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Review

The Application of Non-Thermal Technologies for Wine Processing, Preservation, and Quality Enhancement

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Abstract: Recently, non-thermal wine processing technologies have been proposed as alternatives to conventional winemaking processes, mostly with the aims to improve wine quality, safety, and shelf-life. Winemakers typically rely on sulfites (SO_2) to prevent wine oxidation and microbial spoilage, as these processes can negatively affect wine quality and aging potential. However, SO_2 can trigger allergic reactions, asthma, and headaches in sensitive consumers, so limitations on their use are needed. In red winemaking, prolonged maceration on skins is required to extract enough phenolic compounds from the wine, which is time-consuming. Consequently, the wine industry is looking for new ways to lower SO_2 levels, shorten maceration times, and extend shelf life while retaining wine quality. This review aggregates the information about the novel processing techniques proposed for winemaking, such as high-pressure processing, pulsed electric field, ultrasound, microwave, and irradiation. In general, non-thermal processing techniques have been shown to lead to improvements in wine color characteristics (phenolic and anthocyanin content), wine stability, and wine sensory properties while reducing the need for SO_2 additions, shortening the maceration time, and lowering the microbial load, thereby improving the overall quality, safety, and shelf life of the wines.

Keywords: wine; non-thermal technologies; high-pressure processing; ultrasound; pulsed electric field; microwave; irradiation

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1. Introduction

Wine is a widely consumed beverage that is typically produced from grapes that have undergone partial or full alcoholic fermentation [1]. The wine market was worth USD 364.25 billion globally in 2019 and is expected to grow to USD 444.93 billion by 2027 [2]. In 2021, global wine production was about 260 million hectoliters, with Italy, France, and Spain being the countries with the largest production [3]. Despite its strong links with tradition, the vitivinicultural sector has proven to be attentive to adopting innovations if they can lead to higher quality wines, lower production costs, safer products with extended shelf-life, and more recently, more sustainable productions. The winemaking process includes different stages in which microbial spoilage can occur, which can alter the quality, shelf life, and hygienic conditions of the wine. It requires the control of the load of micro-organisms at different processing stages, such as grape pressing (equipment used in the grape reception area), during fermentation, and post-fermentation, in order to ensure the imposition of starter cultures for appropriate alcoholic or malolactic fermentation [4]. The principal spoilage organisms include several yeast strains (e.g., *Zygosaccharomyces*, *Brettanomyces*, *Hanseniaspora*, *Pichia*, *Candida*, etc.), acetic bacteria (e.g., *Acetobacter* and *Gluconobacter*), and lactic bacteria (e.g., *Lactobacillus*, *Leuconostoc*, *Pediococcus*, etc.) [5,6].

The activity of micro-organisms (yeast, molds, and bacteria) can be controlled by hygiene practices, low temperatures, low pH, minimizing the oxygen level, adding preservatives (such as SO_2), or using thermal and non-thermal technologies [7–10]. Thermal technologies are highly energy-consuming preservation methods that are commonly used in the food industry to control/inactivate micro-organisms. The heat during processing may cause protein denaturation; undesirable changes in physical, sensory, and nutritional properties; and the loss of volatile components, resulting in decreased food quality [11–13]. On the other hand, non-thermal technologies have proven to be an efficient technique for developing safe foods with high-quality attributes [14].

In this context, the non-thermal technologies that are applied in the food and beverage sectors have typically been used as alternatives to pasteurization, for example, to inactivate undesirable microbes and enzymes, but also as techniques to facilitate extractions, homogenization, drying, and aging of different food and beverages. Recently, the potential for these technologies to be useful also in the wine sector has been recognized by researchers, a fact that, in the past 15 years, has led to the production of an increasing number of peer-reviewed articles dedicated to assessing the impact of technologies such as high-pressure processing, pulsed electric fields, ultrasound, microwave, irradiation, ozone, and ohmic heating on wine quality. Indeed, an in-depth analysis of the research outputs in this field, which was conducted by using the Scopus database, indicates that the first articles on the subject were published in 2007 and that today, 109 articles have been published on the application of non-thermal technologies for wine processing, preservation, and quality enhancement. By analyzing the keywords of these 109 articles, and by merging them when appropriate (e.g., phenolics merged with polyphenols, phenols, tannins), a total of 24 keywords were selected, and their frequency is depicted in Figure 1.

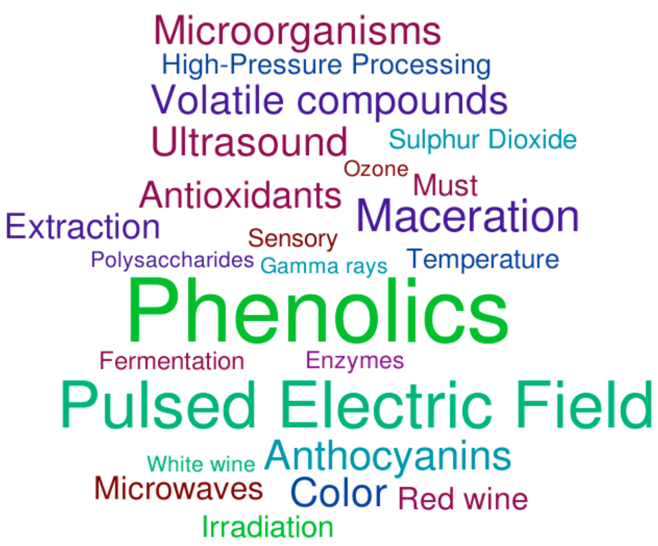

Figure 1. Word cloud representation of the main keyword occurrences in publications found during a Scopus search executed on the 28th of February 2023 (n = 109, publication range 2006–2023). Created with worditout.com. The total number of mentions was 569, with each word mentioned as follows (number of occurrences enclosed in parentheses): phenolics (111), pulsed electric field (73), maceration (41), anthocyanins (34), ultrasound (31), micro-organisms (31), color (31), volatile compounds (31), antioxidants (27), extraction (24), microwaves (19), red wine (18), irradiation (16), must (14), high-pressure processing (12), sulfur dioxide (11), temperature (11), sensory (8), fermentation (7), enzymes (5), white wine (4), polysaccharides (4), ozone (3), gamma rays (3). Only keywords found for a minimum of 3 times are shown.

Figure 1 shows that non-thermal technologies are investigated mostly in relation to their effects on wine composition and microbial stability. Indeed, the keywords phenolics, anthocyanins, color, volatile compounds, enzymes, and polysaccharides account for over one third (37.2%) of the total frequency of the keywords, indicating that the impact on wine composition of non-thermal technologies is investigated mostly by analyzing these wine components, most frequently in red wines. The second most represented category of keywords (34.8% of total keyword frequency) is related to the types of non-thermal techniques used, which are, in order of frequency, pulsed electric field, maceration, ultrasound, microwaves, irradiation, high-pressure processing, ozone, and gamma rays. This gives an idea of the different levels of scientific exploration of these innovative techniques in the wine sector. The frequency of the keywords related to the impact of non-thermal technologies on micro-organisms and wine oxidation (micro-organisms, antioxidants, sulfur dioxide, fermentation) was 13.4%, indicating that this is also an important area of investigation that is analyzed by researchers, particularly in relation to the production of wines that are free from spoilage and with lower needs for sulfur dioxide additions.

In general, Figure 1 clearly indicates that the wine sector is currently exploring the potential of novel non-thermal technologies, as these can be useful tools for improving wine quality and stability and controlling microbial activity [15–17]. As a result of their application, non-thermal technologies can aid in reducing the need for preservatives such as SO_2, can speed up maceration, enhance color stability, control microbial activity, and accelerate the maturation process [4,18,19], all of which are aspects that are expected to be beneficial for the wine sector.

2. Novel Processing Techniques

2.1. High-Pressure Processing (HPP)

High-Pressure Processing is a non-thermal and commercial technology that can be used to inactivate undesirable microbes and enzymes by applying uniform pressures to foods and beverages, typically by using a range between 100 and 600 MPa. HPP has been recently tested in fruit juices, wine, and beer, and the results showed that it could inactivate spoilage-causing micro-organisms such as mold and yeast [20], with minimal effects on sensory properties and the anthocyanin content of wine and must [10,20]. The effects of HPP on wine are summarized in Table 1.

HPP treatment (80 to 120 MPa for 2 h) significantly enhanced the mouth-feel characteristics of red wine and sped up the aging process [21]. Recently, Wyk et al. [22] studied the effect of HPP (600 MPa for 5 min) on different white (Sauvignon blanc and Pinot gris), red (Syrah and Pinot noir), and rosé (Pinot gris, Merlot, Malbec) table wines after processing and two months of storage at 15 °C. In general, HPP treatments did not lead to significant modifications ($p < 0.05$) in terms of pH values, while the antioxidant activity was not significantly affected in 4 of the 5 wines tested, with only Pinot noir showing a moderate decrease (−23%). Furthermore, HPP did not significantly affect the total phenolic content (TPC) for Pinot noir, Sauvignon blanc, and Pinot gris, while a 15% increase in TPC was noted for Syrah. The rosé was the wine most affected by the treatment, with a 27% decrease in total phenolic content. The color density (A420 nm + A520 nm + A620 nm) generally increased (Syrah + 4%; Pinot noir + 2%; Rosé + 11%; Sauvignon blanc + 25%) except for Pinot gris (−7.5%). Furthermore, after two months of storage, all the treated wines showed non-significant differences in antioxidant activity, TPC, color density, and pH compared to the untreated wine.

Puig et al. [23] treated white and red finished wines (total SO_2 40–50 mg/L for both) via HPP at 500 MPa for 5 min at 40 °C for microbiological and biochemical stabilization. Both wines were inoculated with acetic (*A. aceti* and *A. pasteurianus*) and lactic (*Lactobacillus plantarum* and *Oenococcus oeni*) acid bacteria (109 CFU/L) and yeasts (*Saccharomyces cerevisiae* and *Brettanomyces bruxellensis*: 109 CFU/L). The results showed that HPP treatment inactivated all the micro-organisms without impacting wine parameters such as alcohol content, pH, free and total SO_2, total and volatile acidity, malic acid, lactic acid, protein stability, reducing sugars, and polyphenol oxidase activity. In addition, there was no discernible organoleptic difference between treated and untreated wines.

Table 1. Key literature findings for High-Pressure Processing (HPP).

Conditions	Type of Wine	Effect	References
500 MPa for 5 min at 40 °C	White and red	■ Yeasts and lactic and acetic acid bacteria completely inactivated. ■ No effect on polyphenol oxidase activity, alcohol concentration, total and volatile acidity, free and total SO_2, protein stability, malic acid, lactic acid, reducing sugars, and pH. ■ No variations in organoleptic quality. ■ No change in antioxidant activity. ■ Color parameters by CIELAB: no change in b*, decrease in L* and a*.	[18,23]
600 MPa for 5 min	Syrah, Pinot Noir, Rosé, Sauvignon blanc, Pinot Gris	■ No significant changes in pH. ■ General decrease in antioxidant activity. ■ General increase in total phenolic content. ■ General increase in color density. ■ No effect on wine quality parameters.	[22]
100–350 MPa, 25 °C, 0–30 min	Low-alcohol red	■ Complete inactivation of yeasts and lactic and acetic acid bacteria. ■ No differences in aroma, taste, mouthfeel, and overall sensory quality between the HHP-treated and -untreated samples.	[24]
600 MPa, 70 °C, 30 min and 1 h	Dornfelder	■ 25% degradation of cyanidin-3-*O*-glucoside. ■ Decrease in the concentration of malvidin-3-*O*-glucoside.	[25]
650 MPa for 15 min	Red wine	■ No change in sensory parameters. ■ Decrease in total phenolic content, tartaric esters, flavonols, and tannins.	[21]
551 MPa for 10 min	Red grape must	■ No difference in color of final wine. ■ Minor differences in final wine sensory properties.	[26]
350 MPa for 10 min at 8 °C	Red wine	■ Reduction in micro-organisms. ■ Reduction in SO_2. ■ No difference in color, antioxidant activity, phenolic composition, and tannin structural characteristics.	[27]
200–600 MPa for 5 min at 20 °C	Red raspberry wine	■ Affected aroma components. ■ Alcohol content decreased at 400 MPa or more. ■ Micro-organisms inactivated.	[28–30]

Mok et al. [24] studied the effect of HPP on low-alcohol red wine. After 14 weeks of storage, the wine was treated with HPP at 100 to 350 MPa for 0 to 30 min at 25 °C. The results showed that the chemical composition (alcohol, pH, acidity, and total sugar) changed slightly due to the treatments, while sensorially, the wines were not distinguishable from the untreated controls. The microbial count greatly decreased from 5.6 log10 to 2.3 log10 at 2500 atm for 30 min. After 20 min at 300 MPa, the aerobic bacteria count dropped below the detection limits. All yeasts were inactivated by 300 MPa for 30 min, whereas all lactic acid bacteria were inactivated by 300 MPa for 20 min or 350 MPa for 5 min.

Takush and Osborne [26] studied the effect of HPP on a Pinot noir grape must at 551 MPa for 10 min. *Oenococcus oeni*, *Brettanomyces bruxellensis*, *Lactobacillus hilgardii*, *Saccharomyces cerevisiae*, and *Acetobacter aceti* were all inoculated into the must. Must pH, sugar content, and titratable acidity were unaffected by the HPP treatment, while no viable microbial cells were detectable in HPP-treated musts. Upon winemaking, no significant difference in wine color (A520 nm) and hue (A420 nm/A520 nm) were observed between the wine produced with HPP and the untreated control. However, the total phenolic content greatly increased (+72%) in the wine produced from HPP-treated grapes, an occurrence that was likely due to a cell wall breakdown upon HHP treatment, leading to greater extraction of phenolic compounds during fermentation.

Christofi et al. [27] used HPP to limit the use of SO_2 in wine. Red wine added to increasing amounts of SO_2 (range 0–100 mg/L) was subjected to HPP treatment (350 MPa for 10 min at 8 °C), and the effects on wine composition were monitored over 12 months. No significant variations were found in the chemical composition of the HPP-treated vs. the untreated wines during the first 4 months. During aging, the color intensity decreased, and the hue increased in both wines (HPP-treated or -untreated). However, from 6 months onwards, HPP-treated wines displayed lower anthocyanin content than untreated wines (−15% after 6 months, −29% after 1 year). A similar pattern was also seen for the flavonol content (−26% after 6 months, −64% after 1 year). Additionally, HPP-treated wines containing <60 mg/L SO_2 were found to be less aromatic, more oxidized, and with higher dried fruit, fruit jam, and spicy aromas compared to control wines, an occurrence that can be attributed to the fact that a sufficient level of SO_2 slows down the polymerization reaction of the polyphenols and prevents wine oxidation [30,31].

In general, it can be stated that HPP represents a useful tool for winemaking. Indeed, their use in enology was allowed by the OIV in 2019 with the resolution OENO 594A-2019 [32], in which the treatment of grapes and musts via discontinuous HPP at pressures higher than 150 MPa was admitted, with the aims of reducing the microbial load of grapes, of limiting the use of SO_2, and of accelerating maceration in red winemaking. The reports in the literature highlight the effectiveness of HPP in improving the shelf life of wines as well as some wine quality characteristics. Interestingly, their use has been reported also to increase the availability of bioactive compounds, a factor that, alongside the above-mentioned effects, could increase the commercial uptake of this technique.

2.2. Ultrasound (US)

Ultrasound is a non-thermal processing technology that is relatively inexpensive, non-hazardous, and considered environmentally acceptable [33]. US is widely utilized in the food and beverage industry as an energy-saving technology for ultrasonic-assisted extraction, homogenization, freezing-thawing, microbial inactivation, sterilization, cleaning, drying, and aging. Typical sound intensity conditions for US is 10–1000 W/cm^2, producing waves with a low frequency of 20–100 kHz [34–36]. When US is employed on liquid samples, it results in acoustic cavitation, which is the development, growth, and implosive collapse of bubbles. Acoustic cavitation generates high localized temperatures and pressure, which increase reaction rates and trigger various chemical reactions [37,38].

In wine, US is used as a rapid technique to extract color, aroma compounds, anthocyanins, phenolics, and condensed tannins at various stages of winemaking [39]. The effects of ultrasound processing on wine are summarized in Table 2.

Celotti et al. [40] investigated the effect of sonication amplitude (30%, 60%, and 90%) and time (5 and 10 min) on the protein stability of two heat-unstable Italian white wines. The results showed that, for both wines, the heat instability decreased with increasing amplitude % and time, and wines were fully stabilized with US treatment at 90% amplitude for 10 min.

Table 2. Key literature findings for ultrasound (US).

Conditions	Type of Wine	Effect	References
Flat tip probe US (30, 60, 90% amplitude; 20 kHz frequency; 5, 10 min; 13 mm diameter)	White wine	■ Higher amplitude and treatment time increase protein stability. ■ Decrease in heat stability test comparable to bentonite fining. ■ Decrease in turbidity.	[40]
US bath (40, 60, 80, 100% amplitude; 20, 40, 60 °C; 20, 50, 65, 90 min) US probe (diameter 12.7, 19.1, 25.4 mm; 3, 6 and 9 min; immersion depth: 2 cm)	White wine	■ No significant color changes. ■ Higher bath temperature caused degradation of volatile compounds. ■ Larger probe diameter and higher ultrasound amplitude showed a favorable effect on phenolic and volatile composition. ■ Reduction in SO_2.	[15]
Ultrasound < 100 kHz	Rice wine	■ Alcohol content reduction. ■ Acetaldehyde content decrease. ■ Ethyl acetate content increases. ■ Polyol concentration decrease. ■ Aging time reduced.	[39]
US probe power levels (90, 180, 270, 360 W), treatment time (10, 20, 30, 40 min), treatment cycles (1, 2, 3, and 4 cycles), frequency 20 kHz, probe diameter 10 mm	Blueberry wine	■ Improved color and anthocyanin content at the early aging stage. ■ Improved anti-oxidative capacity.	[41]
US at 20 kHz. Accelerated aging cycles (0, 4, 8, 12 and 16 times)	Monastrell red grapes	■ Increase in phenolic compounds and color extraction. ■ Change in epidermal cell structure. ■ No significant change in pH and acidity. ■ Maceration time reduction. ■ Improved chromatic characteristics. ■ Minor impact on wine sensory properties.	[42,43]
US probe at 20 kHz, 950 W, 16 °C for 14 & 28 min. 70 days storage	Cabernet sauvignon	■ Increased color density and visual characteristics. ■ No effect on phenolic composition. ■ Accelerated wine aging.	[44]

In another study, Lukić et al. [15] investigated the short- and long-term impact of high-power US on the quality characteristics of a young Graševina dry white wine. US was applied to the wine by using an ultrasonic bath and probe. The results showed that the US application mode impacted wine composition, but wine color was unaffected by treatments with both methods. When the chemical composition of wines produced by applying US with the ultrasonic probe versus the ultrasonic bath was compared, some significant differences emerged. US applied with a probe yielded wines with more phenolic acids (+11%), more flavan-3-ols (+58%), more total phenolics (+9%), and more higher alcohols (+30%), while the content in total esters decreased with increases in US intensity.

Zhang and Wang [44] studied the impact on the phenolic compounds and color properties of Cabernet sauvignon red wine after applying US treatments that were set at a frequency of 20 kHz, 950 W, 16 °C for 14 min and 28 min. The results demonstrated that the wine treated for 28 min and stored for 70 days had the highest color density (12.70) and browning index (0.427). US treatment led to an increase in the proportion of red color, while the proportion of blue color was constant, and that of yellow color and color hue decreased with an increase in storage time. The concentration of malvidin-3-*O*-glucoside showed a decreasing trend during storage time. The color density increased with increasing US time, which might be because of the instantly high temperatures and pressures created by acoustic cavitation, which can mediate free radicals and chain reactions, leading to more colored pigments [45].

Recently, Pérez-Porras et al. [42] investigated the impact of high-power US on the physico-chemical and chromatic properties of Monastrell red wine. The US treatments were applied during skin maceration at 20 and 28 kHz frequencies for 48 and 72 h, while control wines were macerated for 48 and 72 h without US treatment, and another wine sample was macerated for 7 days. The results showed that grape cells treated with US exhibited uniform coloring, a minor epicarp compression, plasmolysis of subepidermal cells, a degree of mesocarp collapse, and a higher number of cells without coloration. Contrarily, control grapes exhibited a highly homogenous distribution of cells with a very tiny spherical inclusion. The 20 kHz sonicated grapes exhibited the slowest fermentation rate during the first few days of fermentation, which was ascribed to a decrease in endogenous microbial load caused by the impact of the sonication on the populations of micro-organisms [43]. At the end of maceration, the sample treated with a 28 kHz frequency for 72 h had the highest color intensity (21.66), total phenol index (68.25), and total anthocyanin content (776 mg/L), whereas the sample macerated for 7 days without US treatment had the highest methyl cellulose precipitable tannins (1707 mg/L) and polymeric anthocyanins (27 mg/L). Furthermore, at the conclusion of alcoholic fermentation and bottling, the sample macerated for 7 days without US treatment had the highest values for all the above parameters. The total tannin extraction was higher after skin maceration (1112 mg/L), at the conclusion of alcoholic fermentation (1040 mg/L), and at bottling (988 mg/L) in all US-treated samples as compared to control samples. The lowest alcohol value (14.92%) was observed for the 7-day maceration control sample, a fact attributed to the more intense ethanol evaporation occurring at higher temperatures, as well as to the longer skin maceration time. However, no significant changes were observed in the other samples. There were no significant changes in malic acid, tartaric acid, and volatile acidity. The methanol concentration for the sample treated with 28 kHz frequency for 72 h was lower than that of the sample macerated for 7 days without US treatment (173 mg/L vs. ad 265 mg/L). In general, this experiment yielded auspicious results and indicated that US treatment helps to reduce skin maceration time, increase color intensity, and improve the chromatic properties of red wines.

Indeed, the effectiveness of US treatments in the wine sector has been recognized by the OIV, and the practice has been admitted for use in enology in 2019 with the resolution OENO 616-2019 [32]. In particular, the resolution recommends the use of ultrasound on crushed grapes for rapid extraction of grape compounds during pre-fermentation maceration, after destemming and crushing. As a result of the treatment with US, winemakers can expect to accelerate grape processing by increasing the concentration of phenolic compounds, thus reducing the maceration time compared to traditional processes. Additionally, US can be used to limit the release of seed tannins that are present thanks to the shorter maceration time, a fact especially important for grapes with incomplete phenolic maturation.

2.3. Pulsed Electric Field (PEF)

Pulsed Electric Field is one of the most innovative pasteurization technologies for food and beverages thanks to its ability to inactivate pathogenic and spoilage-causing bacteria at room temperature without compromising the quality of products [46,47]. PEF treatment is applied through a material placed between two electrodes for a short duration (microseconds) by using high-strength electric field (0.1 to 50 kV/cm) pulses (exponential or square) [48]. Table 3 summarizes the effects of PEF treatments on wine.

In wine, PEF has been used to improve skin maceration rate and accelerate the aging process. PEF has been shown to inactivate wine-spoilage micro-organisms, to encourage the extraction of phenolic compounds from skin cells during maceration, and to enhance the quality of the wine [49]. Puértolas, López, et al. [46] studied the impact of PEF on the inactivation of spoilage yeasts and bacteria. The electric field strengths utilized in this study ranged from 16 to 31 kV/cm, from 10 to 350 kJ/kg at 24 °C, from 0 to 100 pulses, with individual pulse energies ranging from 1.02 to 3.77 kJ/kg and a frequency of 1 Hz. Optimized PEF parameters (186 KJ/Kg at 29 kV/cm) led to a 99.9% reduction in the spoilage-causing microbes of must and wine, thus restricting the undesirable effects of microbes of the genera *Brettanomyces* and *Lactobacillus*. PEF treatment (32 kV/cm and 250 Hz for 51.2 s) on contaminated wines showed modest effectiveness in lowering the load of *B. bruxellensis* [50]. However, the *B. bruxellensis* population was reduced by 3 orders of magnitude in PEF-treated wine at 50 kV/cm, demonstrating that the electric field strength has a greater impact on *Brettanomyces* spp. inactivation than the amount of energy applied [51].

Table 3. Key literature findings for pulsed electric field (PEF).

Conditions	Type of Wine	Effect	References
23 kV/cm, 95 KJ/Kg, 8 µs, continuous flow, T < 22 °C	Tempranillo	■ *Brettanomyces/Dekkera* inactivation in aged wine. ■ Lactic acid bacteria inactivation in young wine. ■ No variations in organoleptic quality.	[52]
50 kV/cm, 117–121 KJ/kg, 1.7 µs, square bipolar pulses, T = 10 °C	Red wine	■ No significant changes in sensory attributes. ■ Antimicrobial effect: 3 log CFU/mL reduction. ■ No significant changes in Fe, Cr, and Ni ion concentrations. ■ No effect on wine quality parameters.	[51]
16–31 kV/cm, 10–350 KJ/kg, decay waveform pulses, T = 24 °C	Red wine and must	■ Reduction/inactivation of spoilage microbes in must and wine. ■ Reduction/elimination of the SO_2 requirement. ■ No differences in the aroma, taste, mouthfeel.	[46]
1.5 kV/cm, 8 µs at 11 kJ /kg and 16 µs at 22 kJ/ kg, square wave pulses, frequency of 600 Hz, T = 20 °C	Garganega white wine	■ Rate of alcoholic fermentation unaffected. ■ Increased extraction of varietal aroma precursors. ■ Increase in juice yield at pressing. ■ No significant change in sugar level. ■ No significant change in wine pH. ■ Decrease in wine alcohol level. ■ Increase in wine color intensity and phenolics. ■ No difference in taste and mouthfeel.	[53]
1.5 kV/cm, 1 µs at 2 kJ /kg, 5 µs at 10 kJ /kg and 10 µs at 20 kJ/ kg, square wave pulses, frequency 400 Hz at 22 °C	Rondinella red wine	■ Rate of alcoholic fermentation unaffected. ■ Increase in juice yield at pressing. ■ No significant change in basic compositions of the wine. ■ Increased wine color intensity and stability. ■ Increase in anthocyanins and total tannins. ■ Decrease in total dry extract. ■ No significant sensory difference in sensory.	[54]

Table 3. *Cont.*

Conditions	Type of Wine	Effect	References
3 kV/cm, 3 and 10 kJ/kg, 3 s. Rectangular wave pulses at 15 °C + enzymes	Traminer and Grüner Veltliner white wines	■ Increased extraction of primary varietal aroma compounds. ■ No difference in juice yield. ■ Increase in released nitrogen (variety-dependent). ■ Reduction in fermentation time (variety-dependent). ■ Increased turbidity and higher amount of polyphenols (variety-dependent).	[55]
0.9–3 kV/cm, 10.4–32.5 kJ/kg, square waveform pulses, 1500 Hz frequency for 10 µs	Sangiovese red grape must and wine	■ Increased wine color intensity and stability. ■ Enhanced extraction of bioactive compounds (polyphenols and pigments) in musts. ■ Minor difference in final wine sensory properties. ■ No significant change in wine pH and titratable acidity. ■ Protection of musts/wines from oxidation.	[56]

Comuzzo et al. [53] studied the effect of PEF on the composition and volatile compounds of white wine (cv. Garganega grapes). PEF treatments were performed on crushed grapes at 20 °C by using square wave pulses with a frequency of 600 Hz and an electric field intensity of 1.5 kV/cm with single pulse lengths of 0 µs (no pulse, untreated), 8 µs (total specific energy of 11 kJ/kg), and 16 µs (total specific energy of 22 kJ/kg). The results indicated that PEF enhanced wine yield during pressing by 8.9% and 4.3% for samples treated at 11 kJ/kg and 22 kJ/kg, respectively, as compared to the control sample. PEF treatment led to no significant changes in the sugar level of the juice and yeast-assimilable nitrogen concentration, although an increase in the pH of musts and a decrease in total acidity was observed, an occurrence that was possibly linked to the higher degree of salification of organic acids because of an increased cation extraction from the skins. The kinetics of alcoholic fermentation were unaffected by PEF treatments, and there was no significant change in the total acidity, volatile acidity, and pH of the wine. PEF-treated wines had higher total polyphenols concentration and were more intense in color, while no significant change in the aroma compounds (such as alcohols, esters, and fatty acids) compared to the control sample was reported.

The same authors [54] investigated the effect of PEF on red wine (cv. Rondinella) by treating crushed grapes at 22 °C by using square wave pulses with a frequency of 400 Hz and an electric field intensity of 1.5 kV/cm with single pulse lengths of 0 µs (no pulse, untreated), 1 µs (total specific energy of 2 kJ /kg), 5 µs (total specific energy of 10 kJ /kg), and 10 µs (total specific energy of 20 kJ/ kg). The results indicated that the yield at pressing increased (+4.4–18.3%) in all PEF-treated samples. At the end of alcoholic fermentation, PEF-treated wines at 10 and 20 kJ/kg had higher color intensity (~30%) and total phenolic index (~40%) compared to the untreated wine. However, the wine that resulted from grapes treated at 2 kJ/kg was poor in color and polyphenol extraction, in addition to being the one with the lowest total dry extract. The wines were monitored for 12 months after fermentation, and PEF wine basic composition parameters (e.g., pH, reducing sugar, alcoholic strength, total acidity) did not change during aging. Color intensity (5.1, 4.3), total phenolic index (40.8, 44.8), anthocyanins (225 mg/L, 78 mg/L), and total tannins (2.3, 2.4 g/L) were significantly higher for the wine made from grape samples that were treated at 20 kJ/kg when compared to untreated wines after 2 and 12 months of storage, respectively. Ultimately, sensory evaluation did not show a significant difference for characteristics such as wine body and fruity and vegetal/herbaceous aroma.

Furthermore, the effects of combined PEF and enzymatic treatments on Traminer and Grüner Veltliner wines were investigated by Fauster et al. [55]. Crushed grapes were treated with PEF by using rectangular wave pulses at 15 °C with an electric field strength of 3 kV/cm and specific energy of 3 and 10 kJ/kg for 3 s. Immediately after PEF treatment, 3 g/hL of pectolytic enzymes and 50 mg/L of SO_2 were added to both PEF-treated and -untreated musts, and skin macerations were performed at 15 °C for 4 or 24 h. The results showed that the low-intensity PEF treatment did not impact the overall juice yield. An increase in fermentation rate was observed for the Traminer, with fermentation time reduced from 16 to 14 days for wines macerated for 4 h, and from 20 to 16 days for wine macerated for 24 h, an occurrence that was tentatively ascribed to the 10% increase in total assimilable nitrogen present in PEF-treated grapes. However, this effect was observed only in the Traminer wine, as fermentation rates for Grüner Veltliner were not affected. After 10 months of storage, PEF-treated Grüner Veltliner and Traminer wines had greater total polyphenols and a higher concentration of hydroxycinnamates than the control wines. The aroma composition (tested esters and terpenes) of the Grüner Veltliner was not significantly affected by the combination of PEF and enzymes, while, for Traminer, the application of 10 kJ/kg and 24 h maceration time resulted in a significant increase in the concentration of some esters such as ethyl-trans-2-decenoate (+150%), ethyl dodecanoate (+110%), and ethyl decanoate (+87%), as well as a significant increase for selected terpenes compared to samples treated by enzymes alone.

Ricci et al. [56] examined the effects of PEF with square waveforms at a frequency of 1500 Hz for 10 μs with an electric field intensity of 0.9–3 kV/cm and a specific energy of 10.4–32.5 kJ/kg on Sangiovese red wine that was produced from early harvested grapes (16.9°Brix, 3.26 pH, and 10.4 g/L titratable acidity). The results indicated that while PEF treatment enhanced the conductivity of the juice, it had no discernible impact on the pH, titratable acidity, or sugar levels of the juice. PEF-treated wines had more total phenolics (+16–23%), with a maximum increase in juice color intensity (+51% compared to the control) observed for the 23.8 kJ/kg treatment. PEF-treated wines showed no significant change in alcohol content, pH, and total acidity, while the wine that was treated at 10.4 kJ/kg had the highest volatile acidity (0.7 g/L) among all the wines. The parameters associated with phenolic compounds (total phenolic content, tannin content, color intensity) were generally higher in the PEF-treated wines than untreated ones, thus suggesting PEF as a promising technique to improve the maceration in red winemaking.

The positive findings on the use of PEF in winemaking led to this technique being admitted in 2020 by the OIV (resolution OIV-OENO 634-2020) for the treatment of red and white destemmed and crushed grapes, with the aims of facilitating and increasing the extraction of valuable substances such as polyphenols (for reds), yeast available nitrogen, aroma compounds including precursors, and other substances that are located inside the grape cells. In addition, PEF is recommended by the OIV to reduce maceration time, while the OIV resolution does not mention the use of PEF to inactivate wine spoilage micro-organisms, despite reports from several authors on its effectiveness also in this aspect [46,57].

2.4. Microwave (MW)

Microwave is one of the most innovative food-processing techniques, and it can be used for baking, thawing, pasteurizing, tempering, drying, and sterilizing food and beverages [58]. MW processing is more popular nowadays due to its rapid heating rate, shorter cooking time, consistent heating, safety, convenience, and cheap maintenance cost [59]. Microwaves are electromagnetic waves with wavelengths ranging from 1 m to 1 mm, the frequency of which varies within 300 MHz to 300 GHz. Industrial microwaves operate at frequencies ranging from 915 MHz to 2.45 GHz, whereas domestic microwaves typically operate at 2.45 GHz [60,61]. Recently, MW has been experimented with in winemaking scenarios with promising findings, and the effects of MW on wine are summarized in Table 4.

In 2014, MW treatments applied during the skin maceration step resulted in wines that are richer in total phenols, anthocyanins, tannins, and pigmented tannins while reducing the overall yeast population [62]. Several authors observed that the growth rate of numerous *Brettanomyces* spp. strains increased when low-intensity MW (low specific adsorption ratio and low exposure period) were applied. On the other hand, high-intensity MW negatively affects yeast growth, with a reported increase in mortality due to cell collapse and electroporation phenomena. Casassa et al. [63] studied the effect of MW-assisted extraction on the phenolic chemistry and color of Merlot red wine produced from grapes collected at three different stages of maturity. MW treatments were given at 1200 Watts for 10 min after crushing, and the results showed that MW treatment increased the alcohol level as compared to control wine for the sample with intermediate maturity, while no significant difference in pH, tartaric, citric, malic, lactic acid, and acetic acid were noted. The most important impact of MW was on the anthocyanin content, which increased by over 200% in the two wines produced from the grapes at low and intermediate ripeness. In comparison, for the wine produced with the ripest grapes, the increase in anthocyanins was 89%. This improvement in the extraction of anthocyanins resulted in wines with ~50% higher color intensity and higher amounts of total pigments.

Sánchez-Córdoba et al. [64] investigated the effect of MW on Tempranillo red wine production via olfactometric and sensory evaluation. MW treatments applied during the pre-fermentative maceration of Tempranillo grapes (400 W, 10 min, 30 °C) resulted in wines with a lower pH and alcohol content as compared to untreated wines, while no differences in sulfite content and total acidity were noticed. When the fermentation process was completed, the sensory and olfactometric assessment revealed no discernible differences between the treated and untreated wines, while positive changes in the sensory profiles of wines emerged during aging.

Muñoz García et al. [65] studied the impact of MW maceration and SO_2-free vinification on the volatile composition of red wine. In this study, MW treatment (700 W for 12 min) was applied to crushed Cabernet sauvignon grapes. MW-treated grapes in the presence of 50 mg/L of SO_2 yielded wines with the highest values in free volatile compounds (as 1-hexanol, cis-3-hexen-1-ol, trans-3-hexen-1-ol, cis-2-hexen-1-ol, and trans-2-hexen-1-ol) when compared to the control and MW-treated wine without SO_2. The MW-macerated wine without SO_2 showed faster fermentation kinetics and increased fermentation yields, which are facts that are likely due to the lack of inhibition of yeast by SO_2, a finding in line with results from other studies performed on Pinot noir with MW maceration at high potency [62,63]. Sensorially, MW-macerated wines had higher intensity in red berry and floral notes, along with the overall aroma intensity, a fact attributed to the higher amount in esters and acetates in MW-treated wines which, additionally, showed higher odor-active values in all fatty acid esters.

Table 4. Key literature findings for microwave (MW).

Conditions	Type of Wine	Effect	References
1150 W, for 2 min, 1 min and 14–40 s	Pinot noir red wine	■ Increased total concentrations of phenolics, anthocyanins, and tannins after 18-months' bottle ageing. ■ Decreased maceration time. ■ Decreased grape-associated yeast population. ■ Reduced need for SO_2 at crushing. ■ Higher color intensity.	[62]
1200 W, for 10 min	Merlot red wine	■ No significant changes in pH and acidity. ■ Increased anthocyanin content. ■ Formation of polymeric pigment. ■ Increase in wine color. ■ More extraction of tannins.	[63]

Table 4. *Cont.*

Conditions	Type of Wine	Effect	References
400 W, for 10 min	Tempranillo red wine	■ No significant sensory differences with pre-fermentative maceration ■ Positive sensory changes when used during aging. ■ Minor decrease in pH and alcohol level during pre-fermentative maceration. ■ No significant difference in free SO_2, total SO_2 and total acidity.	[64].
200 W and 300 W	Wine lees (Syrah grapes & Port wine lees)	■ Enhanced anthocyanin extraction. ■ Reduced extraction time. ■ Increased oxygen radical absorbance capacity. ■ Increased total phenolic content.	[66,67]
700 W for 12 min	Cabernet sauvignon red wine	■ Higher amount of C6 alcohols, terpenes, and norisoprenoids in free form. ■ Faster fermentation rates, shorter lag phase. ■ Increase in volatile compounds such as alcohols, esters, and acetates, but decrease when SO_2 was not present. ■ Improved sensory rating	[65]
500 W at 5, 10, 15, and 20 min	Red wine	■ Decrease in total phenolic, total monomeric anthocyanin, titratable acidity, and DPPH-free radical scavenging activity. ■ No significant changes in electrical conductivity and pH. ■ Increase in color parameters (L*, a*, b*).	[68]
Industrial microwave at 70 °C (whites) or 60 °C (reds) for 4 min 0 W, for 10 min	Red and white wine	■ Good extraction of total phenolics and color. ■ Reduced extraction time. ■ Change in color extraction (variety-dependent).	[69]
Domestic microwave 700 W for 4 min repeated 3 times	Cabernet sauvignon red wine	■ Increase in color intensity and anthocyanin content. ■ Increase in total phenolic index and tannins.	[70]

In addition, Yuan et al. [68] treated young Cabernet sauvignon red wine by MW (500 W for 5, 10, 15, and 20 min) and investigated its impact on physicochemical properties. No appreciable changes in electrical conductivity or pH were reported, while decreases in the levels of total phenolic compounds, total monomeric anthocyanins, titratable acidity, and DPPH-free radical scavenging activity were noticeable in correspondence with an increase in the treatment duration.

Recently, Pérez-Porras et al. [70] microwaved (700 W for 12 min) Cabernet sauvignon grape must, containing 50 mg/L SO_2. The results showed a significant increase in color intensity (+16%), total phenolic index (+14%), total anthocyanins (+14%), polymeric anthocyanins (+17%), and total methylcellulose precipitable tannins (41%) in the wine produced from MW-treated grapes compared to control wine. The increase in tannins content was attributed to the over-extraction of tannins during the process, a fact that may result in astringent and bitter wines. Conversely, Carew et al. [62] found that MW-treated wine had a fuller, softer mouthfeel and higher palate length than the untreated wines.

Overall, MW maceration has been shown to be an effective technique to extract phenolics as well as in sanitizing musts. In general, the fields of application are like other non-thermal techniques such as HPP, US, and PEF, so its potential use in commercial winemaking could lead to savings in processing times and in the need for preservatives. However, MW, unlike HPP, US, and PEF, is not currently listed in the International Code of Oenological practices [32]; therefore, its future commercial uptake will depend on its admission as an allowed practice in enology.

2.5. Irradiation (IR)

Irradiation is a cold pasteurization technique of food which is performed by exposing the foodstuff to an ionizing energy source, which includes radio waves, infrared radiation, gamma rays (^{60}Co), X-rays, γ- radiation, and electrons [71,72]. Depending on the radiation, IR treatments reduce or kill foodborne pathogens. Irradiations are interesting, as they are reported to cause a negligible or acceptable loss of nutrients and sensory qualities of food and beverage compared to thermal techniques [9]. In particular, UV radiations do not alter the taste and color profiles of juices but help in reducing the microbial load to acceptable levels [73]. Indeed, gamma and UV radiations have been used to inactivate the microorganisms in pomegranate, carrot, kale, orange, and guava-and-pineapple juices [73–75].

IR has also been proposed for utilization in winemaking, and its effects on wine are summarized in Table 5. Recently, Błaszak et al. [76] used E-Beam irradiation to preserve wine instead of using SO_2. Red wine was treated with an IR dose of 1–10 kGy, and the findings showed that, independently of the IR level used, a considerable reduction in yeast counts was achieved, ranging from a 95% decrease for 1 kGy to a 99.9% yeast elimination for the 10 kGy IR dose. The wine treated with 10 kGy IR was over 30% brighter than the control wine. Several phenolic substances, including hydroxycinnamic acids and their derivatives, as well as flavonols, have been shown to be rather resilient to the effects of irradiation. The authors suggested that the 2.5 kGy dose allowed for adequate wine microbial stabilization, resulting in a wine with a lower content of phenolics but a negligible change in color. Similarly, Morata et al. [77] reported that yeast counts in fresh grapes were significantly reduced at low IR doses (0.5 and 1 kGy) and completely eliminated at 10 kGy. The color of the wine prepared with irradiated grapes was more intense thanks to its higher anthocyanin content.

Parish-Virtue et al. [78] studied the impact of UV light irradiation of harvested grapes on the thiol content of Sauvignon blanc. UV treatments (334 W/m^2 for 30 min) were applied to both hand-harvested and machine-harvested grapes. The results indicated that none of the main juice parameters (sugar content, titratable acidity, yeast assimilable nitrogen) changed. Moreover, there were no significant differences in ethanol content, free and total SO_2, pH, and titratable and volatile acidity parameters between wines produced from UV-treated grapes and untreated wine. UV treatments did not result in substantial quantitative changes in the thiol precursors GSH-3MH and Cys-3MH in the juices, while higher levels of β-damascenone were found in wine produced from UV-treated and machine-harvested grapes. The wine produced from UV-treated hand-harvested grapes had the greatest level of isoamyl acetate.

Mihaljević Žulj et al. [79] used gamma irradiation (the panoramic ^{60}Co source) at four doses (0.67, 1.3, 2.0, 2.7 kGy) as a pre-fermentative treatment on Merlot and Traminer grapes. The treatments did not affect wine ethanol concentration, pH, and titratable acidity. Merlot and Traminer wines produced with 2.7 kGy-treated grapes had the highest concentration of sugar-free extract and the lowest volatile acidity. Similar conclusions were drawn by Gupta et al. [80], as they reported that irradiation treatments did not significantly impact wine ethanol content, pH, or reducing sugars. Traminer musts derived from grapes that were irradiated at 1.3 kGy showed a 60% decrease in total amino acids, while no significant differences were found at 0.67, 2.0, and 2.7 kGy. In Merlot, the IR treatment also affected the total amino acid content, with the lowest values (−38% vs. control) found in grapes irradiated at 2.0 kGy. The gamma irradiation affected the content of anthocyanins in the wine, with the highest concentration of total anthocyanins observed at 2.7 kGy. The total amount of flavonol molecules was not significantly different, but several specific flavonols, such as myricetin-3-glucoside and kaempferol, were present only in samples that were exposed to radiation. Finally, gamma irradiation impacted wine volatiles, with doses of up to 2.0 kGy resulting in an increase in fruity–floral compounds such as monoterpenes and C13 norisoprenoids. However, at the highest irradiation dose (2.7 kGy), higher levels of furfural and furfuryl alcohols were found, leading to greater toasted and caramel notes in the wine.

Table 5. Key literature findings for irradiation.

Conditions	Type of Wine	Effect	References
E-Beam irradiation 1–10 kGy	Red wine	■ Up to 99.9% reduction in yeast count. ■ No significant change in organoleptic and chemical properties. ■ 2.5 kGy enabled microbial stabilization of wine. ■ Acceptable change in color parameters.	[76,77]
UV light irradiation 334 W/m^2 for 30 min	Sauvignon blanc grapes and wine	■ No significant difference in °brix, ethanol, pH, titratable acidity, or volatile acidity of juice and wine. ■ Reduction of 3 MHA (lower 3-mercaptohexyl acetate) in wines. ■ Impact on thiol precursors. ■ Reduction in hexane-1-ol in wine. ■ Increase in temperature of grape juice.	[78]
Gamma irradiation panoramic ^{60}Co at 670, 1300, 2000, 2700 Gy	Traminer and Merlot grapes and wine	■ Negative impact on amino acid content of musts. ■ Decreased volatile acidity. ■ Better extraction of color compounds. ■ Increased concentrations of anthocyanins. ■ Enhanced aroma profile up to 2000 Gy. ■ No effect on flavonols and flavan-3-ols.	[79,80]
UV-vis irradiation 400 W for 3 h and 30 min	Xarel·lo and Parellada white wines	■ Partial inactivation of polyphenol oxidase. ■ Reduced volatile acidity. ■ No significant differences in pH, tartaric acid, alcohol content. ■ Color modification (higher redness, lower brightness). ■ Useful for reducing the amount of SO_2.	[16]

Falguera et al. [16] used UV-vis IR (400 W for 3 h and 30 min) as an alternate method to reduce SO_2 in Xarel·lo and Parellada white wines. Polyphenol oxidase (PPO) was partially inactivated (−70% in Xarel·lo and −82% in Parellada) in all UV–vis irradiated samples, which are findings that are in line with the results from white grape varieties (Victoria and Dauphine) reported by Falguera [81]. The IR treatments did not result in significant wine color changes. Irradiated samples showed slower fermentation kinetics than untreated and SO_2-added samples, most likely because the natural microbiota of the musts was inactivated during the process. UV application on grape bunches was very effective in leading to higher phenolic compound extraction to produce Pinot noir, which exhibited a higher color density (+79%), total phenolics content (+85%), anthocyanins content (+106%), tannins content (+202%), and total pigments content (+66%) [82]. Indeed, the exposure of grape berries to UV radiation may activate genes of the phytopropanoid pathway, which leads to an increase in flavonol and flavonoid synthesis [83]. Furthermore, UV-C treatment has been found to inactivate micro-organisms in grape must [84].

Overall, IR treatments have shown promise for application in wine production, even if their impact on secondary grape metabolites such as phenolic and volatile compounds needs to be better comprehended. As stated for MW, also IR treatments are still in the research stage, and for them to be admitted by the OIV, additional and more comprehensive data on the impact of this technique on wine quality are required.

2.6. Other Non-Thermal Technologies

Some other novel technologies, such as ozone (O_3) [85,86] and ohmic heating [87–89] have been recently proposed as novel winemaking tools.

2.6.1. Ozone (O_3)

Due to its numerous uses in the beverage sector, such as in fermentation, for microbial inactivation, and for post-harvest treatments, ozone (O_3) can be considered as cutting-edge, eco-friendly, and versatile technology. Ozone, an oxygen allotrope, is formed when atmospheric oxygen molecules (O_2) are split apart by lightning or UV radiation (phytochemical technique). Nowadays, UV light with a wavelength of 188 nm and a powerful electrical field are the major sources of ozone production (e.g., corona discharge methods) [85,86,90–92].

Ozone treatment (20 g/h with 6% *w*/*w* O_3) to Petit verdot grapes just after harvesting increased the anthocyanin content (+12.5%), phenolics (+2%), and color index (+4%) of the wines, while decreasing the free SO_2 (−78%) and total SO_2 (−72%) content in wine compared to a wine produced from untreated grapes. Furthermore, during the sensory assessment, O_3-treated wine had a high score for the fruity, blackberry, red fruits, cherry liqueur, spicy aroma, and overall quality compared to the untreated wine [93]. Moreover, Cravero et al. [94] studied the effect of gaseous (24 h) and aqueous (6 min) O_3 treatment on Barbera grapes. The results indicated that O_3 treatment effectively reduced (by 0.5 Log CFU/mL) the yeast population on the grape berry surface. In the wines produced from grapes treated with aqueous O_3 (6 min at 5 mg/L), an increase in several volatile compounds such as total fatty acids (+27%), total alcohols (+6%), terpenes, and C_{13}-norisoprenoid (+73%) was reported, while the content in total esters decreased (−17%) when compared to a control wine. In the wine treated with gaseous O_3, fatty acids (+70%) and total alcohols (+14%) increased, and total ester decreased (−43%), while no effect was observed on terpenes and C13-norisoprenoid as compared to the control wine.

Recently, García-Martínez et al. [95] studied the oenological characteristics of Cabernet sauvignon grown in vineyards that were treated with ozonated water. The authors reported that using ozonated water in vineyards minimized the need for pesticides and prevented fungal growth, with an additional positive impact on grape characteristics such as color, phenolic content, and aromatic potential.

2.6.2. Ohmic Heating (OH)

Ohmic heating is the process in which an electric current passes through the material and generates heat within the product at extremely rapid rates (a few seconds to a few minutes). OH has a wide range of applications, such as blanching, evaporation, dehydration, fermentation, extraction, sterilization, pasteurization, and heating of foods to serving temperature [96,97]. A recent study [89] investigated the effects of OH (before alcoholic fermentation) on the extraction of polyphenols from Aglianico and Barbera grape berries. The results indicated that the phenolic content of the must was double in OH-treated grapes (E = 55 V/cm, t = 60–90 s, and T = 72 °C) compared to conventional thermally treated grapes. Wines produced from OH-treated grapes must show total polyphenolic content that is higher by 17% and 30% in comparison to wines produced from conventional heated and untreated must, respectively. Conversely, no significant variation was observed in the total tannin and anthocyanin concentrations of wines produced from OH and conventionally heated must. Furthermore, some aromatic esters showed 30 to 200% increases in wines from OH-treated must, thus indicating that this approach can lead to the compositional modifications of wines with quality impacts.

3. Conclusions

Transforming grapes into wine involves a numerous series of decisions by the winemakers, the combination of which dictates the final composition, quality, and style of the wines produced. In this context, different techniques and technologies can be adopted for the conduction of each processing step to deliver a consistent, high-quality, and safe product to consumers. Although winemaking maintains strong links with traditional processing methods, in the past few decades, technological advancements have allowed wine to reach unprecedented quality levels. However, recent challenges in the food and beverage production sectors have led to the proposal of novel, more efficient technologies, many of which have been trialed with varying success for winemaking.

The latest findings related to the application of the most promising non-thermal technologies to winemaking, such as high-pressure processing, pulsed electric field, ultrasound, microwave, irradiation, ozone, and ohmic heating, were reviewed. In general, the wine aspects that were mostly affected by the application of novel processing techniques were related to the extraction of phenolic compounds leading to differences in wine color characteristics, particularly for red wines. Indeed, most experiments investigated the use of non-thermal technologies on crushed crapes, with or without skins, and particularly on the impact of these technologies on the extraction of quality-relevant compounds during maceration steps. This typically resulted in the modification of the composition in wine secondary metabolites, a fact that led, at times, to modifications in wine sensory properties and volatile profiles.

Another aspect that was investigated relates to the impact that these novel technologies have on juice and wine microbial load. Indeed, several studies have reported a great decrease in microbial load after these treatments, a fact that can reduce the use of sulfites to protect the wines, which is in line with the current requests by consumers of wines with low or no sulfite added.

To date, the most promising techniques, possibly thanks to the higher research attention that they received, are pulsed electric field, ultrasound, and microwave for improving the extraction of valuable compounds from grape skins, while for grape sanitation, the most promising techniques seem to be high-pressure processing, microwave, and irradiation. Nevertheless, the least-studied non-thermal options (e.g., ozone, ohmic treatment) have also shown the potential to yield encouraging results, and as the body of knowledge related to their use in wine production will increase in the coming years, it will become possible to benchmark their effectiveness with the other more studied non-thermal techniques.

It must be noted that the here-reviewed technologies are at different levels of development, with some technologies such as high-pressure processing, pulsed electric field, and ultrasound being already in use for other beverages and admitted by the OIV for use in winemaking. Conversely, technologies such as microwave, irradiation, ozone treatment, and ohmic heating, although promising, are at a lower stage of development, and more research is needed for their future commercial application in winemaking. Undoubtedly, the modern wine consumer's growing demand for healthier, preservative-free, quality wines represents a stimulus for the development of non-thermal technologies also in the wine sector, and this, in turn, is expected to result in an increase in the scientific production over the next few years. This fact should, in the next decade, lead to the availability, on a commercial scale, of at least a couple more of these technologies also for the wine industry.

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