

Article

Investigation of the Combined Impact of Location and Processing on the Quality Characteristics of Commercial Malagousia Wines from Northern Greece

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Abstract

Malagousia represents one of the most promising white native Greek grapevine varieties, producing wines of excellent quality. This study aimed to explore the quality characteristics of Malagousia wines from Northern Greece (Macedonia and Thessaly regions) and evaluate the impact of location and processing. We hypothesized that processing can exceed the *terroir* effect on most compositional traits. To verify this hypothesis, 28 commercial single-varietal Malagousia wines were chosen, varying in location, processing, and vintage. Wines were examined for alcohol content, pH, color, phenolic content, antioxidant activity, elemental composition, and sensory attributes. There was a significant variation in the parameters measured among the wine samples depending on the processing applied, such as skin contact, lees aging, and barrel maturation. While aging on lees affected antioxidant activity and aroma complexity, wines aged in oak or acacia barrels displayed higher phenolic content. Common sensory descriptors included citrus (such as lemon and lime), chamomile, and peach, with some wines exhibiting unique notes like caramel or peppermint. Cluster and Principal Component analyses showed distinct clusters based on winemaking methods and, to a lesser degree, place of origin. The results highlight Malagousia's varietal potential and the significance of carefully managed processing in expressing stylistic and *terroir*-driven complexity.

Keywords: white wine; antioxidant activity; elemental composition; ICP-OES; total phenolic content; sensory analysis



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1. Introduction

Among the autochthonous Greek white grapes (*Vitis vinifera* L.), Malagousia (Greek Μαλαγουζιά) represents a variety with exceptional winemaking quality. Being almost extinct till the 1970s, nowadays it represents one of the most widespread varieties throughout Greek territory and is considered a world-class wine grape [1].

The resulting wines can result in a sophisticated structure with moderate acidity and intermediate alcohol levels. Free and bound volatile profiling of compounds from Malagousia grape skin revealed the presence of intense herbaceous, floral, and fatty aromas [2]. On

the other hand, Malagousia wines may develop a very large aromatic profile characterized by peaches, basil, green bell pepper, floral, lemon, grapefruit, citrus blossom, mushroom, and earthy notes [1,3,4]. Malagousia is used in producing blends and in single-varietal wines. These wines are produced by applying various technologies and styles (aged or not), resulting in a large variety of wines. Single-varietal Malagousia wines show excellent aging potential if oaked. Moreover, sweet versions exist that are made with late-harvest grapes. In addition, depending on the desired wine style, the producers choose the appropriate vinification technique, leading to further diversification of Malagousia wine in the market. Vinification techniques significantly influence composition and volatile compounds, modifying the aroma and flavor profile of white wines. Extraction, maceration (pellicular: before, during, or after alcoholic fermentation; prolonged; post-fermentative), cryoextraction, and supra-extraction techniques affect the phenolic composition, color intensity, and final aroma profile in wine [5–8]. Moreover, aging on lees, where the wine remains in contact with dead yeast cells, enhances mouthfeel, aromatic integration, and oxidative stability [9,10]. A recent review reveals variations in volatiles provided by different types of wood used in aging vessels, which can contribute to the formation of distinct sensory characteristics in wines. Acacia wood, in particular, is known to impart more subtle vanilla notes in comparison to oak [11]. These factors are particularly relevant for a variety like Malagousia, known for its delicate yet complex aromatic expression.

Beyond vinification techniques, the chemical composition of wine is significantly influenced by other factors such as location, cultivation practices, and the ripening stage at harvest [12,13]. Among them, *terroir* plays a crucial role in the quality of wines. Although Malagousia is grown throughout Greece, it seems that the climate of Northern Greece favors its cultivation, considering the excellent quality of the wines produced. Compounds such as phenolics affect the color, taste, and aging of wine and benefit human health [14]. The literature reports the presence of phenolics, such as tyrosol, caftaric, and caffeic acid, in Malagousia wines at concentrations greater than 10 mg/L and notes the higher antioxidant capacity of the wines despite the high variation observed in the literature regarding native and foreign white wines [15].

In addition, the elemental profile influences the final composition of wine and its characteristics (color, flavor, aroma), while the quantity is a consequence of soil composition and the agricultural practices adopted [16]. Besides determining trace elements in wine linked to contamination and the legal limits set, monitoring the content of certain salts added during processing determines the metal contribution to flavor and wine quality [17]. Currently, elemental analysis is considered a valuable method to authenticate the geographical origin of wines [18,19]. The aroma of wines is influenced by the volatile compounds in grapes, while the winemaking technology contributes to the final aromatic profile, playing a critical role in their identification [20,21].

Despite growing interest, there is limited knowledge about Malagousia wines, with most studies focusing on the phenolic composition and antioxidant activity in only a few samples [15], in experimental wines [1], as part of testing methods regarding the detection of aromatics in wine samples [21], or included in quality factor studies [22].

This study aimed to address this gap by evaluating single-varietal Malagousia wine samples from various regions in Northern Greece and unveiling their quality-defining characteristics. Specifically, we investigated the effect of location and processing techniques (such as skin contact, lees aging, and barrel maturation) on the composition and sensory expression of these wines. To accomplish this aim, 28 commercial Malagousia wines from different vintages and production methods were analyzed for pH, color, phenolic content, antioxidant activity, macro- and microelemental composition using Inductively Coupled Plasma – Optical Emission Spectrometry (ICP-OES). These parameters were

selected due to their known influence on wine quality traits such as flavor intensity, aroma complexity, color stability, aging potential, and health-related properties. Additionally, a trained sensory panel assessed the wines' aromatic and taste profiles. We hypothesized that vinification practices may have a more pronounced impact on compositional traits than geographical origin alone. To evaluate this, multivariate statistical methods including Principal Component Analysis (PCA) and Hierarchical Cluster Analysis (HCA) were employed to identify patterns and classify wines based on both origin and processing style. This study aims to deepen our understanding of the varietal potential of Malagousia and highlight the importance of processing decisions in producing unique wines that reflect their regional origin.

2. Materials and Methods

2.1. Chemicals and Reagents

Standard solutions (1000 mg/L) of the following single elements were purchased from Sigma Chem (St. Louis, MO, USA) for the elemental profile of the wine: As, Ca, Cd, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn. To avoid cross-contamination during analysis of trace metals, all glassware and plastic containers were washed with nitric acid and rinsed with ultra-pure water.

DPPH (2,2-diphenyl-1-picrylhydrazyl) was from Sigma Aldrich, (St. Louis, MO, USA), whereas Trolox ((S)-(-)-6-hydroxy-2,5,7,8-tetramethylchroman-2-carboxylic acid) and gallic acid were from J&K Scientific GmbH, Pforzheim, Germany. Folin–Ciocalteu reagent and sodium hydroxide were obtained from Chem-Lab NV, Zedelgem, Belgium. Sodium carbonate and sodium nitrite were from Merck, KGaA, Darmstadt, Germany. HPLC (High-Performance Liquid Chromatography) gradient-grade methanol and water were purchased from Chem-Lab NV (Zedelgem, Belgium). The rest of the chemicals and reagents were of analytical grade.

2.2. Sample Collection

A total of 28 samples of white wine produced exclusively from the white cultivar Malagousia (single-varietal wines) were collected from 15 wine producers across 9 locations within the geographic regions of East Macedonia and Thrace, Central Macedonia, West Macedonia, and Thessaly, Greece. All wines were marketable and of the 2011–2020 vintage. These wines were produced according to the practices followed by each winemaker and bottled in glass bottles. Their coded names and additional information are reported in Figure 1 and Table 1. Wines were chosen to encompass the diversity of winemaking practices applied to Malagousia that are commercially available, regardless of market share or price. To do so, both conventional and alternative winemaking techniques across vintages were selected. To explore the impact of vintage, wines from the same winemaking process were selected across different years.

The wine samples are a combination of various alternative steps used during white winemaking, including, but not limited to, prolonged contact with skin, aging on lees, and maturation in oak and acacia barrels. They can be considered to derive from ten different winemaking processes. The first group comprises samples obtained from winemaking procedures involving no special treatment, and they are a result of a classic vinification of white wines. It contains the following subgroups: no contact with skin or lees and not aged, skin contact and not aged, lees contact and not aged, skin and lees contact and not aged, skin and lees contact and aged in oak barrels, skin and lees contact and aged in acacia barrels. The second group includes samples coming from a special winemaking procedure, including subgroups such as no contact with skin or lees and aged in an oak barrel, skin contact and not aged, skin contact and aged in an oak barrel, and lees contact and not aged.

The special winemaking techniques identified include extended maceration and natural additive-free practices, particularly in S22, S23, S24, S25, and S27. Several of the same samples also underwent prolonged oak maturation (>12 months). Minimal intervention winemaking with lees contact was observed in S26 and late harvest combined with barrel fermentation characterized S28.

The obtained samples were stored in the dark and at a low temperature. An aliquot from each stored sample was poured into a glass tube, tightly sealed with Teflon liner caps, and stored in a freezer till analysis for a maximum of one week. The glass tubes were previously washed with nitric acid and then with HPLC-grade water to avoid cross-contamination.

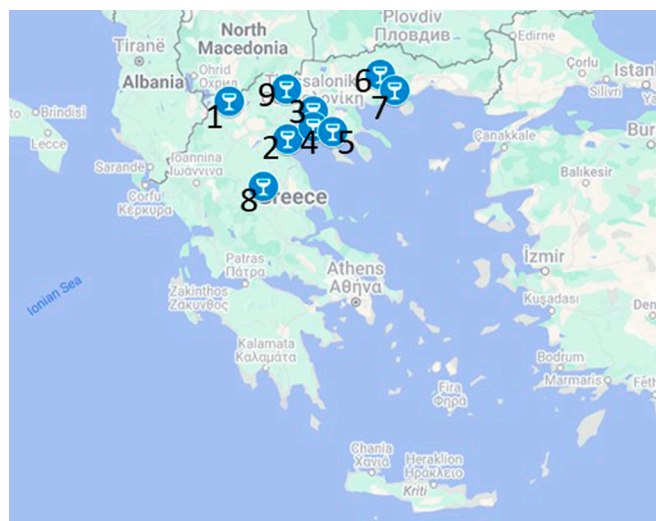


Figure 1. Variation map of Greece (Google, n.d.) depicting the wine samples' origin. Numbers refer to location, as presented in Table 1.

2.3. Determination of Elemental Composition of Wine

Two different subsamples (replicates) were taken from each wine sample. Wine samples were allowed to rest in a water bath till alcohol evaporation and then filled up to the original volume with ultra-pure water acidified with nitric acid (8% *v/v*). When needed, the samples were diluted with the same acidic solution. This method gives similar results to the sample mineralization method when metals' detection in wine is performed with ICP-OES [23], allowing the minimization of signal-suppressing effects of organic constituents without losing sensitivity at the ppb concentration range. Samples were analyzed at least in duplicate on a Perkin-Elmer 8300 DV (ICP-OES) Inductively Coupled Plasma Optical Emission Spectrometer (Perkin-Elmer, Waltham, MA, USA). Detection was performed using the method reported by Skendi et al. [24], developed according to the IUPAC guidelines [25]. Operating conditions comprised a nebulizer flow of 0.8 L/min, auxiliary gas flow of 15 L/min, sample uptake rate of 1.50 mL/min, plasma power of 1300 W, and integration time of 15 s. There were measured trace elements (As (188.979), Pb (220.353), Cd (228.802), Ni (231.604), and Cr (267.716)), microelements (Fe (238.204), Cu (327.393), Zn (206.200), Mn (257.610)), and macroelements (K (766.490), Na (589.592), Ca (317.933) and Mg (285.213)). Numbers in brackets show the wavelength (nm) used for each element. The detection limit was 0.0027, 0.0042, 0.0097, 0.0046, 0.0014, 0.0059, 0.0100, 0.0150, and 0.0070 mg/kg for Cd, Pb, Cu, Fe, Mn, Zn, Cr, Ni, and Co, respectively. A blank sample was run after every five samples to detect possible interferences or contamination.

Table 1. Sample description of wines analyzed.

Sample	Vintage	Sub-Region	Location	Producer	Winemaking Technique			Winemaking Process ***	Alcohol Content (% vol) ****	pH	Classification Based on Sugar Content
					Special Winemaking	Contact with Skin and Lees *	Aged in Barrels **				
S1	2020	West Macedonia	1	1	0	3	0	6	13.0	3.38 ± 0.01	dry
S2	2020	Central Macedonia	2	2	0	1	0	3	12.5	2.82 ± 0.02	dry
S3	2020	Central Macedonia	3	3	0	1	0	3	13.0	3.25 ± 0.01	dry
S4	2020	Central Macedonia	4	4	0	3	1	7	13.5	3.11 ± 0.01	dry
S5	2019	Central Macedonia	4	4	0	3	1	7	13.5	3.11 ± 0.01	dry
S6	2020	Central Macedonia	5	5	0	3	0	6	13.5	3.14 ± 0.01	dry
S7	2019	Central Macedonia	5	5	0	3	0	6	13.5	3.37 ± 0.01	dry
S8	2020	East Macedonia	6	6	0	3	0	6	13.5	2.87 ± 0.01	dry
S9	2019	East Macedonia	6	6	0	3	0	6	13.0	2.87 ± 0.01	dry
S10	2020	East Macedonia	6	7	0	3	2	8	12.0	2.84 ± 0.01	dry
S11	2019	East Macedonia	6	7	0	3	2	8	12.5	2.84 ± 0.01	dry
S12	2020	East Macedonia	7	8	0	0	0	1	13.5	3.47 ± 0.01	dry
S13	2019	East Macedonia	7	8	0	0	0	1	13.0	3.68 ± 0.01	dry
S14	2019	Central Macedonia	4	9	0	2	0	5	11.8	3.19 ± 0.01	dry
S15	2019	East Macedonia	7	10	0	3	0	5	13.0	3.37 ± 0.01	dry
S16	2020	Central Macedonia	3	11	0	3	0	6	13.8	3.17 ± 0.01	dry
S17	2019	Central Macedonia	3	11	0	3	0	6	13.9	3.38 ± 0.01	dry
S18	2018	Central Macedonia	3	11	0	3	0	6	13.5	3.27 ± 0.01	dry
S19	2017	Central Macedonia	5	11	0	3	0	6	13.0	3.38 ± 0.01	dry
S20	2018	Central Macedonia	4	12	0	3	2	8	12.5	3.19 ± 0.01	dry
S21	2019	Central Macedonia	3	11	0	3	2	8	12.5	3.19 ± 0.01	dry
S22	2018	Thessaly	8	13	1	0	1	2	12.6	3.34 ± 0.01	dry
S23	2016	Thessaly	8	13	1	0	1	2	12.5	3.44 ± 0.01	dry
S24	2018	Central Macedonia	9	14	1	1	1	4	13.5	3.19 ± 0.01	dry
S25	2018	Central Macedonia	9	14	1	1	1	4	12.0	3.83 ± 0.01	dry
S26	2020	Central Macedonia	9	15	1	2	0	10	12.5	3.62 ± 0.01	dry
S27	2011	Central Macedonia	2	2	1	3	0	9	14.5	3.88 ± 0.01	dry
S28	2016	Central Macedonia	3	4	1	0	1	2	13.5	3.20 ± 0.01	sweet

* Skins and lees contact codes: 0 = none; 1 = skin contact only; 2 = lees aging only; 3 = both skin contact and lees. ** Barrel aging was coded as follows: 0 none, 1 aging in oak barrels, and 2 aging in acacia barrels. *** Winemaking process is a combination of the three winemaking techniques. **** As mentioned in the wine label.

2.4. Determination of Color and pH

The chromatic properties of wines were measured in a Thermo Helios Alpha UV–Vis Spectrophotometer (Thermo Electron Corporation, Altrincham, Cheshire, England). Absorbances at 420 nm, 520 nm, and 620 nm measured in a 10 mm path-length cuvette were used to calculate the percentage of yellow (yellow%), red (red%), and blue (blue%), respectively, as well as the color intensity index (CI) and hue, in each wine. Absorbance measured at 420 nm after appropriate dilution was used to detect the “browning index” in white wines [26]. The measurements were performed at least in triplicate. pH values were determined according to the OIV method MA-AS313-15 [27].

2.5. Determination of Total Phenolic Content and Antioxidant Activity

Wines were centrifuged (4500 rpm for 15 min), and the supernatants were used for analyzing TPC (total phenolic content) and DPPH antioxidant activity. TPC and DPPH were determined by the Folin–Ciocalteu method and the DPPH assay, respectively. A more detailed explanation of the procedure is given by Skendi, Papageorgiou, and Stefanou [24]. The results were expressed as equivalents of gallic acid (mg GAE/mL) and as mg Trolox equivalents (mg TE/mL), respectively. All measurements were performed at least in triplicate.

2.6. Sensory Tests

Wines were evaluated by a panel of 10 professional enologist judges aged from 30 to 60 (5 women and 5 men). They were all competent and experienced judges with more than 10 years of wine-tasting experience. These panelists received the necessary instructions to evaluate the qualitative and quantitative variations in the wines. Single-variety Malagousia commercial wines of decent average quality without flaws were used to assess the panelists' performance. Wines were tasted using the defined procedures of International Organization for Standardization (ISO) (ISO 3591 and ISO 4121) [28,29]. The wines were blind-tasted and given in a random order. Each sample was randomly coded with a non-consecutive 3-digit code. The testing room was temperature-controlled, and the wines were presented in ISO wine-tasting glasses at a temperature range from 10 to 12 °C [28] and covered by plastic Petri dishes. The glasses were filled with 30 mL of wine, which was opened about 30 min before the session. Water was provided to clean the palate between each session. The wines were assessed under natural light.

The test consisted of a specific evaluation sheet that contained five-point structured sensory (appearance, color intensity, aroma intensity) and gustatory (acidity, tannins/astringency, alcohol, oiliness (creamy texture), and body/structure) descriptors. In addition, the quality of wine aroma was also examined for the presence/absence of specific olfactory characteristics using yes/no questions. The questionnaire contained predefined olfactory characteristics such as citrus fruits (lemon, lime), tropical fruits (grapefruit, pineapple, mango, lychee), tree fruits (peach, apricot, apple), floral (chamomile, jasmine), spice/herbs (peppermint, spearmint), sweet aromas (nuts, honey, caramel), and other undesirable aromas (grass/herbaceous, butter, reduction, oxidation). Multiple responses per sample were allowed. In addition, the panelists were given the opportunity to identify/describe different aromas as “other”. The frequency of mostly perceived odorous attributes was reported. The overall assessment of the wine was made on a scale ranging from 0 to 10.

All the judges–participants involved were informed about the study before obtaining their consent. The study was conducted in accordance with the Declaration of Helsinki and approved by the Democritus University of Thrace Research Ethics Committee (approval code 61435/435, date 19 July 2024).

2.7. Statistical Analysis

To recognize the presence of a relationship between the parameters studied, Pearson linear correlation (2-tailed, $p < 0.05$) or the non-parametric Spearman's was employed. The abovementioned statistical analysis was performed using SPSS Statistics 25.0 software (SPSS Inc., Chicago, IL, USA).

Differences between groups or within groups were compared (at $p < 0.05$) using parametric (Analysis of Variance, ANOVA) and the respective non-parametric (Kruskal–Wallis) tests when data lacked normality, followed by the respective post-tests. The mean scores of sensory attributes were examined to generate radar graphs with the sensory profile of the wines.

The mathematical processing of the standardized data was performed by Hierarchical Cluster Analysis (HCA) using Ward's method, and the results were presented as a dendrogram. Moreover, Principal Component Analysis (PCA), using the pairwise estimation method, was performed on all the data to obtain information regarding the possible relationships with the factors studied. HCA and PCA analyses were performed using JMP 18 (SAS Institute Inc., Cary, NC, USA).

3. Results and Discussion

3.1. Color, Phenolic Content, and Antioxidant Capacity of Wines

Color is recognized as one of the wine attributes that most affect consumer preference. After fermentation, white wine is prone to non-enzymatic reactions that cause oxidative browning, which affects the wine's color [30]. The variation in the browning index is visible in Figure 2a. It was observed that the processes applied significantly affected browning (mean ranks varied among the processes applied) in the Malagousia wines tested, as confirmed by the Kruskal–Wallis test at $p < 0.05$. According to Singleton [31], the yellow-brown hue of wines is due to phenols, which are first oxidized to quinones that, in turn, are prone to polymerization condensation reactions. Epicatechin level is considered a principal agent in browning, because it undergoes a high degree of oxidation/polymerization, producing pigmented compounds that affect color [32,33]. It was observed that the special treatments increased the browning of the wines compared to when no special treatment was applied (except in the case when the wine was aged in an acacia barrel and on lees). It was noted that the browning index positively correlated with the pH of wines (Spearman $r = 0.547$, $p < 0.01$), but no correlation was observed with alcohol content. The literature reports that a higher pH accelerates the browning of wines [34]. On the other hand, as expected, the browning index was negatively correlated with vintage (Spearman's $r = -0.730$, $p < 0.01$).

In general, the processing affected the color proportions of the wine (Figure 2b). Special treatments, involving a more extended time of contact with skin and lees, led to an increase in the proportion of blue and red color, whilst the proportion of yellow color was decreased compared to the wines where no special treatments were employed. Based on statistical analysis (ANOVA at $p < 0.05$) of the data, the proportion of yellow color increased in the following order: lees contact $\leq$ skin contact $\leq$ no contact $\leq$ skin and lees contact. The opposite was observed for proportions of red and blue.

Aging on lees contributed to color stabilization and may reduce browning by consuming oxygen and releasing antioxidants (glutathione, mannoproteins). Therefore, a reduction in yellow/brown tones occurs over time. For example, Chardonnay wines aged *sur lie* have been shown to maintain a paler color than control wines, and their browning potential was lower [35]. Skin contact in white wine production leads to an increase in yellow and brown pigments [36]. This is primarily due to the extraction of phenolic compounds (like catechins, flavonols, and hydroxycinnamic acids) from the grape skins, which then undergo

oxidation, leading to the formation of colored polymers [37]. Unlike red wines, white wines lack anthocyanins, so skin contact does not contribute to red or blue coloration.

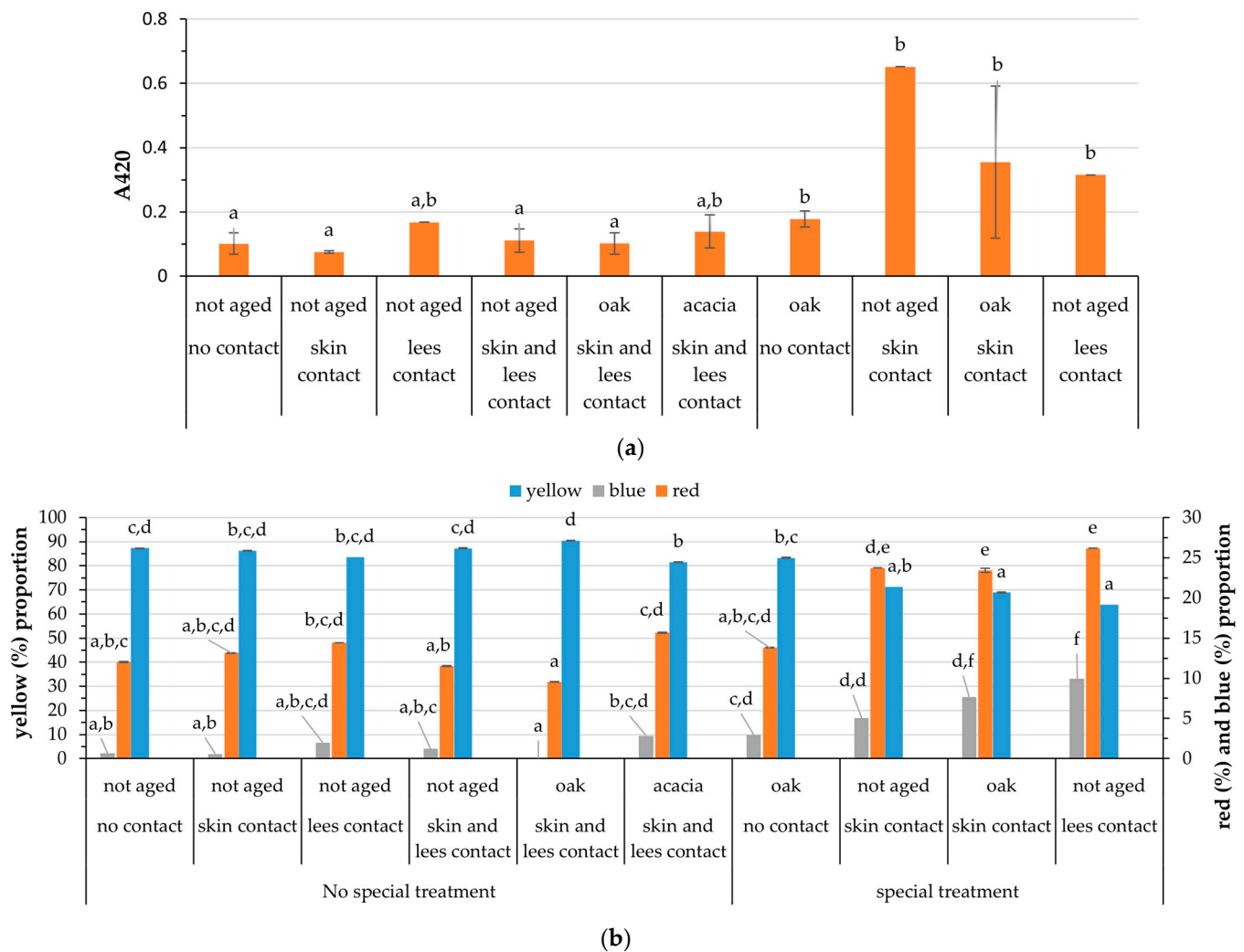


Figure 2. Variation in color parameters of wines depending on the winemaking process applied in Malagousia wines from Northern Greece: (a) mean values of absorbance at A420 nm and (b) yellow, red, and blue color percentages. Similar letters above bars of the same color are not significantly different ($p < 0.05$) as determined by the Kruskal–Wallis test followed by Dunn’s pairwise tests adjusted using the Bonferroni correction.

The alcohol content does not correlate with the color proportions of wines, which corroborates the knowledge that it is not a direct determinant of color, especially in white wines. On the other hand, pH correlated negatively with yellow (Pearson’s $r = -0.523$, $p < 0.01$), and positively with red (Pearson’s $r = 0.507$, $p < 0.01$) and blue (Pearson’s $r = 0.520$, $p < 0.01$) proportion. Actually, a higher pH increases yellowing in white wines, as oxidation reactions (such as enzymatic browning from polyphenol oxidase) are more likely to occur at a higher pH [38]. Vintage correlated positively with yellow (Pearson’s $r = 0.394$, $p < 0.05$) color but negatively with red (Pearson’s $r = -0.407$, $p < 0.05$).

The TPC and DPPH varied among the wine samples depending on the winemaking procedure applied, as confirmed by the Kruskal–Wallis test (Figure 3). Previous studies have reported total phenolic content (TPC) values for Malagousia wines in the range of 150–250 mg GAE/L [15,23]. The highest TPC was observed for process 10 (Table 1), which uses a special treatment that involves contact with lees but no aging in barrels. Notably,

wines aged in acacia barrels or subjected to special treatments involving prolonged skin contact showed higher phenolic concentrations. These results confirm previous findings that skin contact and barrel aging enhance phenolic extraction [5,8]. Moreover, processes 6, 10, 1, and 5 resulted in wines with the highest DPPH mean range. Our findings corroborate the work of Strati, Tataridis, Shehadeh, Chatzilazarou, Bartzis, Batrinou, and Sinanoglou [1], who demonstrated that processing choices (e.g., tannins' addition or oak aging) significantly influence antioxidant capacity. Wines in our study exhibited higher DPPH activity when prolonged skin contact and a special treatment were applied. It was observed that wines subjected to both skin and lees contact showed significantly lower TPC and DPPH mean ranges than those subjected to only skin contact. Although skin contact extracts a significant amount of phenolics, subsequent lees contact could lead to a reduction in the soluble TPC in the final wine due to the absorption of tannins and other polyphenols [39].

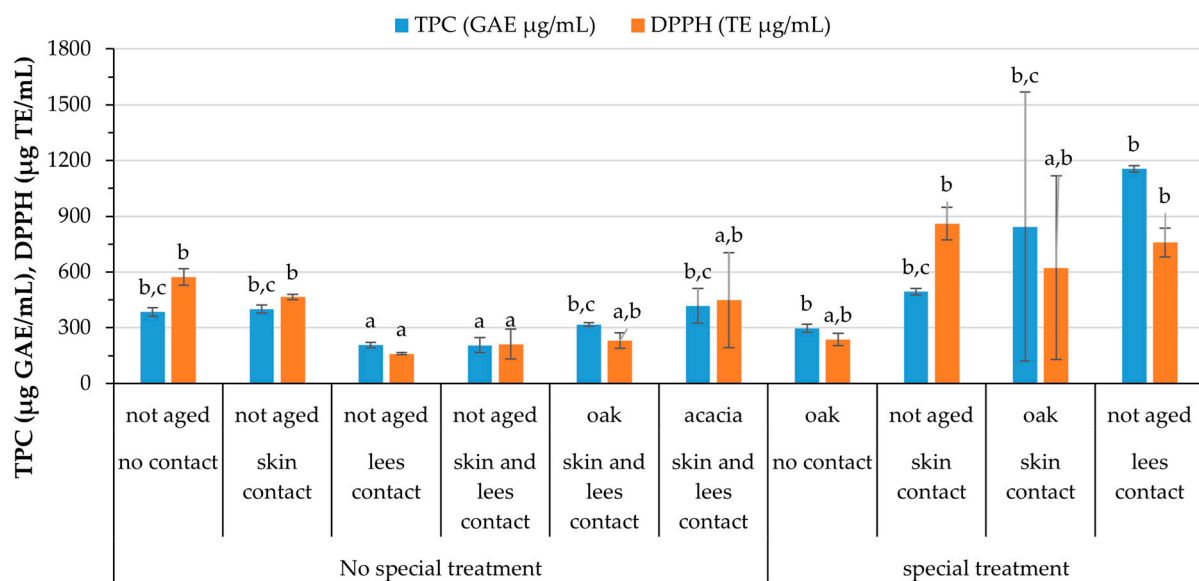


Figure 3. Mean values of total phenolic content (TPC) and antioxidant capacity (DPPH) depending on the winemaking process applied in Malagousia wines from Northern Greece. Similar letters (a, b, c) above the bars for the same parameter are not significantly different ($p < 0.05$) as determined by the Kruskal–Wallis test, followed by Dunn’s pairwise tests adjusted using the Bonferroni correction.

Moreover, it was observed that the technique of “aging in a barrel” does not affect the DPPH content, whilst affecting the TPC. Aging in acacia barrels seems to increase the amount of TPC measured in wine. Barrel aging, particularly in oak, increases TPC, primarily due to the extraction of phenolic compounds from the wood itself, including ellagitannins, phenolic acids, and volatile phenols [40]. The lack of a significant effect on DPPH, despite an increase in TPC, can be attributed to the nature of the extracted phenolics, as some compounds might contribute to TPC but have reduced DPPH scavenging activity [41]. Specifically, the phenolics extracted during barrel aging, particularly ellagitannins from oak or acacia wood, may not significantly contribute to antioxidant activity as measured by the DPPH assay. Ellagitannins are high-molecular-weight hydrolysable tannins with complex redox behavior. While they contribute to wine’s structure and oxidative stability, recent studies indicate that their direct radical-scavenging capacity is relatively low, especially in the DPPH assay, which primarily detects hydrogen atom transfer (HAT) reactions [42]. Furthermore, ellagitannins may undergo oxidation and condensation reactions during barrel aging, producing polymeric derivatives that are less reactive toward DPPH radicals but still active in metal chelation or oxygen scavenging via other mechanisms. Therefore,

the antioxidant measurements are assay-dependent, and an increase in TPC from barrel aging does not necessarily reflect an enhanced radical-quenching capacity [43].

According to the Spearman correlation (-0.335 , $p < 0.05$), it appears that the alcohol content of wines correlates with TPC values, whereas this is not the case for pH and vintage.

3.2. Elemental Composition of Wines

The total concentrations of macroelements ranged from 239.7 to 1150.9 mg/L for K, 14.5 to 43.6 mg/L for Ca, 47.5 to 118.0 mg/L for Mg, and 10.0 to 79.6 mg/L for Na. The Kruskal–Wallis test showed strong evidence of a difference ($p < 0.05$) between the mean ranks of at least one pair of processes applied for the K, Ca, and Na, while no differences were observed in the case of Mg (Table 2). Wines derived from process 1 (no treatment, skin contact, not aged), 3 (no treatment, skin contact, not aged), 9 (special, skin contact, not aged), and 10 (special, lees contact, not aged) have significantly higher K mean ranks than the rest of the processes but similar between them. The highest Ca and Na concentration was observed in wines deriving from processes 3 and 8 (no treatment, skin and lees contact, acacia) in the case of Ca and 8 in the case of Na.

Table 2. Variation in macroelements (mg/L) and microelements (mg/L) in wine samples according to process applied ¹.

Special Winemaking	Contact with Skin and Lees	Aged in Barrels	K	Ca	Mg	Na
			Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
No special treatment	no contact	not aged	972.3 ^b $\pm$ 199.8	20.3 ^a $\pm$ 1.4	82.07 ^a $\pm$ 6.02	32.3 ^{b,c} $\pm$ 0.5
	skin contact	not aged	658.5 ^{a,b} $\pm$ 137.0	34.6 ^b $\pm$ 10.2	78.05 ^a $\pm$ 21.16	41.6 ^{b,c} $\pm$ 22.0
	lees contact	not aged	494.5 ^a $\pm$ 5.0	27.7 ^{a,b} $\pm$ 0.2	48.90 ^a $\pm$ 1.43	33.1 ^{b,c} $\pm$ 0.8
	skin and lees contact	not aged	463.9 ^a $\pm$ 156.2	27.2 ^{a,b} $\pm$ 7.3	84.18 ^a $\pm$ 20.21	37.5 ^{b,c} $\pm$ 17.6
	skin and lees contact	oak	511.4 ^a $\pm$ 18.1	25.7 ^{a,b} $\pm$ 0.7	86.31 ^a $\pm$ 2.20	41.4 ^{b,c} $\pm$ 1.6
	skin and lees contact	acacia	418.0 ^a $\pm$ 169.8	31.4 ^b $\pm$ 5.0	80.95 ^a $\pm$ 15.53	53.1 ^c $\pm$ 20.5
Special treatment	no contact	oak	628.8 ^a $\pm$ 203.1	26.3 ^{a,b} $\pm$ 5.3	89.47 ^a $\pm$ 19.20	27.7 ^{b,c} $\pm$ 7.3
	skin contact	not aged	971.9 ^b $\pm$ 5.4	20.3 ^a $\pm$ 0.2	90.91 ^a $\pm$ 1.65	17.3 ^{a,b,c} $\pm$ 0.1
	skin contact	oak	526.2 ^a $\pm$ 205.8	29.5 ^{a,b} $\pm$ 2.6	69.48 ^a $\pm$ 2.71	12.6 ^a $\pm$ 3.0
	lees contact	not aged	950.3 ^{a,b} $\pm$ 7.2	23.7 ^{a,b} $\pm$ 0.01	47.65 ^a $\pm$ 0.25	13.5 ^{a,b} $\pm$ 0.4
			Fe	Cu	Zn	Mn
			Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
No special treatment	no contact	not aged	0.653 ^a $\pm$ 0.322	0.079 ^a $\pm$ 0.062	0.448 ^{a,b} $\pm$ 0.373	1.034 ^{c,d} $\pm$ 0.066
	skin contact	not aged	0.716 ^a $\pm$ 0.179	0.112 ^a $\pm$ 0.023	0.373 ^{a,b} $\pm$ 0.271	0.817 ^{c,d} $\pm$ 0.072
	lees contact	not aged	0.281 ^a $\pm$ 0.006	0.271 ^a $\pm$ 0.006	0.215 ^{a,b} $\pm$ 0.012	1.027 ^{b,c,d} $\pm$ 0.027
	skin and lees contact	not aged	0.703 ^a $\pm$ 0.418	0.111 ^a $\pm$ 0.090	0.248 ^{a,b} $\pm$ 0.069	0.742 ^{a,b} $\pm$ 0.228
	skin and lees contact	oak	0.687 ^a $\pm$ 0.060	0.079 ^a $\pm$ 0.025	0.250 ^{a,b} $\pm$ 0.011	0.671 ^a $\pm$ 0.025
	skin and lees contact	acacia	0.531 ^a $\pm$ 0.178	0.176 ^a $\pm$ 0.109	0.613 ^{a,b} $\pm$ 0.350	1.007 ^{b,c,d} $\pm$ 0.301
Special treatment	no contact	oak	0.512 ^a $\pm$ 0.222	0.124 ^a $\pm$ 0.050	0.187 ^a $\pm$ 0.060	0.630 ^a $\pm$ 0.102
	skin contact	not aged	0.664 ^a $\pm$ 0.023	0.397 ^a $\pm$ 0.002	0.406 ^b $\pm$ 0.011	1.147 ^{a,b,c} $\pm$ 0.023
	skin contact	oak	1.062 ^a $\pm$ 0.148	0.112 ^a $\pm$ 0.053	0.206 ^{a,b} $\pm$ 0.091	1.865 ^d $\pm$ 0.167
	lees contact	not aged	1.363 ^a $\pm$ 0.013	0.058 ^a $\pm$ 0.002	0.169 ^a $\pm$ 0.005	1.204 ^{c,d} $\pm$ 0.001

¹ Similar superscript letters within the same column do not differ ($p < 0.05$) as determined by the Kruskal–Wallis test followed by a Dunn’s pairwise tests adjusted using the Bonferroni correction.

Although the presence of macro- and microelements derives from the composition of the soil as well as the agronomic practices applied, the final composition of wine depends on the applied process [44]. The literature reports a decrease in K and Ca due to precipitation as tartrate salts, not only during fermentation but also during aging [45].

According to the Kruskal–Wallis test, processes involving no contact demonstrated a significantly higher mean rank of potassium (K) levels compared to those involving both skin and lees contact. This pattern, however, was not observed for calcium (Ca). The combination of potential adsorption by lees and enhanced precipitation of potassium bitartrate during processes involving skin and lees contact could explain the lower final

potassium levels compared to wines with no such contact [46]. While this may be the case for potassium, yeast lees are generally less efficient at adsorbing calcium compared to potassium or other metallic ions [40].

Geographical location appears to exert a significant influence on the concentrations of macroelements in wine, except for magnesium (Mg). The mineral composition of wine is largely influenced by the grapevines' uptake of elements from the soil. The specific soil composition (geology, parent material, pH, and organic matter content), climate, and viticultural practices in a given geographical location (*terroir*) directly impact the availability and uptake of macroelements (like K, Ca, Na) by the grapevines [40]. In particular, proximity to coastal areas notably increases sodium (Na) levels in wine [47]. Indeed, the samples from locations next to the sea (locations, 3 Thessaloniki and 4 Epanomi) were those producing wines with the highest Na mean ranks among the samples. This may be attributed to the combination of direct deposition from sea sprays and potential root uptake from saline soils in vines from coastal regions [40].

Microelements play an important role in the metabolism of yeasts, influencing the fermentation process. Specifically, they contribute not only to supporting efficient alcoholic fermentation but also to activating prosthetic metalloenzymes that are essential for yeast metabolism. Minerals such as zinc, magnesium, manganese, copper, and iron promote key biochemical pathways in yeast, influencing enzyme stability, energy production, and redox balance [48]. Iron, in particular, is involved in yeast's respiratory metabolism, but its concentration must be carefully balanced, as excess Fe can lead to oxidative instability in the wine [49]. The concentrations of metal ions in wine can fluctuate throughout the winemaking process. This is due to various treatments like filtering, pH adjustment, adding yeast hulls, and bentonite fining [50,51]. Beyond their metabolic functions, these elements also influence the physical and sensory qualities of wine. Specifically, copper and iron have been shown to affect the stability, clarity, and color of the final product, with potential impacts on its organoleptic properties such as taste and aroma [52]. The literature reveals that iron and copper are important factors in oxidative browning in white wine, primarily via Fenton-like reactions that convert oxygen into reactive radicals. It was proposed that copper, by interacting with oxygen, facilitates the redox cycling of iron [53]. Manganese and possibly zinc also contribute through less direct, supportive roles [49].

Proper management of these microelements is therefore essential to ensure both fermentation efficiency and the overall quality of the wine [48]. Microelements such as Fe, Cu, Zn, and Mn vary in the range of 0.198–1.430, 0.02–0.398, 0.112–0.957, and 0.246–2.022 mg/L among the wines studied, respectively. According to the International Organization of Vine and Wine (OIV), excess levels of copper (1.0 mg/L) and zinc (5 mg/L) can destabilize wine [54]. Although the EU and USA do not specify a strict legal maximum for iron in wine, it is generally accepted as good manufacturing practice to maintain iron levels less than 10 mg/L. The levels found in all Malagousia wines are below these limits.

The applied winemaking processes appear to significantly affect only the concentrations of Zn and Mn (Table 2). Apparently, skin and lees contact influences Mn concentrations, which is probably due to its presence in grape solids, while aging in barrels affects Zn content. Specific research by Bekker et al. [55] indicates that the sequestering of Al, Cu, Ni, and Zn by wine lees is significantly affected by oxygen treatment. Their findings show that lees from oxidatively treated wines sequestered significantly greater amounts of Cu and Zn, removing these metals from the wine supernatant.

Various techniques are employed to reduce the levels of microelements that are responsible for the formation of haze. The literature reports that the amount of certain microelements is significantly affected not only by the clarifying agents themselves but also by the timing of additions. The clarifying agents do not affect Fe if added before

fermentation, nor Zn and Mn after fermentation, whilst Mg and Ca levels seem to be constant throughout the whole winemaking process, making them a possible tool for origin studies [56]. On the other hand, statistical analysis of our data revealed that location represents a significant factor affecting the content of most microelements except Zn.

3.3. Sensory Evaluation of Wines by Panellists

The wines under the study were evaluated by a panel for visual, textural, and olfactory features. The mean scores for each parameter, evaluated on a five-point scale, are shown in a radar chart (Figure 4a). The overall impression evaluated on a 10-point scale is reported in Figure 4b. The Kruskal–Wallis test revealed that all the parameters evaluated (appearance, color intensity, aroma intensity, acidity, tannins, alcohol, oiliness, body) significantly differ among the processes applied (Figure A1). It was observed that wines of no special treatment did not differ in their appearance and color intensity. They are classified as light yellow and showed the lowest color intensity, except for process 5 (no special treatment, lees contact, not aged). Moreover, the special winemaking processes resulted in wines with a higher color hue and intensity than the rest. The aroma intensity was higher in wines subjected to skin and lees contact, followed by aging in the barrel, compared to the rest of the wines that underwent no special treatment; at the same time, these wines did not differ from those that underwent special treatment. These findings suggest that aroma intensity is more sensitive to treatments. Aroma is affected by aging in the barrel as well as special treatments, whereas color changes are mostly due to the application of special treatments.

Wines from process 3 (no special treatment, skin contact, not aged) showed the lowest acidity among the rest, while processes 4 and 10 produced wines with a similar astringency (tannins) but the highest level compared to the rest, which did not differ between them. It seems that processes 4 and 10, belonging to “special treatment” and involving skin and lees contact, respectively, could ensure the migration of a higher quantity of tannins into the wine. It was observed that acidity and astringency increased if aging was performed in oak barrels compared to not-aged wines. Although process 2 resulted in wines scored with the highest value for alcohol content, they differ only from the wines derived from processes 1, 6, and 8. In general, wines of “no contact with skin and/or lees” showed a higher alcohol content. Processes 3 and 6 resulted in wines with a significantly lower oiliness (creamy texture) than the rest, while processes 3, 6, 8, and 10 produced wines with a body that can be ranked lower than the rest. When the technique of “aged in barrels” was examined, it was observed that aging in the oak barrel increases both the oiliness and the body of the wines.

The overall impression depends on the winemaking process applied (Figure 4b). The process involving skin contact, aging on lees, and aging in oak barrels gained the highest score from the panellists; however, no statistical difference compared to the wines of special treatments exists (except for the winemaking process involving contact with lees without any aging). The wine obtained without contact with skin and lees gained the lowest overall score.

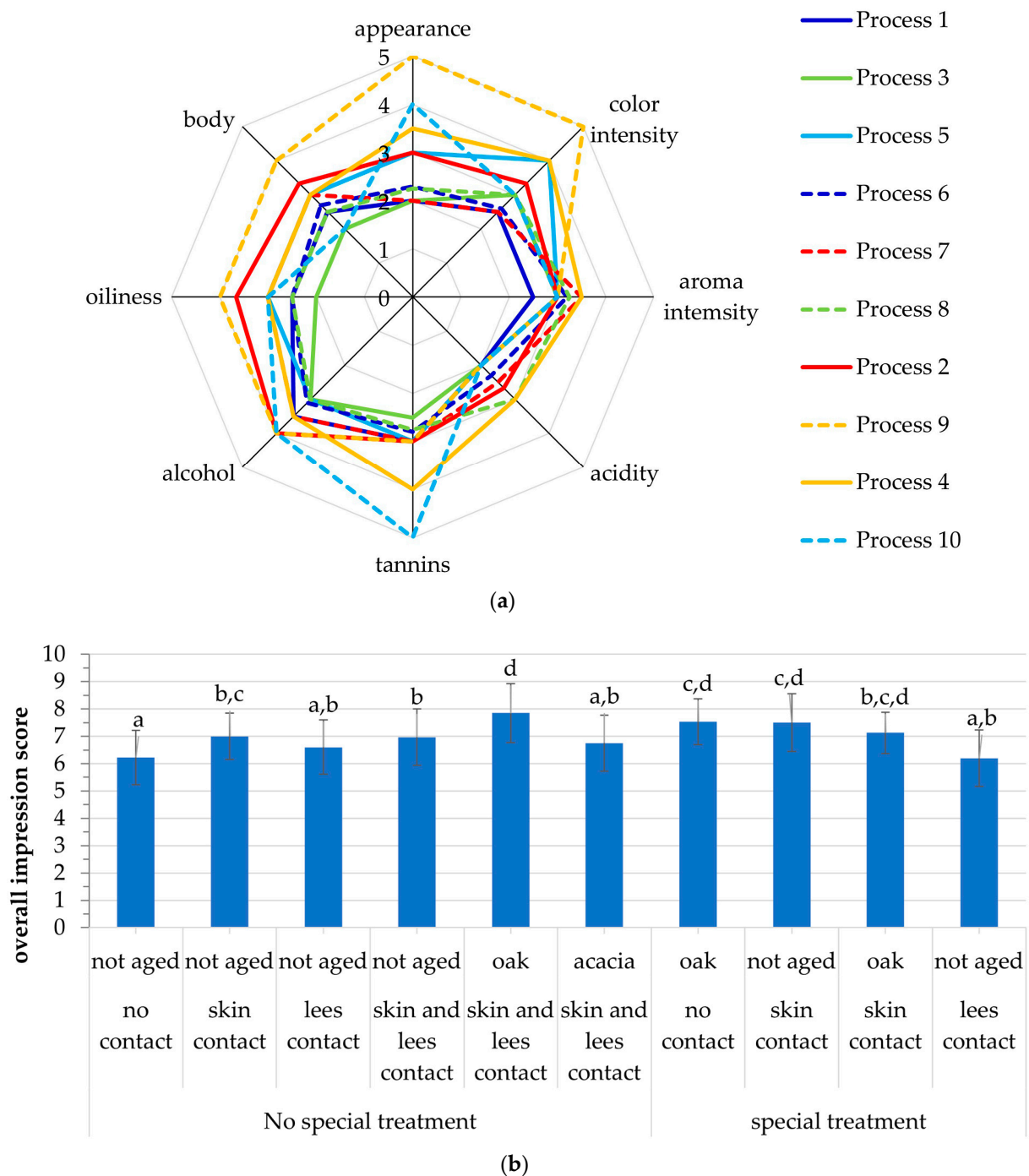


Figure 4. The mean score of Malagousia wines from the sensory test depends on the winemaking process applied: (a) Radar graphs from the sensory attributes on a five-point scale and (b) overall impression on a ten-point scale. Similar letters (a, b, c, d) above the bars are not significantly different ($p < 0.05$) as determined by the Kruskal–Wallis test followed by Dunn’s pairwise tests adjusted using the Bonferroni correction. Radar graphs were obtained from the sensory attributes on the evaluation test for each process. (Process numbers are as follows: Process 1: No special treatment, no contact, not aged. Process 2: special treatment, no contact, oak. Process 3: No special treatment, skin contact, not aged; Process 4: special treatment, skin contact, oak; Process 5: No special treatment, lees contact, not aged. Process 6: No special treatment, skin and lees contact, not aged. Process 7: No special treatment, skin and lees contact, oak. Process 8: No special treatment, skin and lees contact, acacia. Process 9: special treatment, skin contact, not aged. Process 10: special treatment, lees contact, not aged.

To determine if a wine possesses a scent, panelists examined wines in a yes/no experiment. The results regarding the four most frequently identified are shown in Table 3. The Malagousia wines from Northern Greece are mostly characterized by notes of chamomile, peach, lemon, and lime, followed by jasmine and grapefruit. Nanou, Mavridou, Milienos, Papadopoulos, Tempère, and Kotseridis [3] reported that the Malagousia wines examined have lemon, grapefruit, and citrus characteristics. They further noted that samples, depending on the location, develop distinct elements, such as honey, earthy, and peach ones. In their study, they examined four Malagousia wines, with two from Northern Greece (Pieria and Drama in the Macedonia region), while the other two were from Southern Greece (Attica and Evia) [3].

Table 3. The four scent notes frequently identified by the panel for each wine sample *.

Process	Sample	Aroma 1		Aroma 2		Aroma 3		Aroma 4	
		Scent Note	Proportion (%)	Scent Note	Proportion (%)	Scent Note	Proportion (%)	Scent Note	Proportion (%)
6	S1	peach	70	pineapple	60	grapefruit	50	mango	40
3	S2	peppermint	60	chamomile	40	spearmint	40	grass/herbal	40
3	S3	peach	50	grapefruit	40	lime	40	chamomile	20
7	S4	peach	60	jasmine	50	grapefruit	40	lime	40
7	S5	chamomile	80	jasmine	60	lemon	50	honey	50
6	S6	lemon	60	lime	60	chamomile	50	grapefruit	50
6	S7	chamomile	60	lemon	40	peach	30	mango	30
6	S8	lime	50	lemon	40	peach	40	chamomile	30
6	S9	lime	40	jasmine	40	peach	30	chamomile	30
8	S10	off-aroma	70	jasmine	20	chamomile	20	peppermint	20
8	S11	peppermint	70	honey	50	chamomile	30	spearmint	30
1	S12	lime	60	chamomile	30	off-aroma	30	grapefruit	30
1	S13	caramel	60	apricot	30	honey	30	chamomile	20
5	S14	nuts	40	chamomile	20	apple	20	off-aroma	20
6	S15	chamomile	50	apple	50	pineapple	40	peach	40
6	S16	peach	70	lime	50	mango	50	jasmine	40
6	S17	lemon	50	lime	40	peach	30	chamomile	30
6	S18	apple	40	off-aroma	40	lemon	20	chamomile	20
6	S19	off-aroma	70	lemon	30	peppermint	30	chamomile	20
8	S20	jasmine	50	lemon	30	lime	30	lychee	30
8	S21	chamomile	70	peach	50	jasmine	20	lychee	10
2	S22	peach	60	jasmine	40	chamomile	20	lychee	20
2	S23	chamomile	70	lime	40	apricot	30	spearmint	20
4	S24	apple	40	apricot	40	peach	30	chamomile	30
4	S25	apricot	80	peach	30	bergamot	30	mango	20
10	S26	off-aroma	30	peach	20	grapefruit	20	kumquat	20
9	S27	apricot	80	nuts	60	lemon	20	jasmine	20
2	S28	peach	80	apricot	70	floral	40	lemon	40

* Proportion of selection from panelists.

In contrast, Karampatea, Vrhovsek, Tsakiris, Dimopoulou, Kourkoutas, and Skavdis [4] observed a sensory profile that was primarily fruity, with a reduced floral expression, in experimental samples from East Macedonia, produced with different yeast strains, suggesting that in some regions, the fruit-driven aspects of Malagousia, such as stone fruit and tropical notes, can dominate, possibly due to warmer ripening conditions or yeast strains that suppress floral terpenes. The official profile from the National Interprofessional Organization of Vine and Wine - EDOAO (Wines of Greece) [57] lists peaches, green bell peppers, fresh herbs, and flowers as common descriptors of Malagousia wines. The presence of green bell pepper and herbal notes may indicate less ripe grapes or cooler microclimates, where methoxypyrazines and green terpenes are more prevalent. In summary, although

Malagousia is typified by a floral–fruity aromatic identity, its actual sensory expression can vary significantly.

The sensory panel also frequently identified caramel, peppermint, and nut aromas that were not widely reported in earlier studies. These notes appear particularly tied to barrel aging (oak and acacia) and lees contact.

Indeed, in addition to *terroir*, the winemaking process affects the wine's aroma. It is worth noting that white vinification without skin/lees contact or aging in barrels results mostly in peach/apricot, lime/grapefruit, and chamomile notes, while chamomile, peppermint, and lime notes occurred when a prolonged skin contact was applied but no aging on lees; nuts (i.e., hazelnut, walnut, almond), chamomile, but also off-aromas were detected when aging on lees was applied; chamomile, peach, and lemon were noted when both skin contact and aging on lees were applied. It is noteworthy that aging on lees appears to trigger the development of off-aromas, such as reductive or sulfurous ones, which aligns with literature highlighting the challenges of oxygen management in lees-aged white wines [10].

Malagousia wines produced without skin or lees contact showed eight and seven aromas when the unoaked and oaked versions were assessed, respectively (Figure 5a). The main scents detected were white fleshy fruit, citrus, and tropical fruit for unoaked wines, whereas white fleshy fruit, citrus, floral, and honey were detected for oaked samples. Unpleasant aromas were identified in several samples. In the unoaked group, S12 displayed notes of reduction, rotten apple, and burnt rubber, while S13 had a yogurt aroma. Among the oaked samples, S23 exhibited an undesirable earthy character.

Wines from a prolonged skin contact showed distinct aromatic profiles. Unoaked versions presented eight scents, while oaked wines displayed five. Differences were observed between the four main scents present in unoaked versus oak-aged samples (Figure 5b). Oak barrel aging primarily imparted white fleshy fruit aromas (like peach, apricot, apple) to Malagousia wines, with tropical (i.e., mango) and floral (i.e., chamomile) notes being less prominent, while the unoaked samples mostly exhibited white fleshy fruit, citrus, floral, and grass/herbal scents (i.e., peppermint, spearmint). Off-aromas were reported in one not-aged sample (S3: mouse taint) and in one sample aged in an oak barrel (S24: bitter almond).

When lees aging was applied without prolonged skin contact, the two unoaked Malagousia wines (samples 14 and 26) exhibited aromas of white fleshy fruit (e.g., peach, apple), nuts (e.g., walnut), and grass/herbal notes (Figure 5c). However, these samples also revealed some aromatic deviations; sample 14 showed reduction and oxidation notes, while sample 26 displayed leather and animal aromas.

Wine samples that underwent both skin contact and aging on lees displayed a rich array of flavors, with over eight distinct aromas identified depending on the specific aging process (Figure 5d). In unoaked samples, ten flavors were detected, with the four most frequently observed being as follows: white fleshy fruit, tropical, citrus, and floral. For oaked wines, a honey scent emerged alongside white fleshy fruit, tropical, citrus, and floral. Nevertheless, there are noticeable differences in aromas depending on the aging process. Sensory defects were detected in four unoaked wines: S8 presented medicinal notes; S9 showed signs of oxidation; S18 exhibited unpleasant, earthy, soil, and oxidized notes; and S19 exhibited unpleasant, oxidized, earthy, wet earth, and musty notes. Additionally, one wine aged in an acacia barrel (S10) displayed reductive aromas, including boiled cabbage, bitter almond, and unpleasant notes resembling pickles. The literature suggests that aromas such as sweet, pungent, and herbaceous ones at a high intensity can be developed in Malagousia wines, depending on the yeast strain [4]. Acacia wood is known to impart different sensory characteristics, often described as more subtle, floral, or nutty, with less pronounced vanilla or toast notes compared to oak [58].

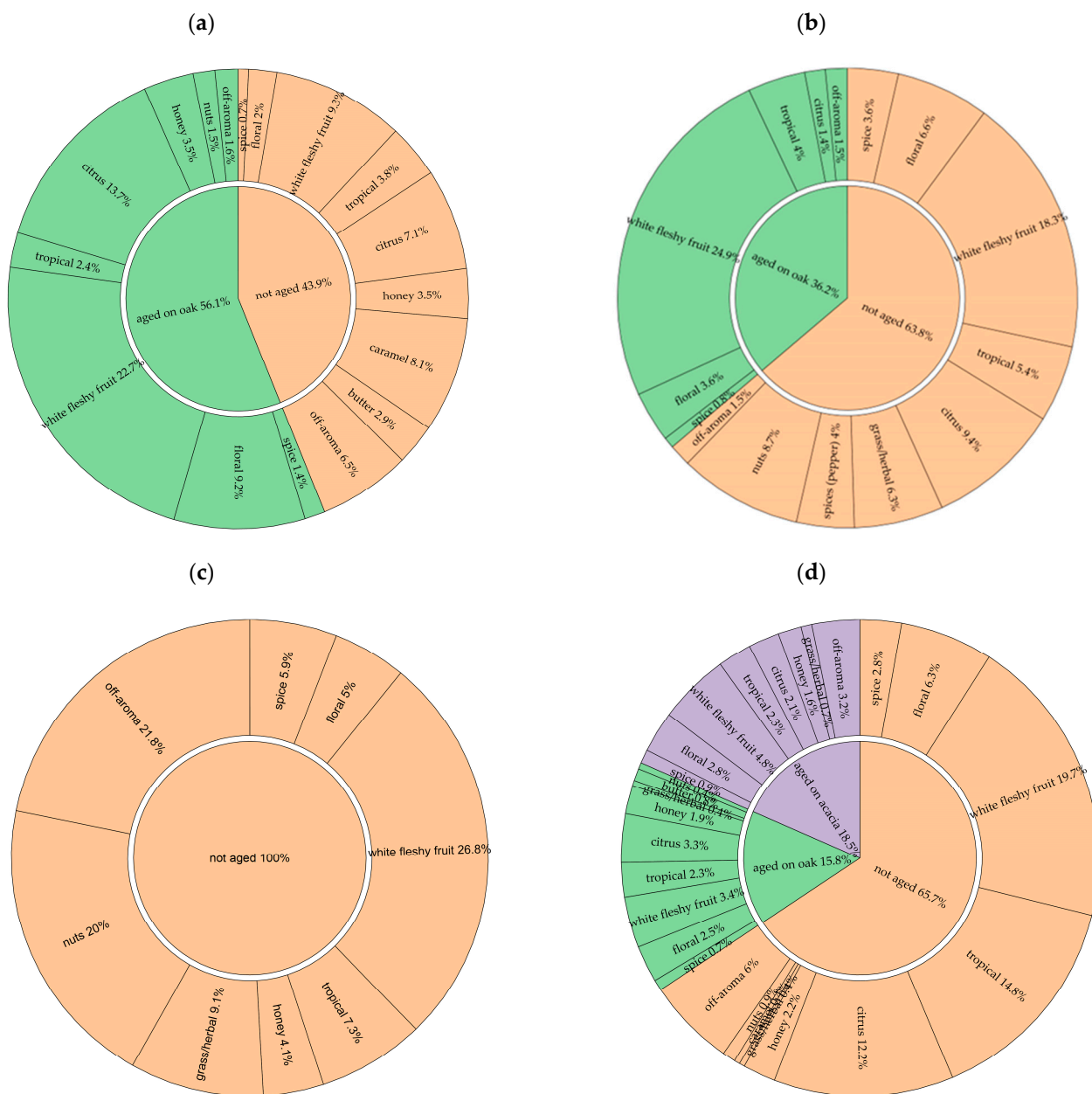


Figure 5. Variation in frequency of aroma scent in Malagousia wine samples when (a) no skin contact or lees aging was applied, (b) only prolonged skin contact was applied, (c) only aging on lees was applied, (d) both skin contact and aging on lees were applied.

Overall, skin contact and lees aging can enrich aromatic and phenolic profiles but must be managed carefully to avoid reduction-related faults. Barrel aging, particularly in oak, increases sensory complexity (e.g., nuttiness, caramel) and enhances mouthfeel attributes such as body and oiliness (creamy texture). Acacia barrels, less commonly used, appear to contribute distinct phenolic enhancements without a strong woody character—offering an alternative aging path for preserving varietal aromas. It should be noted that a combination of factors, the type of yeast used (*Saccharomyces cerevisiae* and various non-*Saccharomyces* strains), the presence of nutrients, and the application of pectinolytic and beta-glucosidase enzymes, along with the specific winemaking methodologies, could have collectively affected the wines' ultimate aromatic expression.

3.4. PCA Analysis

The HCA shows the differences among the wine samples from Northern Greece (Figure 6a). Samples S25, S26, and S27 are clustered separately from the rest. These samples are characterized by high values of red and blue hue, astringency, and pH. These wines are a product of a special treatment that contributed to the values obtained for the abovementioned parameters.

Factor analysis revealed that a smaller number of parameters can explain 77.8% of the variability. In addition, PCA helped group the parameters and identify two main components, Component 1 and Component 2, which, with 58.9% and 18.9% of the variation, respectively, accounted for about 78% of the total variance (Figure 6b,c). The PCA analysis grouped parameters pH, A420, color intensity index (CI), red%, blue%, appearance, color intensity, and tannins/astringency under the positive part of Component 1, while hue and yellow% were under the negative part. Parameters such as alcohol, oiliness (creamy texture), and body were in the positive part of Component 2, whereas TPC and DPPH were on the negative side. It is to be noted that parameters linked with elemental composition do not have significant contributions and are not included in the PCA analysis.

The PCA analysis grouped the wine samples into two distinct groups according to the special treatment performed. The wines that were produced from a special treatment were grouped in the positive part of Component 1, while almost all those considered not to have a special treatment were in the negative part. Regarding *terroir*, although there is not a very clear grouping, it is notable that the wines from East Macedonia tend to cluster separately, in the negative part of Component 1, based on color and phenolic characteristics, while those from West Macedonia show distinct sensory features and were positioned in the positive part of Component 2. Such findings could aid in *terroirs'* delineation, supporting appellations' formation or refinement in Northern Greece. Moreover, consistent detection of chamomile notes across all samples may represent a *terroir*-variety marker for Malagousia from Northern Greece.

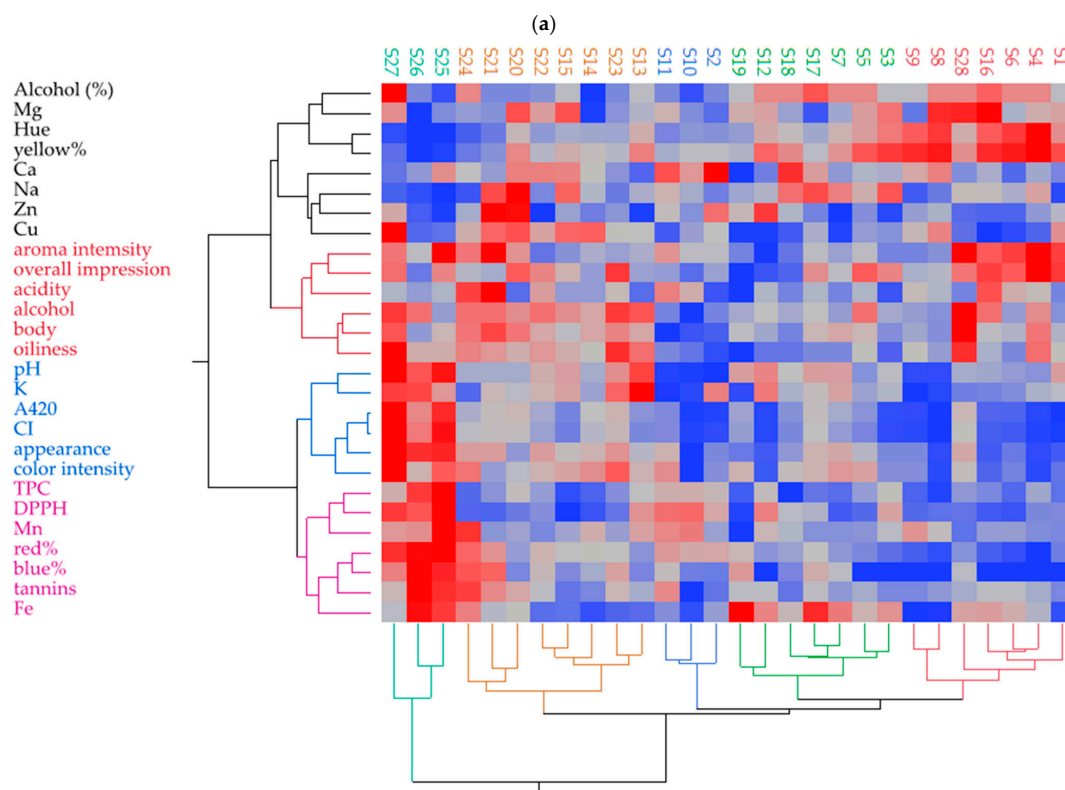


Figure 6. Cont.

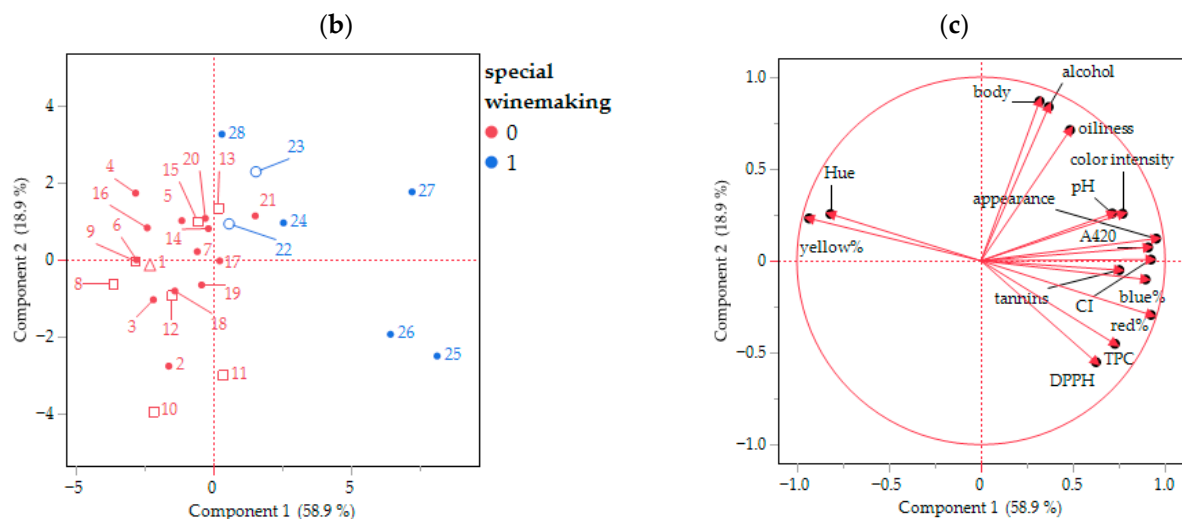


Figure 6. (a) Two-way hierarchical clustering, (b) score plot, and (c) factor loading plot of parameters determined in Malagousia wine from Macedonia region (markers: empty triangles = West Macedonia, empty rectangles = East Macedonia, filled circles = Central Macedonia, empty circles = Thessaly).

4. Conclusions

The Malagousia wines studied reveal the differences in quality, elemental profile, and aromatic characteristics of this Greek variety. Quality parameters and the elemental profile depended on the *terroir*, in addition to the processing applied. The elemental composition is significantly altered by winemaking, and although the individual elements were not direct indicators of quality, some of them could serve in *terroir* mapping of wines. Moreover, sensory analysis indicated differences in the aroma notes, with wines from Northern Greece consistently exhibiting chamomile notes, probably deriving from a combination of *terroir* and varietal expression. In addition, caramel and peppermint emerged as differentiating descriptors associated with processing/aging, alongside citrus notes (lime and lemon). Thus, the findings suggest that an appropriate processing technique could significantly influence the sensory profile of Malagousia, underlining its versatility and potential in winemaking.

From a broader perspective, these results contribute to the characterization of Malagousia as an emerging Greek variety with the capacity to produce wines of a distinctive quality and typicity. However, limitations of this study include the restricted geographical scope and sample size, which may not capture the full diversity of Malagousia across Greece. Future research should therefore expand to include additional regions, vintages, and processing techniques, while integrating consumer preference studies to better connect chemical and sensory findings with market acceptance. Such investigations could provide a more comprehensive understanding of the variety's potential and help guide winemakers in optimizing practices to enhance its quality and international recognition.

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Institutional Review Board Statement: The study was conducted in accordance with the Declaration of Helsinki and approved by the Democritus University of Thrace Research Ethics Committee (approval code 61435/435, date 19 July 2024).

Informed Consent Statement: Informed consent was obtained from all subjects involved in the study.

Data Availability Statement: The original contributions presented in the study are included in the article; further inquiries can be directed to the corresponding author/s.

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

Appendix A

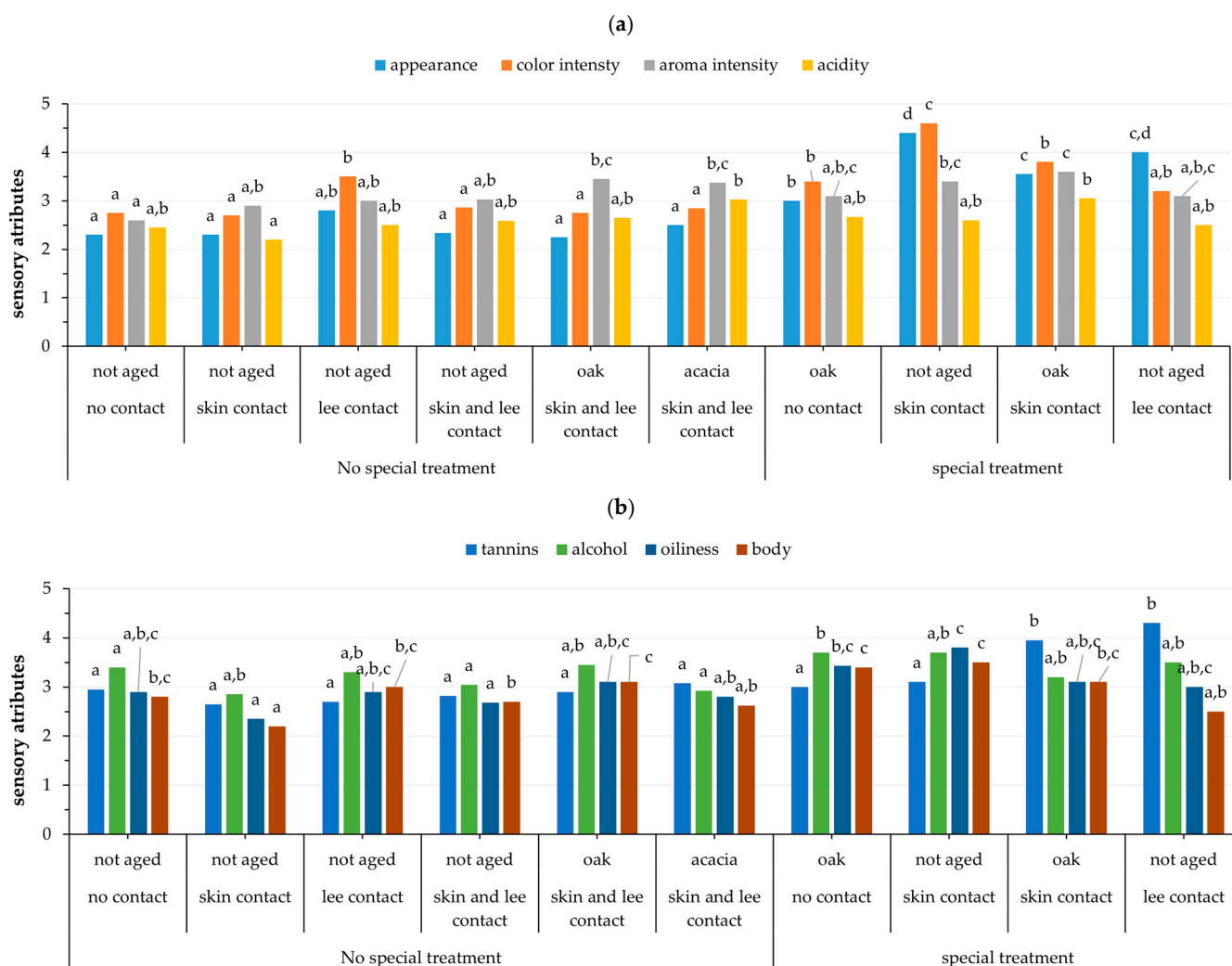


Figure A1. The mean of sensorial parameters, (a) appearance, color intensity, aroma intensity, acidity; (b) tannins, alcohol, oiliness, body. Similar letters above bars of the same parameter are not significantly different ($p < 0.05$) as determined by the Kruskal–Wallis test, followed by Dunn’s pairwise tests adjusted using the Bonferroni correction.

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