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Investigation of Xinomavro Red Wine Aging with Various Wood Chips Using Pulsed Electric Field

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Abstract: This study explored the potential of pulsed electric field (PEF) as an alternative wine-aging method in four Xinomavro red wines with the implementation of several wood chips (apricot, peach, apple, cherry, acacia, and oak trees). The evolution of total polyphenol content (TPC) and sensory properties of the wines were investigated. Sensory evaluation revealed that PEF treatment increased volatile compound extraction from each wood chip, thereby enhancing the overall quality of the wines. The utilization of acacia tree wood chips in Goumenissa wine led to a notable increase of 10.84% in TPC from the control sample, reaching 2334.74 mg gallic acid equivalents/L. A notable outcome was that PEF decreased TPC, a trend that was also verified through correlation analyses. The highest positive impact of PEF was observed in peach tree wood chips in Goumenissa wine, with a significant increase of 11.05% in TPC. The results from the volatile compound analysis revealed an increase in alcohols and esters from 0.24% to 23.82%, with the highest proportion found in 2-phenylethanol (16.92 mg/L) when utilizing peach tree wood chips in the production of Amyndeo wine. This study could provide a benchmark for rapid, efficient, and cost-effective wine aging through the implementation of the PEF process.

Keywords: HS-SPME/GC-MS; pulsed electric field; wine aging; polyphenols; volatile compounds; sensory evaluation; color analysis; protected designation of origin; principal component analysis; multivariate correlation analysis

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1. Introduction

The consumption of wine has endured for centuries and continues to maintain significant acceptance in modern society. Based on the latest data from the International Organization of Vine and Wine (IOV), the global consumption of wine in 2022 amounted to ~246 million hectoliters [1]. The highest consumption of wine was recorded in the United States, France, Italy, Germany, and the United Kingdom, which cumulatively consume an average of ~112 million hectoliters annually. Wine is commonly favored over other alcoholic beverages due to a number of factors, including the vast health benefits, along with the unique sensory characteristics. The protective effects of wine against cancer, cardiovascular diseases, and diabetes have been extensively investigated and documented in several studies [2,3]. The components that are commonly found in wine include alcohol, sugars, and organic acids, as well as various other compounds such as polyphenols and volatile compounds [4]. The reported properties of polyphenols include antioxidant, anti-inflammatory, anti-aging, anti-obesity, and cardioprotective effects. The comparative advantage of red wines over other wines could be also attributed to the presence of resveratrol, a potent antioxidant renowned for its numerous beneficial effects [3,5].

The flavor, aroma, and appearance of wine are greatly influenced by the climate and soil conditions in which grapes are cultivated. The combined impact of topographical and climatic factors on grape and wine characteristics and excellence is commonly denoted by the French term "*terroir*" [6]. The production of high-quality wines is mainly observed in geographical areas where the vigor of grapevines is constrained by environmental conditions and, subsequently, enhanced through the implementation of viticultural practices [7]. A popular method of aging alcoholic beverages, such as whiskey, wine, and brandy, is in barrels made of wood, especially from oak. This process provides unique attributes to the beverages, particularly their aroma. Volatile compounds are produced during the aging process of wine [8]. The main chemical process that occurs during the contact of wine with wooden barrels is extraction [9]. From a sensory point of view, the compounds that contribute to the aroma of coconut and woody notes, smokiness, green wood, almond, and spiciness hold significant importance [10]. Oak lactones, eugenol, and vanillin are prominent compounds that significantly impact the sensory characteristics of wine [11].

Flavoring using natural compounds has increased in the food and beverage industry as a result of consumer demand for "organic" products [12]. Red wines are flavored and aged in oak barrels, which provides high-quality organoleptic properties [10]. Color, appearance, tannin profile, and flavor are all affected by this approach [13,14]. However, barrel aging provides a considerable financial burden to winemakers. This is due to the extended period the wine must spend in barrels, which may range from six months to two years, necessitating the use of a large number of barrels and significant space. In addition, oak barrels can only barely be employed for four cycles before they cease supplying beneficial constituents to the wine. The labor-intensive nature of barrel maintenance, filling, and cleaning also raises the cost of aging [13]. To that end, wood chips are a less expensive option than oak barrels [15]. These chips resemble regular barrels when toasted (burned), particularly when compared to untoasted ones. Chips, due to their larger surface area in direct contact with wine, have an advantage over barrels [16]. Lastly, winemakers can inexpensively age and enhance the flavor of the wine by adding chips directly to the tank.

In recent years, the food industry has been particularly interested in pulsed electric field (PEF) treatment due to its advancements as a mild processing technology with various supplemental processes, such as drying, extracting [17,18], and freezing [19]. Plant tissue is treated with PEF, which consists of brief, repeated high-voltage pulses that cause pores to expand, and this in turn enhances membrane permeability and promotes the efficient extraction of intracellular compounds to the solvent [20]. Since PEF is a nonthermal treatment, it preserves the natural quality characteristics of food, including flavor and nutritional content. PEF is also gaining popularity in enology due to a variety of reasons. Initially, PEF was found to increase the quality of red wine and promote brandy aging [21]. PEF was also studied for its effect on the sensory aspects and polyphenol properties of Cabernet Sauvignon red wines matured in oak barrels [22]. Furthermore, PEF increased color intensity, anthocyanin, and phenol content in Merlot grapes during alcoholic fermentation for up to seven months [23]. Another study discovered that PEF increases the quality and quantity of red wine during cold maceration rather than alcoholic fermentation [24,25].

One of the most prevalent wine products in Greece is Xinomavro red wine, made from the Xinomavro vine [26]. The flagship red variety of northern Greece, Xinomavro is planted in the winegrowing districts of Amyndeo and Naoussa, Western and Central Macedonia, respectively, producing Protected Designation of Origin (PDO) wines [27]. The aim of this study was to provide insight into the effect of PEF on the aging and flavoring processes of four Xinomavro red wines from the Amyndeo, Naoussa, Goumenissa, and Velventos regions of Greece. Using wood chips from six different trees (acacia, apricot, peach, cherry, apple, and oak), the study sought to identify how PEF affected its sensory characteristics and aroma profile, while the proportion of polyphenol enrichment of the wines from each wood chip was investigated. This research might lead to the development of novel procedures for the aging and enrichment of wines that can serve as a benchmark for the production of other alcoholic beverages.

2. Materials and Methods

2.1. Chemicals and Reagents

Methanol, 4-methyl-2-pentanol, and sodium chloride were obtained from Sigma-Aldrich (Darmstadt, Germany). Gallic acid and the Folin–Ciocalteu reagent were bought from Panreac Co. (Barcelona, Spain). Anhydrous sodium carbonate was purchased from Penta (Prague, Czech Republic).

2.2. Wood Chips

The production of chips included the use of the pruning residues of toasted tree species, including Acacia (*Acacia pycnantha*), Armenian apricot (*Prunus armeniaca*), sweet cherry (*Prunus avium*), apple (*Malus domestica*), and peach (*Prunus persica*). The wood chips used in the experiment were of tiny dimensions, measuring roughly 8 mm in length and 3 mm in thickness. These wood chips were subjected to a roasting process for 2 h at 200 °C. For the purpose of benchmarking, commercially available medium roasted wood chips from the European high vanilla oak species (*Quercus robur*) were used.

2.3. Vinification Process

The vinification of the wines began in the 2022 harvest. The length of the fermentation procedure lasted sixteen days. The initial fermentation period lasted for ten days at an average temperature of 22 °C for the first four days, while the temperature was raised to 26 °C for the next six days. The development of fermentation was continuously monitored by measuring density. Systematic monitoring of the fermentation kinetics was achieved through the implementation of regular measurements. *Saccharomyces cerevisiae* was the yeast strain utilized in the fermentation process and was purchased from Martin Vialatte (Magenta, France). Its selection was based on its widely recognized capacity to impart the intended sensory attributes to the end product. Additionally, the vinification process was enhanced through the incorporation of pectinolytic enzymes from *Aspergillus niger* which were obtained from Laffort® (Floirac, France). The degradation of pectin compounds was facilitated by these enzymes, which improved the optical clarity of the fluid and increased the overall stability of the wine.

2.4. Wine Sample

The study used freshly produced red wine from monovarietal Xinomavro grapes, sourced from the Amyndeo, Naoussa, Goumenissa, and Velventos regions in Central and Western Macedonia, Greece. The wines averaged chemical characteristics with the following values: alcohol content of 13.43% vol, density of 0.99 g/mL, reducing sugars of 0.95 g/L, volatile acidity of 0.49 g/L (expressed as acetic acid), total acidity of 5.85 g/L (expressed as tartaric acid), active acidity (pH) of 3.48, malic acid content of 0.3 g/L, and lactic acid content of 1.48 g/L. Statistically significant differences ($p < 0.05$) were mostly observed between the samples in both acidity values, both acid contents, and reducing sugars. More detailed information about the chemical characteristics of each wine is included in Table 1. In this study, a control sample of each wine was examined without the addition of wood chips. Additionally, wine samples that included chips, either treated or not with PEF, were also examined. For additional comparison, a wine model solution that emulated genuine wine samples was introduced to the samples in order to facilitate the aging process aided by the PEF technique. This solvent was an alcoholic solution of 13.5% v/v ethanol with 7 g/L of tartaric acid (total acidity) and a pH value of 3.5.

Table 1. Chemical characteristics of the four Xinomavro wine samples.

Parameter	Amyndeo	Naoussa	Goumenissa	Velventos
Alcohol content (% v/v)	13.8 ± 0.77 [a]	14.1 ± 0.38 [a]	12.8 ± 0.83 [a]	13 ± 0.87 [a]
Density (g/mL)	0.99 ± 0.07 [a]	0.99 ± 0.07 [a]	0.99 ± 0.07 [a]	0.99 ± 0.04 [a]
Reducing sugars (g/L)	0.4 ± 0.03 [c]	1.4 ± 0.05 [a]	1.0 ± 0.05 [b]	1.0 ± 0.07 [b]
Volatile acidity (g/L acetic acid)	0.54 ± 0.03 [a]	0.5 ± 0.03 [a]	0.38 ± 0.02 [b]	0.53 ± 0.04 [a]
Total acidity (g/L tartaric acid)	6.5 ± 0.4 [a]	5.1 ± 0.31 [b]	7.0 ± 0.32 [a]	4.8 ± 0.13 [b]
pH	3.31 ± 0.2 [a,b]	3.66 ± 0.25 [a,b]	3.17 ± 0.18 [b]	3.79 ± 0.27 [a]
Malic acid (g/L)	0.1 ± 0 [c]	0.3 ± 0.01 [b]	0.5 ± 0.02 [a]	0.3 ± 0.01 [b]
Lactic acid (g/L)	1.4 ± 0.05 [b]	1.4 ± 0.05 [b]	1.3 ± 0.06 [b]	1.8 ± 0.09 [a]

Significant differences at $p < 0.05$ are indicated by different letters (e.g., [a–c]) in the same column.

2.5. PEF Apparatus and Treatment

A stationary bench scale system was employed as the PEF apparatus. The system included a treatment chamber, a digital oscilloscope (UTD 2062C, ELV Electronic AG, Munich, Germany), a pulse generator (UPG 100, ELV Electronic AG), and a high-voltage power generator (Ensco, Delhi, India). The PEF generator produced rectangular monopole pulses. In order to observe voltage, current, frequency, and pulse waveforms, a digital oscilloscope was used. A copper cylinder (4 mm metal wall, 125 mm length, 28 mm diameter) served as the positive electrode in the treatment chamber (Val-Electronic, Nea Erithrea, Greece). The copper cylinder was fitted with a "U"-shaped cylinder for liquid filling (20 mm in diameter and 130 mm in height). The electric field strength (E) at the present settings was set at 1.1 kV/cm. The duration of the pulses (pulse width) was specified at 10 μs, while the time interval between pulses (pulse period) was set at 1000 μs. Each treatment had a total duration of 20 min.

2.6. Sensory Evaluation

Ten panel members with extensive backgrounds in wine sensory analysis assessed the organoleptic characteristics of wines that were both PEF-treated and non-PEF-treated. A quantity of 20 mL of Xinomavro red wine samples was tagged with three-digit random numbers, placed in conventional wine-tasting glasses, and covered with watch glasses to reduce the possibility of volatile components escaping, in accordance with standard 3591 [28]. The Department of Food Science and Nutrition, University of Thessaly, Karditsa, Greece, provided standard sensory analysis chambers for the assessment [29]. These chambers had separate booths, a consistent source of lighting, no noise or distracting stimuli, and an ambient temperature of 19–22 °C throughout the day. Each panelist tasted and smelled each sample, with a sensory evaluation made on their own. Every wine sample was assessed by the panelists twice. The entire process adhered to the ethical guidelines for online research set forth by the European Society for Opinion and Market Research [30]. This included obtaining informed and explicit consent from all respondents before their participation and ensuring the protection of their personal data. All respondents were fully informed about the objectives of the survey and the use of their provided information. Their informed consent was obtained both before and after their participation in the study. Respondent information was collected anonymously, with the option to choose "do not wish to answer" and without collecting any personally identifiable information.

2.7. Total Polyphenol Content (TPC) Analysis

The wine samples underwent an initial dilution of 1:100 using water before conducting any determination. A volume of 0.10 mL of a diluted wine sample was carefully transferred into a 1.5 mL Eppendorf tube. Additionally, 0.10 mL of Folin–Ciocalteu reagent (2 M) was added to the same tube. The resulting mixture was allowed to react for a duration of 2 min. Then, a volume of 0.80 mL of a 5% w/v sodium carbonate (Na_2CO_3) solution was introduced. Afterward, the mixture was heated in a thermostated water bath (Falc Instruments LBS2, Treviglio, Italy) at 40 °C for 20 min. The absorbance was measured at

740 nm using a Shimadzu UV-1700 PharmaSpec spectrophotometer (Kyoto, Japan). The total polyphenol concentration (C_{TP}) was determined by employing a gallic acid calibration curve from 10 to 100 mg/L in methanol. The quantification of results was conducted by expressing the values as mg of gallic acid equivalents (GAE)/L of wine. The corresponding conversion was achieved using the following equation:

$$\text{TPC (mg GAE/L)} = C_{TP} \times D, \quad (1)$$

where D denotes the dilution.

2.8. Color Analysis

A colorimeter (Lovibond CAM-System 500, The Tintometer Ltd., Amesbury, UK) was used to determine the wine color. To determine color using CIELAB color determination, a 10 mL glass beaker containing the sample was placed in the colorimeter.

Two color coordinates, a^* and b^*, as well as the psychometric index of brightness, L^*, were determined. Additionally, the hue angle (h^o_{ab}) and psychological parameter Chroma (C^*_{ab}) were determined to be:

$$C^*_{ab} = \sqrt{\left(a^*\right)^2 + \left(b^*\right)^2} \quad (2)$$

$$h^o_{ab} = \arctan\left(\frac{b^*}{a^*}\right) \quad (3)$$

Using the following equation, the color difference between the PEF wine sample and the control one (ΔE) for each wood type was computed using the CIE L^* a^* b^* color coordinates [31]:

$$\Delta E = \sqrt{\left(dL^*\right)^2 + \left(da^*\right)^2 + \left(db^*\right)^2} \quad (4)$$

The color properties of wine samples that were diluted 1:5 with water were also measured using a Shimadzu UV-1700 PharmaSpec spectrophotometer (Kyoto, Japan) and a 1 cm quartz cuvette in the UV-Vis absorbance spectrum (200–800 nm). The hue (H) of the wine was determined by dividing the absorbance at 420 nm by the absorbance at 520 nm, and the wine color intensity (CI) by the sum of the absorbance at 420, 520, and 620 nm [32]. Additionally, the following equations were employed for calculating the color composition [33], which is the percentage contribution of each of the three components (yellow, red, and blue) to the overall color as well as the wine brightness (dA %):

$$\text{CI} = A_{420} + A_{520} + A_{620} \quad (5)$$

$$\text{H} = \frac{A_{420}}{A_{520}} \quad (6)$$

$$\text{Yellow (\%)} = \frac{A_{420}}{\text{CI}} \times 100 \quad (7)$$

$$\text{Red (\%)} = \frac{A_{520}}{\text{CI}} \times 100 \quad (8)$$

$$\text{Blue (\%)} = \frac{A_{620}}{\text{CI}} \times 100 \quad (9)$$

$$\text{dA (\%)} = \left(1 - \frac{A_{420} + A_{620}}{2\,A_{520}}\right) \times 100, \quad (10)$$

where the absorbance at wavelength λ is represented with A_λ.

2.9. Volatile Compounds (VCs) Analysis by HS-SPME/GC-MS

The headspace solid-phase microextraction (HS-SPME) methodology was used as a minor modification of a previously published methodology [34]. A coating of divinylbenzene/carboxene/polydimethylsiloxane (DVB/CAR/PDMS) on an SPME fiber was used for HS-SPME (Supelco, Bellefonte, PA, USA). As recommended by the manufacturer, the fiber was conditioned (30 min at 270 °C) before use. A total of 10 mL of the wine sample, 3 g of NaCl, and 2 mg/L of 4-methyl-2-pentanol as an internal standard were added to a 25 mL glass vial for the HS-SPME extraction. The vial was then sealed tightly with a PTFE/silicone septum. For the full duration of both the extraction (40 min) and equilibration (10 min), the vial was kept in a water bath at 40 °C. The fiber was placed above the wine surface in the vial head area. Every experiment was carried out with 250 rpm of continuous stirring. Following extraction, the SPME fiber was taken out of the vial, threaded through the needle, and put into the injector of the gas chromatograph coupled to a mass spectrometer (GC-MS).

GC-MS analysis was performed using a modified technique that was previously reported elsewhere [34]. A capillary column Agilent J&W DB-1 (30 m × 320 µm × 0.25 µm) and an Agilent Technologies (Folsom, CA, USA) gas chromatograph model 7890A linked to a mass selective detector model 5975C were used. The helium carrier gas flowed at a rate of 1.5 mL/min. At 240 °C, the injector was operating in splitless mode. The column was kept at 40 °C for 5 min, then heated to 140 °C at a rate of 2 °C/min. Finally, it was heated for 10 min to 240 °C at a rate of 10 °C/min. There was a 75 min runtime overall. The MSD parameters were as follows: mass range m/z 29–350; source temperature 230 °C; quadrupole temperature 150 °C; and acquisition mode electron impact (EI 69.9 eV). All of the chromatogram peak spectra were assessed using Agilent Technologies (Folsom, CA, USA) MSD Chemstation software (ver. E.02.00.493), and the results were compared with the electron impact mass spectrum libraries NIST11 (NIST, Gaithersburg, MD, USA) and W8N08 (John Wiley & Sons, Inc., Hoboken, NJ, USA). Using the normalization approach, the sample composition was calculated from the GC peak regions (without correction factors). The mean data from repeated GC-MS analyses were used to calculate the amounts of VCs, which were then represented as mg of 4-methyl-2-pentanol equivalents per L of wine.

2.10. Statistical Analysis

The average and standard deviation of the three tests are displayed in the results. Using IBM SPSS Statistics (Version 29.0) statistical software (SPSS Inc., Chicago, IL, USA), the statistical significance of the differences between mean values was evaluated by one-way analysis of variance (ANOVA), with $p < 0.05$ being considered statistically significant. Sensory analysis was not subjected to statistical analysis. The JMP® Pro 16 software (SAS, Cary, NC, USA) was utilized to conduct the principal component analysis (PCA) and multivariate correlation analysis (MCA).

3. Results and Discussion

3.1. Sensory Evaluation

First, an assessment was conducted on the impact of PEF on the sensory characteristics of the four Xinomavro red wines mixed with different types of wood chips. Table 2 displays the results of the sensory evaluation with and without PEF treatment. Wine containing peach tree wood chips displayed a mild aromatic profile with an aggressive acidity. PEF-treated wines, on the other hand, had more intensified peach aromas while contributing to a soft aftertaste, indicating a complex interplay between PEF treatment and the inherent characteristics. Apricot tree wood chips exhibited an aggressive array of flavors in the nose, including peppery, fruity, and woody notes. The implementation of PEF provided better balance in the mouth; however, it also contributed to an oily ending. PEF-treated cherry tree wood chips significantly improved the sensory qualities of the wine, increasing red fruit tastes and extending the pleasant aftertaste. This is consistent with the notion that PEF treatment would improve the extraction of fruity components from wood, resulting in a more enhanced taste profile. PEF had a beneficial influence on flavor in the majority of instances, producing a remarkable velvety mouthfeel. The effects with apple tree wood chips were especially intriguing, with Naoussa and Velventos wines reducing the dry tannin feeling, resulting in a more aggressive mouthfeel. The integration of PEF resulted in desired qualities in the wines, such as a more powerful aromatic profile and jam tones, offering a potential path for improving the taste profile of Xinomavro red wine. Wood chips from acacia trees generally provided a wine with a potent grassy smell and an unbalanced taste. The same outcome was also observed with the employment of PEF treatment, except for Amyndeo and Naoussa wines, which had a softer taste, and Goumenissa wine, which had a more pleasant aftertaste. It could be concluded that PEF treatment had hardly any effect when acacia tree wood chips were used for the aging process. Finally, common oak tree (high vanilla) wood chips showed a significant increase in spicy components, giving an even more complex taste profile. The presence of vanilla in the aromatic compounds was also tasted, and it was more potent after the treatment with PEF. PEF may have facilitated the extraction of compounds that contribute to the sensorial attributes of the wine, as indicated by the potent vanilla aftertaste. In a similar study conducted by Tavares et al. [35], red wines were exposed to cherry, acacia, and oak chips for 90 days. The results showed that oak chips significantly increased the descriptors of vanilla, wood, and coconut, while cherry chips gave fruity notes and acacia chips gave floral and fruity notes. As per our previous study [25], cherry and apple wood chips gave the most favorable outcomes in the sensory evaluation of Xinomavro wines when combined with the PEF technique. The study by Commuzo et al. [36] revealed that the use of PEF led to a slight increase in fruity and woody aroma, along with an astringency aftertaste of Rondinella red wine.

Table 2. Sensory evaluation of wines with several wood chips and with PEF implementation.

Wood Chip	Xinomavro of Amyndeo	Xinomavro of Naoussa	Xinomavro of Goumenissa	Xinomavro of Velventos
Control (no wood)	Aromas of sun-dried tomatoes, olives, and cloves; slightly high acidity with well-defined tannins	Medium aroma intensity with scents of tomato and olive; soft tannins and good balance	Intense aromatic potential, soft and velvety mouthfeel	Rich aromatic potential, oily mouthfeel with a pleasant final taste
PEF Control (no wood)	Reduction in aroma intensity, aggressive acidity, sharper tannins	More flabby nose, but also sharper in the mouth; loses its balance	Medium aromatic intensity, harder mouthfeel with a drier final taste	Medium aromatic intensity, wild mouthfeel with an intense and aggressive final taste
Peach	Low aromatic intensity, fruity with peach notes predominating; tannic mouth with a dry aftertaste and aggressive acidity	More fruity nose, but slightly mismatched to the character of the wine variety; tannic mouth with minor imbalances	Medium aromatic intensity, wild and aggressive in the mouth	Low aromatic intensity with dominant peach notes; tannic mouth with a bitter aftertaste
PEF Peach	Medium aromatic intensity, fruity with dominant peach notes; less tannic on the palate with a dry aftertaste, but also less aggressive acidity	Fruity on the nose, slightly more intense; more rounded mouth, more complete	Sweety nose with a strong presence of small red fruits, velvety mouth	Complex but unbalanced nose, round soft mouth

Table 2. *Cont.*

Wood Chip	Xinomavro of Amyndeo	Xinomavro of Naoussa	Xinomavro of Goumenissa	Xinomavro of Velventos
Cherry	Sweet nose with red fruit notes; very aggressive in the mouth with wild tannins and a dry ending	Varietal character tied with faint notes of cherry; mouth a little tannic and slightly unbalanced	Green nose, with notes of olives and unripe tomatoes; wild, unripe mouth with noticeable acidity	Grassy nose, some unripe cherry and pepper notes; mouth wild and aggressive
PEF Cherry	Sweet, complex nose with cherry notes; less aggressive in the mouth, more peppery, slightly dry ending	Intense notes of cherry on the nose, sweetness; round, velvety mouthfeel with a spicy aftertaste	Cherry jam, olive, and ripe tomato, beautiful acidity, balanced, velvety with a full-bodied aftertaste	Ripe red fruits, varied aromas, with a balanced fruity mouthfeel and long aftertaste
Apricot	Bland nose, strong acidity, imbalance in the mouth; tannic with a dry aftertaste	Closed nose, fruity; round mouth with slightly dry ending	Intense wood characteristics on the nose, dry mouth with intense acidity	Uneven nose, imbalance in the mouth; tannic with a dry aftertaste
PEF Apricot	More aggressive nose, fruity; fuller in the mouth, more oily but with a dry ending	Fruity nose with moderate aromatic intensity; better balance in the mouth, more oily	Complex nose, peppery, the acidity settles down but gives quite a dry ending	Sweet nose of red fruits and ripe tomatoes; round and oily in the mouth
Apple	Medium intensity nose with sweetness; balanced and softer in the mouth	Complexity on the nose, a bit unbalanced with dry tannins and a short ending	Atonic nose, quite hard in the mouth with a strong taste of wood	Medium aromatic intensity, crisp acidity with a dry ending
PEF Apple	Intense aromatic potential, sweeter mouthfeel, more balanced and fattier; calm acidity and a softer ending	More intense aromatic potential, fruity, soft tannins, full mouthfeel, beautiful ending	Sweet nose reminiscent of jams; mouth soft, balanced, and velvety	Sweet complex nose with aromas of forest fruits, soft oily mouth
Acacia	Grassy nose, wild mouth, unbalanced	Grassy nose, unripe, unbalanced	Grassy nose, unripe, unbalanced	Grassy nose, unripe, unbalanced
PEF Acacia	Grassy nose, softer mouth, unbalanced	Grassy nose, softer mouth, unbalanced	Imbalance in the nose, hardness in the mouth, but much more pleasant aftertaste	Unripe nose, hard dry mouth
Oak (high vanilla)	Medium aromatic intensity with the barrel showing faintly in the background; quite tannic and moderately oily on the palate	Medium aromatic intensity; quite tannic and hard on the palate	Medium aromatic intensity; quite tannic and hard on the palate	Medium aromatic intensity, spicy nose; wild tannins with unbalanced acidity
PEF Oak (high vanilla)	Spicy nose with spices and vanilla making their presence felt; full balanced mouth	Peppered nose, soft, balanced round mouth	Complex sweet nose with vanilla notes making their presence felt; fat mouth with a beautiful ending	Aromas of vanilla and smoke in the background and pepper and olive on the back; velvety, soft, oily

In general, the results highlight the significance of novel techniques in the aging of Xinomavro red wine. The observed differences among different varieties of wood chips and PEF treatments highlight the significance of customizing the wood properties, PEF application, and subsequent sensory results. The encouraging improvements observed in particular treatments indicate that the utilization of PEF could accelerate the aging process of Xinomavro red wine and enhance its flavor profile. However, additional research is required to optimize other PEF conditions and combinations of wood chips to produce comparable and desirable sensory results. This thorough investigation offers a valuable contribution to the wider academic discussions regarding innovative methods in viticulture and provides opportunities for further explorations regarding the utilization of PEF in wine aging.

3.2. Polyphenol Enrichment

The polyphenol analysis results for the wines, which are displayed in Table 3, were of considerable interest. To determine the extent of wine enrichment from the wood chips, the wine model solution was initially analyzed. The results revealed that the wood chips obtained from peach and apple trees showed the lowest amount of polyphenol enrichment in the wine model solution at ~2.3 and ~2.6 mg GAE/L, respectively. The wine model solution was subsequently enriched with ~5.1 mg GAE/L using cherry tree wood chips. The contributions of acacia and apricot wood chips to polyphenol content were comparable (~8.5 mg GAE/L), whereas the contribution from oak wood chips (high vanilla content) was the most prominent at ~23 mg GAE/L. The same pattern, however, was not observed in all cases of wine enrichment with wood chips. A general polyphenol enrichment of wines with wood chips was observed. Regarding Xinomavro from Amyndeo, it has been noticed that the utilization of apricot tree wood chips without PEF treatment has proven to be the most beneficial method for enhancing TPC in this particular wine. A statistically significant increase of ~9% ($p < 0.05$) compared to the control sample (3310 mg GAE/L) was recorded. However, the same pattern was observed in Xinomavro of Goumenissa, where the same wood chips would cause a similar increase in TPC (~9.5%) from an initial 2106 mg GAE/L. It should be noted that in several cases, the use of PEF was found to slightly decrease TPC, probably due to polyphenol degradation. This is a well-known pattern that was also documented in prior investigations [37,38] where it appears that polyphenols are likely to be degraded by electrical pulses. This was evidenced in the cases of Xinomavro of both Velventos and Naoussa, in which PEF led to a statistically nonsignificant ($p > 0.05$) decrease in TPC. In these cases, the control (PEF-untreated) samples were found to be the richest in polyphenols, with 3060 and 2642 mg GAE/L, respectively. A similar trend was observed in a similar study [39] where oak tree wood chips were utilized for polyphenol enrichment in Tempranillo red wine. On that occasion, TPC after wood chip treatment was measured at 2364 mg GAE/L, resulting in a ~50% increase in polyphenols. A study from Chinnici et al. [40] investigated the polyphenol enrichment of wine samples (from 85:15 Sangiovese and Merlot grapes) while aging for 1–4 months using steel and wooden casks (from oak and cherry) with 225 and 1000 L capacity. The results showed that an initial polyphenol content of 2390 mg GAE/L increased up to 2480 mg GAE/L after aging for 4 months in a cherry wood cask (1000 L). Nevertheless, this approach necessitated greater time investment compared to the utilization of PEF and wooden chips, in addition to the use of large-volume barrels, which complicates the handling of the samples and requires space. In another study from Teusdea et al. [41], high-quality red wines (Pinot Noir and Merlot) were exposed to several PEF treatments (i.e., drums distance, kV/cm, pulse duration, and frequency) in the maceration process. The results showed that the PEF conditions required thorough examination as TPC ranged from 857 to 1235 mg GAE/L from an initial 886 mg GAE/L in the Merlot grapes. Pinot Noir had an initial 680 mg GAE/L, where PEF exposure led to 642–1378 mg GAE/L. An optimization of PEF parameters was found vital in that research, which could be addressed for each wine or other beverages in a future study.

Table 3. Total polyphenol content (TPC) enrichment and color differences with PEF treatment and wood chips.

Treatment	TPC (mg GAE/L)	*L**	*C**	*h°*	Δ*E*
Wine model solution					
Control	1.0 ± 0.2 [e]	66.7 ± 0.6 [a,b]	4.3 ± 0 [e]	95.3 ± 0 [c]	
PEF No Wood	0.9 ± 0.2 [e]	67.3 ± 0.8 [a]	4.3 ± 0 [e]	95.3 ± 0 [c]	0.6 ± 0.2 [b]
Peach	2.4 ± 0.1 [d,e]	68 ± 0.3 [a]	4.3 ± 0 [e]	95.3 ± 0 [c]	
PEF Peach	2.2 ± 0.3 [e]	67.1 ± 1.1 [a]	4.3 ± 0 [e]	95.3 ± 0 [c]	1.0 ± 0.3 [a,b]
Cherry	5.1 ± 0.3 [c]	66.7 ± 0.6 [a,b]	5.6 ± 0.6 [c,d]	102.4 ± 1.2 [a]	
PEF Cherry	4.8 ± 1.2 [c,d]	67.5 ± 1.6 [a]	5.9 ± 0 [c,d]	93.9 ± 0 [c,d]	1.9 ± 0.7 [a]
Apricot	8.4 ± 0.5 [b]	66.3 ± 0 [a,b]	6.3 ± 0.6 [c]	93.6 ± 0.3 [d]	
PEF Apricot	8.4 ± 0.4 [b]	66.7 ± 1.1 [a,b]	6.3 ± 0.6 [c]	93.6 ± 0.3 [d]	0.8 ± 0.6 [a,b]
Apple	2.6 ± 0.1 [c,d,e]	66.3 ± 1.1 [a,b]	5.6 ± 0.6 [c,d]	102.4 ± 1.2 [a]	
PEF Apple	2.6 ± 0.1 [d,e]	66.9 ± 0.8 [a]	5.2 ± 0 [d,e]	103.2 ± 0 [a]	0.8 ± 0.5 [a,b]
Acacia	8.6 ± 0.9 [b]	66.7 ± 0 [a,b]	7.9 ± 0.5 [b]	98.7 ± 0.5 [b]	
PEF Acacia	7.8 ± 1.5 [b]	66.7 ± 0.6 [a,b]	7.6 ± 0 [b]	99.1 ± 0 [b]	0.6 ± 0.3 [a,b]
Oak (high vanilla)	22.9 ± 2.1 [a]	63.7 ± 0.8 [c]	12.2 ± 0 [a]	91.9 ± 0 [e]	
PEF Oak (high vanilla)	22.6 ± 0.4 [a]	64.3 ± 0.6 [b,c]	12.6 ± 0.5 [a]	91.8 ± 0.1 [e]	0.7 ± 0.5 [a,b]
Xinomavro of Amyndeo					
Control	3310 ± 79 [c,d]	19 ± 0.3 [a]	4.5 ± 0.1 [a,b]	249.2 ± 7.4 [b]	
PEF No Wood	3306 ± 122 [c,d]	17.6 ± 0 [a,b]	3.7 ± 0 [b]	288.9 ± 0 [a]	3.2 ± 0.6 [a]
Peach	3294 ± 107 [d]	17.5 ± 0.2 [a,b]	4.1 ± 0.5 [a,b]	252.7 ± 2.4 [b]	
PEF Peach	3334 ± 36 [b,c,d]	17.3 ± 0 [b]	3.9 ± 0.6 [a,b]	264.1 ± 0.9 [a,b]	0.8 ± 0 [b]
Cherry	3563 ± 119 [a,b,c]	17.3 ± 0 [b]	4.6 ± 0.1 [a,b]	254.7 ± 0.5 [b]	
PEF Cherry	3572 ± 107 [a,b,c]	17.3 ± 0.5 [b]	4.9 ± 0.8 [a]	256.6 ± 11.4 [a,b]	1.0 ± 0.2 [b]
Apricot	3612 ± 87 [a]	17.1 ± 0.3 [b]	4.8 ± 0.5 [a]	264.4 ± 14.2 [a,b]	
PEF Apricot	3576 ± 119 [a,b,c]	17.7 ± 0.1 [a,b]	3.7 ± 0 [b]	251.1 ± 0 [b]	1.7 ± 1 [a,b]
Apple	3587 ± 63 [a,b]	17.7 ± 0.5 [a,b]	3.7 ± 0 [b]	251.1 ± 0 [b]	
PEF Apple	3532 ± 39 [a,b,c]	17.9 ± 0.8 [a,b]	4.2 ± 0.2 [a,b]	252.5 ± 17.3 [b]	1.3 ± 0 [a,b]
Acacia	3463 ± 55 [a,b,c,d]	18.3 ± 1.3 [a,b]	4 ± 0 [a,b]	240.3 ± 0 [b]	
PEF Acacia	3598 ± 67 [a,b]	17.5 ± 0.2 [a,b]	4.4 ± 0.1 [a,b]	264.9 ± 14.8 [a,b]	2.1 ± 1.3 [a,b]
Oak (high vanilla)	3385 ± 104 [a,b,c,d]	17.4 ± 0.1 [a,b]	4.4 ± 0.1 [a,b]	248.5 ± 22.9 [b]	
PEF Oak (high vanilla)	3326 ± 122 [b,c,d]	17.7 ± 1.1 [a,b]	4.9 ± 0.3 [a]	255.3 ± 14.5 [b]	2.4 ± 0.7 [a,b]
Xinomavro of Naoussa					
Control	2642 ± 58 [a]	26.3 ± 0 [a,b]	23.9 ± 1.5 [a,b]	9.5 ± 2 [a,b]	
PEF No Wood	2551 ± 23 [a,b]	27.1 ± 0 [a]	24 ± 1.7 [a]	11.3 ± 0.6 [a]	1.3 ± 0.7 [b]
Peach	2571 ± 24 [a,b]	26.5 ± 0.3 [a,b]	19.7 ± 2.9 [a,b,c,d]	5.5 ± 2.3 [c,d]	
PEF Peach	2558 ± 23 [a,b]	26.3 ± 0 [a,b]	15.3 ± 0 [d]	4.5 ± 0 [d]	4.4 ± 1 [a]
Cherry	2592 ± 35 [a,b]	25.7 ± 0.8 [b,c]	22.5 ± 2.2 [a,b,c]	6.9 ± 0.7 [b,c,d]	
PEF Cherry	2555 ± 21 [a,b]	25.5 ± 0 [b,c,d]	19.8 ± 0.6 [a,b,c,d]	7.8 ± 0.2 [b,c]	2.9 ± 0.5 [a,b]
Apricot	2541 ± 50 [a,b]	25 ± 0.7 [c,d]	20.2 ± 2.2 [a,b,c,d]	7.7 ± 0.9 [b,c]	
PEF Apricot	2517 ± 59 [b]	24.9 ± 0.3 [c,d]	18.6 ± 1.2 [a,b,c,d]	7.2 ± 1.1 [b,c,d]	1.9 ± 0.8 [b]
Apple	2525 ± 12 [b]	25.3 ± 0.3 [b,c,d]	19.3 ± 0 [a,b,c,d]	4.8 ± 1.7 [c,d]	
PEF Apple	2558 ± 47 [a,b]	24.5 ± 0.4 [d]	19.8 ± 3.9 [a,b,c,d]	6.8 ± 0.1 [b,c,d]	3.1 ± 1 [a,b]
Acacia	2538 ± 37 [a,b]	24.7 ± 0.6 [c,d]	17.3 ± 2.8 [c,d]	5.2 ± 1 [c,d]	
PEF Acacia	2593 ± 20 [a,b]	24.9 ± 0.3 [c,d]	19.3 ± 3.4 [a,b,c,d]	4.7 ± 0.9 [c,d]	4.5 ± 1.1 [a]
Oak (high vanilla)	2637 ± 9 [a]	24.7 ± 0.6 [c,d]	17.7 ± 0 [b,c,d]	6.5 ± 0 [b,c,d]	
PEF Oak (high vanilla)	2595 ± 29 [a,b]	24.9 ± 0.3 [c,d]	19.1 ± 0.3 [a,b,c,d]	6 ± 0.1 [c,d]	1.4 ± 0.2 [b]

Table 3. *Cont.*

Treatment	TPC (mg GAE/L)	L^*	C^*	h^o	ΔE
Xinomavro of Goumenissa					
Control	2106 ± 49 ^{c,d}	23.5 ± 0 ^{a}	11.8 ± 0.6 ^{b,c,d}	1.9 ± 0.1 ^{c,d}	
PEF No Wood	2128 ± 78 ^{b,c,d}	23 ± 1.3 ^{a}	15.3 ± 1.1 ^{a}	1.5 ± 0.1 ^{e}	3.7 ± 0.7 ^{a}
Peach	1994 ± 53 ^{d}	22.2 ± 0.3 ^{a}	15.3 ± 0.1 ^{a}	1.5 ± 0 ^{e}	
PEF Peach	2215 ± 53 ^{a,b,c}	23.1 ± 0.6 ^{a}	12.9 ± 0 ^{b,c}	1.8 ± 0 ^{d,e}	2.6 ± 0.2 ^{a,b}
Cherry	2070 ± 45 ^{c,d}	23.5 ± 0 ^{a}	12.1 ± 0.1 ^{b,c,d}	1.9 ± 0 ^{c,d,e}	
PEF Cherry	2218 ± 60 ^{a,b,c}	23.3 ± 0.3 ^{a}	12.6 ± 0.5 ^{b,c}	1.8 ± 0.1 ^{c,d,e}	0.5 ± 0.4 ^{c}
Apricot	2307 ± 104 ^{a,b}	23.5 ± 0 ^{a}	10.6 ± 1.1 ^{d,e}	2.2 ± 0.2 ^{b,c}	
PEF Apricot	2134 ± 13 ^{b,c,d}	23.5 ± 0 ^{a}	12.6 ± 0.5 ^{b,c}	1.8 ± 0.1 ^{c,d,e}	2 ± 0.6 ^{b,c}
Apple	2158 ± 60 ^{a,b,c,d}	23.5 ± 0 ^{a}	12.6 ± 0.5 ^{b,c}	1.8 ± 0.1 ^{c,d,e}	
PEF Apple	2205 ± 59 ^{a,b,c}	23 ± 0.8 ^{a}	11.9 ± 0.6 ^{b,c,d}	5.8 ± 0.3 ^{a}	1.3 ± 0.3 ^{b,c}
Acacia	2335 ± 88 ^{a}	23.3 ± 0.3 ^{a}	11.4 ± 1.1 ^{b,c,d}	2 ± 0.2 ^{c,d}	
PEF Acacia	2192 ± 81 ^{a,b,c}	23.3 ± 0.3 ^{a}	11 ± 0.6 ^{c,d,e}	2.1 ± 0.1 ^{b,c,d}	0.4 ± 0.6 ^{c}
Oak (high vanilla)	2202 ± 43 ^{a,b,c}	22.9 ± 0.3 ^{a}	9.4 ± 0.6 ^{e}	2.4 ± 0.1 ^{b}	
PEF Oak (high vanilla)	2253 ± 27 ^{a,b,c}	22 ± 1.1 ^{a}	13.1 ± 0.2 ^{b}	1.8 ± 0 ^{d,e}	3.8 ± 0.9 ^{a}
Xinomavro of Velventos					
Control	3060 ± 147 ^{a}	22.6 ± 0.2 ^{a}	6.5 ± 1.1 ^{a,b,c,d}	212 ± 5.8 ^{a}	
PEF No Wood	3060 ± 47 ^{a}	22.6 ± 0.2 ^{a}	5.1 ± 0 ^{d}	212.1 ± 0 ^{a}	1.5 ± 1 ^{a}
Peach	3038 ± 37 ^{a}	21.8 ± 0.3 ^{a,b}	7.1 ± 0.3 ^{a,b}	213.4 ± 3.8 ^{a}	
PEF Peach	3055 ± 23 ^{a}	22 ± 0 ^{a,b}	5.6 ± 0.8 ^{b,c,d}	213.3 ± 1.7 ^{a}	1.5 ± 0.5 ^{a}
Cherry	3000 ± 39 ^{a}	21.8 ± 0.3 ^{a,b}	5.6 ± 0.8 ^{b,c,d}	213.3 ± 1.7 ^{a}	
PEF Cherry	2941 ± 20 ^{a}	21.8 ± 0.3 ^{a,b}	5.1 ± 0.6 ^{c,d}	212 ± 10 ^{a}	1.3 ± 0.6 ^{a}
Apricot	2903 ± 20 ^{a}	21.4 ± 0.3 ^{b}	7.6 ± 0.5 ^{a}	214.4 ± 2.4 ^{a}	
PEF Apricot	2882 ± 89 ^{a}	21.6 ± 0.6 ^{a,b}	6.9 ± 0 ^{a,b}	210.7 ± 0 ^{a}	1.2 ± 0 ^{a}
Apple	2909 ± 57 ^{a}	21.4 ± 0.3 ^{b}	6.8 ± 1 ^{a,b,c}	216.3 ± 12.3 ^{a}	
PEF Apple	2884 ± 114 ^{a}	21.2 ± 0.6 ^{b}	6.8 ± 0.1 ^{a,b,c,d}	215.4 ± 6.7 ^{a}	1.9 ± 0.1 ^{a}
Acacia	2903 ± 125 ^{a}	21.6 ± 0 ^{a,b}	6.4 ± 0.4 ^{a,b,c,d}	222.6 ± 3.4 ^{a}	
PEF Acacia	2872 ± 62 ^{a}	21 ± 0.3 ^{b}	7 ± 0.2 ^{a,b}	217.8 ± 10.1 ^{a}	1.5 ± 0.5 ^{a}
Oak (high vanilla)	2908 ± 43 ^{a}	21.6 ± 0.6 ^{a,b}	5.7 ± 0.2 ^{b,c,d}	213.5 ± 8 ^{a}	
PEF Oak (high vanilla)	2981 ± 42 ^{a}	21.2 ± 0.6 ^{b}	6.4 ± 0.3 ^{a,b,c,d}	217.3 ± 4 ^{a}	1.4 ± 0.8 ^{a}

Significant differences at $p < 0.05$ are indicated by different letters (e.g., $^{a–e}$) in the same column and each wine.

3.3. Color Analysis

The color analysis included an evaluation of the progression of the CIELAB color parameters throughout the PEF aging process. The results are displayed in Table 3. To gain a better understanding of the impact of wood chips and PEF on each wine, firstly, the wine model solution was evaluated. Regarding color analysis, the utilization of the functioning wine model solution is crucial for assessing the impact of both PEF and different wood chips. The findings of the C^* parameter analysis indicated statistically significant variations ($p < 0.05$) in PEF utilization across similar wood chips. However, the discrepancy was more noticeable when comparing various wood chip species, with oak exhibiting the highest value (12.6), up to 8 units from the control untreated sample. The findings for the L^* parameter showed a low variation between values, which led to a lack of statistical significance ($p > 0.05$). Simultaneously, a negative association was observed between the use of oak tree wood chips and the brightness of the sample, with the lowest recorded value (~64). Significant statistical changes ($p < 0.05$) were mostly detected in the L^* and C^* values across the various wine samples, rather than among the different treatments, regardless of whether PEF or wood chips were used. A study by Puértolas et al. [42] investigated the chromatic characteristics of wine that aged for 14 months in oak barrels with the assistance of the PEF process. The results showed that all CIELAB color coordinates (L^*, a^*, b^*, C^*, and h^*) significantly decreased during aging. Regarding L^* and C^*, this outcome might not be preferable at all, as it would lead to darker and colorless wines. In our case, most of the differences are statistically significant, meaning that the use of PEF could not deteriorate the chromatic characteristics of the wine samples.

The photometric color analysis of the samples revealed a similar pattern in the parameters % red, % yellow, % blue, CI, and H, as seen in Figures S1–S4. The parameter % dA exhibited inconsistent variation and is a subject deserving of future discussion. Regarding PEF processing, the study from Ricci et al. [43] examined several parameters before and after PEF implementation in wines after fermentation. It was found that some color parameters had a decrease in their values, such as hue (from 1.21 to 0.93) and % yellow (from 49.8 to 42.6). On the other hand, other parameters increased, like % red (from 41.0 to 46.5) and % blue (from 9.1 to 11.5). However, several research articles provide evidence supporting the claim that the utilization of wood chips during the aging process enhances the stability of anthocyanin colors in wine [40,44]. The discrepancy among the various treatments was observed in the h^o and ΔE values. Statistically significant differences ($p < 0.05$) were observed in many wine samples, but considering that ΔE units represent noticeable variations in color that can be perceived by the human eye [39], it has been confirmed that the implementation of both PEF treatment and several wood chips throughout the aging process did not result in visually detectable color alterations in nearly all of the wine samples ($\Delta E < 3$).

3.4. VCs Analysis

Several VCs were identified during the HS-SPME/GC-MS analysis of the wine samples. A variety of VCs that are frequently encountered in wines originated from the fermentation of grapes and yeast strains, as well as from the vinification process [45]. However, only five of the most prevalent VCs were measured in the control sample and also in the other wine samples, which are displayed in Table 4. The wine model solution was utilized to assess the impact of wood chips on the wine in question, as well as to determine the effectiveness of PEF utilization. Table 4 demonstrates that the VCs identified in this sample were furfural, 3-furaldehyde, benzaldehyde, 2-ethylhexanol, and linalool, with cumulative concentrations ranging from 8.25 to 283.94 μg/L. The wine model solution subjected to PEF treatment with apple wood chips revealed that linalool had the highest concentration among all the VCs. Specifically, in this situation, the PEF contribution was 104% higher compared to the absence of PEF.

Table 4. Major VCs concentration as mg of 4-methyl-2-pentanol equivalents per L of Xinomavro red wine samples.

Wine Model Solution (μg/L)						
Treatment	**Furfural**	**3-Furaldehyde**	**Benzaldehyde**	**2-Ethylhexanol**	**Linalool**	**∑ Major VCs**
Control	nd *	nd	nd	nd	nd	na **
PEF No Wood	nd	nd	nd	nd	nd	na
Peach	nd	nd	nd	nd	nd	na
PEF Peach	nd	nd	nd	nd	nd	na
Cherry	nd	nd	8.25 ± 0.62 [b]	nd	nd	8.25 ± 0.62 [g]
PEF Cherry	nd	nd	10.68 ± 0.4 [a]	nd	nd	10.68 ± 0.4 [g] (29.5%)
Apricot	nd	nd	nd	45.14 ± 1.35 [b]	65.25 ± 4.7 [c]	110.39 ± 6.73 [c,d]
PEF Apricot	nd	nd	nd	54.77 ± 3.01 [a]	122.16 ± 8.8 [a]	176.93 ± 10.33 [b] (60.3%)
Apple	nd	nd	nd	nd	61.37 ± 4.42 [c]	61.37 ± 4.42 [f]
PEF Apple	nd	nd	nd	nd	125.27 ± 8.02 [a]	125.27 ± 8.02 [c] (104.1%)
Acacia	nd	nd	nd	18.14 ± 1.23 [d]	67.97 ± 2.99 [c]	86.11 ± 3.72 [e]
PEF Acacia	nd	nd	nd	22.55 ± 1.11 [d]	69.52 ± 3.89 [c]	92.07 ± 5.04 [d,e] (6.9%)

Table 4. *Cont.*

Wine Model Solution (μg/L)						
Treatment	**Furfural**	**3-Furaldehyde**	**Benzaldehyde**	**2-Ethylhexanol**	**Linalool**	**∑ Major VCs**
Oak (high vanilla)	34.25 ± 1.51 [b]	8.73 ± 0.31 [b]	nd	38.89 ± 1.05 [c]	96.44 ± 5.98 [b]	178.31 ± 10.44 [b]
PEF Oak (high vanilla)	44.31 ± 2.35 [a]	83.52 ± 5.35 [a]	nd	46.46 ± 1.53 [b]	109.65 ± 5.37 [a,b]	283.94 ± 16.41 [a] (59.2%)
Xinomavro of Amyndeo (mg/L)						
Treatment	**Ethyl 2-hydroxy propanoate**	**Ethyl hexanoate**	**2-Phenyl ethanol**	**Diethyl butanedioate**	**Ethyl octanoate**	**∑ major VCs**
Control	2.01 ± 0.07 [c]	2.5 ± 0.08 [e,f]	10.51 ± 0.48 [d]	10.46 ± 0.37 [e]	4.17 ± 0.2 [e,f,g]	29.65 ± 1.17 [c]
PEF No Wood	2.05 ± 0.14 [b,c]	2.53 ± 0.11 [d,e,f]	10.8 ± 0.71 [d]	10.65 ± 0.49 [e]	4.2 ± 0.12 [d,e,f,g]	30.24 ± 1.5 [c] [2.0%] (2.0%)
Peach	2.13 ± 0.14 [a,b,c]	2.43 ± 0.17 [f]	12.08 ± 0.36 [c,d]	11.39 ± 0.34 [d,e]	3.75 ± 0.11 [g]	31.79 ± 1.02 [c] [7.2%]
PEF Peach	2.23 ± 0.12 [a,b,c]	2.49 ± 0.16 [f]	16.26 ± 0.39 [a]	14.49 ± 0.84 [a,b]	3.89 ± 0.17 [f,g]	39.36 ± 1.69 [a,b] [32.8%] (23.8%)
Cherry	2.42 ± 0.05 [a]	2.44 ± 0.16 [f]	10.85 ± 0.6 [d]	11.02 ± 0.44 [e]	4.09 ± 0.14 [e,f,g]	30.82 ± 1.46 [c] [4.0%]
PEF Cherry	2.37 ± 0.09 [a,b]	2.78 ± 0.15 [b,c,d,e,f]	13.82 ± 0.3 [b,c]	13.01 ± 0.38 [b,c]	4.64 ± 0.32 [b,c,d,e]	36.61 ± 1.22 [b] [23.5%] (18.8%)
Apricot	2.21 ± 0.12 [a,b,c]	3.19 ± 0.09 [a]	13.34 ± 0.33 [b,c]	12.72 ± 0.37 [c,d]	5.46 ± 0.23 [a]	36.92 ± 1.11 [b] [24.5%]
PEF Apricot	2.31 ± 0.16 [a,b,c]	3.09 ± 0.07 [a,b]	16.92 ± 1.27 [a]	15.14 ± 0.41 [a]	5.15 ± 0.11 [a,b]	42.61 ± 2 [a] [43.7%] (15.4%)
Apple	2.19 ± 0.07 [a,b,c]	2.91 ± 0.12 [a,b,c,d]	12.84 ± 0.49 [b,c]	13.9 ± 0.36 [a,b,c]	4.65 ± 0.13 [b,c,d,e]	36.48 ± 1.18 [b] [23.1%]
PEF Apple	2.24 ± 0.14 [a,b,c]	2.95 ± 0.11 [a,b,c]	12.83 ± 0.35 [b,c]	13.76 ± 0.48 [a,b,c]	4.79 ± 0.3 [b,c,d]	36.57 ± 1.33 [b] [23.4%] (0.2%)
Acacia	2.44 ± 0.06 [a]	2.66 ± 0.07 [c,d,e,f]	13.9 ± 0.36 [b]	13.73 ± 0.92 [a,b,c]	4.83 ± 0.3 [b,c]	37.56 ± 1.82 [b] [26.7%]
PEF Acacia	2.4 ± 0.05 [a]	2.82 ± 0.08 [a,b,c,d,e,f]	14.47 ± 0.43 [b]	14.01 ± 0.36 [a,b,c]	4.36 ± 0.23 [c,d,e,f,g]	38.06 ± 1.28 [b] [28.4%] (1.3%)
Oak (high vanilla)	2.04 ± 0.12 [b,c]	2.88 ± 0.12 [a,b,c,d,e]	10.71 ± 0.78 [d]	11.2 ± 0.35 [e]	4.45 ± 0.17 [c,d,e,f]	31.28 ± 1.52 [c] [5.5%]
PEF Oak (high vanilla)	2.02 ± 0.04 [c]	3 ± 0.22 [a,b,c]	10.52 ± 0.7 [d]	11.38 ± 0.48 [d,e]	4.51 ± 0.09 [c,d,e]	31.44 ± 1.64 [c] [6.0%] (0.5%)
Xinomavro of Naoussa (mg/L)						
Treatment	**3-Methylbutyl ethanoate**	**Ethyl hexanoate**	**2-Phenyl ethanol**	**Diethyl butanedioate**	**Ethyl octanoate**	**∑ major VCs**
Control	1.5 ± 0.03 [f]	2.54 ± 0.18 [c,d,e,f]	4.17 ± 0.27 [f]	3.87 ± 0.22 [b,c,d]	5.02 ± 0.37 [c]	17.09 ± 1.15 [e]
PEF No Wood	1.54 ± 0.07 [e,f]	2.62 ± 0.15 [c,d,e,f]	4.28 ± 0.27 [e,f]	3.94 ± 0.22 [a,b,c,d]	5.15 ± 0.38 [c]	17.53 ± 1.07 [d,e] [2.6%] (2.6%)
Peach	1.84 ± 0.05 [c,d,e]	2.31 ± 0.1 [f]	5.52 ± 0.12 [c,d]	3.57 ± 0.13 [d,e]	5.18 ± 0.24 [c]	18.43 ± 0.71 [b,c,d,e] [7.8%]
PEF Peach	2.23 ± 0.09 [a,b]	2.6 ± 0.19 [c,d,e,f]	5.79 ± 0.31 [b,c,d]	3.99 ± 0.17 [a,b,c,d]	5.71 ± 0.21 [b,c]	20.32 ± 0.94 [a,b,c,d] [18.9%] (10.3%)
Cherry	1.66 ± 0.08 [d,e,f]	2.87 ± 0.08 [a,b,c]	5.07 ± 0.15 [d,e]	4.17 ± 0.25 [a,b,c,d]	6.39 ± 0.26 [a,b]	20.15 ± 0.77 [a,b,c,d] [18.0%]
PEF Cherry	2.2 ± 0.13 [a,b]	3.18 ± 0.2 [a]	5.77 ± 0.3 [b,c,d]	4.02 ± 0.22 [a,b,c,d]	6.79 ± 0.24 [a]	21.97 ± 1.11 [a] [28.6%] (9.0%)

Table 4. *Cont.*

Xinomavro of Naoussa (mg/L)						
Treatment	**3-Methylbutyl ethanoate**	**Ethyl hexanoate**	**2-Phenyl ethanol**	**Diethyl butanedioate**	**Ethyl octanoate**	**∑ major VCs**
Apricot	1.85 ± 0.11 [c,d,e]	2.37 ± 0.07 [e,f]	6.1 ± 0.29 [b,c]	4.51 ± 0.21 [a]	5.09 ± 0.22 [c]	19.92 ± 0.92 [a,b,c,d,e] [16.6%]
PEF Apricot	2.03 ± 0.15 [b,c]	2.8 ± 0.07 [a,b,c,d,e]	6.45 ± 0.47 [a,b]	4.27 ± 0.2 [a,b,c]	5.2 ± 0.1 [c]	20.76 ± 0.93 [a,b] [21.5%] (4.2%)
Apple	2.15 ± 0.09 [b,c]	2.84 ± 0.13 [a,b,c,d]	4.02 ± 0.19 [f]	3.01 ± 0.07 [e]	5.8 ± 0.38 [b,c]	17.82 ± 0.92 [c,d,e] [4.3%]
PEF Apple	2.09 ± 0.05 [b,c]	2.58 ± 0.11 [c,d,e,f]	7.11 ± 0.21 [a]	4.41 ± 0.13 [a,b]	5.79 ± 0.41 [b,c]	21.99 ± 0.99 [a] [28.7%] (23.4%)
Acacia	1.96 ± 0.06 [b,c,d]	2.71 ± 0.15 [b,c,d,e,f]	5.44 ± 0.18 [c,d]	3.68 ± 0.25 [c,d]	5.77 ± 0.2 [b,c]	19.56 ± 0.82 [a,b,c,d,e] [14.5%]
PEF Acacia	1.93 ± 0.12 [b,c,d]	2.42 ± 0.09 [d,e,f]	7.08 ± 0.47 [a]	4.26 ± 0.31 [a,b,c]	6.13 ± 0.44 [a,b]	21.82 ± 1.4 [a] [27.7%] (11.5%)
Oak (high vanilla)	2.21 ± 0.11 [a,b]	2.69 ± 0.17 [c,d,e,f]	5.4 ± 0.16 [c,d]	3.62 ± 0.18 [d]	6.49 ± 0.15 [a,b]	20.42 ± 0.78 [a,b,c] [19.5%]
PEF Oak (high vanilla)	2.51 ± 0.1 [a]	3.13 ± 0.22 [a,b]	5.66 ± 0.12 [b,c,d]	4.11 ± 0.14 [a,b,c,d]	6.43 ± 0.13 [a,b]	21.85 ± 0.73 [a] [27.9%] (7.0%)

Xinomavro of Goumenissa (mg/L)						
Treatment	**3-Methylbutyl ethanoate**	**Ethyl hexanoate**	**2-Phenyl ethanol**	**Diethyl butanedioate**	**Ethyl octanoate**	**∑ major VCs**
Control	1.44 ± 0.11 [a,b]	3.21 ± 0.18 [d]	7.09 ± 0.43 [e]	3.68 ± 0.12 [e]	5.97 ± 0.42 [c]	21.39 ± 1.25 [c]
PEF No Wood	1.44 ± 0.09 [a,b]	3.35 ± 0.22 [c,d]	7.31 ± 0.21 [d,e]	3.89 ± 0.25 [d,e]	5.95 ± 0.14 [c]	21.93 ± 0.92 [b,c] [2.5%] (2.5%)
Peach	1.57 ± 0.05 [a,b]	3.12 ± 0.06 [d]	9.55 ± 0.56 [a,b]	3.92 ± 0.19 [d,e]	5.84 ± 0.18 [c]	23.99 ± 1.05 [a,b,c] [12.2%]
PEF Peach	1.59 ± 0.06 [a,b]	4.09 ± 0.09 [a]	9.7 ± 0.54 [a,b]	4.14 ± 0.16 [c,d,e]	6.22 ± 0.37 [b,c]	25.75 ± 1.21 [a] [20.4%] (7.3%)
Cherry	1.61 ± 0.06 [a,b]	3.95 ± 0.11 [a,b]	7.66 ± 0.37 [d,e]	4.02 ± 0.15 [d,e]	7.22 ± 0.4 [a]	24.46 ± 1.1 [a,b,c] [14.3%]
PEF Cherry	1.66 ± 0.07 [a]	4.14 ± 0.1 [a]	7.73 ± 0.18 [d,e]	4.05 ± 0.19 [d,e]	7.38 ± 0.38 [a]	24.96 ± 0.91 [a,b] [16.7%] (2.1%)
Apricot	1.61 ± 0.09 [a,b]	4.19 ± 0.24 [a]	6.8 ± 0.14 [e]	3.67 ± 0.26 [e]	7.23 ± 0.39 [a]	23.5 ± 1.13 [a,b,c] [9.9%]
PEF Apricot	1.58 ± 0.03 [a,b]	4.13 ± 0.29 [a]	7.15 ± 0.45 [e]	3.86 ± 0.11 [d,e]	6.99 ± 0.37 [a,b]	23.72 ± 1.25 [a,b,c] [10.9%] (0.9%)
Apple	1.47 ± 0.05 [a,b]	3.43 ± 0.12 [c,d]	8.28 ± 0.18 [c,d]	4.2 ± 0.19 [c,d,e]	5.9 ± 0.19 [c]	23.28 ± 0.73 [a,b,c] [8.8%]
PEF Apple	1.46 ± 0.06 [a,b]	3.26 ± 0.12 [d]	10.19 ± 0.2 [a]	5.09 ± 0.23 [a]	6.16 ± 0.41 [b,c]	26.16 ± 1.03 [a] [22.3%] (12.4%)
Acacia	1.41 ± 0.03 [b]	3.79 ± 0.28 [a,b,c]	7.36 ± 0.17 [d,e]	3.9 ± 0.21 [d,e]	6.99 ± 0.2 [a,b]	23.44 ± 0.89 [a,b,c] [9.6%]
PEF Acacia	1.44 ± 0.08 [b]	3.46 ± 0.2 [b,c,d]	8.99 ± 0.4 [b,c]	4.42 ± 0.24 [b,c,d]	5.83 ± 0.27 [c]	24.14 ± 1.2 [a,b,c] [12.8%] (3.0%)
Oak (high vanilla)	1.45 ± 0.08 [a,b]	3.14 ± 0.08 [d]	9.26 ± 0.22 [a,b,c]	4.82 ± 0.1 [a,b]	5.86 ± 0.25 [c]	24.53 ± 0.73 [a,b,c] [14.7%]
PEF Oak (high vanilla)	1.46 ± 0.1 [a,b]	3.1 ± 0.12 [d]	9.55 ± 0.54 [a,b]	4.67 ± 0.31 [a,b,c]	5.83 ± 0.13 [c]	24.62 ± 1.21 [a,b] [15.1%] (0.3%)

Table 4. *Cont.*

Xinomavro of Velventos (mg/L)						
Treatment	**3-Methylbutyl ethanoate**	**Ethyl hexanoate**	**2-Phenyl ethanol**	**Diethyl butanedioate**	**Ethyl octanoate**	**∑ major VCs**
Control	1.34 ± 0.03 c,d,e	1.22 ± 0.07 c,d	5.62 ± 0.35 e	1.03 ± 0.06 e	3.66 ± 0.23 g	12.87 ± 0.74 f
PEF No Wood	1.42 ± 0.1 b,c,d,e	1.24 ± 0.05 c,d	5.6 ± 0.21 e	0.95 ± 0.06 e	3.93 ± 0.12 e,f,g	13.14 ± 0.55 f [2.0%] (2.0%)
Peach	1.61 ± 0.11 a,b	1.39 ± 0.09 b,c	9.05 ± 0.59 b,c	1.54 ± 0.08 b	4.69 ± 0.17 b,c	18.28 ± 1.03 b,c,d [42.0%]
PEF Peach	1.47 ± 0.05 b,c,d,e	1.47 ± 0.04 b,c	9.16 ± 0.21 b,c	1.44 ± 0.08 b,c,d	4.91 ± 0.13 b	18.45 ± 0.52 b,c,d [43.3%] (0.9%)
Cherry	1.51 ± 0.05 a,b,c,d,e	1.27 ± 0.06 c,d	9.45 ± 0.37 b,c	1.48 ± 0.09 b,c,d	4.59 ± 0.31 b,c,d	18.29 ± 0.89 b,c,d [42.1%]
PEF Cherry	1.58 ± 0.07 a,b	1.76 ± 0.09 a	9.94 ± 0.45 b	1.53 ± 0.09 b,c	5.52 ± 0.16 a	20.32 ± 0.86 a,b [57.9%] (11.1%)
Apricot	1.49 ± 0.07 a,b,c,d,e	1.45 ± 0.07 b,c	9.28 ± 0.28 b,c	1.57 ± 0.1 b	3.92 ± 0.2 e,f,g	17.7 ± 0.72 c,d [37.5%]
PEF Apricot	1.65 ± 0.11 a,b	1.36 ± 0.09 c,d	11.75 ± 0.26 a	1.87 ± 0.05 a	4.24 ± 0.17 c,d,e,f	20.87 ± 0.69 a [62.1%] (17.9%)
Apple	1.31 ± 0.08 e	1.46 ± 0.11 b,c	7.08 ± 0.18 d	1.04 ± 0.04 e	3.96 ± 0.28 e,f,g	14.86 ± 0.69 e,f [15.4%]
PEF Apple	1.57 ± 0.09 a,b,c	1.63 ± 0.07 a,b	8.61 ± 0.28 c	1.3 ± 0.09 d	4.19 ± 0.24 c,d,e,f,g	17.31 ± 0.76 d [34.5%] (16.5%)
Acacia	1.56 ± 0.08 a,b,c,d	1.43 ± 0.1 b,c	9.51 ± 0.29 b,c	1.56 ± 0.07 b	3.78 ± 0.14 e,f,g	17.84 ± 0.68 c,d [38.6%]
PEF Acacia	1.51 ± 0.06 a,b,c,d,e	1.34 ± 0.07 c,d	11.34 ± 0.61 a	1.78 ± 0.04 a	3.7 ± 0.13 f,g	19.66 ± 0.91 a,b,c [52.7%] (10.2%)
Oak (high vanilla)	1.33 ± 0.08 d,e	1.11 ± 0.08 d	8.65 ± 0.49 c	1.32 ± 0.04 c,d	4.01 ± 0.14 d,e,f,g	16.42 ± 0.83 d,e [27.5%]
PEF Oak (high vanilla)	1.72 ± 0.08 a	1.74 ± 0.13 a	8.87 ± 0.35 b,c	1.33 ± 0.04 c,d	4.29 ± 0.16 c,d,e	17.95 ± 0.76 c,d [39.4%] (9.3%)

* nd, not detected; ** na, not applicable; The number in parentheses indicates the % PEF difference between each wood chip, and the number in brackets indicates the % difference from the control sample; Significant differences at $p < 0.05$ are indicated by different letters (e.g., a–g) in the same column and each wine.

The measured concentration of total VCs in the wine samples ranged from 12.87 to 42.61 mg/L. The most prevalent VCs were mostly esters (3-methylbutyl ethanoate, ethyl 2-hydroxypropanoate, ethyl hexanoate, diethyl butanedioate, ethyl octanoate) and alcohol (2-phenylethanol). This alcohol was the most abundant VC and its concentration showed statistically significant differences ($p < 0.05$) across the wine samples. Specifically, Xinomavro of Naoussa had the lowest concentration (4.02 mg/L) when apple tree wood chips were employed alongside PEF treatment. On the other hand, Xinomavro of Amyndeo showed a maximum concentration of 16.92 mg/L with the application of PEF treatment when apricot tree wood chips were involved in the aging process. Particularly, in this sample, it was established that the employment of PEF had a favorable impact on the enhancement of the wine with this VC. Additionally, this is known to improve the bouquet of wine by adding scents of rose, honey, and fresh tomato [46,47]. This finding has been previously supported by the sensory evaluation conducted by the group of panelists. The assessment also revealed that the inclusion of PEF led to a significant 43.7% enhancement in comparison to the untreated sample (control) and a 15.4% improvement compared to the use of apricot tree wood chips without the application of PEF. This indicates that PEF treatment may influence the concentration of key components that contribute to the aromatic profile of the wines. In a study by Goulioti et al. [48], six Xinomavro wines were analyzed for their volatile compounds. 2-Phenylethanol was found in considerably higher amounts than in our samples as it was measured at 35.1–53.3 mg/L. However, comparable results were observed in ethyl hexanoate and ethyl octanoate, which ranged from 0.12 to 0.27 mg/L and 1.2 to 1.88 mg/L, respectively. Comuzzo et al. [49] investigated thoroughly the impact of PEF in wine composition and volatile compounds. They found that the concentrations of ethyl hexanoate and ethyl octanoate were decreased under PEF treatment from an initial 1025 and 1927 µg/L; however, both were statistically insignificant. 2-Phenylethanol concentration was significantly decreased from the initial 47,393 µg/L to 40,004 µg/L. In our case, the corresponding compounds followed a different trend as their concentration was found to either increase or decrease. This trend could depend on the type of wood chips.

Aroma compounds like esters were included in the fruity category. Even at low concentrations [50], esters contribute to the fruity flavor of young wines [51]. Yeasts promote the majority of ester synthesis during alcoholic fermentation, whereas malolactic bacteria can alter ester profiles. It is well known that yeast, which is primarily responsible for the specific ester composition of the wines, produces an abundance of esters, which add to the secondary aroma compounds produced by fermentation [52]. Although the contributions of grapes to the production of esters from fermentation is not entirely explained, Ferreira et al. [53] have demonstrated that esters might impact the varietal odor of young red wines. Ethyl hexanoate and ethyl octanoate were found to provide a fruity scent to the wines elsewhere [48]. The highest concentration of both VCs was reported in Xinomavro of Goumenissa at 4.19 and 7.38 mg/L, respectively. To accomplish this, ethyl hexanoate necessitated the use of apricot tree wood chips in the absence of PEF, whereas ethyl octanoate necessitated the utilization of PEF in conjunction with cherry tree wood chips. Diethyl butanedioate offers a reminiscent apple tone to wines [54]. PEF treatment with apricot tree wood chips provided the highest concentration (15.14 mg/L) in the Xinomavro of Amyndeo wine. This treatment achieved increased values from PEF-untreated samples. In particular, a 43.7% increase was observed in the control wine sample and 15.4% from wine with the specific wood chips. Finally, 3-methylbutyl ethanoate concentration reached the highest level (2.51 mg/L) in Xinomavro of Naoussa with PEF-assisted oak tree wood chip extraction. The results obtained from the detailed HS-SPME/GC-MS study demonstrated the complicated effects of using various wood chips in combination with PEF treatment on the chemical composition of Xinomavro red wine. The observed changes in certain compounds provide a glimpse into the possible influence of PEF treatment on the extraction or production of essential aromatic and sensory compounds that eventually influence the sensory attributes of the wine. This research provides a valuable addition to the effective aging of wine and possibly other drinks, achieving desired results within a short period and at a low cost.

3.5. Principal Component Analysis (PCA) and Multivariate Correlation Analysis (MCA)

PCA was used to thoroughly analyze the data and derive more meaningful insights from the available variables (wine samples, wood chips, TPC, color, and VCs). The objective was to explore any correlations between different variables. Figure 1 displays an analysis of two main components based on their eigenvalues > 1, which accounted for a combined 44.00% of the variance. The results showed that there was either a positive or negative relationship between the variables. For instance, parameters such as h^o, 2-phenylethanol, TPC, % red, linalool, and furfural had a positive correlation with PC1, whereas parameters such as 3-methylbutyl butanoate, ethyl octanoate, benzaldehyde, ΔE, and % red had a positive correlation with PC2. Furthermore, it is worth noting that variables that lie opposite in the cycle, such as TPC and L^*, have a negative correlation. This observation is intriguing in the context of the nutritional composition of wine, as it means that the darker the wine color, the higher the TPC. Conversely, there is a positive correlation between variables H and % yellow, as evidenced by the previously mentioned Equations (6) and (7). A significant finding related to TPC and its negative relationship with esters. The observed trend might likely be attributed to the utilization of PEF, as its application has been shown to decrease

TPC, while concurrently enhancing the presence of aroma compounds in wine. Finally, it is also crucial to emphasize the grouping and separation of the various wine samples on the PCA graph, taking into account their respective physicochemical characteristics, TPC, and VCs.

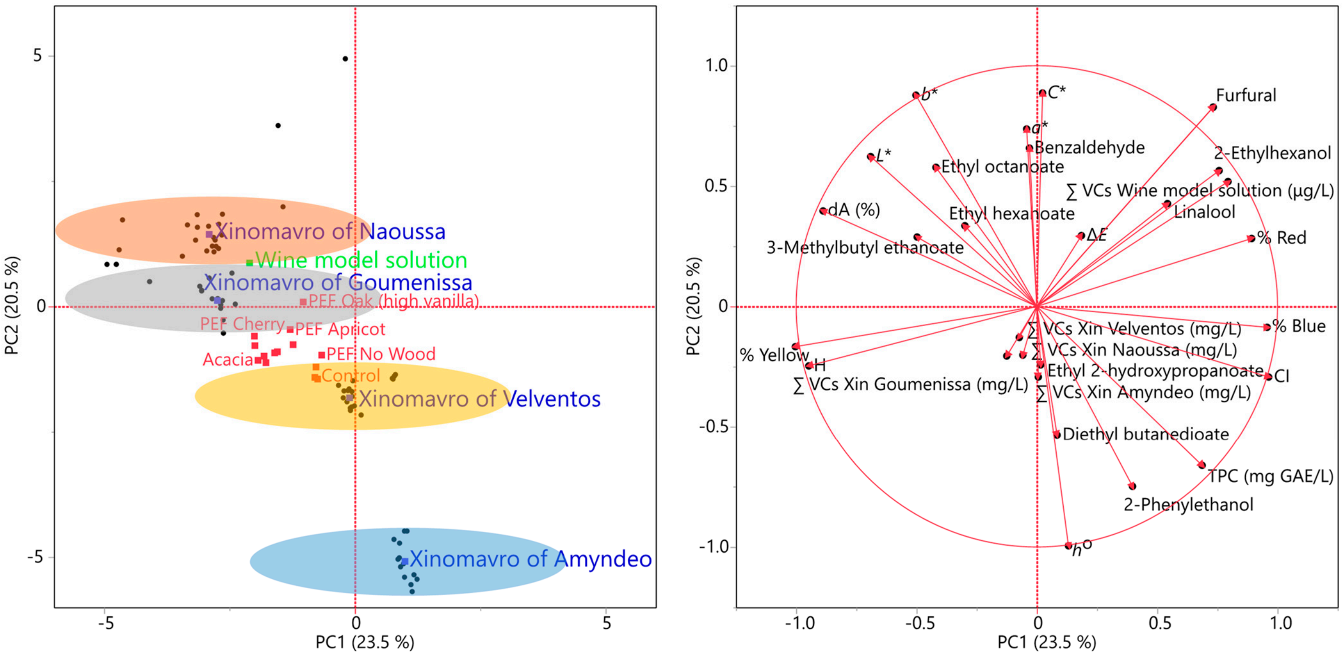

Figure 1. Principal component analysis (PCA) for the measured variables. The axis scores for PC1 and PC2 are displayed. Wine samples were classified with different oval colors.

Furthermore, MCA is illustrated in Figure 2 and was performed to offer additional clarification on the correlation among the examined variables. Correlation values range from −1 to 1 on this map color scale. The strongest positive correlation between the variables is shown with a yellow color. Conversely, a deep orange color signifies a robust negative correlation among the variables. This chart aids in resolving uncertainties and inquiries that may occur from the PCA graph by providing insights into the extent of correlation between variables. An intriguing observation made previously using the PCA graph revealed a negative correlation between TPC and certain VCs. It is now confirmed that there is a strong negative association between TPC and aldehydes (furfural and 3-furaldehyde), whereas the correlation with esters (ethyl hexanoate and ethyl octanoate) is moderate. The correlation between TPC and diethyl butanoate, ethyl 2-hydroxypropanoate, and 2-phenylethanol is moderately positive. An also noteworthy result is the strong negative correlation between TPC and the brightness of the wine samples. These findings indicate that the utilization of PEF had a good impact on improving the aromatic qualities of wine but may have a detrimental effect on TPC.

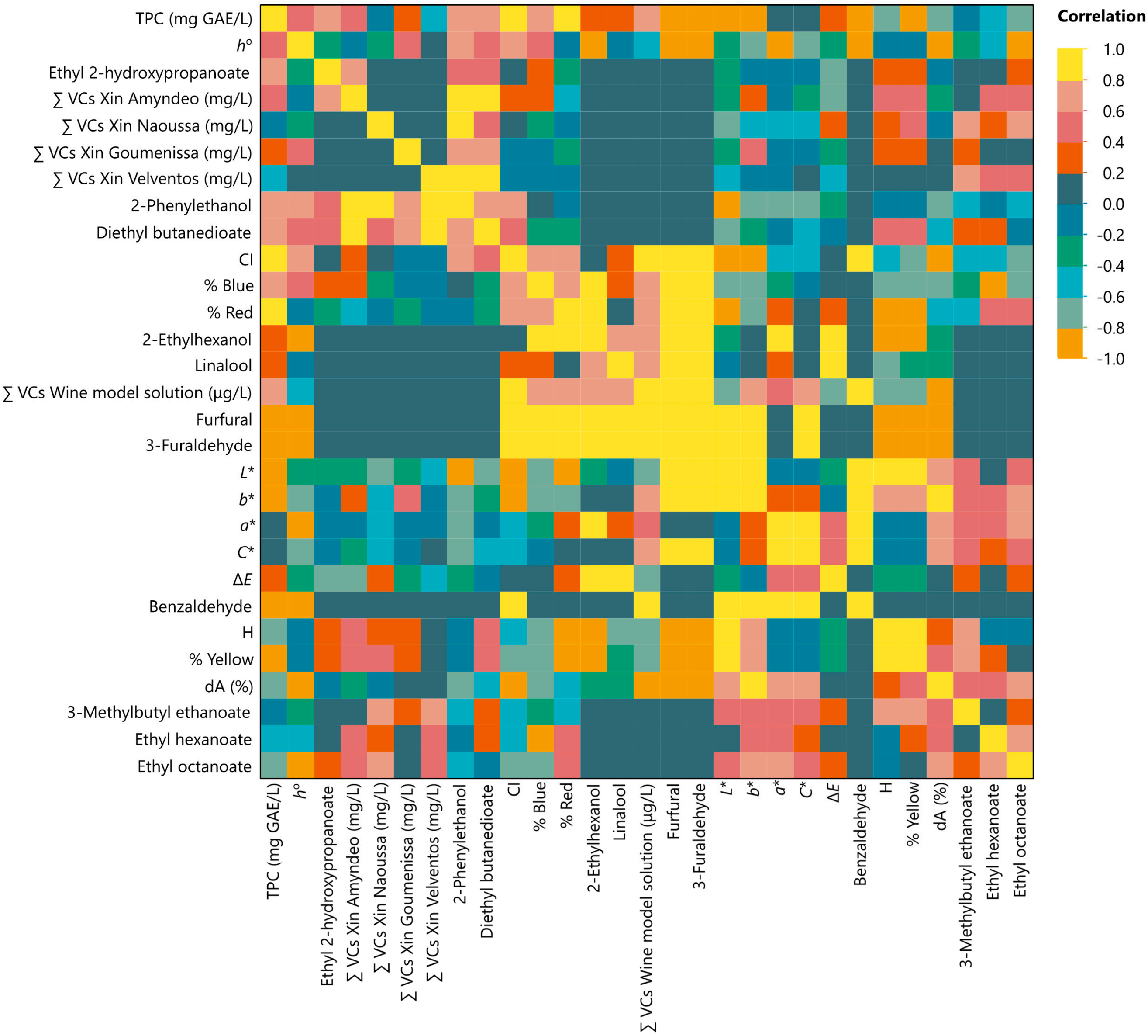

Figure 2. Multivariate correlation analysis of measured variables in all wine samples.

4. Conclusions

This study examined the impact of PEF treatment, six different types of wood chips, and their combined effect on the aging process of four specific Xinomavro red wines. The study also evaluated the increase in the TPC and sensory characteristics enhancement of the wines. The results revealed that the wood chips had a significant effect on the enrichment of polyphenols, while the PEF treatment showed minimal to no effect. Moreover, the utilization of PEF treatment resulted in a considerable increase in the concentration of key VCs (such as esters, alcohols, and aldehydes). This outcome was further confirmed by expert panelists. Additionally, the findings emphasized the significance of carefully choosing wood chips in determining the overall aromatic and taste complexity of Xinomavro red wine. The observed changes in certain compounds' concentration offer insight into the potential impact of PEF treatment on the extraction or generation of crucial aromatic and sensory compounds, eventually affecting the sensory characteristics of the wine. Finally, this research offers an essential contribution to the aging process of wine and potentially other beverages, yielding desirable outcomes in a short timeframe and at little expense.

This study could provide an efficient alternative method of wine aging, which could further be implemented in other beverages.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/beverages10010013/s1, Figures S1–S4 present the color intensity (CI), hue (H), wine brilliance (dA, %), and the color composition of the Xinomavro red wines.

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References

1. IOV. Statistical Report on World Vitiviniculture. The International Organisation of Vine and Wine. Available online: https://www.oiv.int/sites/default/files/documents/OIV_State_of_the_world_Vine_and_Wine_sector_in_2022_2.pdf (accessed on 5 November 2023).
2. Vecchio, R.; Decordi, G.; Grésillon, L.; Gugenberger, C.; Mahéo, M.; Jourjon, F. European Consumers' Perception of Moderate Wine Consumption on Health. *Wine Econ. Policy* **2017**, *6*, 14–22. [CrossRef]
3. Artero, A.; Artero, A.; Tarín, J.J.; Cano, A. The Impact of Moderate Wine Consumption on Health. *Maturitas* **2015**, *80*, 3–13. [CrossRef]
4. Garrido, J.; Borges, F. Wine and Grape Polyphenols—A Chemical Perspective. *Food Res. Int.* **2013**, *54*, 1844–1858. [CrossRef]
5. Poulsen, M.M.; Jørgensen, J.O.L.; Jessen, N.; Richelsen, B.; Pedersen, S.B. Resveratrol in Metabolic Health: An Overview of the Current Evidence and Perspectives. *Ann. N. Y. Acad. Sci.* **2013**, *1290*, 74–82. [CrossRef]
6. Jackson, D.I.; Lombard, P.B. Environmental and Management Practices Affecting Grape Composition and Wine Quality—A Review. *Am. J. Enol. Vitic.* **1993**, *44*, 409–430. [CrossRef]
7. González-Barreiro, C.; Rial-Otero, R.; Cancho-Grande, B.; Simal-Gándara, J. Wine Aroma Compounds in Grapes: A Critical Review. *Crit. Rev. Food Sci. Nutr.* **2015**, *55*, 202–218. [CrossRef]
8. Correia, A.C.; González-SanJosé, M.L.; Ortega-Heras, M.; Jordão, A.M. Preliminary Study of the Effect of Short Maceration with Cherry and Oak Wood Chips on the Volatile Composition of Different Craft Beers. *Beverages* **2023**, *9*, 79. [CrossRef]
9. Tao, Y.; García, J.F.; Sun, D.-W. Advances in Wine Aging Technologies for Enhancing Wine Quality and Accelerating Wine Aging Process. *Crit. Rev. Food Sci. Nutr.* **2014**, *54*, 817–835. [CrossRef]
10. Carpena, M.; Pereira, A.G.; Prieto, M.A.; Simal-Gandara, J. Wine Aging Technology: Fundamental Role of Wood Barrels. *Foods* **2020**, *9*, 1160. [CrossRef]
11. Collins, T.S.; Miles, J.L.; Boulton, R.B.; Ebeler, S.E. Targeted Volatile Composition of Oak Wood Samples Taken during Toasting at a Commercial Cooperage. *Tetrahedron* **2015**, *71*, 2971–2982. [CrossRef]
12. Tsapou, E.A.; Ntourtoglou, G.; Drosou, F.; Tataridis, P.; Dourtoglou, T.; Lalas, S.; Dourtoglou, V. In Situ Creation of the Natural Phenolic Aromas of Beer: A Pulsed Electric Field Applied to Wort-Enriched Flax Seeds. *Front. Bioeng. Biotechnol.* **2020**, *8*, 583617. [CrossRef] [PubMed]
13. Lv, Y.; Wang, J.N.; Jiang, Y.; Ma, X.M.; Ma, F.L.; Ma, X.L.; Zhang, Y.; Tang, L.H.; Wang, W.X.; Ma, G.M.; et al. Identification of Oak-Barrel and Stainless Steel Tanks with Oak Chips Aged Wines in Ningxia Based on Three-Dimensional Fluorescence Spectroscopy Combined with Chemometrics. *Molecules* **2023**, *28*, 3688. [CrossRef] [PubMed]
14. Garde-Cerdán, T.; Ancín-Azpilicueta, C. Review of Quality Factors on Wine Ageing in Oak Barrels. *Trends Food Sci. Technol.* **2006**, *17*, 438–447. [CrossRef]
15. Jordão, A.M.; Cosme, F. The Application of Wood Species in Enology: Chemical Wood Composition and Effect on Wine Quality. *Appl. Sci.* **2022**, *12*, 3179. [CrossRef]
16. Dumitriu, G.D.; Teodosiu, C.; Gabur, I.; Cotea, V.V.; Peinado, R.A.; de Lerma, N.L. Evaluation of Aroma Compounds in the Process of Wine Ageing with Oak Chips. *Foods* **2019**, *8*, 662. [CrossRef] [PubMed]
17. Knorr, D.; Angersbach, A. Impact of High-Intensity Electric Field Pulses on Plant Membrane Permeabilization. *Trends Food Sci. Technol.* **1998**, *9*, 185–191. [CrossRef]

18. Ade-Omowaye, B.I.O.; Angersbach, A.; Taiwo, K.A.; Knorr, D. Use of Pulsed Electric Field Pre-Treatment to Improve Dehydration Characteristics of Plant Based Foods. *Trends Food Sci. Technol.* **2001**, *12*, 285–295. [CrossRef]
19. Barba, F.J.; Parniakov, O.; Pereira, S.A.; Wiktor, A.; Grimi, N.; Boussetta, N.; Saraiva, J.A.; Raso, J.; Martin-Belloso, O.; Witrowa-Rajchert, D.; et al. Current Applications and New Opportunities for the Use of Pulsed Electric Fields in Food Science and Industry. *Food Res. Int.* **2015**, *77*, 773–798. [CrossRef]
20. Janositz, A.; Knorr, D. Microscopic Visualization of Pulsed Electric Field Induced Changes on Plant Cellular Level. *Innov. Food Sci. Emerg. Technol.* **2010**, *11*, 592–597. [CrossRef]
21. Zhang, B.; Zeng, X.A.; Sun, D.W.; Yu, S.J.; Yang, M.F.; Ma, S. Effect of Electric Field Treatments on Brandy Aging in Oak Barrels. *Food Bioprocess Technol.* **2013**, *6*, 1635–1643. [CrossRef]
22. Hernández-Carapia, M.Á.; Verde-Calvo, J.R.; Escalona-Buendía, H.B.; Peña-Álvarez, A. Effect of Maturation with American Oak Chips on the Volatile and Sensory Profile of a Cabernet Sauvignon Rosé Wine and Its Comparison with Commercial Wines. *Beverages* **2023**, *9*, 72. [CrossRef]
23. Delsart, C.; Ghidossi, R.; Poupot, C.; Cholet, C.; Grimi, N.; Vorobiev, E.; Milisic, V.; Mietton Peuchot, M. Enhanced Extraction of Phenolic Compounds from Merlot Grapes by Pulsed Electric Field Treatment. *Am. J. Enol. Vitic.* **2012**, *63*, 205–211. [CrossRef]
24. Feng, Y.; Yang, T.; Zhang, Y.; Zhang, A.; Gai, L.; Niu, D. Potential Applications of Pulsed Electric Field in the Fermented Wine Industry. *Front. Nutr.* **2022**, *9*, 1048632. [CrossRef] [PubMed]
25. Toulaki, A.K.; Bozinou, E.; Athanasiadis, V.; Chatzimitakos, T.; Mantanis, G.I.; Dourtoglou, V.G.; Lalas, S.I. Accelerating Xinomavro Red Wine Flavor Aging Using a Pulsed Electric Field and Various Wood Chips. *Appl. Sci.* **2023**, *13*, 12844. [CrossRef]
26. Koussissi, E.; Paterson, A.; Piggott, J.R. Sensory Flavour Discrimination of Greek Dry Red Wines. *J. Sci. Food Agric.* **2003**, *83*, 797–808. [CrossRef]
27. Koufos, G.C.; Mavromatis, T.; Koundouras, S.; Fyllas, N.M.; Theocharis, S.; Jones, G.V. Greek Wine Quality Assessment and Relationships with Climate: Trends, Future Projections and Uncertainties. *Water* **2022**, *14*, 573. [CrossRef]
28. *ISO 3591:1977*; Sensory Analysis—Apparatus—Wine-Tasting Glass. ISO: Geneva, Switzerland, 1977.
29. *ISO 8589:2007*; Sensory Analysis—General Guidance for the Design of Test Rooms. ISO: Geneva, Switzerland, 2007.
30. European Society for Opinion and Market Research. Available online: https://esomar.org/ (accessed on 13 January 2024).
31. Vicaş, S.I.; Bandici, L.; Teuşdea, A.C.; Turcin, V.; Popa, D.; Bandici, G.E. The Bioactive Compounds, Antioxidant Capacity, and Color Intensity in Must and Wines Derived from Grapes Processed by Pulsed Electric Field. *CyTA-J. Food* **2017**, *15*, 553–562. [CrossRef]
32. Martínez-Pérez, M.P.; Bautista-Ortín, A.B.; Pérez-Porras, P.; Jurado, R.; Gómez-Plaza, E. A New Approach to the Reduction of Alcohol Content in Red Wines: The Use of High-Power Ultrasounds. *Foods* **2020**, *9*, 726. [CrossRef]
33. Ribéreau-Gayon, P.; Glories, Y.; Maujean, A.; Dubourdieu, D. *Handbook of Enology, Volume 2: The Chemistry of Wine Stabilization and Treatments*; John Wiley & Sons: New York, NY, USA, 2021; ISBN 978-1-119-58776-7.
34. Hjelmeland, A.K.; King, E.S.; Ebeler, S.E.; Heymann, H. Characterizing the Chemical and Sensory Profiles of United States Cabernet Sauvignon Wines and Blends. *Am. J. Enol. Vitic.* **2013**, *64*, 169–179. [CrossRef]
35. Tavares, M.; Jordão, A.M.; Ricardo-da-Silva, J.M. Impact of Cherry, Acacia and Oak Chips on Red Wine Phenolic Parameters and Sensory Profile. *OENO One* **2017**, *51*, 329. [CrossRef]
36. Comuzzo, P.; Voce, S.; Grazioli, C.; Tubaro, F.; Marconi, M.; Zanella, G.; Querzè, M. Pulsed Electric Field Processing of Red Grapes (Cv. Rondinella): Modifications of Phenolic Fraction and Effects on Wine Evolution. *Foods* **2020**, *9*, 414. [CrossRef] [PubMed]
37. Ribas-Agustí, A.; Martín-Belloso, O.; Soliva-Fortuny, R.; Elez-Martínez, P. Enhancing Hydroxycinnamic Acids and Flavan-3-Ol Contents by Pulsed Electric Fields without Affecting Quality Attributes of Apple. *Food Res. Int.* **2019**, *121*, 433–440. [CrossRef] [PubMed]
38. Sotelo, K.A.G.; Hamid, N.; Oey, I.; Pook, C.; Gutierrez-Maddox, N.; Ma, Q.; Ying Leong, S.; Lu, J. Red Cherries (*Prunus avium* Var. Stella) Processed by Pulsed Electric Field—Physical, Chemical and Microbiological Analyses. *Food Chem.* **2018**, *240*, 926–934. [CrossRef] [PubMed]
39. Gordillo, B.; Cejudo-Bastante, M.J.; Rodríguez-Pulido, F.J.; González-Miret, M.L.; Heredia, F.J. Application of the Differential Colorimetry and Polyphenolic Profile to the Evaluation of the Chromatic Quality of Tempranillo Red Wines Elaborated in Warm Climate. Influence of the Presence of Oak Wood Chips during Fermentation. *Food Chem.* **2013**, *141*, 2184–2190. [CrossRef] [PubMed]
40. Chinnici, F.; Natali, N.; Sonni, F.; Bellachioma, A.; Riponi, C. Comparative Changes in Color Features and Pigment Composition of Red Wines Aged in Oak and Cherry Wood Casks. *J. Agric. Food Chem.* **2011**, *59*, 6575–6582. [CrossRef] [PubMed]
41. Teusdea, A.C.; Bandici, L.; Kordiaka, R.; Bandici, G.E.; Vicas, S.I. The Effect of Different Pulsed Electric Field Treatments on Producing High Quality Red Wines. *Not. Bot. Horti Agrobot. Cluj-Napoca* **2017**, *45*, 540–547. [CrossRef]
42. Puértolas, E.; Saldaña, G.; Álvarez, I.; Raso, J. Effect of Pulsed Electric Field Processing of Red Grapes on Wine Chromatic and Phenolic Characteristics during Aging in Oak Barrels. *J. Agric. Food Chem.* **2010**, *58*, 2351–2357. [CrossRef]
43. Ricci, A.; Parpinello, G.P.; Banfi, B.A.; Olivi, F.; Versari, A. Preliminary Study of the Effects of Pulsed Electric Field (PEF) Treatments in Wines Obtained from Early-Harvested Sangiovese Grapes. *Beverages* **2020**, *6*, 34. [CrossRef]
44. Gallego, L.; Del Alamo, M.; Nevares, I.; Fernández, J.; de Simón, B.F.; Cadahía, E. Phenolic Compounds and Sensorial Characterization of Wines Aged with Alternative to Barrel Products Made of Spanish Oak Wood (*Quercus pyrenaica* Willd.). *Food Sci. Technol. Int.* **2012**, *18*, 151–165. [CrossRef]

45. Jiang, B.; Zhang, Z. Volatile Compounds of Young Wines from Cabernet Sauvignon, Cabernet Gernischet and Chardonnay Varieties Grown in the Loess Plateau Region of China. *Molecules* **2010**, *15*, 9184–9196. [CrossRef]
46. Fang, Y.; Qian, M. Aroma Compounds in Oregon Pinot Noir Wine Determined by Aroma Extract Dilution Analysis (AEDA). *Flavour Fragr. J.* **2005**, *20*, 22–29. [CrossRef]
47. Sooklim, C.; Samakkarn, W.; Thongmee, A.; Duangphakdee, O.; Soontorngun, N. Enhanced Aroma and Flavour Profile of Fermented *Tetragonula pagdeni* Schwarz Honey by a Novel Yeast *T. Delbrueckii* GT-ROSE1 with Superior Fermentability. *Food Biosci.* **2022**, *50*, 102001. [CrossRef]
48. Goulioti, E.; Jeffery, D.W.; Kanapitsas, A.; Lola, D.; Papadopoulos, G.; Bauer, A.; Kotseridis, Y. Chemical and Sensory Characterization of Xinomavro Red Wine Using Grapes from Protected Designations of Northern Greece. *Molecules* **2023**, *28*, 5016. [CrossRef] [PubMed]
49. Comuzzo, P.; Marconi, M.; Zanella, G.; Querzè, M. Pulsed Electric Field Processing of White Grapes (Cv. Garganega): Effects on Wine Composition and Volatile Compounds. *Food Chem.* **2018**, *264*, 16–23. [CrossRef] [PubMed]
50. Jiang, B.; Xi, Z.; Luo, M.; Zhang, Z. Comparison on Aroma Compounds in Cabernet Sauvignon and Merlot Wines from Four Wine Grape-Growing Regions in China. *Food Res. Int.* **2013**, *51*, 482–489. [CrossRef]
51. Escudero, A.; Campo, E.; Fariña, L.; Cacho, J.; Ferreira, V. Analytical Characterization of the Aroma of Five Premium Red Wines. Insights into the Role of Odor Families and the Concept of Fruitiness of Wines. *J. Agric. Food Chem.* **2007**, *55*, 4501–4510. [CrossRef]
52. Falcao, L.D.; Lytra, G.; Darriet, P.; Barbe, J.-C. Identification of Ethyl 2-Hydroxy-4-Methylpentanoate in Red Wines, a Compound Involved in Blackberry Aroma. *Food Chem.* **2012**, *132*, 230–236. [CrossRef]
53. Ferreira, V.; López, R.; Cacho, J.F. Quantitative Determination of the Odorants of Young Red Wines from Different Grape Varieties. *J. Sci. Food Agric.* **2000**, *80*, 1659–1667. [CrossRef]
54. Pittari, E.; Moio, L.; Piombino, P. Interactions between Polyphenols and Volatile Compounds in Wine: A Literature Review on Physicochemical and Sensory Insights. *Appl. Sci.* **2021**, *11*, 1157. [CrossRef]