiveness for industrial treatments like pressing, extraction, drying and diffusion [31]. The reversible electroporation or the electrical membrane breakdown are due to the intrinsic composition and electric properties of cell membranes, which induce amplification of the external electric field. More specifically, the conductivity of the intact cell membrane is several orders of magnitude lower than that of the medium and cytoplasm where it is immersed. When an external electric field is applied, the opposite charges migrate and accumulate at the interface of membrane with the medium, increasing the transmembrane potential. Due to the thickness of the a typical vegetal cell membrane (≈ 5 nm), which is very low compared to a typical plant cell radius (≈ 100 μm), the electric field accumulates distributing opposite charges at the two interfaces (inner/outer) of the membrane itself; the electrostatic attraction of opposite charges operates along the membrane, inducing a squeezing of tissues. When the electric field reaches a critical value (E_c), ranging 0.2–1 V/m for vegetal cells, the compression induces a reversible ($E \approx E_c$) or irreversible ($E \gg E_c$) formation of pores [32,33].

In Figure 2 the time course of the electroporation process is schematically represented, showing that it is a non-instantaneous, dynamic process. The kinetic of electroporation is the reason for the key role played by technological parameters such as the intensity, duration and the pulse shape in a typical PEF treatment; moreover, the degree of degradation of cell tissues influences the kinetic of extraction of desired compounds.

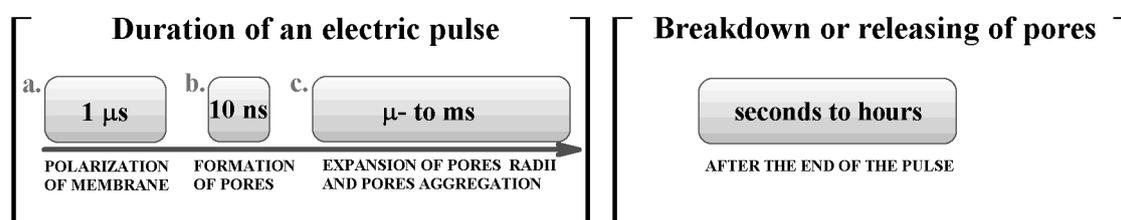


Figure 2. Time-course of a typical PEF experiment after releasing pulses on a generic eukaryote vegetable cells.

4. PEF Technology in Red Winemaking (Decade 2007–2017)

Grapes skin contain a large number of phenolic compounds and natural pigments, which are protected in the cell walls and cytoplasmic membranes of the skin vacuoles, and have high technological relevance for the oenological industry; nevertheless, due to the presence of cellular barriers that increase

their resistance to the mass transfer, they are only partially (and slowly) extracted and released in wine during traditional maceration processes that usually lasts up to 2–3 weeks. The main phenolic compounds contained in red grapes are anthocyanins, polyphenolic monomers, condensed tannins and pigmented polymers, all contributing to the color quality and stability. The final content and composition of polyphenols in wine is affected by several factors like grape variety, cultivation factor, winemaking technique, efficient extraction yield of the maceration step. For instance, the extraction of wine phenolics can be enhanced using technological alternatives to traditional maceration, but each of them has showed limitations in terms of cost-effectiveness and potentially have a negative impact on the sensory profile of wines. PEF has been recently introduced as an alternative pre-maceration treatment to increase and speed-up polyphenolic extraction without altering the sensory properties, highlighting effectiveness in improving wine stability and color quality [34]. An early-stage trial conducted using a PEF-assisted juice expression of red grapes resulted in an increasing anthocyanins content juice compared to non-thermal processes, such as high pressure treatment, supercritical CO₂, or the subjection to ultrasounds [35]. In 2007, the experiment was extended to Muscadelle, Sauvignon and Semillon white grape varieties, with the aim of increasing the expression and quality of juice: the PEF-assisted expression provided an increase of juice yield from 50% to 80% following a 5 bar pressing for 45 min [36]. Following the improvement in grape juice quality, an increasing number of experiment were conducted in the years 2008–2009, aimed to monitor not only the improvement of juice expression, but also the possibility to increase the polyphenols extraction in grape juice. The PEF-assisted low-pressure mechanical expression (maximum pressure: 1 bar) was also tested to assay Chardonnay white grapes, increasing juice yield from 67% to 75%, and producing a 15% increase of the polyphenolic content; moreover, the visual aspect of the juice was improved while reducing the juice turbidity with respect to the control [37].

The promising preliminary results on grape juices have stimulated an increasing number of experiments aimed to applying PEF prior to the maceration step of red wines. López et al. [38] have investigated the effects of pre-treating Tempranillo grape skin with pulsed electric field treatments (5 and 10 kV/cm) on the total polyphenols and anthocyanins content, color attributes. It was observed a generic increase and improvement of the three parameters when the electric energy irradiation raised from 5 to 10 kV/cm. After 50 h maceration the maximum index of polyphenols and anthocyanins content was obtained in PEF-treated samples, while the same value was obtained after 96 h in the control. Moreover, the total polyphenols index in PEF treated wines was 13.7% higher (5 kV/cm treatment) and 29.0% higher (10 kV/cm treatment) with respect to the control after 96 h maceration. At the end of fermentation the Tempranillo treated wines showed a color intensity of 23.93 (control), 27.04 (5 kV/cm treatment), and 29.33 (10 kV/cm treatment), confirming the color improvement in induced by PEF pre-treatment [38]. The same Authors have investigate the influence of the grape variety on the effectiveness of PEF treatments in red wine, performing the pulsed electric field on autochthonous Spanish grape varieties (Garnacha, Mazuelo and Graciano). Irradiation treatments of 2, 5 and 10 kV/cm were applied to improve color intensity, anthocyanins and total polyphenols index, guaranteeing a low energy consumption to obtain cell permeabilization of grape skins (0.4–6.7 kJ/kg) and short processing times. The PEF treatment was more effective in Mazuelo variety than in Garnacha and Graciano, reaching color intensity of 21.2% (2 kV/cm), 35.3% (5 kV/cm), 49.8% (10 kV/cm) and anthocyanins 20.3% (2 kV/cm), 28.6% (5 kV/cm), 41.8% (10 kV/cm) higher than the control after 120 h maceration [39]. Nevertheless, according to a study after Luengo et al. that was conducted few years later, in 2014, the PEF treatment can be modulated to achieve optimal polyphenols extraction and color expression in Garnacha red wine [40].

Tempranillo, Graciano and Garnacha Spanish grape varieties were also used as a template to demonstrate that a PEF treatment induce an increase in the extraction yield of *trans*-resveratrol and piceid-like compounds (stilbenes), which have a major antioxidant and nutraceutical impact but are usually available in low concentrations in red wines, being difficult to release from grape tissues using traditional extraction methods [41].

Cabernet sauvignon is a native grape variety from the Bordeaux region, which has been widespread in different geographical areas due to its ductility and excellent sensorial properties. It produces intensely colored wines, with high contents in tannins and flavors, suitable for aging; long maceration times and aging in oak barrels could enhance the sensory properties of pure or blended Cabernet sauvignon wines. Due to its peculiar properties, Cabernet sauvignon has been one of the main grape variety assayed to evaluate the advantages of PEF-assisted winemaking.

The intermediate 5 kV/cm PEF treatment was applied to the grape pomace of Cabernet Sauvignon, with an irradiation energy of 2.1 kJ/kg. The aim of the experiment was to evaluate the evolution on quality parameters and anthocyanins content on finished wine obtained after different maceration times: 48, 72, 96, 248 h, using PEF as a pre-treatment, and comparing with the same wine without applying electrical pulses to the grape juice. The PEF treatment of Cabernet sauvignon grapes was confirmed to produce intensely colored wines at bottling, with shorter maceration times: evaluations concerning the PEF experiment have highlighted the possibility of reducing the maceration time from 268 h (control) to 72 h (PEF treatment), obtaining comparable anthocyanins and polyphenols extraction yields [42]. Nevertheless, a major concern regarded the evolution of polyphenolic and color profile throughout aging in bottles. For this reason, the same grape variety was used to make a comparative study between PEF-assisted maceration of the grape mass pumped through a co-linear treatment chamber, and the use of 2 commercial enzymatic preparations in Cabernet sauvignon grapes under static conditions. PEF treatment conditions were defined on the basis of previous experiment after Lopez et al., and consisted of 50 pulses of 5 kV/cm at a frequency of 122 Hz, resulting in a total specific energy of 3.67 kJ/kg. The following parameters were monitored: color intensity (CI), anthocyanins content (AC) and total polyphenol index (TPI), from grape crushing to 3 months of wine aging in bottle. After 3 months, both enzymatic preparations were increasing the CI level of 5% with respect to the control, and only one of them reached the maximum increase of 11% (AC) and 3% (TPI). PEF was evaluated as the best alternative, with higher increase of CI, AC, and TPI parameters (28%, 26%, and 11%, respectively), compared to the control. The HPLC analysis also highlighted the improved extraction of non-anthocyanins polyphenols in PEF-assisted maceration [43].

A further experiment after Puértolas et al. [44] provided the application of a PEF treatment (50 pulses, 122 Hz frequency, 5 kV/cm electric field strength, 3.67 kJ/kg total specific energy) before crushing of the Cabernet sauvignon grapes; musts obtained from PEF-treated grapes were fermented concurrently with untreated grape must, and the evolution of the two bottled wines during 12 months of storage was compared in terms of color intensity, anthocyanins, polyphenols as measured using the Folin–Ciocalteu method. Assuming that the monitored parameters were higher on the PEF-treated sample, it was found that aging did not affect the initial color intensity in both wines, whereas the Folin–Ciocalteu index decreased. Individual polyphenolic compounds showed similar evolution patterns during the 12 months storage, and the content of flavonoids and hydroxycinnamic acids, which are valuable compounds for improving wine aging, was constantly higher in PEF wines [44].

The main challenge in the application PEF for improving winemaking provides the design of a device operating in continuous flow; such a configuration would make feasible the introduction of the PEF technology on the oenological industry scale. A continuous flow treatment should avoid the backfilling and compaction of grape pomaces to be treated, to provide a constant flow steam and ensure homogeneous distribution of electric pulses. Puértolas et al. [45] have developed a pilot-scale system operating in continuous flow, powered by a progressive cavity pump to obtain a grape mass flow rate of 118 kg/h which ensure a resident time in the treatment zone of 0.41 s/unit of mass. The device was equipped with a co-linear treatment chamber; the co-linear design provided two treatment zones of 2 cm between the electrodes, with the inner diameter of 2 cm. The simulation of non-uniform distribution of the electric field in co-linear configuration (see Figure 1) was supported by the Comsol Multiphysics software (Comsol Inc., Stockholm, Sweden). PEF parameters were consistent with the treatments previously applied in Cabernet sauvignon to obtain an enhancement in color and extractability [42,44], obtaining a moderate increase in the temperature of the treated mass

(+2 °C maximum). Results of the PEF pilot-scale experiment confirmed previous achievements of experiment conducted in batch systems of low capacity [45].

An ultimate study on Cabernet sauvignon berries was conducted comparing PEF treatment of low strength, long duration and high energy (0.7 kV/cm, 200 ms, 31 Wh/kg) with high-strength treatment (4 kV/cm, 1 ms, 4 Wh/kg); the experiment was mainly focused on the evaluation of amounts and composition of extractable anthocyanins and tannins. In particular, the first treatment have highlighted a major capacity in extracting the parietal tannins of the skin (+34%), while the second showed higher effectiveness in anthocyanins extraction (+19%) and the resulting must was richer in vacuolar tannins. In both cases, a depolymerisation of high-molecular weight fraction of skin tannins was observed, improving the diffusion of small polymers along the cell membrane pores. Enological parameters were monitored and they do not exhibit significant modifications; however, the sensory impact in terms of astringency produced by low molecular weight tannins has not been tested in this work [46].

The same authors previously investigated the effect of pulsed electric field treatments with variable energies (0.5–0.7 kV/cm) and duration (40–100 ms) of the treatment in Merlot grapes. Kinetic models provided the evolution of total polyphenols, anthocyanins and color intensities content in juices, while keeping the temperature variation below 5 °C. The increase in extractability was demonstrated using kinetic parameters, and the sensory evaluation of treated wines evidenced an improvement in the sensory properties of PEF-treated wines compared to the control [47].

The combination between pulsed electric field treatment and oenological practices to maximize color quality in wine has been investigated in a study after Puértolas et al. The experimental design was aimed to study the effect of maceration time (0–6 h), and maceration temperature (4–20 °C) on the anthocyanin content during rose vinification of Cabernet sauvignon grapes, while keeping constant parameters for the PEF treatment (5 kV/cm, 50 pulses). A surface response model analysis was used to identify optimal process parameters, showing that after 2 h treatment the PEF treatment allowed to obtain an anthocyanin level of 50 mg/L at the temperature of 4 °C; the same result was obtained for the control (untreated) sample using a 20 °C temperature. Since an increasing processing temperature results in the speed-up of oxidation mechanisms and loss of flavors, the PEF treatment showed to be a promising technique to minimize temperature in rose vinification, avoiding undesirable side-effects [48].

The use of PEF to improve polyphenols, anthocyanins and tannins extraction for Cabernet franc grapes was investigated by El Darra et al. comparing moderate (0.8 kV/cm, 42 kJ/kg) and high (5 kV/cm, 53 kJ/kg) intensities PEF treatments with moderate thermal (MT) and ultrasound-assisted (US) extractions. Despite all pre-treatments have provided improved polyphenolic and color profiles compared to the control, PEF treatments showed the high extraction yields of total polyphenols (+51% for moderate and +62% for high-intensity treatments, respectively), and the highest color intensities (+20% for moderate and +23% for high-intensity treatments, respectively) at the end of maceration [49].

According to our knowledge only two autochthonous Italian varieties, Aglianico and Piedirosso grapes, were subjected to PEF treatments to increase the polyphenolic content of related red wines, and different electrical field strength were applied (0.5–1–5 kV/cm) obtaining specific energy inputs ranging from 1 to 50 kJ/kg. It was observed that PEF had a major effect on Aglianico, increasing the release of polyphenols (+20%), anthocyanins (+75%), color intensity (+20%), and enhancing the antioxidant activity of the wine (+20%); contrariwise, same treatments had a minor impact in Piedirosso composition in comparison to the control [50].

The contribution of PEF treatment coupled to conventional red wine fining techniques has also been investigated. The evolution of chromatic and phenolic profiles of Cabernet Sauvignon during aging in oak barrels and following bottling was studied, showing that the stabilising effect of applying pulsed field prior must fermentation is maintained and even enhanced during aging in American oak barrels: in the study, a panel triangle test was used to demonstrate that the wine quality remained

unchanged in terms of color and phenolic content after 8 months bottling, regardless the bottling was preceded by storage in wood under oxidative conditions [51].

Based on the results of published studies, we can conclude that the mass diffusion of valuable polyphenols, anthocyanins, tannins and pigments is improved using PEF-assisted maceration, in different extent when modulating engineering (field strength, specific energy, treatment time) and technological parameters (grape variety, winemaking technology, storage time), and these findings could support both red winemaking and the valorization of production wastes obtained during the red vinification [52]. Table 1 summarizes the main findings of studies listed in this review, to obtain a more generic overview of PEF applications which have showed to improve the red winemaking practice so far.

Table 1. Summary of the main findings in PEF experiments in relation to grape varieties and process parameters. Abbreviation: Total Polyphenols Index (TPI), Color Intensity (CI), Anthocyanins Content (AC).

Grape Variety	PEF Parameters	Major Achievements (Compared to Control Wine)	Ref.
Mazuelo	(a) 2 kV/cm; 0.4 kJ/kg (b) 5 kV/cm; 1.8 kJ/kg (c) 10 kV/cm; 6.7 kJ/kg	TPI + 19.8%; CI + 21.2%; AC + 20.3% (120 h maceration) TPI + 24.0%; CI + 35.3%; AC + 28.6% (120 h maceration) TPI + 31.0%; CI + 49.8%; AC + 41.8% (120 h maceration)	[39]
Tempranillo	(a) 5 kV/cm; 1.8 kJ/kg (b) 10 kV/cm; 6.7 kJ/kg	TPI + 13.7%; CI + 11.5%; AC + 21.5% (96 h maceration) TPI + 29.0%; CI + 18.4%; AC + 28.6% (96 h maceration)	[38]
Garnacha	4.3 kV/cm	TPI + 23.5%; CI + 12.5%; AC + 25% (7 days maceration)	[40]
Cabernet sauvignon	5 kV/cm; 2.1 kJ/kg	TPI + 45.2%; CI + 48.4%; AC + 42.2% (268 h maceration)	[42]
Cabernet sauvignon	5 kV/cm; 3.67 kJ/kg	TPI + 17%; CI + 28% (12 months aging); AC + 17% (end of maceration)	[43]
Cabernet sauvignon	5 kV/cm; 3.67 kJ/kg	TPI + 23%; CI + 29%; AC + 26% (4 months aging)	[44]
Cabernet sauvignon	5 kV/cm; 3.67 kJ/kg	TPI + 23%; AC + 34% (48 h maceration); CI + 38% (4 months aging)	[45]
Cabernet sauvignon	5 kV/cm; 3.67 kJ/kg	Decrease in maceration T from 20 °C to 4 °C to have comparable results with control	[48]
Cabernet sauvignon	(a) 0.7 kV/cm; 31 Wh/kg (b) 4 kV/cm; 4 Wh/kg	Tannins extraction + 19% Anthocyanins extraction + 19%	[46]
Merlot	(a) 0.7 kV/cm; 40 ms (b) 0.7 kV/cm; 100 ms (c) 0.5 kV/cm; 100 ms	TPI + 18% (all) CI—no significant differences Increasing kinetic of extraction with increasing process parameters	[47]
Cabernet franc	(a) 0.8 kV/cm; 42 kJ/kg (b) 5 kV/cm; 53 kJ/kg	TPI + 51%; CI + 20%; AC + 49% TPI + 62%; CI + 23%; AC + 60%	[49]
Aglianico	(a) 1 kV/cm; 50 kJ/kg (b) 1.5 kV/cm; 10 kJ/kg (c) 1.5 kV/cm; 25 kJ/kg	TPI + 13%; CI + 6%; AC + 9% (following treatment) TPI + 31%; CI + 12%; AC + 54% (following treatment) TPI + 38%; CI + 19%; AC + 76% (following treatment)	[50]

Regardless the obvious advantages in PEF-assisted winemaking, the development of pulsed electric fields in the oenological industry have been limited due to the limited understanding of the impact of this treatment on wine composition and quality parameters. A recent review after Yang et al. highlighted some concerning related to the use of PEF in the food industry: in particular, it has been proven that the release of metals under the effect of the external electric field is the main latent effect of PEF. Corrosion and migration of electrodes material can occur under specific conditions, and this could result in food contamination and adulteration [53]. As an example, a study conducted in beer has shown a significant increase in Fe, Cr, Zn, Mn concentrations, which are oxidation catalysts; in this study, the impact of increasing metals concentration in the flavor of beer was determined by the sensory panel [54]. Contrariwise, any sensory analysis conducted on PEF-treated wines has highlighted detrimental modifications in comparison with the control wine, but there is a lack in a detailed study of elemental and compositional modifications occurring in wines after the application of electric treatments. A further negative effect following the application of PEF in wine could be the selective electrochemical degradation of valuable chemical compounds, depending on the electrodes used. A recent study compared the effect of three electrodes materials in aqueous solution of anthocyanin-based compounds, showing that stainless steel retained cyanidin-3-glucoside and cyanidin-3-sophoroside, while pure titanium and titanium-based alloy caused a higher extent of degradation [55]. Lastly, the corrosion or migration of electrode materials should be investigated to improve safety and prevent undesirable sensorial modifications in wines.

A further observation regards the limited number of publications made available in recent times, the reduced number of technological parameters monitored, and the limited selection of grape varieties

investigated. According to the information made available so far, the authors of this review consider pulsed electric field a challenging solution for improving red winemaking, to be deepened and extended to several case studies for a better understanding of electrochemical processes involved and a safe exploitation of the technique in industrial applications.

5. Conclusions

The most recent findings in the field of red wine processing using the pulsed electric field (PEF) technology have been summarized in this review. It has been demonstrated that the use of PEF could enhance the extraction of phenolic compounds and increase color intensity in red wines. In the studies presented, color stability was also assisted by the extraction of valuable polyphenolic compounds, monomers (flavonoids, hydroxycinnamic acids, tannins) and polymers (condensed tannins from grape skin). The main mechanism responsible for the increasing mass transfer was the electroporation of vegetable cell membranes, which also enabled to reduce the maceration process, and to enhance the extraction of bioactive compounds from grape using a low-cost technology. Regardless the advantages reported for the application of PEF in red winemaking, the impact of the treatment in the overall composition of wine has not been investigated in detail so far, and a major concern regards the potential electrochemical contaminations induced by the electrodes. Moreover, a limited selection of grape varieties was investigated, and there is a need for a more comprehensive study about the impact of PEF treatments in the chemical and sensory properties of different red wines. The authors encourage a more systematic study of PEF technique applied to winemaking, for improving safety and promoting the development of this technology on an industrial scale.

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