

Article

Volatile Compounds as Markers of Terroir and Winemaking Practices in Fetească Albă Wines of Romania

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Abstract: This study evaluates the influence of terroir on the physico-chemical characteristics and aromatic profiles of Fetească albă wines from five major Romanian wine regions. By analysing key factors such as soil types, climatic conditions, and winemaking techniques, the study aims to understand their impact on wine composition and quality. The study includes the analysis of superior alcohols, fatty acids, esters, carbonyl compounds, terpenes, and 4-mercapto-4-methylpentan-2-one, which are essential in defining the aromatic complexity of the wines. The results show how fermentation conditions, temperature control, microbial activity, and oxidative exposure contribute to the evolution of these compounds, influencing the sensory profiles. Significant differences in compound concentrations were observed across the regions, with wines from Dealu Mare and Murfatlar exhibiting high ester content and aromatic complexity, while those from Dealul Bujorului and Panciu showed elevated volatile acids and aromatic alcohols, suggesting distinct fermentation dynamics. Climatic factors, such as temperature and precipitation, played a crucial role in shaping the volatile composition, with elevated temperatures in 2021 enhancing ester formation and higher alcohol production. This study demonstrates the critical role of terroir and winemaking practices in shaping the aromatic and sensory characteristics of Romanian Fetească albă wines.

Keywords: terroir; Fetească albă; aromatic profile; volatile compounds; winemaking techniques; climatic influence



Academic Editors: Elisabeth Koussissi and Maria Kyraleou

Received: 13 March 2025

Revised: 11 April 2025

Accepted: 24 April 2025

Published: 7 May 2025

Citation: Bedreag, I.C.; Cioroiu, I.-B.; Niculaua, M.; Nechita, C.-B.; Cotea, V.V. Volatile Compounds as Markers of Terroir and Winemaking Practices in Fetească Albă Wines of Romania. *Beverages* **2025**, *11*, 67.

<https://doi.org/10.3390/beverages11030067>

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1. Introduction

Fetească albă is a native Romanian grape variety, cultivated on approximately 12,000 hectares annually, with a productivity ranging from 9 to 20 tons per hectare. Known for producing dry, semi-dry, sweet, and sparkling wines, it is celebrated for its finesse, balanced alcohol content (11.5–12%) and acidity, as well as its exceptional sugar accumulation potential. Grapes typically contain 180–220 g/L of sugar, but under overripe conditions, this can increase to 270 g/L [1].

Vitivinicultural terroir is a term that encompasses aspects related to the interaction between key factors contributing to the development of wines with specific individual characteristics. These include physical, biological, location, soil, pedoclimatic influences, and vitivinicultural practices, all of which provide distinctive traits for the products originating from the studied areas [2].

Wine is one of the agricultural products the aroma and taste of which are influenced by its place of origin. The specific environment in which the vine has grown plays a very important role, being reflected in the aroma and bouquet of the wine produced from it [3].

Wines are characterized chemically, organoleptically, and microbiologically throughout their evolution to understand, preserve, and enhance their qualities through optimal care and conditioning [4]. Being a complex system, constant monitoring of quality characteristics is essential and involves evaluating physico-chemical parameters (density, alcohol concentration, reducing sugar content, total acidity, pH, volatile acidity, total and non-reducing dry extract content, total and free sulfur dioxide content) as well as sensory parameters (olfactory and taste characteristics) [5].

The inclusion of key terroir elements in a coherent and predictable layout begins with the locations occupied by the vineyards. These locations are characterized by unique environmental factors, as well as the properties and geology of the soils. These two factors are correlated and directly connected to other aspects such as slope orientation and vineyard zoning, which shape the microclimatic conditions that define the unique terroir of a region [6].

Pedoclimatic factors have a significant influence on the character of the wine, even when the variety remains the same. Soil composition, climate (maximum and minimum temperatures, precipitation, winds, number of sunny days), vineyard exposure, and harvesting and processing methods all contribute to the quality of the final wine [7]. The quality of the soil is very important in the formation of aromas because the vine accumulates chemical elements that can persist or penetrate its layers to a greater or lesser extent [8].

A quality index was developed to evaluate different soil types, identifying peyrosol (gravelly soil on quaternary alluvium) as a key soil type. The highest wine quality was associated with planosol (heavy clay subsoil of tertiary origin), arenosol (sandy soil of quaternary aeolian origin), brunisol (sandy-gravel soil on quaternary alluvial terraces), and peyrosol. In contrast, lower-quality wines were linked to colluviosol (deep sandy soil on colluvium), luvisol (leached sandy clay soil on quaternary alluvium), and reductisol (sandy soil with a permanent water table in valley areas) [8]. Several soil characteristics influence grape growth and maturation, including limestone, clay, silt, sand, organic matter, stones, and drainage capacity. White, calcareous soils tend to produce more elegant, fruity wines with silky tannins and a higher aging potential [9]. Romania's wine regions are defined by diverse soil types and climates that influence wine characteristics. Key soil types include clay-rich, calcareous, and loamy soils for structure and minerality, limestone, marl, and volcanic soils for complexity and aging potential, and alluvial and sandy soils for warmth and fruit-forward flavours. Loess-rich soils also enhance aromatic qualities, contributing to the diversity of wines produced across the country [10].

Soil and pedoclimatic factors play a crucial role in the maturity of grapes, which directly impacts the quality of wine [11]. This includes technological maturity (referring to sugar accumulation and acid reduction), phenolic maturity (accumulation of anthocyanins and tannins), and aromatic maturity (accumulation of primary aromas). The sugar accumulation process continues when full grape maturity is reached. Prolonged exposure to sunlight enhances the formation of important aroma compounds. In cooler climates, increased sunlight exposure boosts the levels of glycosidic precursors, including monoterpenes and norisoprenoid aglycones [12]. During alcoholic fermentation, terpenes in grapes undergo transformations, with geraniol converting into linalool and nerol cyclizing into α -terpineol. This leads to the formation of citronellol, giving the wine a distinct "green lemon" aroma due to higher concentrations of terpineol and citronellol [13].

In this context, aroma is a key factor in the quality of all foods, but in wine, it is one of the most important aspects contributing to overall quality. A large number of chemical compounds with varying volatilities and polarities are responsible for wine aroma, and during vinification and aging, various reactions and interactions occur that can influence the perception of the wine's bouquet [14,15].

Understanding the volatile composition of wine is essential, as these compounds are closely linked to its aroma. Although hundreds of chemical compounds have been identified in grapes and wines, only a few significantly contribute to the sensory perception of wine's aromatic properties [16]. Aroma perception results from numerous interactions between various chemical compounds and sensory receptors. Alcohols, acids, and higher esters are quantitatively dominant in wine aroma and play a vital role in its sensory properties and overall quality [17]. Small quantities of higher alcohols enhance wine quality, while excessive amounts can negatively impact it. Esters contribute to the wine aroma, and relatively high concentrations of fatty acids produce a noticeable, strong aroma [18]. Gas chromatography coupled with mass spectrometry (GC-MS) is a widely used method for isolating and identifying volatile compounds in wines and foods due to its high sensitivity and reproducibility [19].

Integrated vineyard management strategies that incorporate mechanization are widely used by grape growers and are increasingly gaining interest. However, the concept of terroir may not easily align with mechanization, which requires adaptable approaches to remain relevant and address the challenges posed by climate change [20].

Oenological practices significantly influence the expression of terroir, with winemakers using techniques like harvest timing, fermentation methods, maceration, aging, and blending to accentuate or modify the natural characteristics of the grapes and their environment [21]. Otherwise, wild fermentation with native yeasts can highlight terroir-driven qualities, while oak aging may complement or obscure them [22]. Practices like minimal agricultural interventions preserve subtle flavours, allowing the wine to reflect its origin [23]. The balance between respecting terroir and applying oenological techniques ultimately shapes the unique profile of wine.

It has been found that oenological practices related to conditioning and stabilization lead to variations in volatile compounds in samples treated with different fining agents (potassium sorbate, gum arabic, cellulose gum). Various studies have shown that fining treatments applied to wines, including Fetească albă, result in changes in the concentration of aromatic compounds due to their adsorption or by catalysing reactions that lead to the formation of higher molecular weight compounds with a different sensory impression [24].

The present study aims to evaluate the influence of terroir on the physico-chemical characteristics and aromatic profile of white wines from different Romanian wine regions. By analysing key soil types, climate conditions, and viticultural practices, the study aims to elucidate how these factors shape wine composition and quality. Additionally, the impact of oenological treatments on volatile compounds and sensory attributes will be assessed to determine their role in preserving or altering the terroir expression in wines.

2. Materials and Methods

2.1. Reagents and Standards

Acetic aldehyde, ethyl acetate, methanol, butan-2-ol, propan-1-ol, 2-methylpropan-1-ol, isoamyl acetate, butan-1-ol, 2-methylbutan-1-ol, 3-methylbutan-1-ol, pentan-1-ol, ethyl lactate, hexan-1-ol, 3-ethoxypropanol, ethyl octanoate, propane-1,2-diol, diethyl succinate, hexanoic acid, 2-phenylethanol, 4-methyl-pentan-2-ol were purchased from Sigma–Aldrich (Steinheim, Germany). Sodium chloride (NaCl) was obtained from Merck (Darmstadt, Germany).

2.2. Wine Samples

The vineyards and wineries included in this study, together with their sample codes, geographic locations, altitudes, and soil types, are summarized in Table 1, providing a clear framework for the origin of the analysed wine samples. Representative Fetească Albă (FA) samples, a white wine grape variety, were collected over two vintages, 2019 and 2021, from five major Romanian wine regions: Dealurile Munteniei și Olteniei, Banat, Colinele Dobrogei, Podișul Transilvaniei, and Dealurile Moldovei. Each region is characterized by its specific terroir and winemaking traditions, with wines sourced from a diverse set of vineyards and wineries, as detailed in the table. The study focused on wines at two technological stages: raw wines, collected prior to filtration and conditioning, and conditioned wines, subjected to clarification, fining, stabilization, and filtration processes adapted to each regional practice.

Table 1. Characterization of vineyards locations according to latitude (°), longitude (°) and altitude (m) and soil type of wine regions and wineries.

Sample Codes (sp.)	Vineyard/Winery	Lat. (°)	Long. (°)	Alt. (m)	Soil Types
Domeniile Boieru	Aiud Vineyard (Domeniile Boieru Winery)	23.70	46.30	275	Pseudogleyic and albic luvaceous soils
Ceptura	Dealul Mare Vineyard (Ceptura Winery)	26.40	45.00	175	Cambic chernozemic
Davino	Dealul Mare Vineyard (Davino Winery)	26.31	45.02	255	Cambic chernozemic
Aurelia Vișinescu	Dealul Mare Vineyard (Aurelia Vișinescu Winery)	26.50	45.00	170	Alluvial soils and alluvial protosols
SCDVV Bujoru	Dealul Bujorului Vineyard (SCDVV Bujoru)	28.00	45.70	100	Levigated chernozems
Aramic	Dealurile Silagiului Vineyard (Aramic Winery)	21.60	45.60	250	Erodisollic alluvial and alluvial protosols
Jelna	Lechința Vineyard (Jelna Winery)	24.60	46.60	400	Brown eu-mesobasic, acidic and luvaceous
Panciu	Panciu Vineyard (Panciu Winery)	27.00	45.90	150	Cambic chernozems
Sarica Niculițel	Sarica Niculițel Vineyard (Sarica Niculițel Winery)	28.20	44.60	75	Weakly compacted chernozems, alkaline (pH 8.0–8.2), moderate calcium carbonate
Jidvei	Târnave Vineyard (Jidvei Winery)	24.10	46.20	260	Pseudorezibic, clay-illuvial brown soils
Viișoara	Murfatlar Vineyard (Viișoara Winery)	28.40	44.20	75	Steppe chernozemic mollisols, typical and lithic rendzinas

Vinification followed conventional methods, including grape processing, must clarification, and controlled fermentation at 12–18 °C in stainless steel tanks. Post-fermentation stabilization was carried out using fining agents such as bentonite, gelatine, or cellulose gum, with gum arabic used as a protective colloid, helping to stabilize the colloidal clarity of the wine. This was followed by cold stabilization (−4 °C) and cross-flow or sterile filtration. Physico-chemical parameters were assessed according to OIV standards, including reducing substances, total acidity, density, alcohol content, volatile acidity, and sulfur dioxide levels.

2.3. Climatic Parameters

Climatic data were collected for each vineyard location during the grape ripening period, specifically between August 1 and October 31, which represents a critical phase influencing grape composition and subsequent wine quality. The parameters analysed included average temperatures (AvT, °C), sum of active temperatures (SumACtT, °C), precipitation (PP, mm), wind speed (WndSp, m/s), solar radiation (SolRad, W/m²), UV index (UVIndex, nm), actual sunshine duration (ASD, h), and the oenoclimate aptitude index (IAOe), which provides an integrated assessment of viticultural climatic suitability.

Historical weather data for the vineyard locations were retrieved from Visual Crossing Weather (www.visualcrossing.com, accessed on 22 December 2024), ensuring standardized climatic information across all sites.

2.4. Sample Preparation

A total of 36 wine samples, originated from the five wine regions, were manufactured using classical fermentation conditions. Main volatiles and aroma compounds in raw and conditioned wine samples were determined by HS-GC-FID and ITEX-GC-MS analysis, respectively.

Sample preparation for determination of main volatiles (acetaldehyde, ethyl-acetate, methanol, 1-propanol, isobutanol, 1-butanol, isoamyl alcohol, and 1-hexanol) in the wine samples by HS-GC-FID was carried out by adding 50 µL of internal standard solution (4-methyl-2-pentanol 10 g/L in ethanol) as an internal standard to 10 mL of wine. A mixture of reference standards is made by mixing corresponding volumes of stock solutions to obtain solutions ranging from 10–200 mg/L.

Aromatic compounds were analysed using ITEX-GC-MS with the salting-out method. Into a 20 mL screw cap headspace vial fitted with a PTFE/silicone septum, 10 mL of wine was pipetted then chilled to 2 °C for 6 h. A quantity of 10 µL of internal standard solution (4-methyl-2-pentanol 50 g/L in ethanol) was added, then chilled to 2 °C for 6 h and 3.5 g NaCl was added to the vials. The trapping material used was TENAXTM-TA (Buchem B.V., Minden, The Netherlands), pre-cleaned at 260 °C for 10 min to eliminate potential contaminants. The incubation process was carried out at 50 °C for 10 min with an agitation speed of 500 rpm to enhance the release of volatile compounds. A total of 20 extractions were carried out at 20 µL/s fill-up and 50 µL/s dispense speed. The syringe temperature was maintained at 55 °C, while the trap was set at 50 °C to facilitate compound adsorption. The extraction was performed using 20 strokes, with a total extraction volume of 1500 µL, ensuring a comprehensive collection of volatiles. Desorption was carried out at 250 °C with a flow rate of 200 µL/s, followed by an injection of 1500 µL into the analytical system.

2.5. GC-FID and GC-MS Analysis

The analysis of main volatile compounds was conducted using gas chromatography with a flame ionization detector (GC-FID) on an Agilent 7890B system (Agilent Technologies (Santa Clara, CA, USA)), equipped with a GC Sampler 80 featuring headspace technology. Separation was performed using an Agilent CP-Wax 57 CB column (50 m length, 0.25 mm internal diameter, 0.2 µm film thickness).

For the headspace injection, samples were incubated at 76 °C for 10 min, with the syringe maintained at 78 °C. A 1.5 mL volume was injected into the MMI injector (990 µL internal volume liner), operating at a 10:1 split ratio at 250 °C. Hydrogen was used as the carrier gas, flowing at 1.5 mL/min. The temperature program began at 30 °C (held for 10 min), followed by a 2 °C/min ramp up to 50 °C (5 min hold isothermal), then a 5 °C/min increase to 60 °C (5 min hold isothermal), then a 10 °C/min increase to 150 °C (5 min hold isothermal) and finally 15 °C/min increase to 210 °C (10 min hold isothermal), resulting

in a total run time of 60 min. The FID detector operated at 300 °C, with an acquisition rate of 50 Hz, 350 mL/min synthetic air, makeup 25 mL/min nitrogen and combined total 35 mL/min hydrogen.

Additionally, GC–MS analysis of aroma compounds was performed using a Shimadzu GC-2010, coupled with a Shimadzu quadrupole mass spectrometer QP2010plus (Shimadzu Corporation, Kyoto, Japan). A polar Thermo TR-WAXms capillary column (60 m length, 0.25 mm diameter, 0.25 µm film thickness, 280 °C maximum) facilitated separation. The temperature program started at 40 °C for 5 min hold and increased to 80 °C at 4 °C/min, followed by an 8 °C/min ramp to 200 °C, then with a rate of 20 °C/min to a final 250 °C for finally 9.5 min isothermal hold. Helium 5.0 served as the carrier gas in linear velocity flow control, column flow 1.9 mL/min (linear velocity 35.2 cm/s). A 1500 µL injection was performed in 10:1 split mode with a sampling time of 0.5 min at 260 °C. Mass spectra were acquired using electron ionization (EI 70 eV) at 200 °C ion source and a detection range of 20–300 amu. The transfer line temperature was 250 °C.

2.6. Statistics

Prior to conducting the analysis of variance (ANOVA), data were assessed for normality using the Kolmogorov–Smirnov and Lilliefors tests. Variables such as alcohol content, volatile acidity, and total sulfur dioxide exhibited normal distributions ($p > 0.20$ in both tests), supporting the use of parametric methods. In contrast, free sulfur dioxide and reducing sugars did not meet the normality assumptions (Lilliefors $p < 0.01$), while relative density and total acidity showed borderline or uncertain normality characteristics.

Accordingly, ANOVA and subsequent Tukey's HSD test for multiple comparisons were applied only to those parameters that fulfilled both normality and homogeneity of variance assumptions. All results are expressed as mean $\pm$ standard deviation (SD), based on three replicates.

For the volatile compounds, normality was similarly assessed. Compounds meeting the criteria for normal distribution ($W > 0.95$ and $p > 0.05$) were analysed using one-way ANOVA, followed by Tukey HSD tests for pairwise comparisons between sample groups (e.g., regions or winemaking techniques). Compounds with distributions deviating from normality ($W < 0.95$ and/or $p < 0.05$) were analysed using the non-parametric Mann–Whitney U test, ensuring statistical robustness and reliable interpretation of variation across the wine samples.

Correlation analysis between volatile compounds was also conducted. Pearson correlation was applied to variables with normal distribution, while Spearman correlation was used for variables not meeting normality assumptions, as it is less sensitive to deviations from normal distribution.

To reduce skewness and prepare the data for multivariate analysis, volatile compound concentrations were log-transformed and standardized (mean-centred and scaled to unit variance). Principal Component Analysis (PCA) was performed to reduce dimensionality and identify clustering patterns among samples. Correlation matrices were constructed to explore relationships between variables, and Hierarchical Cluster Analysis (HCA) was applied to reveal natural groupings of samples based on their volatile profiles.

All statistical analyses were performed using StatSoft Statistica, version 14.0. Data visualization, including PCA biplots and dendrograms, was carried out in R version 4.4.2 using RStudio version 2023.12.0.

3. Results

3.1. Distribution Based on Soils and the Geographical Origin of the Samples

The diversity of soil types (Table 1) in wine regions of Romania [25] plays a fundamental role in shaping the growth of vines and the characteristics of grapes, ultimately influencing the quality of the wines. In Aiud vineyard, the pseudogleyic and albic luvaceous soils provide moderate water retention, ensuring balanced vine growth and enhancing the acidity and minerality of the grapes [26]. In Dealu Mare vineyard, cambic chernozems from Ceptura and Davino wineries offers well-drained, nutrient-rich soils that promote deep root development. Alluvial and protosol soils in Aurelia Vişinescu winery encourage vigorous vine growth due to their high fertility, resulting in fresh and aromatic grapes [27].

In Dealul Bujorului vineyard, the levigated chernozems help retain moderate moisture, providing vines with steady hydration and ensuring that the grapes develop a balanced ratio of sugars-to-acidity [28]. Similarly, in the Dealurile Silagiului vineyard, the erodisollic alluvial and alluvial protosols support proper drainage while in Lechința vineyard, the brown eu-mesobasic, acidic, and luvaceous soils are characteristic of a cooler climate.

In Panciu region, the cambic chernozems are rich in nutrients and well-aerated, supporting optimal grape maturity and enhancing aromatic complexity. Meanwhile, in Sarica Niculițel vineyard, the weakly compacted chernozems, with an alkaline pH (8.0–8.2) and moderate calcium carbonate content, improve mineral uptake in vines. The pseudorezibic, clay-illuvial brown soils of Târnave vineyard help regulate water availability, ensuring slow grape maturation [29]. Finally, in Murfatlar vineyard, the steppe chernozemic mollisols with typical and lithic rendzina properties contain high calcium levels, which enhance grape structure and contribute to the production of well-balanced, fruit-forward wines [30].

3.2. Physico-Chemical Analysis of Wine Samples

The physico-chemical characteristics are presented in Table 2. The results exhibited a range of variations, from negligible differences in relative density to significant modifications with high variability.

Table 2. Physico-chemical analysis of wine samples (mean $\pm$ STDEV, $n = 3$).

Sample (sp.)	(% vol)	Total Acidity (g/L)	Volatile Acidity (g/L)	Red. Sugars (g/L)	Density (g/mL)	Free SO ₂ (mg/L)	Total SO ₂ (mg/L)
Ceptura	13.0 $\pm$ 0.03	6.60 $\pm$ 0.11	0.15 $\pm$ 0.03	1.71 $\pm$ 0.80	0.9910 $\pm$ 0.0002	36 $\pm$ 2.07	118 $\pm$ 16.3
Aramic	13.4 $\pm$ 0.14	6.56 $\pm$ 0.06	0.45 $\pm$ 0.04	2.19 $\pm$ 0.33	0.9910 $\pm$ 0.0020	25 $\pm$ 2.33	115 $\pm$ 8.81
Jidvei	11.6 $\pm$ 0.10	6.82 $\pm$ 0.12	0.21 $\pm$ 0.02	2.24 $\pm$ 0.12	0.9920 $\pm$ 0.0040	28 $\pm$ 5.25	79 $\pm$ 8.56
Domeniile Boieru	11.5 $\pm$ 0.45	5.49 $\pm$ 0.44	0.27 $\pm$ 0.03	1.46 $\pm$ 1.15	0.9920 $\pm$ 0.0030	48 $\pm$ 1.67	96 $\pm$ 3.88
SCDVV Bujoru	12.4 $\pm$ 0.20	5.93 $\pm$ 0.37	0.40 $\pm$ 0.07	3.80 $\pm$ 1.25	0.9900 $\pm$ 0.0002	29 $\pm$ 2.01	148 $\pm$ 5.83
Panciu	13.1 $\pm$ 0.13	6.80 $\pm$ 0.55	0.39 $\pm$ 0.01	3.87 $\pm$ 0.49	0.9910 $\pm$ 0.0006	31 $\pm$ 3.67	72 $\pm$ 6.75
Aurelia Visinescu	13.1 $\pm$ 0.33	5.76 $\pm$ 0.20	0.25 $\pm$ 0.02	3.30 $\pm$ 0.48	0.9930 $\pm$ 0.0003	58 $\pm$ 2.05	96 $\pm$ 10.6
Sarica Niculițel	12.6 $\pm$ 0.10	7.11 $\pm$ 0.09	0.36 $\pm$ 0.01	1.75 $\pm$ 0.45	0.9910 $\pm$ 0.0006	23 $\pm$ 0.50	70 $\pm$ 4.30
Davino	13.5 $\pm$ 0.25	6.11 $\pm$ 0.11	0.28 $\pm$ 0.05	0.38 $\pm$ 0.25	0.9890 $\pm$ 0.0020	38 $\pm$ 2.25	55 $\pm$ 4.40
Viișoara	12.2 $\pm$ 0.25	6.10 $\pm$ 0.20	0.25 $\pm$ 0.06	2.65 $\pm$ 0.62	0.9920 $\pm$ 0.0002	38 $\pm$ 1.25	87 $\pm$ 12.2
Jelna	14.3 $\pm$ 0.30	7.07 $\pm$ 0.35	0.56 $\pm$ 0.10	0.92 $\pm$ 0.10	0.9900 $\pm$ 0.0021	37 $\pm$ 1.55	103 $\pm$ 10.3

Based on the Tukey HSD test analysis, the results highlight significant differences among the studied wineries in terms of alcohol content, volatile acidity, and relative density,

emphasizing the impact of terroir and winemaking styles across Romania. The alcohol content (% vol.) is significantly higher in the Jelna ($14.3 \pm 0.3\%$ vol.) compared to Domeniile Boieru ($11.5 \pm 0.45\%$ vol., $p = 0.0002$), Jidvei ($11.6 \pm 0.1\%$ vol., $p = 0.001$) and SCDVV Bujoru ($12.4 \pm 0.2\%$ vol., $p = 0.002$). Additionally, wineries in Ceptura, Davino, and Aurelia Vişinescu exhibit high and similar alcohol content values ($p > 0.9$), whereas Aiud and Târnave regions show significantly lower levels ($p < 0.05$).

For volatile acidity (VA), which also exhibited normal distribution, Jelna (0.56 ± 0.1 g/L acetic acid equivalent) stands out significantly compared to Dealu Mare V. (Ceptura, 0.15 ± 0.03 g/L, $p = 0.0002$), Târnave V. (Jidvei, 0.21 ± 0.02 g/L, $p = 0.006$), and Aiud V. (Domeniile Boieru, 0.27 ± 0.03 g/L, $p = 0.002$). Moreover, samples from Dealu Mare V. (Ceptura) have significantly lower volatile acidity than Dealurile Silagiului V. (Aramic, 0.45 ± 0.04 g/L, $p = 0.000758$) and Panciu V. (Panciu, 0.39 ± 0.01 g/L, $p = 0.005$).

Comparative analysis of total and free SO₂ showed concentrations ranged from a minimum of 23 ± 0.50 mg/L at Sarica Niculiţel to a maximum of 58 ± 2.05 mg/L at Aurelia Vişinescu. Total SO₂ levels varied from 55 ± 4.40 mg/L at Davino to 148 ± 5.83 mg/L at SCDVV Bujoru. Wineries like Ceptura (36 ± 2.07 mg/L free SO₂ and 118 ± 16.3 mg/L total SO₂) and Jelna (37 ± 1.55 mg/L free SO₂ and 103 ± 10.3 mg/L total SO₂) demonstrated close values, while Davino showed both low total SO₂ (55 ± 4.40 mg/L) and a moderate free SO₂ (38 ± 2.25 mg/L), indicating efficient sulfur management. Conversely, SCDVV Bujoru presented the highest total SO₂ (148 ± 5.83 mg/L) but relatively low free SO₂ (29 ± 2.01 mg/L), indicating a lower proportion of active sulfur dioxide. The ratio of free to total SO₂ varied significantly, with values exceeding 60% at Davino and Aurelia Vişinescu, suggesting more active SO₂ presence relative to the total form.

These differences can be attributed to both winemaking practices and wine chemistry. Wineries with high free SO₂ despite lower total SO₂, such as Davino and Aurelia Vişinescu, benefit from clean fermentations with fewer SO₂ binding compounds (like aldehydes) and optimized pH levels, preserving the active antimicrobial and antioxidant effects of free SO₂. In contrast, wines like SCDVV Bujoru, with high total but lower free SO₂, suggest extensive SO₂ binding, potentially due to higher levels of acetaldehyde or residual sugars, or aggressive SO₂ additions during production.

Regarding relative density, although this parameter did not clearly meet the normality assumption based on the Lilliefors test ($p < 0.15$), the ANOVA results still suggested limited differences between regions. Most pairwise comparisons showed no significant differences ($p > 0.05$), though marginally significant variations were observed between Ceptura and Viişoara, $p = 0.07$, and between Dealul Bujorului (SCDVV Bujoru) and Aurelia Vişinescu ($p = 0.016$).

3.3. Distribution of Main Classes of Compounds According to Location Distribution

The analysed compounds—superior alcohols, fatty acids, esters, carbonyl compounds, terpenes, and dihydro-tetramethyl-furanone—are all essential in defining the aromatic and sensory profile of wines. Their selection for analysis is justified by their role in wine composition, their impact on flavour and aroma, and their potential relationship with environmental factors such as altitude and latitude.

Analysis confirms, as shown in Table 3, that higher-altitude wineries such as Jelna (400 m), Domeniile Boieru (275 m), and Jidvei (260 m) tend to have higher fatty acid concentrations and lower alcohol levels. Conversely, lower-altitude wineries like Sarica Niculiţel (75 m) and Viişoara (75 m) have the highest alcohol content and lower fatty acid levels.

Table 3. Average equivalent concentrations of main classes of compounds according to wineries distribution (nd.—not detected, $n = 3$).

Sample (sp.)	Superior Alcohols (mg/L)	Fatty Acids (mg/L)	Esters (mg/L)	Carbonylic Compounds (mg/L)	Terpenes (μ g/L)
Aurelia Vişinescu	60.0 $\pm$ 10.3	8.64 $\pm$ 2.70	30.2 $\pm$ 3.80	220 $\pm$ 57.9	nd.
Davino	69.7 $\pm$ 8.91	8.79 $\pm$ 1.63	28.5 $\pm$ 4.27	211 $\pm$ 18.0	2.58 $\pm$ 0.64
Ceptura	66.6 $\pm$ 7.08	9.03 $\pm$ 3.61	24.4 $\pm$ 2.25	187 $\pm$ 53.1	2.17 $\pm$ 0.25
Aramic	60.2 $\pm$ 16.9	12.7 $\pm$ 1.75	34.9 $\pm$ 9.03	320 $\pm$ 116	12.2 $\pm$ 0.25
Sarica Niculişel	66.3 $\pm$ 10.0	12.2 $\pm$ 1.80	27.9 $\pm$ 2.30	209 $\pm$ 53.0	1.14 $\pm$ 0.20
Jidvei	60.6 $\pm$ 8.19	6.60 $\pm$ 1.79	24.8 $\pm$ 1.43	108 $\pm$ 26.4	3.59 $\pm$ 0.12
Domeniile Boieru	59.8 $\pm$ 13.7	12.4 $\pm$ 2.56	26.6 $\pm$ 2.30	162 $\pm$ 48.8	11.9 $\pm$ 5.56
SCDVV Bujoru	51.3 $\pm$ 25.3	11.7 $\pm$ 0.75	14.9 $\pm$ 2.50	164 $\pm$ 20.8	38.4 $\pm$ 21.8
Jelna	51.0 $\pm$ 13.2	11.9 $\pm$ 2.03	27.9 $\pm$ 7.82	270 $\pm$ 54.1	6.27 $\pm$ 4.78
Panciu	31.1 $\pm$ 12.3	9.31 $\pm$ 1.25	28.8 $\pm$ 4.78	161 $\pm$ 22.2	nd.
Viişoara	69.0 $\pm$ 13.8	12.0 $\pm$ 1.73	25.8 $\pm$ 3.27	261 $\pm$ 24.2	3.71 $\pm$ 2.2

Key compound trends further emphasize these correlations: high superior alcohol content is observed in Viişoara (69 $\pm$ 13.8 mg/L), Ceptura (66.6 $\pm$ 7.08 mg/L), and Davino (69.7 $\pm$ 8.91 mg/L), which are typically located in lower-altitude regions. High fatty acid concentrations are found in Jelna (11.9 $\pm$ 2.03), Aramic (12.7 $\pm$ 1.75), and Domeniile Boieru (12.4 $\pm$ 2.56 mg/L), which are all high-altitude wineries.

High ester content is observed in Aramic (34.9 $\pm$ 9.03 mg/L), Davino (28.5 $\pm$ 4.27 mg/L), and Sarica Niculişel (27.9 $\pm$ 2.30 mg/L), suggesting that altitude plays a lesser role in ester concentrations, with winemaking techniques likely having a stronger influence. High terpene levels are recorded in Aramic (12.2 $\pm$ 0.25 μ g/L), SCDVV Bujoru (38.4 $\pm$ 21.8 μ g/L), and Domeniile Boieru (11.9 $\pm$ 5.56 μ g/L), showing no clear altitude-dependent pattern, although SCDVV Bujoru stands out.

The vineyards and wineries included in this study were selected considering their absolute geographic locations and altitudes, with respect to Romania's geographical position.

Spearman correlation analysis as presented in Figure 1 reveals a strong positive correlation (0.739) between latitude and altitude, indicating that wineries at higher latitudes tend to be situated at higher altitudes. Fatty acids exhibit a very strong positive correlation (0.997) with altitude, suggesting that vineyards at higher elevations tend to have increased fatty acid concentrations, as confirmed in Table 1.

Superior alcohols show a moderate negative correlation (−0.685), meaning that wines from higher-altitude vineyards tend to have lower alcohol content. A similar trend is observed for esters, which also present a moderate negative correlation (−0.613), indicating that ester concentrations tend to decrease as altitude increases. In contrast, carbonyl compounds display a weak positive correlation (0.144), suggesting that altitude has minimal influence on their levels.

Terpenes show a moderate negative correlation (−0.414), indicating that their concentration generally decreases with altitude, which confirms the distribution of the concentrations found for the mean values of the samples grouped according to the details of the locations of the wineries.

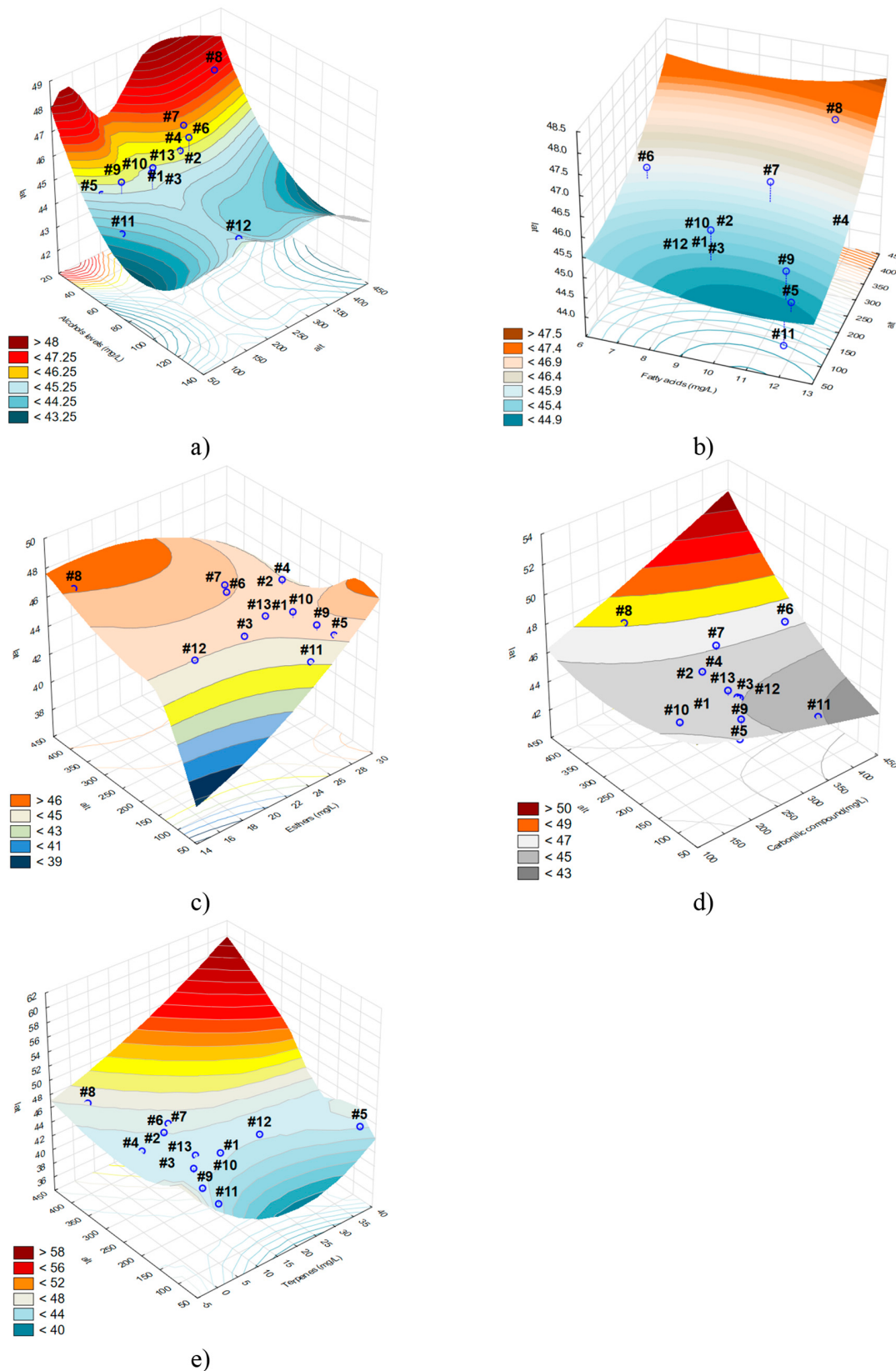


Figure 1. Correlation between main compound aromatic classes and latitude (°) and altitude (m): (a) alcohols (mg/L) vs. lat (°) and alt (m); (b) fatty acids (mg/L) vs. lat (°) and alt (m); (c) esters (mg/L) vs. lat (°) and alt (m); (d) carbonylic compounds (mg/L) vs. lat (°) and alt (m); (e) terpenes (µg/L) vs. lat (°) and alt (m). Sample codes: #1—Aurelia Vişinescu; #2—Davino; #3—Ceptura; #4—Aramic; #5—Sarica Niculiţel; #6—Jidvei; #7—Domeniile Boieru; #8—Jelna; #9—SCDVV Bujoru; #10—Panciu; #11—Vişoara; #12—Aurelia Vişinescu (2); #13—All groups (mean values).

These quantitative variations provide a foundation for differentiation among the wines in the PCA. Principal Component Analysis (PCA) in this study was applied to reduce the complexity of multidimensional chemical data and identify key patterns that differentiate wines based on their volatile composition. Given the influence of terroir, winemaking practices, and fermentation conditions on the formation of esters, alcohols, and volatile acids, PCA highlighted relationships between chemical parameters and regional characteristics and the distribution is summarized in Figure 2.

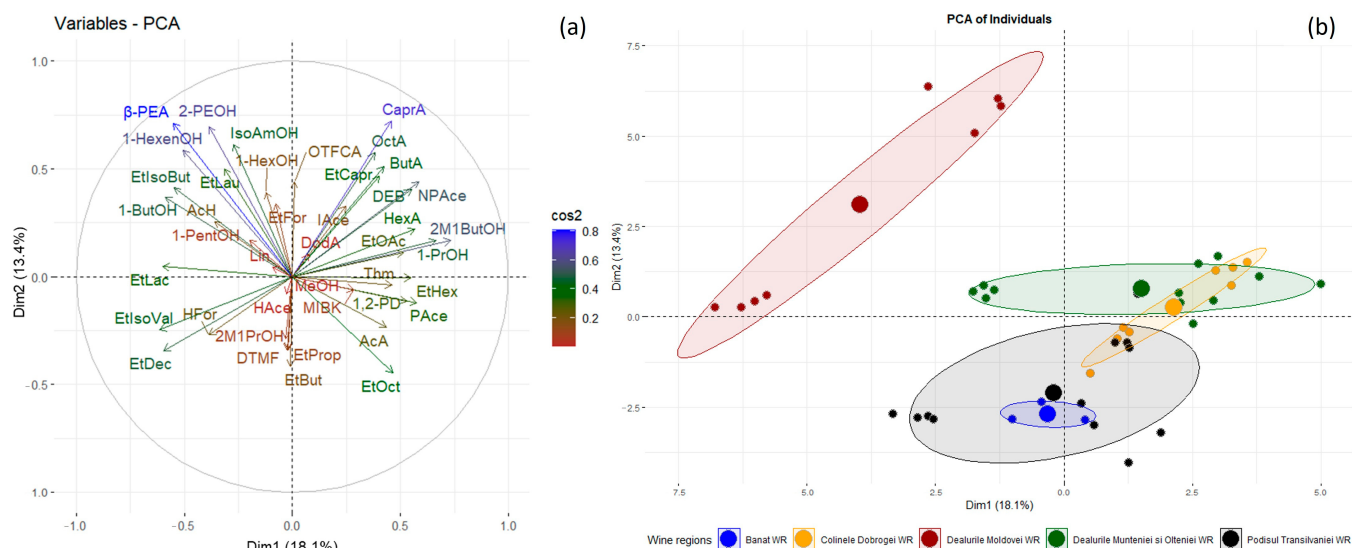


Figure 2. PCA differentiation of wine regions: (a) projection of chemical variables on the factor map; (b) distribution of wine samples by region ($\cos^2 \geq 0.00$). Labels correspond to Wine Region (WR).

Principal Component Analysis (PCA) results highlight the differentiation of wines based on their aromatic chemical composition. Factor 1 (Dim 1) and Factor 2 (Dim 2) explain 18.1% and 13.4% of the dataset's variance, respectively, summing up to a cumulative variance of 31.5% (Figure 2a).

The principal component analysis highlights clear differentiation among the wines (Figure 2b), with Factor 1 explaining the variation in esterification patterns and alcohol content: wines with high Dim 1 scores, such as Davino (Dim 1: 3.56), Viișoara (3.23), and Aurelia Vișinescu (2.45), exhibit elevated levels of medium-chain esters, specifically diethyl butanedioate (loading: 0.623), ethyl caprate (0.560), neopentyl acetate (0.610), and ethyl hexanoate (0.510), while wines with negative Dim 1 scores like Panciu (−6.14), Jelna (−2.80), and Târgu Bujor (−2.60) show lower esterification activity alongside higher primary alcohol and volatile acid concentrations.

Factor 2 accounts for differences in volatile aromatic benzylic compounds, with wines such as SCDVV Bujoru (Dim 2: 6.28) and Panciu (0.37) displaying higher concentrations of 2-phenylethanol (loading: 0.750), isoamyl alcohol (0.630), and β -phenylethyl acetate (0.770), indicative of a strong fermentation-derived aromatic profile. In contrast, wines with negative Dim 2 scores, such as Domeniile Boieru (−3.12), Jelna (−2.73), and Aramic (−2.66), present lower aromatic complexity. Group analysis based on PCA results positions Dealul Bujorului (Dim 1: −2.60, Dim 2: 6.28) and Panciu (−6.14, 0.37) in Group 1, defined by high volatile acid and alcohol content. Wines from Aiud (1.01, −3.12), Lechința (−2.80, −2.73), and Aramic (−0.30, −2.66) fall into Groups 2 and 3, characterized by reduced ester and aromatic alcohol levels. Clusters 4 and 5 include Aurelia Vișinescu (2.45, 0.31), Davino (3.56, 1.27), Viișoara (3.23, 1.23), and Sarica Niculițel (0.98, −0.71).

3.4. Volatile Compounds Assessment and Correlation with Sensorial Perception

The complex aroma and flavour profile of wine arises from a diverse combination of alcohols, acids, esters, and other volatile compounds, each contributing distinct sensory characteristics, data that are summarised in Table 4. Prior to sensory and quantitative interpretation, the distribution normality of each compound was evaluated. As previously, compounds with normal distribution were assessed using the Tukey post-hoc test, while those with non-normal distribution were analysed using the Mann-Whitney U. For example, compounds such as methanol, 1-propanol, 2-methyl-1-propanol, and 3-methyl-1-butanol demonstrated a normal distribution, while others like 1-hexanol, certain esters, and acids showed deviations from normality. From the sensorial impact, alcohols such as 1-propanol impart ripe fruit and alcoholic notes, while 2-methyl-1-propanol adds a bitter fusel character [31,32]. Higher alcohols like 3-methyl-1-butanol introduce burnt, cocoa, and malt aromas, whereas 1-hexanol brings fresh, green grass nuances [32]. 2-phenylethanol, known for its floral scent, enhances the wine's aromatic complexity [33].

In the case of 1-propanol, data followed a normal distribution, supporting the application of the Tukey test. Both Davino (65.7 ± 18.9 mg/L) and Vișoara (62.5 ± 8.70 mg/L) exhibited significantly elevated concentrations, indicative of robust fermentation dynamics confirmed by statistically significant differences ($p < 0.05$, Tukey test). Conversely, Panciu presented notably lower levels (20.3 ± 6.91 mg/L), suggesting a milder fermentation style or specific yeast metabolic pathways.

Higher alcohols like 3-methyl-1-butanol, which followed a normal distribution pattern, introduce burnt, cocoa, and malt aromas. The analysis via Tukey test revealed that SCDVV Bujoru had the highest concentration (177 ± 12.8 mg/L), significantly exceeding the levels in other wineries ($p < 0.01$). Davino (168 ± 9 mg/L), Ceptura (166 ± 20.9 mg/L), and Panciu also recorded high values, all statistically distinguishable, which strongly contributes to the fruity aromatic complexity. These elevated levels are particularly relevant, considering the low odour detection threshold of 3 mg/L [31], ensuring perceptible impact on the final wine profile.

On the other hand, 1-hexanol, responsible for fresh, green grass nuances [31], exhibited a non-normal distribution across samples. Therefore, the Mann-Whitney U test was applied, revealing that Sarica Niculițel (1.91 ± 0.41 mg/L) and Jidvei (1.92 ± 0.41) had significantly higher concentrations compared to other wineries ($p < 0.05$), enhancing the herbaceous character of these wines. The distribution anomaly here suggests potential terroir influences or specific viticultural practices affecting precursor availability.

2-phenylethanol, known for its floral scent [32], followed a normal distribution and was assessed through Tukey testing. The compound was consistently present across wineries, contributing to the wine's aromatic complexity, with statistically significant higher values observed in wines from Davino (42.2 ± 3.75 mg/L) and SCDVV Bujoru (62.8 ± 0.6 mg/L). Acids also play a crucial role, with hexanoic acid and octanoic acid contributing cheese-like and fatty notes, while acetic acid imparts the sharp pungency characteristic of vinegar [34].

Acetic acid concentrations also vary significantly among the wineries. Davino emerges as the winery with the highest levels of acetic acid (35 ± 0.44 mg/L), suggesting a tangy flavour profile often associated with this compound. Meanwhile, Jidvei (21.2 ± 1.45 mg/L) and Panciu (22.6 ± 1.21 mg/L) show lower acetic acid concentrations, showing more restrained acidity in their wines. These differences may be attributed to variations in fermentation practices, microbial activity, and storage conditions [35].

Table 4. Total compounds average equivalent concentrations of main classes of compounds according to wine types (mean $\pm$ standard deviation) (nd.—not detected, $n = 3$) (concentrations expressed as mg/L, exc. linalool and thymol $\mu\text{g/L}$).

Compounds	Aurelia Vişinescu	Davino	Ceptura	Aramic	Sarica Niculiţel	Jidvei	Domeniile Boieru	Jelna	SCDVV Bujoru	Panciu	Viişoara	Sensation [31,32,34,36–38]
SUPERIOR ALCOHOLS												
methanol	48 $\pm$ 11.4	20.9 $\pm$ 4.8	41 $\pm$ 12.2	32.4 $\pm$ 4	31.9 $\pm$ 8.1	40.4 $\pm$ 1.28	30.8 $\pm$ 2.5	33.5 $\pm$ 0.12	29.5 $\pm$ 5.7	35.9 $\pm$ 7.32	39.2 $\pm$ 10.3	not aromatic
1-propanol	48.5 $\pm$ 18.3	65.7 $\pm$ 18.9	37.6 $\pm$ 20.9	33.7 $\pm$ 1.8	29.3 $\pm$ 1.45	43.9 $\pm$ 8.1	23.9 $\pm$ 3.7	40.3 $\pm$ 0.24	32.5 $\pm$ 1.4	20.3 $\pm$ 6.91	62.5 $\pm$ 8.7	alcohol
2-methyl 1-propanol	22.7 $\pm$ 5.2	13.8 $\pm$ 8.9	17.1 $\pm$ 13.8	19.2 $\pm$ 4	27.7 $\pm$ 2.4	14.5 $\pm$ 0.85	36.1 $\pm$ 4.1	16.2 $\pm$ 2.52	22.6 $\pm$ 1.43	20.9 $\pm$ 12.1	12.8 $\pm$ 2.5	bitter fusel
1-butanol	1.28 $\pm$ 0.4	0.94 $\pm$ 0.19	0.66 $\pm$ 0.1	0.89 $\pm$ 0.14	0.99 $\pm$ 0.03	0.60 $\pm$ 0.07	0.67 $\pm$ 0.11	0.61 $\pm$ 0.04	0.82 $\pm$ 0.39	0.47 $\pm$ 0.07	1.45 $\pm$ 0.31	soap-like
2-methyl 1-butanol	25.7 $\pm$ 5.8	26.0 $\pm$ 1.2	32.2 $\pm$ 7.5	25.9 $\pm$ 3.7	26.3 $\pm$ 1.19	22.8 $\pm$ 3.7	27.5 $\pm$ 3.32	22.4 $\pm$ 5.26	37.3 $\pm$ 1.3	30.4 $\pm$ 5.1	17.8 $\pm$ 1.6	astringent
3-methyl 1-butanol	136 $\pm$ 16.6	168 $\pm$ 9	166 $\pm$ 20.9	138 $\pm$ 17.9	114 $\pm$ 6.36	135 $\pm$ 7.6	122 $\pm$ 19.7	129 $\pm$ 16.5	177 $\pm$ 12.8	161 $\pm$ 20.3	146 $\pm$ 23.3	malt/cocoa
1-hexanol	1.64 $\pm$ 0.34	0.60 $\pm$ 0.08	0.78 $\pm$ 0.23	1.36 $\pm$ 0.1	1.91 $\pm$ 0.19	1.92 $\pm$ 0.41	1.17 $\pm$ 0.07	1.17 $\pm$ 0.52	2.21 $\pm$ 0.54	1.57 $\pm$ 0.09	1.81 $\pm$ 0.37	green grass
2-phenylethanol	11.7 $\pm$ 2.6	42.2 $\pm$ 3.75	35.9 $\pm$ 30.5	27.6 $\pm$ 16.4	9.0 $\pm$ 3.50	22.5 $\pm$ 1.28	13.9 $\pm$ 0.7	8.22 $\pm$ 1.21	62.8 $\pm$ 0.6	41.7 $\pm$ 0.29	23.0 $\pm$ 1.95	floral (rose-like)
1-pentanol	354 $\pm$ 316	314 $\pm$ 12	388 $\pm$ 23.8	301 $\pm$ 14.3	188 $\pm$ 3.26	286 $\pm$ 28.3	199 $\pm$ 11.6	nd.	290 $\pm$ 29.2	329 $\pm$ 2.41	264 $\pm$ 27	mild fusel-like
1-hexenol	0.51 $\pm$ 0.88	nd.	nd.	0.44 $\pm$ 0.58	0.74 $\pm$ 0.16	nd.	0.37 $\pm$ 0.04	nd.	1.41 $\pm$ 0.15	nd.	nd.	fruity
FATTY ACIDS												
octanoic acid	8.77 $\pm$ 4.91	10.1 $\pm$ 8.15	9.93 $\pm$ 4.06	7.26 $\pm$ 0.52	10.6 $\pm$ 8.14	7.75 $\pm$ 1.57	7.53 $\pm$ 0.53	2.35 $\pm$ 0.25	8.40 $\pm$ 2.45	6.91 $\pm$ 2.01	10.9 $\pm$ 4.87	fatty/cheese
hexanoic acid	7.17 $\pm$ 5.13	6.88 $\pm$ 4.37	5.50 $\pm$ 5.98	4.88 $\pm$ 4	12.5 $\pm$ 1.22	7.54 $\pm$ 1.89	7.65 $\pm$ 0.33	5.15 $\pm$ 0.79	8.48 $\pm$ 0.28	2.15 $\pm$ 0.50	7.16 $\pm$ 4.12	cheese
5-oxotetrahydrofuran-2-carboxylic acid	6.54 $\pm$ 3.3	4.10 $\pm$ 0.94	5.87 $\pm$ 5.36	2.96 $\pm$ 2.43	9.00 $\pm$ 6.5	15.9 $\pm$ 2.65	3.52 $\pm$ 1.44	4.30 $\pm$ 0.56	8.85 $\pm$ 0.32	5.73 $\pm$ 2.78	5.02 $\pm$ 7.02	neutral
capric acid	18.8 $\pm$ 11.3	20.5 $\pm$ 8.36	14.8 $\pm$ 4.47	12.4 $\pm$ 8.24	17.0 $\pm$ 9.3	21.5 $\pm$ 1.59	15.8 $\pm$ 7.8	11.2 $\pm$ 0.77	24.7 $\pm$ 5.18	7.23 $\pm$ 3.8	22.7 $\pm$ 1.61	musty
acetic acid	27.6 $\pm$ 12.2	35.0 $\pm$ 0.44	19.2 $\pm$ 2.46	30.6 $\pm$ 10.5	26.1 $\pm$ 1.25	21.2 $\pm$ 1.45	26.4 $\pm$ 2.8	23.4 $\pm$ 1.25	22.5 $\pm$ 3.27	22.6 $\pm$ 1.21	21.4 $\pm$ 5.67	vinegar-like (pungent)
butyric acid	0.93 $\pm$ 0.39	0.65 $\pm$ 0.64	0.73 $\pm$ 0.56	0.37 $\pm$ 0.04	1.42 $\pm$ 1.05	1.51 $\pm$ 0.25	0.42 $\pm$ 0.17	nd.	1.35 $\pm$ 0.53	0.20 $\pm$ 0.05	1.19 $\pm$ 0.18	rancid butter
dodecanoic acid	9.54 $\pm$ 0.45	2.67 $\pm$ 0.11	8.36 $\pm$ 0.71	nd.	nd.	6.87 $\pm$ 1.42	nd.	nd.	7.15 $\pm$ 2.25	3.75 $\pm$ 0.52	7 $\pm$ 0.25	coconut
ESTERS												
ethyl lactate	26.1 $\pm$ 21.3	16.3 $\pm$ 6.02	15.2 $\pm$ 6.22	13.3 $\pm$ 4.46	9.40 $\pm$ 2.67	9.93 $\pm$ 0.88	30.2 $\pm$ 2.9	8.65 $\pm$ 2.1	27.0 $\pm$ 3.59	98.2 $\pm$ 5.26	9.84 $\pm$ 3.03	lactic
isoamyl acetate	2.74 $\pm$ 2.03	2.38 $\pm$ 2.39	5.33 $\pm$ 1.11	1.49 $\pm$ 0.7	1.71 $\pm$ 0.41	3.47 $\pm$ 0.34	2.58 $\pm$ 2.06	2.31 $\pm$ 0.57	2.66 $\pm$ 0.4	1.45 $\pm$ 1	4.33 $\pm$ 3.28	banana
ethyl acetate	64.4 $\pm$ 33.4	54 $\pm$ 18.1	58.0 $\pm$ 6.49	43.5 $\pm$ 11.4	39.8 $\pm$ 1.38	40.0 $\pm$ 8.1	47.79 $\pm$ 5.22	34.1 $\pm$ 2.56	33.7 $\pm$ 8.68	48.1 $\pm$ 9	70.3 $\pm$ 1.49	solvent-like fruity
ethyl octanoate	0.86 $\pm$ 0.27	0.90 $\pm$ 0.26	1.05 $\pm$ 0.08	1.19 $\pm$ 0.07	0.94 $\pm$ 0.11	1.26 $\pm$ 0.25	1.28 $\pm$ 0.31	0.96 $\pm$ 0.05	0.76 $\pm$ 0.21	0.59 $\pm$ 0.22	1.15 $\pm$ 0.02	sweet floral, fruity
pentyl acetate	15.5 $\pm$ 1.36	21.3 $\pm$ 1.25	3.14 $\pm$ 0.13	32.5 $\pm$ 1.25	nd.	22.6 $\pm$ 1.22	9.43 $\pm$ 9.92	nd.	8.65 $\pm$ 1.89	6.33 $\pm$ 2.52	28.2 $\pm$ 2.56	banana
ethyl butanoate	24.1 $\pm$ 1.71	10.9 $\pm$ 6.59	24.6 $\pm$ 2.33	32.8 $\pm$ 13.2	31.3 $\pm$ 1.03	29.5 $\pm$ 1.5	34.48 $\pm$ 15.16	18.0 $\pm$ 1.25	15.2 $\pm$ 5.84	26.7 $\pm$ 9.6	19.6 $\pm$ 1.39	pineapple
ethyl isovalerate	3.65 $\pm$ 1.1	6.21 $\pm$ 1.81	7.73 $\pm$ 1.18	5.44 $\pm$ 4.51	5.85 $\pm$ 3.38	5.43 $\pm$ 0.69	2.78 $\pm$ 1.32	9.97 $\pm$ 0.57	5.02 $\pm$ 0.75	9.65 $\pm$ 3.01	4.05 $\pm$ 2.18	strawberry
ethyl hexanoate	86.1 $\pm$ 31.8	78.6 $\pm$ 33.7	73.3 $\pm$ 4.92	89.4 $\pm$ 19.2	80.0 $\pm$ 6.8	91.6 $\pm$ 2.96	105 $\pm$ 38.1	49.4 $\pm$ 2.56	85.8 $\pm$ 4.74	56.4 $\pm$ 1.63	80.5 $\pm$ 2.29	fruity banana
ethyl propionate	1.81 $\pm$ 0.53	2.01 $\pm$ 0.91	3.46 $\pm$ 0.68	151 $\pm$ 25.7	4.37 $\pm$ 2.87	2.78 $\pm$ 0.36	1.07 $\pm$ 0.38	2.93 $\pm$ 0.52	3.99 $\pm$ 0.41	2.85 $\pm$ 0.82	3.09 $\pm$ 1.91	pineapple
ethyl caprate	28.2 $\pm$ 3.52	44.7 $\pm$ 40.1	28 $\pm$ 1.61	28.2 $\pm$ 9.49	18.8 $\pm$ 5.26	24.8 $\pm$ 6.72	26.68 $\pm$ 8.63	17.6 $\pm$ 1.25	44.4 $\pm$ 5.84	10.2 $\pm$ 0.96	30.2 $\pm$ 9.66	tropical fruit
diethyl butadienoate	30.8 $\pm$ 13.7	40.2 $\pm$ 3.76	21.6 $\pm$ 7.58	13.5 $\pm$ 1.2	27.4 $\pm$ 12.8	17.7 $\pm$ 4.26	19.2 $\pm$ 2.1	nd.	26.6 $\pm$ 1.35	13.3 $\pm$ 3.01	29.9 $\pm$ 5.57	(pineapple, grape)
ethyl	0.92 $\pm$ 0.5	5.35 $\pm$ 3.64	8.7 $\pm$ 6.53	2.78 $\pm$ 0.42	13.9 $\pm$ 2.12	8.22 $\pm$ 1.29	0.42 $\pm$ 0.02	9.6 $\pm$ 0.25	13.7 $\pm$ 2.36	9.93 $\pm$ 3.74	6.73 $\pm$ 8.01	grape
isobutanoate	120 $\pm$ 20.7	90.1 $\pm$ 3.55	108 $\pm$ 11.97	nd.	95.9 $\pm$ 10.5	113 $\pm$ 23.3	97.2 $\pm$ 1.24	nd.	128 $\pm$ 7.93	128 $\pm$ 17.2	122 $\pm$ 7.9	strawberry
ethyl formate	0.96 $\pm$ 0.25	1.5 $\pm$ 0.06	4.01 $\pm$ 0.22	nd.	nd.	1.03 $\pm$ 0.51	3.29 $\pm$ 1.47	nd.	1.97 $\pm$ 0.61	3.36 $\pm$ 1.78	2.13 $\pm$ 2.42	rum-like
ethyl decanoate	6.2 $\pm$ 0.48	6.49 $\pm$ 3.82	9.42 $\pm$ 1.24	10.2 $\pm$ 0.52	nd.	5.12 $\pm$ 0.24	6.94 $\pm$ 2.78	1.69 $\pm$ 0.24	16.1 $\pm$ 8.72	nd.	2.14 $\pm$ 0.12	cognac/brandy
ethyl laurate	1.48 $\pm$ 0.92	nd.	3.29 $\pm$ 0.92	2.71 $\pm$ 0.49	3.95 $\pm$ 0.52	3.98 $\pm$ 1.97	2.37 $\pm$ 0.25	nd.	2.11 $\pm$ 0.22	1.89 $\pm$ 0.78	1.91 $\pm$ 0.08	fatty, floral-petal
hexyl acetate	4.05 $\pm$ 0.88	nd.	2.20 $\pm$ 2.13	2.20 $\pm$ 0.05	nd.	5.83 $\pm$ 0.52	4.72 $\pm$ 2.61	36.3 $\pm$ 2.1	8.67 $\pm$ 1.02	5.44 $\pm$ 0.91	5.52 $\pm$ 0.88	green apple
hexyl formate	5.18 $\pm$ 0.56	5.12 $\pm$ 0.45	3.58 $\pm$ 0.58	1.58 $\pm$ 0.25	nd.	2.15 $\pm$ 2.01	1.85 $\pm$ 0.77	1.72 $\pm$ 0.5	3.63 $\pm$ 0.07	1.58 $\pm$ 0.8	5.16 $\pm$ 0.25	green fruit
neopentyl acetate	nd.	0.79 $\pm$ 0.02	1.59 $\pm$ 0.4	0.59 $\pm$ 1.25	0.94 $\pm$ 0.14	0.3 $\pm$ 0.02	0.27 $\pm$ 0.02	nd.	4.73 $\pm$ 1.02	nd.	0.80 $\pm$ 0.22	apple-like
β -phenylethyl acetate	nd.	0.79 $\pm$ 0.02	1.59 $\pm$ 0.4	0.59 $\pm$ 1.25	0.94 $\pm$ 0.14	0.3 $\pm$ 0.02	0.27 $\pm$ 0.02	nd.	4.73 $\pm$ 1.02	nd.	0.80 $\pm$ 0.22	floral (lilac)
ALDEHYDES, DIOLS AND LACTONES												
acetaldehyde	48.5 $\pm$ 2.36	12.1 $\pm$ 0.62	38.6 $\pm$ 18.8	53.4 $\pm$ 11.3	44.5 $\pm$ 18.9	31.3 $\pm$ 2.64	20.2 $\pm$ 7.56	51.2 $\pm$ 1.24	61.6 $\pm$ 4.35	35.7 $\pm$ 1.78	37.7 $\pm$ 11.1	green apple
1,2-propandiol	523 $\pm$ 40.9	723 $\pm$ 3.64	748 $\pm$ 18.2	701 $\pm$ 24.4	534 $\pm$ 16.5	1227 $\pm$ 9.24	864 $\pm$ 21.7	576 $\pm$ 22.2	580 $\pm$ 12.5	380 $\pm$ 2.24	987 $\pm$ 18.5	mouthfeel enhancer
4-mercapto-4-methylpentan-2-one	6.89 $\pm$ 1.34	4.95 $\pm$ 1.55	6.77 $\pm$ 1.56	7.37 $\pm$ 5.26	11.7 $\pm$ 3.66	9.24 $\pm$ 1.75	9.18 $\pm$ 1.23	9.94 $\pm$ 1.25	8.26 $\pm$ 3.07	7.47 $\pm$ 2.31	6.83 $\pm$ 3.4	blackcurrant, box tree
TERPENES												
linalool	1.39 $\pm$ 0.54	2.17 $\pm$ 0.24	1.37 $\pm$ 0.25	nd.	nd.	nd.	1.50 $\pm$ 0.84	nd.	1.14 $\pm$ 0.07	3.97 $\pm$ 0.22	3.71 $\pm$ 0.05	blossom, petitgrain
thymol	22.4 $\pm$ 2.52	nd.	3.19 $\pm$ 0.51	nd.	38.4 $\pm$ 3.80	12.1 $\pm$ 0.25	15.8 $\pm$ 0.52	nd.	nd.	3.21 $\pm$ 0.14	nd.	herbal/earthy/spicy

Capric acid, known for its fatty and creamy sensory characteristics, is particularly abundant in SCDVV Buhjoru (24.7 ± 5.18 mg/L) and Târnave (21.5 ± 1.59 mg/L). On the other hand, Panciu demonstrates the lowest concentration (7.23 ± 3.80 mg/L), which could contribute to a cleaner and lighter mouthfeel. Similarly, octanoic acid is found in higher concentrations in Sarica Niculițel (10.6 ± 8.14 mg/L) and Vișoara (10.9 ± 4.87 mg/L), while Jelna exhibits lower levels (2.35 ± 0.25 mg/L). These variations in fatty acid levels have a major impact on the body and texture of the wines.

The ester profile analysis revealed variable concentrations across wineries, with statistically significant differences confirmed by non-parametric tests (Kruskal–Wallis and Dunn's post-hoc with Bonferroni correction, $p < 0.05$). Ethyl hexanoate concentrations were highest in Domeniile Boieru (105 ± 38.1 mg/L), Jidvei (91.6 ± 2.96 mg/L), and Aramic (89.4 ± 19.2 mg/L). Ethyl acetate showed elevated levels in Vișoara (70.3 ± 1.49 mg/L), Aurelia Vișinescu (64.4 ± 33.4 mg/L), and Ceptura (58.0 ± 6.49 mg/L). For ethyl butanoate, the highest concentrations were detected in Domeniile Boieru (34.48 ± 15.16 mg/L) and Aramic (32.8 ± 13.2 mg/L). Isoamyl acetate peaked in Ceptura (5.33 ± 1.11 mg/L), followed by Jidvei (3.47 ± 0.34 mg/L) and SCDVV Bujoru (2.66 ± 0.4 mg/L).

Ethyl decanoate was most abundant in Panciu (3.36 ± 1.78 mg/L) and Ceptura (4.01 ± 0.22 mg/L). Pentyl acetate levels were notably high in Aramic (32.5 ± 1.25 mg/L), Davino (21.3 ± 1.25 mg/L), and Vișoara (28.2 ± 2.56 mg/L). Ethyl caprate reached its maximum in Jidvei (67.3 ± 3.25 mg/L) and SCDVV Bujoru (44.4 ± 5.84 mg/L). Phenylethyl acetate was predominantly found again in SCDVV Bujoru (4.73 ± 1.02 mg/L) and Ceptura (1.59 ± 0.4 mg/L). Finally, diethyl succinate was present in Ceptura (21.6 ± 7.58 mg/L), Davino (40.2 ± 3.76 mg/L), and Aurelia Vișinescu (30.8 ± 13.7 mg/L).

3.5. Influence of Soil Type on the Wines and Aroma Profiles of the Wines

The comparative analysis of wines from various Romanian vineyards highlights the crucial influence of soil type on their chemical composition. In the Dealu Mare, Aurelia Vișinescu showed higher concentrations of methanol (47.9 ± 5.1 mg/L), 1-propanol (48.5 ± 8.19 mg/L; t -test, $p = 0.032$), and fatty acids such as hexanoic acid (7.17 ± 2.29 mg/L) and octanoic acid (8.77 ± 2.20 mg/L; t -test, $p = 0.041$) compared to Ceptura, suggesting an impact of alluvial soils on amino acid metabolism and fermentation pathways.

In contrast, Ceptura wines exhibited higher levels of monoterpenes like linalool (2.17 ± 0.10 μ g/L; Mann–Whitney U test, $p = 0.019$) and another terpene as thymol (22.4 ± 2.52 μ g/L), as well as esters like isoamyl acetate (2.38 ± 1.38 mg/L) and ethyl acetate (54.0 ± 10.4 mg/L; Mann–Whitney U test, $p = 0.027$), reflecting the potential influence of cambic chernozems on aromatic compound formation.

In Dealul Bujorului vineyard, leached chernozem soils contributed to elevated concentrations of esters such as ethyl hexanoate (85.8 ± 22.3 mg/L; t -test, $p = 0.011$) and ethyl caprylate (47.3 ± 10.2 mg/L), along with significant levels of acetaldehyde (61.6 ± 22.6 mg/L) and 1,2-propanediol (579 ± 62.2 mg/L; t -test, $p = 0.008$), indicating their role in higher alcohol and organic acid synthesis. However, SCDVV Bujoru wines contained increased butyric acid (1.35 ± 0.38 mg/L), which may suggest less favourable soil conditions for fatty acids formation. Panciu, grown on cambic chernozems, had higher concentrations of ethyl lactate (98.2 ± 5.43 mg/L), ethyl acetate (33.7 ± 4.34 mg/L), and linalool (3.21 ± 0.12 μ g/L), underlining the influence of soil fertility on aromatic complexity along with technological processes [39].

The Transylvania wine region displayed diverse chemical profiles shaped by varying soil types. Aiud wines, from grapes grown on pseudogleyic and albic luvisols, were rich in octanoic acid (7.53 ± 1.26 mg/L), 1-hexanol (1.17 ± 0.1 mg/L), and ethyl lactate (30.2 ± 4.5 mg/L), suggesting a well-balanced nutrient retention. Târnave wines, from

pseudorezibic soils, featured high levels of ethyl octanoate (1.26 ± 0.13 mg/L), thymol (12.1 ± 1.25 µg/L), and 2-phenylethanol (22.5 ± 7.4 mg/L), indicating significant sources for enhanced synthesis of aromatic esters.

Lechința wines, grown on nutrient-stressed acidic brown luvisols, contained higher concentrations of methanol (33.4 ± 1.2 mg/L), 1-propanol (40.3 ± 5.26 mg/L), and hexyl formate (36.3 ± 2.56 mg/L), revealing a distinctive volatile profile linked to soil stress. In Sarica Niculițel and Murfatlar, weakly compacted chernozems and eu-mezobasic brown soils favoured the formation of esters like ethyl acetate (39.81 ± 3.68 mg/L in Sarica Niculițel), while promoting balance with higher alcohols and organic acids.

Furthermore, hierarchical cluster analysis grouped wines into distinct clusters largely consistent with their geographic origin and soil characteristics, highlighting the observed soil–wine chemical composition relationships.

The heat map (Figure 3) highlights clear clustering patterns, suggesting that certain vineyards share similar aromatic profiles, likely due to a combination of soil composition and specific winemaking techniques.

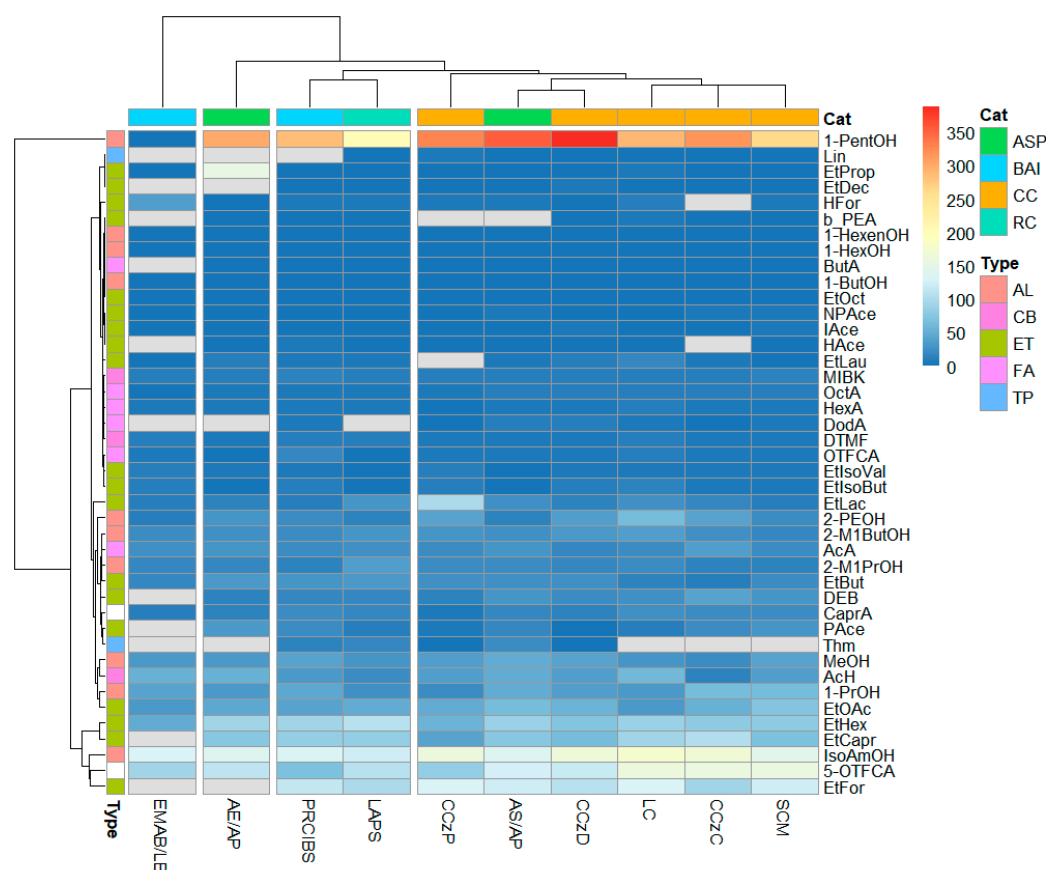


Figure 3. Cluster and heatmap analysis of the correlation between sensorial aromatic compounds and soil type categories. Type: AL—superior alcohols; CB—carbonylic compounds; ET—esters; FA—fatty acids; TP—terpenes. Cat: (soil categories classification)—CC: chernozems and similar soils (cambic chernozemic; levigated chernozems; weakly compacted chernozems, alkaline (pH 8.0–8.2), moderate calcium carbonate; steppe chernozemic mollisols; alluvial soils and protocols); ASP: alluvial soils and alluvial protocols (erodisollic alluvial and alluvial protocols); BAI: brown and argillic-illuvial soils (brown eu-mesobasic, acidic, and luvic soils; pseudogleyic and albic luvic soils; pseudorezibic, clay-illuvial brown soils); RC: rendzic and calcareous soils (lithic rendzinas).

The clustering analysis highlights distinct relationships between soil types, vineyard locations, and volatile profiles in the wines, quantified by proximity values.

- o Cluster 1, comprising eu-mesobasic, acidic brown soils, and luvic brown soils (EMAB/LB), includes Dealurile Silagiului Vineyard (Aramic) and Lechința Vineyard (Jelna). This cluster is tightly grouped with a distance value of 0, indicating a strong association with 1-pentanol (1-PentOH).
- o Cluster 2 is defined by alluvial erodissols and alluvial protosols (AE/AP), encompassing Dealu Mare Vineyard (Aurelia Vișinescu) and Aiud Vineyard (Domeniile Boieru). Wines from this cluster present high levels of isoamyl alcohol (IsoAmOH) (34) and ethyl lactate (EtLac) (23.7).
- o Cluster 3, grouping pseudorezibic soils and clay-illuvial brown soils (PRCIBS), includes Târnavă Vineyard (Jidvei) and Dealu Mare Vineyard (Davino). Notable compounds associated with this cluster include methanol (MeOH) (8.29), 1-propanol (1-PrOH) (17), and ethyl acetate (EtOAc) (20.7).
- o Cluster 4 combines cambic chernozems (CCzC (Ceptura), CCzD (Davino), CCzP (Panciu)), steppe chernozemic mollisols (SCM), levigated chernozems (LC), and alluvial soils (AS/AP), covering Dealu Mare Vineyard (Ceptura), Panciu Vineyard (Panciu), Sarica Niculițel Vineyard (Sarica Niculițel), and Dealul Bujorului Vineyard (SCDVV Bujoru). Compounds characteristic of this cluster include 1-butanol (1-ButOH) (6.43), 1-hexanol (1-HexOH) (5.88), and hexanoic acid (HexA).

3.6. Evaluation According to the Influence of the Climatic Parameters

Wind speed and solar radiation influence growth and productivity, and the UV index can enhance tannin structure. Sunshine duration determines sugar and acid balance, and the oenoclimate amplitude index, reflecting temperature variation, shapes flavour complexity and aging potential [40]. Together, these factors define the unique profile of wines from the selected regions [41].

Regarding the differences between the compounds, statistical analysis revealed several significant changes across years. The Mann–Whitney U Test highlighted the following: 4-methyl-2-pentanol showed a significant increase with a p -value of 0.002, indicating that this compound was notably higher in 2021 compared to 2019. 1-Pentanol also exhibited a significant rise with a p -value of 0.0004, suggesting a marked increase in its presence. Hexanoic acid was significantly higher in 2021 with a p -value of 0.01, pointing to a higher concentration in the later vintage. Acetic acid and ethyl lactate also showed notable increases with p -values of 0.018 and 0.003, respectively, highlighting a consistent trend of increasing concentrations.

Analysis of Variance (ANOVA) revealed additional significant increases: Caprylic acid ($p = 0.0009$) and dodecanoic acid ($p = 0.030$) demonstrated significant changes, indicating a shift in these fatty acids' presence. Pentyl acetate ($p = 0.006$) and ethyl caprylate ($p = 0.008$) exhibited similar increases, further confirming the overall impact of climate on ester and fatty acid profiles. Other compounds such as isoamyl acetate ($p = 0.0005$) and ethyl isovalerate ($p = 0.015$) were also significantly different in 2021, showing that the overall volatile compound composition of the wines in 2021 was distinctly altered due to climatic conditions.

The evaluation was conducted during the grape ripening period, specifically between 1 August 2019 and 31 October 2019, and between 1 August 2021 and 31 October 2021, covering the stages from the onset of ripening to phenolic maturity. The mean values are presented in Table 5. Main parameters were directly collected from source databases and calculated as mean values, whereas ASD—actual sunshine duration (hours) and IAOe—oenoclimate aptitude index were calculated according to data validated in the literature [42].

Table 5. Climatic characterization of the areas selected for the study (AvT—average temperatures (°C); SumACtT—sum of active temperatures (°C); PP precipitations (mm); WndSp—wind speed (m/s); SolRad—solar radiation (W/m²); UVIndex—index of UV component of daylight (nm); ASD—actual sunshine duration (hours); IAOe—Oenoclimate aptitude index in 2019 and 2021.

	Domeniile Boieru	Ceptura	Davino	Aurelia Vişineşcu	SCDVV Bujoru	Aramic	Jelna	Panciu	Sarica Niculiţel	Jidvei	Viişoara
2019	AvT	35.2	33.9	16.55	16.39	14.44	15.15	13.78	16.08	15.65	18.09
	SumACtT	3215	3120	1523	1508	1328	1394	1267	1463	1440	1664
	PP	0.25	0.1	0.00	93	107	134	130	167	81.4	95.8
	WndSp	15.6	18.8	18.9	12.2	14.4	11.2	9.73	13.7	13.6	16.9
	SolRad	274	286	283	166	520	163	160	167	164	133
	UVIndex	8.59	9.34	9.33	5.65	5.52	5.45	5.5	5.73	5.65	5.02
	ASD	288	289	289	153	146	150	148	152	151	122
	IAOe	3753	3659	3659	1833	1797	1594	1681	1534	1698	1760
2021	AvT	33.6	34.0	34.1	18.7	17.5	18.3	16.3	18.2	17.2	20.6
	SumACtT	3090	3099	3056	1717	1607	1559	1683	1499	1587	1895
	PP	0.00	0.1	0.2	66.7	94.8	127	59.1	109	134	111
	WndSp	21.4	20.6	21.3	12.2	11.4	14.5	13.1	8.67	13.3	13.3
	SolRad	270	271	270	180	171	172	174	169	170	201
	UVIndex	8.99	9.26	9.25	6.04	5.75	5.85	5.86	5.76	5.88	5.95
	ASD	249	245	266	165	157	158	160	123	160	162
	IAOe	3588	3594	3571	2065	1919	1840	2034	1763	1951	1888

In 2021, severe drought conditions were recorded at Ceptura and Davino, with precipitation levels dropping to just 0.1–0.2 mm. Domeniile Boieru experienced zero precipitation, further contributing to vineyard dryness. Simultaneously, wind speeds rose notably, from 15.6 km/h to 21.4 km/h at Domeniile Boieru, and from 18.9 km/h to 21.3 km/h at Davino, likely increasing evapotranspiration and accelerating grape dehydration while reducing fungal risks.

Wind intensification was a common trend across all vineyards, enhancing drying effects. Temperatures in 2021 were generally higher compared to previous years, supporting faster sugar accumulation and ripening. For example, Viişoara saw an increase from 18.09 °C to 20.6 °C, and Jelna from 15.15 °C to 18.3 °C. Solar radiation also rose moderately in many areas, including Aurelia Vişinescu (from 166 to 180 W/m²) and Jidvei (from 164 to 176 W/m²), further promoting ripening, although SCDVV Bujoru experienced a significant decline, from 520 to 171 W/m².

Sunshine duration slightly decreased in most regions, as seen in Ceptura (from 289 to 245 days), yet some areas, like Viişoara, recorded an increase from 122 to 185 days. The IAOe index, reflecting cumulative thermal units, showed a consistent rise across vineyards, such as Jelna, which increased from 1681 to 2034, indicating greater heat accumulation favourable for grape ripening.

These climatic shifts—marked by higher temperatures, reduced precipitation, and increased heat accumulation—significantly impacted the volatile compound profile of wines, as evidenced by the variations observed between 2019 and 2021 (Table 5). In the Ceptura region, prolonged drought and elevated temperatures accelerated grape ripening and altered the synthesis of key aromatic and volatile compounds. Notable high temperatures were recorded in Viişoara (20.6 °C), Ceptura (34 °C), and cooler conditions in Jidvei (17.2 °C) and Lechinţa (18.3 °C) in 2019.

Solar radiation levels varied, with Ceptura recording the highest value (270.1 W/m²), while lower levels were noted at Aurelia Vişinescu (180 W/m²) and Lechinţa (174 W/m²) in 2019. Notably, only a few compounds were revealed to be key factors, and these are detailed in Table 6.

Table 6. Average concentrations of compounds with significant differences ($p < 0.05$) in the comparison between 2019 and 2021 ($\bar{X}$ —mean value, SD—standard deviation of repetitions, N—number of samples found in each year 2019 and 2021).

Year	3-Methyl-1-pentanol		3-Etoxy-1-propanol		Butyric Acid		Dodecanoic Acid		Pentyl Acetate	
	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N
2019	Nd.	0	Nd.	0	0.78 ± 0.29	7	3.25 ± 0.51	2	0.25 ± 0.02	3
2021	1.09 ± 0.26	6	1.43 ± 0.27	5	0.89 ± 0.13	11	6.92 ± 0.69	9	18.2 ± 3.01	11
	ethyl laurate		hexyl acetate		neopentyl acetate		β -phenylethyl acetate		linalool	
	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N	$\bar{X} \pm \text{SD}$	N
2019	2.54 ± 0.63	4	1.86 ± 0.11	1	3.09 ± 1.1	4	1.86 ± 0.11	1	3.09 ± 1.1	4
2021	8.24 ± 1.45	11	2.65 ± 0.27	11	3.47 ± 0.5	11	2.65 ± 0.27	10	3.47 ± 0.5	11

Linalool showed an increase in average content, rising from 3.09 ± 1.1 $\mu\text{g/L}$ in 2019 to 3.47 ± 0.5 $\mu\text{g/L}$ in 2021. β -Phenylethyl acetate also exhibited a concentration increase, from 1.86 ± 0.11 $\mu\text{g/L}$ to 2.65 ± 0.27 $\mu\text{g/L}$.

Pentyl acetate demonstrated the most dramatic rise, increasing from an average concentration of 0.25 ± 0.02 $\mu\text{g/L}$ in 2019 (three samples) to 18.2 ± 3.01 $\mu\text{g/L}$ in 2021 (13 samples).

Fatty acids also showed substantial variations. Dodecanoic acid increased from 3.25 ± 0.51 $\mu\text{g/L}$ in 2019 (two samples) to 7.12 ± 0.69 $\mu\text{g/L}$ in 2021 (nine samples), and butanoic acid rose from 0.78 ± 0.29 $\mu\text{g/L}$ in 2019 (seven samples) to 0.89 ± 0.13 $\mu\text{g/L}$ in 2021 (17 samples). Ethyl laurate was detected in four samples in 2019, with an average concentration of 2.54 ± 0.63 $\mu\text{g/L}$, and in 13 samples in 2021, increasing to 8.24 ± 1.45 $\mu\text{g/L}$.

The contribution of each compound to the overall volatile profile was determined using Spearman correlation coefficients, enabling a quantitative evaluation of meteorological effects. The results, summarized in Figure 4, highlight the extent to which climatic variations influenced the aromatic profile of wines across different vintages.

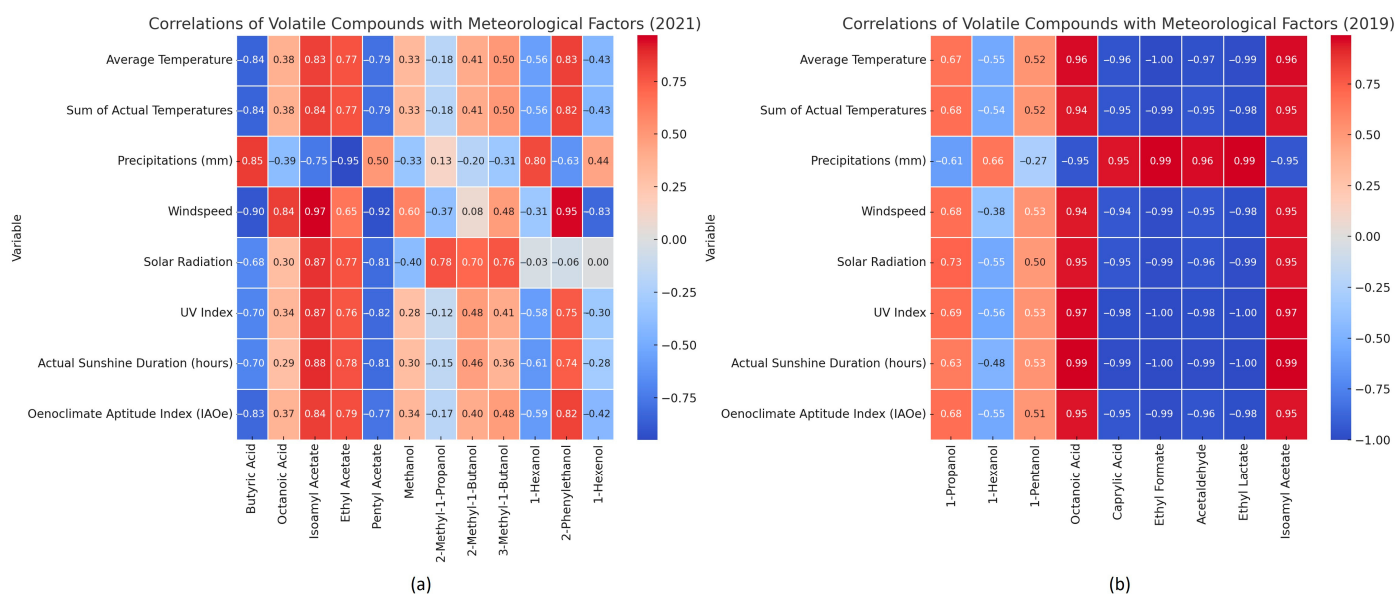


Figure 4. Correlation of the statistical compounds affected by the variations of the climatic parameters during 2021 (a) and 2019 (b).

In 2021 (Figure 4a), higher average temperatures showed a negative correlation with butyric acid (-0.84), while positively influencing acetate compounds such as isoamyl acetate (0.83) and ethyl acetate (0.77). Similarly, the total temperature sum demonstrated a comparable effect.

Precipitation exhibited a strong positive correlation with butyric acid (0.85) and 1-hexanol (0.80), while negatively affecting ethyl acetate (−0.95). Wind speed positively correlated with acetate compounds like isoamyl acetate (0.97) and phenylethanol (0.95), while reducing the concentrations of butyric acid (−0.90) and pentyl acetate (−0.92).

Solar radiation and sunshine duration promoted ester formation, enhancing isoamyl acetate levels (0.87, 0.88) and higher alcohols such as 2-methyl-1-butanol (0.70, 0.46), while slightly decreasing green/herbaceous aromas like 1-hexanol (−0.03, −0.61).

In 2019 (Figure 4b), stronger correlations were observed between temperature and fatty acids such as octanoic acid (0.96) and capric acid (−0.96), as well as esters like ethyl formate (−1.00).

Precipitation displayed significant positive correlations with aldehydes and grassy notes, including ethyl lactate (0.99) and acetaldehyde (0.96), while reducing octanoic acid concentrations (−0.95). Wind speed, solar radiation, and sunshine duration strongly influenced ester production, with sunshine duration showing near-perfect correlations with octanoic acid (0.99), ethyl formate (−1.00), and isoamyl acetate (0.99).

The oenoclimate aptitude index (IAOe) consistently reflected the overall climate impact, showing strong correlations with octanoic acid (0.95 in 2019; 0.79 in 2021) and ethyl formate (−0.99 in 2019; 0.34 in 2021).

Overall, the wines from 2019 exhibited a more ester and alcohol-dominant profile, benefiting from warm and sunny conditions, whereas 2021 wines showed stronger precipitation effects, leading to increased volatile acidity and herbaceous notes, potentially resulting in less balanced aromatic profiles [43].

3.7. Evolution of Conditioning Stages in Winemaking

The wines were vinified using classical white winemaking methodologies, with the most significant variables observed during one of the key stages of conditioning. At this stage, the use of oenological products could significantly impact the sensory properties of the wine.

The transition from raw to conditioned wine revealed significant changes in chemical composition, illustrating the impact of technological processes on wine characteristics (Figure 5).

Higher alcohols, such as 1-propanol, generally decreased in concentration, as observed in Ceptura, where levels decreased from 44.95 ± 14.9 mg/L (raw) to 26.49 ± 1.3 mg/L (conditioned). Similarly, 2-phenylethanol showed notable reductions, particularly in Jidvei, with concentrations dropping from 31.07 ± 13.5 mg/L to 13.9 ± 0.14 mg/L.

The analysis of acid–ester pairs across different wineries and winemaking conditions highlights significant variability in esterification patterns. Hexanoic acid, with an average concentration of 6.63 ± 3.5 mg/L (range: 2.03 ± 0.47 to 16.2 ± 7.95 mg/L), exhibited a strong correlation with ethyl hexanoate, which averaged 80.6 ± 4.63 mg/L (46.8 ± 12.6 to 112 ± 10.5 mg/L) ($p = 1.4 \times 10^{-8}$). Octanoic acid showed a mean concentration of 8.36 ± 0.75 mg/L (2.35 ± 0.2 to 16.52 ± 2.36 mg/L), while its corresponding ester, ethyl octanoate, remained relatively stable at 0.99 ± 0.04 mg/L (0.56 ± 0.15 to 1.33 ± 0.26 mg/L) ($p = 1.4 \times 10^{-8}$), suggesting a possible threshold effect in its formation.

The isoamyl alcohol–isoamyl acetate pair followed a comparable trend, with isoamyl alcohol averaging 27.3 ± 1.09 mg/L (18.0 ± 0.23 to 37.4 ± 0.32 mg/L), and isoamyl acetate at 2.92 ± 0.37 mg/L (1.04 ± 0.11 to 5.39 ± 2.52 mg/L). As shown in Figure 5, raw wines generally exhibited higher ester concentrations compared to their conditioned counterparts, likely due to extended yeast metabolism and controlled oxygen exposure [44].

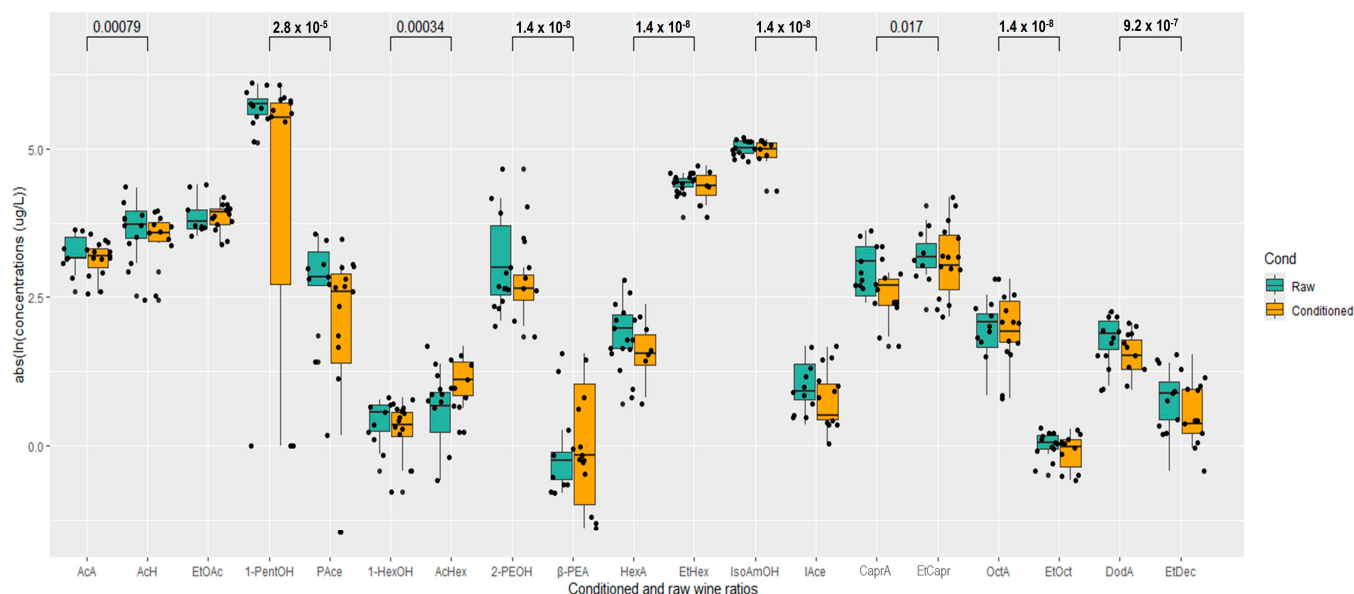


Figure 5. Distribution of the compounds involved in evolution of conditioning stages of the wines (AcA—acetic acid; AcH—acetaldehyde; EtOAc—Ethyl acetate; 1-PentOH—1-pentanol; PAce—pentyl acetate; 1-HexOH—1-hexanol; AcHex—hexyl acetate; 2-PEOH—2-phenylethanol; β -PEA— β phenylethyl acetate; HexA—hexanoic acid; EtHex—ethyl hexanoate; IsoAmOH—isoamyl alcohol; IAce—isoamyl acetate; CaprA—capric acid; EtCapr—ethyl caprate; OctA—Octanoic acid; EtOct—ethyl octanoate; DodA—acid dodecanoic; EtDec—ethyl dodecanoate).

In Visineşcu, capric acid levels decreased significantly, from 33.6 ± 1.2 mg/L (raw) to 13.9 ± 3.94 mg/L (conditioned). Acetic acid also showed noticeable variation, with a marked decrease in Jidvei, from 37.7 ± 2.52 mg/L (raw) to 12.97 ± 2.46 mg/L (conditioned).

Ethyl acetate displayed substantial variability, ranging from 80.7 ± 17.5 mg/L in Visineşcu (raw) to 37.8 ± 7.69 mg/L in Târgu Bujor (raw). Ethyl lactate was particularly dominant in Panciu (162 ± 80.7 mg/L), a trend mirrored in Aramic wines (volatile acidity: 0.453 g/L), where ethyl acetate levels reached 57.9 ± 0.97 mg/L post-conditioning. Similarly, isoamyl acetate, which was prominent in Ceptura (5.39 ± 2.89 mg/L, raw), showed significant reductions in conditioned wines from Aramic (1.62 ± 0.52 mg/L).

Pentyl acetate, formed from 1-pentanol and acetic acid, showed significant concentrations in Aramic (32.6 ± 2.56 mg/L, raw) and Vişoara (21.1 ± 2.25 mg/L, conditioned) ($p = 2.8 \times 10^{-5}$). Hexyl acetate was most abundant in Ceptura (2.64 ± 0.25 mg/L, raw) and Jidvei (2.59 ± 0.12 mg/L, raw). Neopentyl acetate, a minor ester, exhibited notable values in SCDVV Bujoru (3.63 ± 0.11 mg/L, conditioned) and Ceptura (3.98 ± 1.1 mg/L, raw).

2-Phenylethanol and β -phenylethyl acetate ($p = 1.4 \times 10^{-8}$) were most abundant in Târgu Bujor (4.73 ± 0.38 mg/L, conditioned), followed by Ceptura and Panciu. Acetaldehyde, a product of ethanol auto-oxidation, reached its highest concentrations in SCDVV Bujoru (77.3 ± 5.25 μ g/L, raw) and Panciu (41.24 ± 17.8 mg/L, raw).

The precursor–product relationship between 5-oxotetrahydrofuran-2-carboxylic acid and dihydro-tetramethyl-furanone is further supported by data from various vineyards close to Romania [45].

4-Mercapto-4-methylpentan-2-one, a sulfur-containing compound, is significant in certain wine varieties like Sauvignon Blanc, contributing aromas described as black-currant, box tree, and, at higher concentrations, cat urine [46]. In Sarica Niculişel (11.7 ± 3.66 mg/L 4MMP), where O5-oxotetrahydrofuran-2-carboxylic acid levels are relatively high (9 ± 6.5 mg/L), active conversion is evident, potentially enhanced by yeast-driven esterification and oxidative pathways.

Târnave shows the highest 5-oxotetrahydrofuran-2-carboxylic acid levels (15.9 ± 2.65 mg/L) and moderate 4-mercapto-4-methylpentan-2-one (9.24 ± 1.75 mg/L). In Lechința (9.94 ± 1.25 mg/L 4MMP) and Aiud (9.18 ± 1.23 mg/L 4MMP), elevated 4-mercapto-4-methylpentan-2-one suggests enhanced yeast-driven thiol release, despite moderate 5-oxotetrahydrofuran-2-carboxylic acid (4.3 ± 0.56 mg/L and 3.52 ± 1.44 mg/L). These results imply that regions like Târnave and Sarica Niculițel favour oxidative aroma development, while cooler areas such as Lechința and Aiud promote yeast-derived fruity, blackcurrant notes typical of Sauvignon Blanc.

The Esterification Conversion Ratio (R) reflects the relationship between reactants (acids/alcohols) and the resulting esters at equilibrium and was calculated as the ratio of ester to acid/alcohol concentrations, considering their molecular weights. Ideally, for complete esterification, the ratio should approach 1:1 [47]. However, if the reaction reaches equilibrium without full conversion, the ratio will indicate the extent of the reaction, influenced by factors such as reactant concentration, temperature, catalysts, and other wine constituents, which can affect the equilibrium position and ester formation, especially in non-aqueous systems.

The most significant correlations were observed between acids or alcohols as sources and esters as reaction products. Esterification reactions were key observations in the results, emphasizing the critical role of winemaking stages. Figure 6 illustrates how vineyard conditions and winemaking techniques impact ester formation, underscoring the importance of each winemaking stage—from fermentation to aging—in optimizing the wine's flavour profile. These stages require precise control to influence esterification reactions and achieve the desired sensory characteristics.

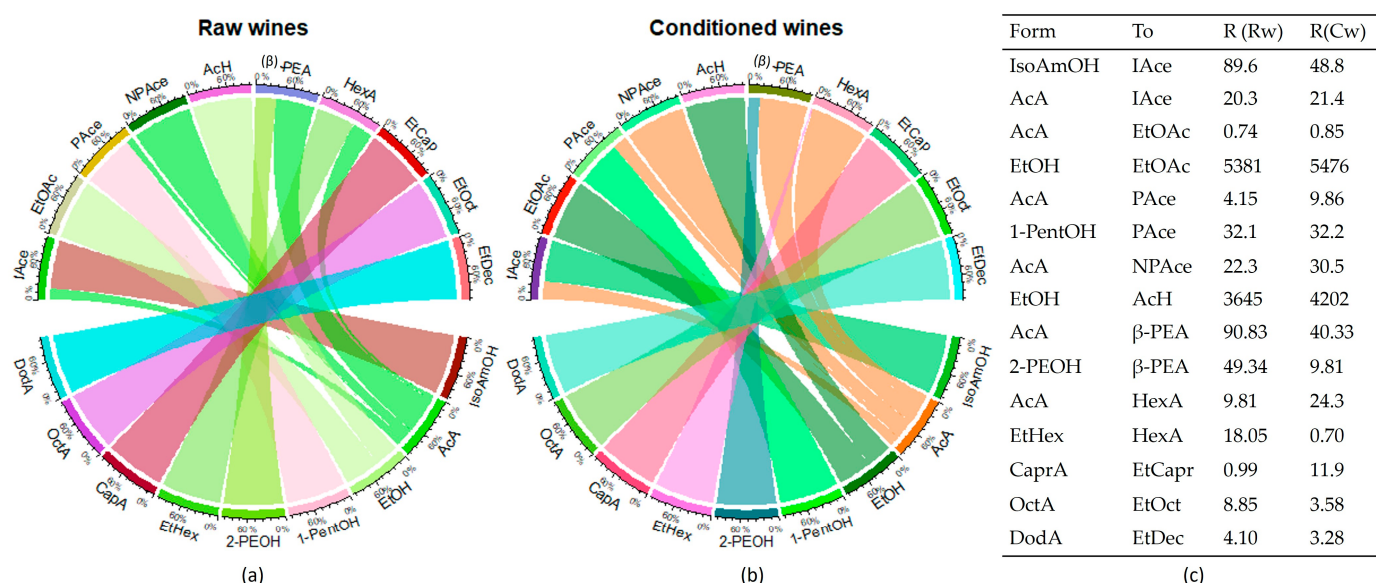


Figure 6. Esterification interaction map for (a) raw wines (Rw), (b) conditioned wines (Cw); (c) esterification reaction ratios. (R): reactant-to-product conversions.

Significant differences in esterification reactions were observed. The isoamyl alcohol/isoamyl acetate ratio decreased from 89.6 in raw wine to 48.8 in conditioned wine. The acetic acid/isoamyl acetate ratio slightly increased from 20.3 to 21.3, while the acetic acid/ethyl acetate ratio also rose from 0.74 to 0.85. The ethanol/ethyl acetate ratio increased from 5381 to 5476, and the acetic acid/pentyl acetate ratio more than doubled, from 4.15 to 9.86. In contrast, the 1-pentanol/pentyl acetate ratio remained nearly unchanged, moving from 32.0 to 32.19. The acetic acid/neopentyl acetate ratio increased from 22.2 to 30.51, while the ethanol/acetaldehyde ratio rose from 3645 to 4202. The acetic acid/ β -phenylethyl

acetate ratio declined from 90.8 to 40.3, and the phenylethyl alcohol/ β -phenylethyl acetate ratio dropped notably from 49.3 to 9.81. The acetic acid/hexyl acetate ratio sharply increased from 9.81 to 24.2, while the hexanol/hexyl acetate ratio drastically decreased from 18.0 to 0.7. Regarding fatty acid esters, the capric acid/ethyl caprate ratio increased from 0.99 to 11.8, whereas the octanoic acid/ethyl octanoate ratio decreased from 8.85 to 3.58, and a slight decline was observed in the dodecanoic acid/ethyl dodecanoate ratio, from 4.1 to 3.28.

4. Discussion

4.1. Correlation with the Main Geographical Locations

Significant variability was observed in Fetească albă wines based on alcohol content, sugar levels, acidity, and sulfite use, which are essential factors in winemaking that influence stability, aging potential, and microbiological safety.

The distribution of aromatic compounds highlights distinct characteristics, particularly for Jelna, which stands out due to its lower terpene, ester, and carbonyl compound content. While the cluster analysis separated groups based on the statistically significant ratio between esters and higher alcohols, as well as fatty acids and carbonyl compounds, the correlation analysis further confirms these distributions while providing a clearer picture of their variations.

Wines from Jelna exhibit higher alcohol content, elevated acidity and the highest volatile acidity. These characteristics may indicate a longer or more complete fermentation process, potentially influenced by higher initial sugar content in the grapes. The elevated volatile acidity suggests possible microbial activity or oxidation risks, which must be carefully managed during production and storage [48]. Wines from Domeniile Boieru show lower acidity and the highest free SO₂ content. This suggests an intentional preservation strategy using sulfites to enhance microbiological stability and prolong shelf life. Wines from Panciu and SCDVV Bujoru contain higher residual sugar, which may result from interrupted fermentation, a cooler fermentation temperature, or controlled yeast strain selection to retain natural sugars. This could enhance wine stability while maintaining balance, though higher residual sugar requires careful sulfite management to prevent unwanted secondary fermentation [49].

Viișoara has high acidity and the lowest free SO₂. This may indicate minimal intervention winemaking with lower sulfite additions, requiring greater attention to hygiene and bottling conditions to prevent oxidation and microbial spoilage. The high acidity suggests earlier grape harvest or specific terroir influences, which could contribute to enhanced natural preservation but may require adjustments in winemaking to maintain structural balance [50].

The analysis reveals that Factor 1 primarily differentiates the wines based on their esterification patterns and alcohol content, with wines such as Aurelia Vișinescu, Davino, and Viișoara showing high Dim 1 scores and elevated concentrations of medium-chain esters like diethyl butanedioate, ethyl caprate, neopentyl acetate, and ethyl hexanoate, while wines such as Jelna, Panciu, and Târgu Bujor, with negative Dim 1 scores, exhibit reduced esterification and increased levels of primary alcohols and volatile acids.

Factor 2 separates the wines according to their content of volatile aromatic benzylic compounds, with high Dim 2 score wines like SCDVV Bujoru and Panciu showing elevated levels of 2-phenylethanol, isoamyl alcohol, and β -phenylethyl acetate, indicating a richer fermentation-derived aromatic profile, whereas wines with negative Dim 2 scores, such as Domeniile Boieru, Jelna, and Aramic, present lower levels of these compounds, resulting in simpler aromatic profiles.

PCA grouping further categorizes the wines into distinct clusters: Group 1 (high Dim 2, negative Dim 1), including Dealul Bujorului and Panciu from Dealurile Moldovei, is defined by high volatile acid and alcohol content; Groups 2 and 3 (negative Dim 1 and Dim 2), including Aiud, Lechința, and Aramic from Podișul Transilvaniei and Banat, are characterized by lower ester and aromatic alcohol concentrations; while Clusters 4 and 5 (positive Dim 1, mixed Dim 2), comprising Aurelia Vișinescu, Davino, Murfatlar-Viișoara, and Sarica Niculițel from Dealu Mare and Colinele Dobrogei, stand out for their pronounced esterification activity and fruity, floral aromatic profiles.

4.2. Relation Between the Aromatic Compounds and Impact on Wine Sensorial Properties

Overall, wineries situated at higher altitudes (Jelna, Jidvei, Domeniile Boieru) tend to produce wines with elevated fatty acid concentrations and lower alcohol levels. In contrast, those located at lower altitudes (Sarica Niculițel, Viișoara, Panciu, Ceptura) typically exhibit higher alcohol content and increased terpene concentrations. The levels of esters and carbonyl compounds appear less directly correlated with altitude, suggesting that winemaking practices, yeast selection, and terroir factors may play a more decisive role in their variability.

Superior alcohol levels varied notably across samples, reflecting both fermentation dynamics and vineyard influence. Wines from Davino and Viișoara showed elevated 1-propanol, suggesting intense fermentation activity, while Panciu indicated a milder process.

SCDVV Bujoru, along with Davino, Ceptura, and Panciu, stood out for high 3-methyl-1-butanol, enhancing fruity complexity. Elevated 1-hexanol in Sarica Niculițel and Jidvei pointed to terroir effects, contributing to herbaceous notes. Lastly, Davino and SCDVV Bujoru exhibited higher 2-phenylethanol, reinforcing the floral character of these wines [51].

Notably, some wineries—such as Ceptura, Davino, and Aurelia Vișinescu—employ vinification techniques that enhance wine complexity, potentially through extended fermentation, the use of specific yeast strains, or tailored aging methods. On the other hand, Viișoara and Domeniile Boieru often display lower concentrations of various compounds, suggesting lighter, more straightforward wine styles that may appeal to consumers preferring fresh and approachable profiles.

The significant variation in ester profiles, particularly in compounds like ethyl lactate and isoamyl acetate, underscores the influence of both grape varietal and fermentation conditions on the aromatic character of the wines. Differences in organic acid concentrations, such as acetic and capric acid, further illustrate the impact of terroir, microbial activity, and fermentation management.

Additionally, dihydro-tetramethyl-furanone contributes a sweet, caramel-like creaminess, while linalool imparts petit grain and citrusy floral nuances. The aroma profile of the wines reflects both yeast metabolism and regional influences. Regions like Sarica Niculițel and Jidvei, with higher dihydro-tetramethyl-furanone levels, show active oxidative processes, leading to more complex, aged aromas. Meanwhile, Jelna and Domeniile Boieru display strong yeast-driven thiol release, enhancing fresh, fruity, and blackcurrant-like notes, characteristic of Sauvignon Blanc [52].

Regarding specific aroma-active esters, elevated levels of ethyl hexanoate in Domeniile Boieru, Jidvei, and Aramic contribute fresh, fruity notes reminiscent of apple and pineapple. High concentrations of ethyl acetate in Murfatlar, Aurelia Vișinescu, and Ceptura enhance overall fruitiness, though they may introduce subtle volatile notes at elevated levels. The presence of ethyl butanoate in Aramic and Domeniile Boieru reinforces sweet, buttery, and tropical nuances, complementing the fruit-forward character [53].

Isoamyl acetate, abundant in Ceptura and Jidvei, imparts distinctive banana and pear aromas, adding a playful dimension to the aromatic profile. Similarly, ethyl octanoate in

Murfatlar and Ceptura brings exotic tropical fruit notes, contributing to a perception of freshness. In Aramic and Davino, higher levels of pentyl acetate intensify pear and banana fragrances, enriching the wines' fruity appeal [54].

The abundance of ethyl caprate in Jidvei and Davino enhances waxy, fruity notes, often associated with a richer mouthfeel and greater aromatic complexity. Meanwhile, phenylethyl acetate, notably present in SCDVV Bujoru and Ceptura, introduces elegant floral nuances such as rose and honey, elevating the aromatic finesse of these wines [55].

Finally, elevated diethyl succinate levels in Ceptura, Davino, and Aurelia Vişinescu suggest a more complex, aged character, contributing mild fruity, nutty, and caramel notes that balance and round out the fresher, fruit-driven elements of the aromatic profile. More distinctive compounds such as thymol provide a multifaceted profile, including woody, spicy, and earthy tones, enhancing the wine's depth and complexity [56].

4.3. Influence of Soil Types on the Aromatic Compounds of Wines

Overall, soil types significantly influenced microbial processes and the formation of volatile compounds resulting in wines with distinct aromatic complexities.

Wines from Dealu Mare and Dealu Bujorului formed separate clusters, characterized by elevated higher alcohols and fatty acids, while Transylvanian wines clustered together due to shared ester and terpene profiles, underlining the role of cooler climates and specific soil types. Wines from Sarica Niculiţel Vineyard and Murfatlar Vineyard, sharing similarities in soil fertility and climate, clustered closely, reflecting comparable ester concentrations. These clusters not only confirm the differentiation based on volatile profiles but also emphasize the importance of terroir, offering valuable insights for viticulturists and winemakers aiming to optimize vineyard management and oenological practices according to soil composition and regional conditions.

Eu-mesobasic, acidic brown soils, and luvic brown soils from Aramic and Jelna are characterized by moderate pH levels and good drainage, supporting balanced nutrient uptake and moderate water retention [57]. These conditions enhance the synthesis of volatile alcohols, particularly 1-pentanol (1-PentOH) (distance: 0), which shows a particularly strong correlation with the soil type. The moderate pH and good drainage likely promote the synthesis of alcohols during primary fermentation, with 1-pentanol being the most significantly correlated compound in this cluster. Its strong presence suggests that soil conditions facilitate the production of alcohols, which are important in defining the wine's aromatic profile.

Alluvial erodissols and alluvial protosols from Aurelia Vişinescu and Domeniile Boieru, rich in minerals and organic matter, are typically located along river valleys and are ideal for vine growth [58]. The elevated levels of isoamyl alcohol and ethyl lactate observed in these wines highlight their enhanced aromatic complexity. Isoamyl alcohol is known for its fruity and banana-like notes, contributing to the fresh and fruity characteristics of the wines. Ethyl lactate, with its creamy and smooth properties, likely adds a subtle complexity and roundness to the wine's overall aromatic profile. These compounds are important markers of the impact of nutrient-rich soils on aromatic diversity [54].

Pseudorezibic soils and clay-illuvial brown soils from Jidvei and Davino have high clay content and moisture retention, influencing root-zone conditions and fermentation pathways [59]. High correlations with methanol, 1-propanol, and ethyl acetate indicate the significant role of these soils in modulating fermentation processes. Methanol and 1-propanol are fermentation-derived alcohols, which are often associated with the production of certain esters like ethyl acetate, contributing to the fruity, ethereal notes in the wine. The higher moisture content in these clay-rich soils likely facilitates these fermentation reactions, resulting in wines with strong alcohol and ester profiles.

Cambic chernozems, steppe chernozemic mollisols, levigated chernozems, and alluvial soils are present at Ceptura, Panciu, Sarica Niculițel, and SCDVV Bujoru. These types of soils are characterized by soils with high organic matter content, good moisture retention, and rich nutrient profiles [59]. Cambic chernozems, steppe chernozemic mollisols, and alluvial soils support a wide range of aromatic compounds, including 1-butanol, 1-hexanol, and hexanoic acid, contributing to the wines' fruity, floral, and savoury notes. The high organic content fosters microbial activity, supporting the production of higher alcohols and esters during fermentation, which enhance the complexity of the wines. The connection of soil fertility, microbial activity, and climatic factors shapes the aromatic profile, making these wines rich and full-bodied. Key esters like ethyl propionate and ethyl octanoate further evolve the fruity and tropical aromas, while ethyl isovalerate adds a fruity and floral note.

4.4. Impact of Climatic Conditions on the Wine Properties

High humidity in Jidvei, along with increased rainfall in Dealurile Silagiului and Sarica Niculițel vineyards, plays a crucial role in maintaining acidity levels. However, this high moisture content may also dilute the flavours, leading to a less concentrated aromatic profile. Furthermore, the increased humidity raises the risk of fungal diseases, which necessitates additional protection measures in the vineyards to safeguard the fruit quality [60]. Cooler conditions contribute to the production of wines that are fresher, with a more elegant and balanced structure, offering better aging potential.

High temperatures were registered in regions such as Vișoara and Ceptura, significantly promoting sugar accumulation in the grapes and accelerating ripening. This temperature-driven process leads to a faster development of sugar and aroma precursors, which are essential for the overall flavour profile of the wine. In contrast, cooler regions like Jidvei and Lechința experience slower ripening, which allows for better preservation of acidity.

High solar radiation in Ceptura supports sugar accumulation and flavour development, while lower radiation in Aurelia Vișinescu and Lechința wineries may delay ripening, leading to lighter wines.

In regions with reduced precipitation, such as Davino, water stress is minimized due to alluvial and protosol soils, which promote rapid drainage and contribute to flavour concentration. Climate modifications, particularly increased temperatures and reduced precipitation, have significantly influenced the volatile compound profile of wines, as demonstrated by the differences observed between 2019 and 2021. The Ceptura region experienced higher average temperatures and prolonged drought periods, which accelerated grape ripening and altered the biosynthesis of key aromatic and volatile compounds.

Precipitation had a strong positive correlation with some fatty acids and alcohols with high numbers of carbon atoms, indicating increased volatile acidity and herbaceous notes. Wind speed played a key role in enhancing fermentation efficiency, positively correlating with acetate compounds like isoamyl acetate and phenylethanol, while reducing butyric acid and pentyl acetate.

In 2019, a stronger relationship was observed between temperature and fatty acids such as octanoic acid, as well as esters like ethyl formate, indicating a direct impact on aroma balance. Wind speed, solar radiation, and sunshine duration strongly influenced ester production, with sunshine duration showing near-perfect correlations with octanoic acid, ethyl formate, and isoamyl acetate.

Referring to the comparison between 2021 and 2019, in 2021, elevated temperatures accelerated grape ripening, leading to higher ester production [61], as seen in the rise

of esters like neopentyl acetate and hexyl acetate, which contribute to fresh and fruity characteristics.

Linalool, a key terpene contributing to floral aromas, was present in more samples in 2021 compared to 2019. Similarly, β -phenylethyl acetate, responsible for fruity and floral notes, saw a noticeable increase in its presence across the samples.

A notable increase in the number of samples containing specific volatile compounds was observed in 2021 compared to 2019, emphasizing the climate-driven impact on wine composition. Pentyl acetate, associated with ripe fruit aromas, showed one of the most dramatic increases between the two vintages.

4.5. Evolution of Chemical Parameters in Winemaking Processes

Higher alcohols, such as 1-propanol, generally decreased in concentration, as observed in Ceptura, likely due to minor losses during stabilization and filtration. Similarly, 2-phenylethanol showed notable reductions, particularly in Jidvei, highlighting the role of filtration and clarification processes in diminishing volatile aromatic compounds.

The isoamyl alcohol–isoamyl acetate pair followed a comparable trend, demonstrating a strong correlation where elevated alcohol levels favoured esterification. Capric acid concentrations were significantly reduced in many samples, indicating effective acidity stabilization. Acetic acid levels also showed a notable decrease, suggesting effective control over volatile acidity. However, some samples exhibited slight increases, potentially due to auto-oxidation of ethanol or secondary fermentations [62]. For example, in SCDVV Bujoru, a slight increase in butyric acid could be linked to residual chemical activity.

Ester profiles displayed more variability, reflecting both technological adjustments and initial wine compositions. Ethyl acetate, the most abundant acetate ester, showed a direct correlation with volatile acidity (VA), particularly evident in the raw wines from Vişinescu and Târgu Bujor. Ethyl acetate levels were generally elevated in wines with higher VA, supporting the esterification relationship. After conditioning, however, ethyl acetate concentrations typically decreased, likely due to hydrolysis or interactions with other wine compounds [63].

Ethyl lactate was especially dominant in Panciu (162 ± 80.7 mg/L), suggesting acidity correction with lactic acid [50]. This trend was also observed in Aramic wines, where volatile acidity and ethyl acetate levels were in direct correlation, after post-conditioning, confirming the relationship between elevated acetic acid and enhanced esterification. After conditioning, ethyl acetate concentrations generally declined, probably due to hydrolysis or complexation reactions.

Similarly, isoamyl acetate was initially high in Ceptura but decreased significantly in conditioned wines, likely due to volatilization or enzymatic degradation. Nevertheless, significant concentrations of isoamyl acetate persisted in Aramic and Vişoara wines, indicating that precursor alcohol availability plays a key role in its synthesis.

Hexyl acetate, contributing fruity-green aromas, was most abundant in Ceptura and Jidvei, where moderate total acidity supported ester formation. Neopentyl acetate, a minor ester imparting floral and honey-like notes, showed relevant concentrations in SCDVV Bujoru (conditioned wines) and Ceptura (raw wines), suggesting microbial activity and raw material differences in its synthesis.

The impact of total acidity (TA) and volatile acidity (VA) was evident. Wines with higher VA, like those from Vişinescu, exhibited elevated ethyl acetate concentrations in raw samples. However, excessive VA, as in Jelna, produced degradation acetate esters, likely due to chemical hydrolysis.

The variability in concentrations of 5-oxotetrahydrofuran-2-carboxylic acid and 4-mercapto-4-methylpentan-2-one is influenced by environmental factors, as previously

noted, but is more significantly determined by winemaking practices and yeast activity, particularly involving *Saccharomyces cerevisiae* strains known for their thiol-releasing capabilities [64]. Mercapto-4-methylpentan-2-one originates from non-volatile grape precursors and is released during fermentation through the enzymatic activity of these yeasts. Post-conditioning, acetaldehyde levels generally declined, likely due to sulfur dioxide binding or polymerization reactions. Notably, this decrease was particularly evident in wines from SCDVV Bujoru, reflecting reduced oxidation and improved chemical stability. This trend was consistent across other wines, maintaining the principle of possible reduction through wine conditioning. These changes collectively indicate enhanced esterification in conditioned wines, likely influenced by fermentation dynamics and temperature control.

In addition, changes in specific chemical ratios provide valuable insights into fermentation and aging dynamics. A slight increase in the acetic acid/isoamyl acetate ratio suggests altered esterification pathways due to microbial activity and oxidative processes, while growth in the ethanol/ethyl acetate ratio points to ongoing ethanol conversion under specific winemaking conditions. The marked rise in the acetic acid/pentyl acetate ratio highlights significant pentyl acetate formation, whereas the stable 1-pentanol/pentyl acetate ratio implies minimal impact of conditioning on pentanol esterification. Additionally, the increase in the acetic acid/neopentyl acetate ratio underscores the role of oxidative aging and microbial interactions in ester synthesis. Higher ethanol/acetaldehyde ratios reflect acetaldehyde accumulation as a result of oxygen exposure.

Declines in both the acetic acid/ β -phenylethyl acetate and phenylethyl alcohol/ β -phenylethyl acetate ratios suggest that phenolic esters are particularly vulnerable to volatilization and oxidation. Likewise, the sharp increase in the acetic acid/hexyl acetate ratio, combined with the drop in the hexanol/hexyl acetate ratio, indicates preferential hexyl acetate formation and reduced hexanol availability, likely driven by oxidation or volatilization. For fatty acid esters, an increase in the capric acid/ethyl caprate ratio points to favourable conditions for caprate ester formation, potentially influenced by oxidative processes or malolactic fermentation. Conversely, decreases in the octanoic acid/ethyl octanoate and dodecanoic acid/ethyl dodecanoate ratios reflect reduced esterification, likely due to oxidative degradation or volatilization.

5. Conclusions

Meteorological conditions directly affected alcoholic fermentation and aroma development, with the differences between 2019 and 2021 noticeably impacting wine composition. Higher temperatures in 2021 accelerated fermentation, resulting in increased levels of higher alcohols and esters, which intensified the aroma profile. This also created challenges for maintaining consistency, requiring adjustments in vineyard and fermentation practices. The higher presence of acetate esters in 2021 wines contributed to fresher, floral, and citrus-like aromas, enhancing their sensory characteristics.

The results demonstrate clear differentiation among Romanian wines based on their chemical compositions. Wines from Dealu Mare and Murfatlar exhibited high ester content and enhanced aromatic complexity, while those from Dealul Bujorului and Panciu showed elevated levels of volatile acids and aromatic alcohols, suggesting distinct fermentation dynamics. The conversion of specific compounds, such as 5-oxotetrahydrofuran-2-carboxylic acid into dihydro-tetramethyl-furanone, further emphasized the influence of environmental conditions and winemaking practices on the aromatic complexity of aged wines.

This study confirms the balance between winemaking techniques and terroir effects, where factors such as fermentation conditions, temperature control, microbial activity, and oxygen exposure shape the chemical composition of wines. The evolution of esters and

acids throughout various winemaking stages significantly influences the sensory profile, contributing to aromatic complexity and overall quality.

Author Contributions: Conceptualization, I.C.B. and V.V.C.; methodology, I.-B.C., C.-B.N. and M.N.; software, I.-B.C.; validation, C.-B.N., M.N. and V.V.C.; formal analysis, I.-B.C., C.-B.N. and M.N.; investigation, I.C.B.; resources, I.C.B.; writing—original draft preparation, I.C.B.; writing—review and editing, I.-B.C.; supervision, V.V.C.; project administration, V.V.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The original data presented in the study are openly available in the Research Centre for Oenology, Romanian Academy, Iași Branch, 9th Mihail Sadoveanu Alley, 700490 Iași, Romania, ccoiasi@gmail.com.

Conflicts of Interest: The authors declare no conflicts of interest.

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