

ABSTRACT

Keywords: Pedoclimatic integration; soil–climate –aroma relationships; odor activity values (OAVs); regional discrimination; interannual sensory stability; varietal authenticity and typicity, Sauvignon blanc, Fetească albă.

The wine regions of Romania are distinguished by a pedoclimatic diversity that explains the typicity of their wines. The Wine Region of Dealurile Munteniei and Olteniei, characterized by limestone relief and a temperate-continental climate, includes the Dealu Mare vineyard, renowned for complex and extractive red wines. The Wine Region of Banat, influenced by the Mediterranean climate, produces aromatic white wines and elegant, well-structured reds. The Wine Region of Colinele Dobrogei, with an arid climate moderated by the Black Sea, offers traditional wines from centers such as Sarica Niculițel and Murfatlar. In the Wine Region of Podișul Transilvaniei (300–320 m altitude), the cool climate and marked diurnal variations favor freshness and fine aromas in white wines from Târnave, Lechința, and Aiud, supporting their acidity and typicity. On the other hand, the Wine Region of Dealurile Moldovei, the country's largest, located on fertile chernozem soils, stands out for its diversity, producing wines ranging from sparkling to full-bodied reds. The low-lying vineyards of Colinele Dobrogei (Murfatlar – 41 m, Sarica Niculițel – 86 m) are characterized by hot summers and water deficit, yielding wines with high aromatic intensity and a distinct character. (Cotea et al., 2005).

The study focused on a comparative analysis of climatic and pedological conditions in eleven representative Romanian vineyards, through reference wineries: Jidvei, Domeniile Boieru, Jelna, Ceptura, Davino, and Aurelia Vișinescu, Panciu, Bujor Hill – SCDVV Bujoru, Sarica Niculițel, Vișoara, and Aramic. The analysis covered the period 2019–2021, examining global variations of climatic and water parameters, with direct impact on grape ripening and wine typicity, particularly for Fetească Albă and Sauvignon Blanc varieties.

Wineries in Transylvania (Jidvei, Domeniile Boieru, Jelna) have fertile, well-structured soils, brown clay-loamy or eumezobasic, favorable for moderate water retention and uniform vine growth. In Dealu Mare, cambic chernozems and soils with anthrosol influences provide efficient drainage and nutrient supply, while at Aurelia Vișinescu, alluvial soils and protosols are lighter, with variable water retention. At Panciu and SCDVV Bujoru, cambic and leveled chernozems offer a balance between fertility and drainage, supporting uniform grape maturation. In Dobrogea, Sarica Niculițel has loamy-sandy soils, lightly compacted and slightly alkaline, while Vișoara presents molisols and carbonate chernozems, well-drained, assuring moderate water stress and aromatic concentration. At Aramic, erodisol and alluvial soils ensure fertility and adequate drainage, explaining regional differences in physico-chemical and aromatic profiles of wines (Cotea et al., 2005).

Climatic analysis of the period 2019–2021 in the eleven studied vineyards (Târnave – Jidvei, Aiud – Domeniile Boieru, Lechința – Jelna, Dealu Mare – Ceptura, Davino, and Aurelia Vișinescu, Panciu – Panciu, Dealu Bujorului – SCDVV Bujoru, Sarica Niculițel – Sarica Niculițel, Murfatlar – Vișoara, and Dealurile Banatului – Aramic) highlights significant inter-annual differences, directly impacting grape ripening and wine aromatic profiles. The year 2021 was cooler and wetter compared to 2019, with lower temperatures in September–October and higher precipitation, that favoured maintenance of acidity and slower sugar ripening (Ciucure et al., 2025a, p. 44). Statistical analysis (ANOVA) confirmed a significant effect of the year on mean temperature ($F = 6.45$; $p = 0.003$) and relative humidity ($F = 5.87$; $p = 0.005$), indicating an inverse relationship between temperature and humidity (Allen, 1998).

Climatic variations among vineyards were moderate, which allowed data aggregation and their correlation with soil type and soil water holding capacity (CRAS). Hydric and agroclimatic parameters, such as the actual sunshine duration (ASD), the oenoclimatic aptitude index (IAOe), reference evapotranspiration (ET_0), the deficit relative to field capacity (DFc), total soil water deficit, the Winkler thermal index (WI), the Huglin heliothermal index (HI), crop evapotranspiration (ETc), and the crop coefficient (Kc), played a decisive role in sugar accumulation and the preservation of acidity (Y Zhang et al., 2022, p. 107883).

For Fetească Albă and Sauvignon blanc, differences were relevant: FA demonstrated a better capacity to maintain freshness and acidity under variable climatic conditions, while SB reflected greater sensitivity to water availability and solar radiation.

Physico-chemical analysis of musts for Fetească Albă (FA) and Sauvignon blanc during 2019–2021 shows the direct influence of pedoclimatic factors on sugar accumulation and acidity maintenance. Total sugar values ranged between 182 and 252 g/L, and total acidity between 4.2 and 7.3 g/L, with notable differences between vineyards and harvest years. FA exhibited relatively stable evolution, with sugars around 200–220 g/L and acidity 5.5–6.7 g/L, preserving freshness even under advanced ripening conditions. In contrast, SB showed greater variation, with total sugars between 192 and 252 g/L and acidity between 4.5 and 7.3 g/L, reflecting sensitivity to solar radiation and water availability.

Pearson correlations indicate that for FA, total acidity (TA, g/L tartaric acid) is moderately negatively correlated with the sum of active temperatures (SumActT, $r = -0.52$) and total UV radiation / oenoclimatic aptitude index (IAOe, $r = -0.54$), but positively correlated with vineyard altitude (Alt., $r = 0.56$), latitude (Lat., $r = 0.50$), and days with moderate water deficit (DFc, $r = 0.43$), suggesting that high temperatures and intense radiation reduce total acidity, while altitude and controlled water stress favor its accumulation. Sugars in Fetească Albă correlate positively with SumActT ($r = 0.67$), IAOe ($r = 0.67$), DFc ($r = 0.59$), total precipitation (Precip, $r = 0.61$), and ETc ($r = 0.58$), indicating that insolation and balanced water supply support photosynthesis and sugar accumulation (Procopenco, 2024, p. 81).

For Sauvignon blanc, total acidity (TA) is negatively correlated with SumActT and IAOe ($r = -0.29$) and positively correlated with DFc ($r = 0.50$) and altitude (Alt., $r = 0.63$), while total sugars (ZT) show negative correlations with TA ($r = -0.77$) and DFc ($r = -0.39$) and positive correlations with SumActT ($r = 0.42$) and IAOe ($r = 0.40$), indicating that excessive water stress or high altitudes may reduce sugar accumulation.

Volatile acidity (VA, g/L acetic acid) in Fetească Albă decreases with ETc ($r = -0.486$, $p = 0.041$) and DFc ($r = -0.502$, $p = 0.034$), whereas in Sauvignon blanc, VA correlates negatively with heliothermal indices HI ($r = -0.497$, $p = 0.042$) and WI ($r = -0.546$, $p = 0.024$), reflecting differences in adaptation to water and thermal stress.

Physico-chemical analysis of Fetească Albă and Sauvignon blanc wines from major Romanian vineyards highlights the impact of technological stages on wine quality, particularly alcohol content, total and volatile acidity, density, and sulfur dioxide levels. Depending on oenological strategies and climatic conditions, three categories of wineries were identified: Dealu Bujorului and Aurelia Vișinescu, with high SO_2 levels associated with intensive conservation practices and warmer climates; Jelna, Domeniile Boieru, and Sarica Niculițel, with moderate SO_2 levels, where interventions were essential for antioxidant and microbiological control; and Jidvei, with low SO_2 levels, reflecting minimal intervention and cooler climate (Morgan et al., 2017, p. 96).

Technological interventions influenced wine physico-chemical parameters. At Domeniile Boieru, controlled addition of free SO₂ (35 mg/L) and the use of enzymatic preparations allowed maintenance of alcohol and density stability (0.991 ± 0.002 g/mL) and reduced residual sugars (2.11 ± 1.70 g/L), facilitating extraction of essential aromatic compounds. Fermentations, carried out with selected yeasts at 12–18 °C, were uniform. At Panciu, higher SO₂ doses (50 mg/L) and extraction enzymes ensured stable density (0.992 ± 0.001 g/mL) and residual sugars of 8.70 ± 4.67 g/L, indicating nearly complete fermentation. At Sarica Niculițel and SCDVV Bujoru, moderate protection strategies allowed acidity maintenance between 6.1 and 7.7 g/L and low VA (0.28–0.63 g/L), demonstrating effectiveness without SO₂ overdose.

Overall, acidity and pH remained relatively stable, highlighting the role of oenological interventions in maintaining balance and wine longevity (Koone et al., 2014, p. 158).

Analysis of the aromatic profile of Fetească Albă (FA) and Sauvignon blanc (SB) wines shows a significant influence of terroir and altitude on concentrations of major aroma compound classes. In FA wines, higher alcohols were elevated in Viișoara (69 mg/L), Ceptura (66.6 mg/L), and Davino (69.7 mg/L), vineyards located at lower altitudes, whereas volatile acids were more concentrated in Jelna (11.9 mg/L), Aramic (12.7 mg/L), and Domeniile Boieru (12.4 mg/L), higher-altitude sites. Esters predominated in Aramic (34.9 mg/L), Davino (28.5 mg/L), and Sarica Niculițel (27.9 mg/L), indicating a stronger influence of winemaking techniques than altitude. Terpenes reached maximum values in SCDVV Bujoru (38.4 μg/L), Aramic (12.2 μg/L), and Domeniile Boieru (11.9 μg/L), without a clear altitude-dependent pattern. Spearman correlations confirmed these trends: volatile acids were strongly positively correlated with altitude ($r = 0.997$), higher alcohols and esters had moderate negative correlations ($r = -0.685$ and $r = -0.613$), and terpenes had a moderate negative correlation ($r = -0.414$) (Jouanneau et al., 2012, p. 329).

In SB wines, higher alcohols ranged from 43.0 mg/L (Aurelia Vișinescu) to 94.5 mg/L (Ceptura), with higher accumulation in warm, low-altitude vineyards. Volatile acids varied less, from 3.44 to 12.21 mg/L. Esters, responsible for fruity aroma, ranged from 18.8 mg/L (Jelna) to 38.7 mg/L (Ceptura), reflecting fermentation activity and variability between wineries. Aldehydes and diols showed the greatest dispersion (107 ± 34.1 mg/L at Aurelia Vișinescu to 716 mg/L at Jidvei), while furanones and lactones were relatively constant (0.39 μg/L at Târgu Bujor to 14.87 μg/L at Aurelia Vișinescu) (Lei et al., 2025, p. 102575).

Multivariate analysis of volatile compounds highlighted clear differentiation between FA and SB wines, correlating aromatic profiles with terroir and winemaking technology. In FA, factor 1 (20.8% variance) separated wines rich in 1-propanol, 2-methyl-1-butanol, and medium-chain esters from those dominated by ethyl lactate and ethyl decanoate, while factor 2 (16.1%) reflected variations in 2-phenylethanol, β-phenylethyl acetate, and capryl acetate. Wines from Davino, Viișoara, and Aurelia Vișinescu exhibited more intense fruity esters, while Panciu and Jelna were dominated by primary alcohols and volatile acids.

For SB, factor 1 (19.8%) was associated with variations in fermentative esters (isoamyl acetate, hexyl acetate, ethyl caproate, ethyl hexanoate), and factor 2 (15.2%) highlighted differences from 2-phenylethanol, β-phenylethyl acetate, and short-chain alcohols. Unlike FA, the SB sample distribution was more compact, suggesting a more uniform aromatic profile across regions, indicating a stronger influence of winemaking technology than geographic location (Molina et al., 2007, p. 675).

The low variance explained by the first two PCA dimensions (35%) is justified by the high complexity of the aromatic profile, composed of hundreds of compounds, of which only a subset is discriminant, and by intra-regional effects induced by winemaking technology—yeast type, fermentation

regime, or maturation methods—which may generate greater variation than inter-regional differences, reducing PCA separation clarity (Coetzee & Du Toit, 2012, p. 287).

Analysis of volatile compound concentrations in FA and SB wines, correlated with sensory perception, highlights the dominant role of volatile esters in defining the aromatic profile. Odor Activity Values (OAVs) were calculated, allowing comparison of effective compound concentration to olfactory perception thresholds, providing an objective view of relevant aromatic compounds (Zhu et al., 2020, p. 2257; Chicco et al., 2025, p. 56).

In FA, major volatile esters had OAVs significantly above perception thresholds: ethyl hexanoate (EtHex, 352.9–750), ethyl acetate (EtAc, 4.49–8.59), ethyl caprate (EtCap, 7.05–38), and ethyl octanoate (EtOct, 295–595), providing consistent fruity notes and aromatic uniformity across wineries. In SB, the same compounds showed similar values: EtHex 271–668, EtAc 6.3–12, EtCap 11–100, and EtOct 29–64, highlighting the predominance of esters in defining fruity aromas (Scutarașu et al., 2022, p. 2897).

Higher alcohols, such as 3-methyl-1-butanol (2.85–4.43 OAV in FA and 2.9–4.7 in SB) and 2-methyl-1-butanol (0.64–4.43 in FA and 0.59–1.20 in SB), contribute to texture and subtle complexity without dominating fruity perception. Volatile acids, such as capric acid (CapAc) and hexanoic acid (HexAc), complement the profile (OAV 7.05–38 for FA and 11–100 for SB), enhancing roundness and body. Minor compounds, such as acetaldehyde (0.12–0.62), 1,2-propanediol (1.90–6.14), or other higher alcohols, increase overall aromatic complexity. OAV analysis demonstrates that volatile esters are the primary determinants of fruity notes and consistency across vineyards for FA and SB, while higher alcohols and volatile acids contribute to texture and aromatic depth.

Soil type influences the aromatic profile of FA and SB wines. On cambic chernozems (Panciu, Bujoru, Viișoara), FA develops strong fruity and fermentative aromas supported by higher alcohols, whereas on leveled chernozems (Jidvei, Boieru), wines become rounder, with notes of ripe fruits. Brown luvic soils (Jelna, Aramic) accentuate herbaceous and slightly oxidative character, while alluvial and sandy soils (Ceptura, Sarica Niculițel, Vișinescu, Davino) favor intense fruity aromas (Popescu (Stegarus) et al., 2023a, p. 19; SY Sun et al., 2012, p. 100).

Sauvignon blanc shows a pronounced sensitivity to pedological characteristics: on leveled and alluvial chernozems (Jidvei, Domeniile Boieru) citrus, currant, and vegetal notes predominate; on brown luvic soils, minerality and vegetal notes are evident; while on cambic chernozems a balance between higher alcohols and fruity esters is maintained. Terroir thus influences not only the concentration of volatile compounds but also their aromatic expression, offering opportunities to adapt winemaking to the specifics of each vineyard. For Fetească Albă, pedoclimatic parameters have a significant impact on the aromatic profile: in northern vineyards (Aramic, Jidvei, Ceptura), higher mean active temperatures in 2019 and higher precipitation in 2021 led to moderate increases of esters and alcohols (+3–9%), maintaining volatile acids relatively stable and thus ensuring acid balance and freshness of the wine (Jiang & Zhang, 2010, p. 9184).

In southern vineyards (Panciu, Viișoara, SCDVV Bujoru), moderate water stress associated with lower precipitation and soils with adequate water retention capacity (CRAS 170–180 mm) stimulated aromatic metabolism, leading to more pronounced increases of alcohols and esters (+5–15%), while volatile acids remained relatively stable or slightly decreased (–5% to –2%), preserving complexity and freshness of the wines (Balogh et al., 2011a, p. 1006). High humidity and high precipitation in northern vineyards (Jidvei, Silagi Hills, Sarica Niculițel) help maintain acidity, but may dilute aromas and increase the risk of fungal diseases, requiring additional protective strategies (Sweetman et al., 2014, p. 5975).

Analysis of the dynamics of esterification reactions between 2019 and 2021 shows significant selective conversions in alcohol–ester pairs. For Fetească Albă, ethyl hexanoate (EtHex) decreased from 18.05 mg/L to 0.7 mg/L, and for Sauvignon blanc, the decrease was similar, from 18 mg/L to 0.7 mg/L. In contrast, ethyl caprate (EtCap) increased significantly, from 0.99 mg/L to 11.9 mg/L in Fetească Albă and from 0.95 mg/L to 12 mg/L in Sauvignon blanc. Ethyl octanoate (EtOct) decreased moderately, and ethyl decanoate (EtDec) remained relatively stable. These evolutions reflect both the influence of wine maturation and the efficiency of applied winemaking protocols, indicating adequate control of esterification and post-fermentative chemical transformations (Cao et al., 2022; Moreno-Arribas & Polo, 2009).

Odor activity value (OAV) and linear discriminant analysis (LDA) shows that the differences between cultivars (Fetească albă and Sauvignon blanc) exceed annual variations 2019–2021, highlighting the role of genetic factors (Tredoux et al., 2008; Bedreag et al., 2025). Fetească Albă samples 2019 and 2021 grouped closely, with 2019 higher in persistence and acidity, and 2021 slightly toward sweet-pleasant notes (Filimon et al., 2024).

The analysis shows the influence of terroir on the aromatic profile. Dobrogea stands out for fruity (+18.76), oxidative (+30.86), and acidic (+8.81) notes, with low minerality (−29.94). Moldavian Hills show vegetal and fermentative notes (+27.20), pronounced bitterness (+23.35), and neutral minerality (+0.81), with the mean LD1 differentiation score −0.91, the most distinctive. Transylvania combines sweetness (+9.82), floral (+3.65), minerality (+7.91), and bitterness (+12.01), with the mean LD1 score −0.88, close to Moldova. Dealu Mare is defined by minerality (+12.84), oxidative (+6.62), and fruity (+14.36), with reduced bitterness (−11.35) and mean LD1 score −0.59, intermediate. Banat has fruity (+13.96) and vegetal (+0.69) notes, lower minerality (−4.02), and the most balanced mean LD1 score −0.23.

Differences between cultivars are greater than annual variations, and LDA analysis allows identification of variables with the greatest discriminating power, highlighting the typicity and regional character of the wines (Makhotkina et al., 2012).