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WANG FEI

ARGUMENTATION OF GRAPE-WINE PRODUCTION PATHWAYS ADAPTED TO MARKET REQUIREMENTS

253.03 - TECHNOLOGY OF ALCOHOLIC AND NON-ALCOHOLIC BEVERAGES

Summary of the doctoral thesis in engineering sciences

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CUPRINS

CONCEPTUAL FRAMEWORK OF THE RESEARCH

The actuality of the research and the importance of addressed issues. The contemporary wine industry is undergoing a transition from standardized technological models toward integrated production systems grounded in regional differentiation, predictive quality control, and market-oriented optimization [1-3]. The competitiveness of wines on international markets increasingly depends on the capacity of the "grape-wine" system to generate stable, quantifiable aromatic profiles tailored to consumer demands[4-7].

According to data published by the International Organisation of Vine and Wine (OIV), emerging markets demonstrate a pronounced preference for wines characterized by clearly defined aromatic identity and distinct regional specificity[8-10]. This trend necessitates the development of engineering-based models capable of correlating pedoclimatic factors, raw material composition, and technological process parameters within a coherent decision-support framework.

The study of the aromatic complex of wines has been extensively addressed in international oenological research by C. van Leeuwen, A.L. Robinson, O.A. Antoce et al. [11-13]. In the Republic of Moldova, significant contributions to substantiating the relationship between terroir, grape variety, and aromatic expression have been made by the Moldovan oenological, represented by researchers such as G. Musteață, N. Taran, B. Găina, A. Bălănuță, N. Furtună [14-16], among others who have investigated the biochemical mechanisms underlying volatile compound formation and the influence of pedoclimatic conditions on wine quality.

Nevertheless, existing approaches frequently address these components separately, without integrating them into a unified technological model based on statistical correlations and oriented toward optimizing grape-wine production pathways in accordance with market requirements.

The aromatic profile of wine represents the outcome of the interaction between agro-pedo-climatic conditions (terroir), the metabolic potential of the grape variety, and the parameters of the winemaking process [17-20]. Variability in temperature, water regime, soil composition, and altitude influences the synthesis of volatile organic compounds, including esters, higher alcohols, terpenes, and sulfur compounds, with a direct impact on sensory expression [21,22].

In the Republic of Moldova, the implementation of the Protected Geographical Indication (PGI) system for the Codru, Ștefan Vodă, and Valul lui Traian regions establishes the necessary framework for capitalizing on regional differentiation. However, an integrated technological model capable of transforming this differentiation into an operational optimization instrument is currently lacking.

The scientific problem addressed in the thesis lies in the absence of a technological model capable of quantitatively correlating terroir factors with the profile of volatile organic compounds and with winemaking process parameters, in order to optimize aromatic expression and enhance the competitiveness of Moldovan wines on external markets.

Aim and objectives of the study. The aim of the present research is to develop and validate an integrated technological model for the production of red wines from the Fetească Neagră variety, based on the quantitative correlation of agro-pedo-climatic terroir parameters with the profile of volatile organic compounds and with winemaking process parameters, in order to optimize aromatic expression and adapt the product to market requirements.

To achieve the proposed aim, the following **objectives** were established: 1. Characterization and modeling of the studied terroirs, through the determination of agro-pedo-climatic parameters and the quantification of the regional variability gradient within the three PGI regions. 2. Determination and differentiation of the volatile organic compound profile, through the application of GC-IMS technology and multivariate statistical analyses for the identification of regional aromatic markers. 3. Establishment of functional relationships between pedoclimatic factors and aromatic expression, through multivariate statistical modeling and integrated sensory evaluation. 4. Substantiation, optimization, and validation of differentiated technological pathways, through their implementation under real production conditions and integration into a market-oriented decision-support model.

Working hypotheses. The agro-pedo-climatic variability of terroir units determines significant differences in the composition of volatile organic compounds in wines produced from the Fetească Neagră variety. The volatile profile of Fetească Neagră wines exhibits regional aromatic markers that are instrumentally identifiable and statistically differentiable. Significant functional relationships exist between bioclimatic indicators and the distribution of the principal classes of volatile compounds, enabling the predictive modeling of aromatic expression. The adaptation of technological parameters to specific pedoclimatic conditions allows for the optimization of aromatic expression and differentiated market positioning.

Scientific novelty of the study. The present thesis brings original contributions to the field of wine technology through the substantiation of an integrated technological model correlating terroir with aromatic expression and with winemaking pathways adapted to market requirements.

The novelty of the research lies in the following aspects:The novelty of the research lies in the development of the integrated model “Terroir Volatile-profile Market”, which correlates multicriteria bioclimatic classification, GC-IMS analysis, statistical modeling, and differentiated technological decisions. In this context, the GC-IMS technique was systematically applied to the

Fetească Neagră variety, leading to the identification of 44 volatile organic compounds and demonstrating the regional differentiation of samples through multivariate analyses. Furthermore, key differentiating aromatic markers (OAV > 1) were identified, with terpinolene highlighted as a potential distinctive element for this variety. The research enabled the establishment of functional relationships between pedoclimatic factors and the distribution of volatile compounds, providing a basis for the predictive modeling of aromatic expression, as well as the development and validation of differentiated technological itineraries through industrial-scale implementation.

The major contribution of the study consists in transforming terroir from a descriptive concept into a predictive and decision-oriented technological framework.

Practical value of the thesis. The research results provide applied tools for optimizing parcel selection, determining the optimal harvest timing, and adapting winemaking parameters to specific pedoclimatic conditions, thereby reducing uncontrolled variability and increasing technological efficiency.

GC-IMS technology is substantiated as an instrument for monitoring the aromatic fingerprint and ensuring objective quality control. The proposed model enables the development of differentiated wine styles, oriented both toward the premium segment and toward external markets with specific requirements.

Implementation of the results in practice. The developed technological model was applied at Purcari winery for the production of the premium series “Academia Fetească Neagră”, intended for the Chinese market, resulting in a batch of approximately 3,000 bottles positioned within the premium segment.

In parallel, the technology was implemented at the didactic winery of Leova for the production of a batch of approximately 5,000 bottles destined for the Canadian market (SAQ), thereby confirming the adaptability of the model to different commercial segments. During the period 2023-2025, students of the Leova vocational school participated in practical winemaking workshops conducted in accordance with the developed technology, ensuring the direct transfer of research results into the vocational training process.

Practical validation was confirmed through physicochemical analyses, GC-IMS determinations, multivariate statistical analysis, and sensory evaluation, demonstrating the functionality of the model under real production and commercialization conditions.

Approval and dissemination of the thesis results. The scientific results obtained within the framework of this research were presented and discussed at prestigious international scientific events, including the World Congresses of Vine and Wine (44th edition - Jerez, 2023; 45th edition - Dijon, 2024; 46th edition - Chișinău, 2025), as well as at the international conference CASEE 2023,

“Smart Life Sciences and Technology for Sustainable Development.” The presentation of the results at these forums confirms the scientific relevance and international visibility of the research.

Publication of the Results. The research findings are reflected in 10 scientific publications, including:

- 2 articles published in international journals with impact factor;
- 2 articles published in national journals classified in category B+;
- 1 article published in a national journal classified in category B;
- 8 participations in national and international scientific conferences.

The publications comprehensively cover the research topics addressed in the thesis and validate the scientific character of the obtained results.

Structure and volume of the thesis. The thesis comprises 121 pages of typed text and includes 20 tables, 17 figures, and 6 appendices. The appendices contain: the characteristics of the chemical classes of volatile organic compounds in wines; primary data regarding the climatic conditions during the study period; protocols for the application and testing of the technology under practical conditions; certificates of participation in international scientific conferences and congresses; and the author’s certificate of participation in the OIV International Ampelography Course.

The thesis is structured into five chapters:

The Introduction substantiates the relevance of the research topic and formulates the scientific problem, research aim, working hypotheses, and methodology.

Chapter 1 provides the scientific foundation of the relationship between terroir, volatile organic compounds, and aromatic identity, through an analysis of the specialized literature and international market trends.

Chapter 2 presents the materials and methods employed, ensuring the validity and reproducibility of the results through the application of chemical, sensory, and statistical methods.

Chapter 3 analyzes the agro-pedo-climatic components of the seven experimental parcels, demonstrating the existence of a regional terroir gradient.

Chapter 4 investigates the volatile composition and sensory profile of Fetească Neagră wines using GC-IMS technology and multivariate analysis, highlighting regional differentiation.

Chapter 5 translates the research findings into practical applications through the substantiation and implementation of differentiated technological pathways.

The thesis concludes with general conclusions and practical recommendations, presenting a coherent progression from theoretical substantiation to the practical validation of the proposed technological model.

Main Scientific Results Submitted for Defense. Within the framework of the research, the following principal scientific results were obtained and substantiated:

1. Demonstration of the existence of a regional terroir gradient, through the agro-pedo-climatic characterization of seven vineyards across the three PGI regions and the quantification of bioclimatic and pedological differences.

2. Confirmation of the influence of terroir on volatile composition, highlighting significant variations in the structure of volatile organic compounds in wines produced from the Fetească Neagră variety.

3. Establishment of regional aromatic fingerprints using GC-IMS technology, including the identification of differentiating aromatic markers and the demonstration of statistical separation of wines through multivariate analysis.

4. Determination of functional relationships between pedoclimatic factors and the principal groups of volatile compounds, confirming the feasibility of predictive modeling of aromatic expression.

5. Substantiation of differentiated technological pathways, through the adaptation of maceration, fermentation, and maturation parameters to the specific pedoclimatic characteristics of each terroir unit.

6. Development of the integrated technological model "Terroir-Volatile Profile-Market," which correlates terroir characterization, aromatic expression, and technological decision-making according to market segment requirements.

7. Practical validation of the proposed model, through industrial and commercial implementation, demonstrating the applicability and competitiveness of the developed technology.

THESIS CONTENT

1. SYNTHESIS OF THE RESEARCH METHODOLOGY

The research was conducted on the autochthonous grape variety Fetească Neagră, using seven representative parcels from the three Protected Geographical Indication (PGI) regions of the Republic of Moldova (Codru, Valul lui Traian, and Ștefan Vodă), selected to cover regional pedological, climatic, and topographical variability. Climatic data were obtained through the i-Meteos meteorological station network (ONVV).

Terroir characterization was performed by applying the Multicriteria Climatic Classification System for Geoviticulture (MCC) [23], using the Winkler Index (GDD), Huglin Index (HI), Growing Season Temperature (GST), Dryness Index (DI), Hydrothermal Coefficient (HTC), and Cool Night Index (CI). Pedological mapping was carried out at a scale of 1:2000, and laboratory analyses included the determination of humus content, pH, carbonates, and macro- and microelements, enabling the quantification of the regional terroir gradient.

To eliminate the influence of external technological variables, all samples were subjected to a unified microvinification protocol: controlled destemming and crushing, inoculation with selected yeast (Lalvin Bourgovin RC212™), alcoholic fermentation at 25°C, manual cap management, controlled initiation of malolactic fermentation, stabilization, and bottling under standardized conditions. Process standardization allowed the observed differences to be attributed exclusively to pedoclimatic factors.

The profile of volatile organic compounds was determined using the FlavourSpec® (GC-IMS) system. Samples were incubated at 60°C, with 2-methyl-3-heptanone employed as the internal standard. Semi-quantitative determination was performed based on peak volume ratios, and the odor activity value (OAV) was calculated to assess sensory impact. GC-IMS enabled the acquisition of aromatic fingerprints and the comparison of regional differences.

Physicochemical parameters were determined in accordance with national and international standards. Sensory evaluation was conducted using the Napping® method with a panel of seven experts, and the data were processed through Multifactor Analysis (MFA) to obtain a consensual sensory space.

The research was structured according to the conceptual model "Terroir Components," which integrates the interaction between the natural environment (bioclimatic and pedological indicators), parcel specific characteristics (agrotechnical practices, plant material, training systems), and the production system response (grape parameters, volatile organic compound profile, and sensory expression). The model enabled an integrated approach to the "terroir-volatile profile-technological decision" relationship, ensuring the alignment of experimental stages with the practical validation of results.

Statistical processing was performed in the R programming environment, using analysis of variance (ANOVA) with Tukey's HSD post hoc test, Principal Component Analysis (PCA), Multifactor Analysis (MFA), Spearman correlation, and Partial Least Squares Regression (PLSR). The level of statistical significance was set at $p < 0.05$. The multivariate approach enabled dimensionality reduction, identification of aromatic markers, and modeling of functional relationships between terroir and volatile composition.

2. RESULTS REGARDING THE AGRO-PEDO-CLIMATIC CHARACTERIZATION OF THE STUDIED TERROIRS

The analysis of the seven experimental parcels from the three PGI regions of the Republic of Moldova revealed significant agro-pedo-climatic variability, expressed through quantifiable differences in altitude (70-304 m), exposure, soil types, texture, pH (6.86-8.25), and humus content (1.5-3.7%).

The pedological diversity reflects the existence of distinct terroir units with differentiated potential to influence the secondary metabolism of the vine.

Comparative pedological analysis using heatmap visualization and hierarchical clustering enabled the identification of similarities and differences among parcels (Figure 2.1). The results indicate the clustering of the Speia and Bugeac parcels due to comparable texture and organic matter content, whereas the Mircești parcel is distinguished by elevated nitrogen content. The Purcari parcel exhibits a distinct profile associated with reduced soil fertility and pronounced aridity. The heatmap diagram thus confirms the presence of differentiated pedological structures, likely to generate distinct metabolic responses.

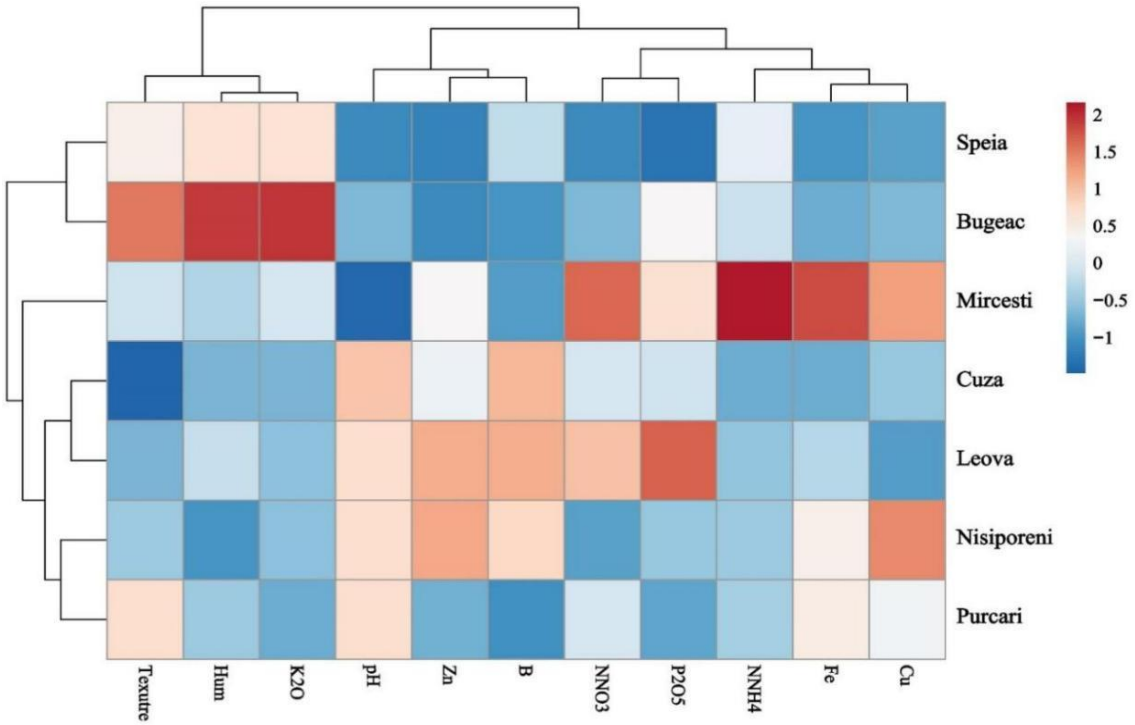

Figure 2.1. Heatmap representation of the correlations between soil parameters and the parcels

The analysis of climate series for the period 2019-2023 highlighted an increase in the annual average temperature of more than 2°C compared to the multi-annual average, along with a reduction in precipitation in most locations, accompanied by pronounced inter annual variability of the drought index (DI).

Huglin index (HI) values ranged from approximately 1800°C to over 2600°C, outlining a clear regional thermal gradient.

The climatic gradient diagram reveals three distinct typologies (Figure 2.2): a moderately cool terroir (Mircești), characterized by HI ≈ 2000°C and a hydrothermal regime favorable for acidity preservation; a warm-arid terroir (Cuza, Speia, Purcari), with HI > 2400-2600°C and frequent episodes of water deficit; and a warm-balanced terroir (Leova, Bugeac, Nisporeni), with

high thermal accumulation but moderate hydric variability [19].

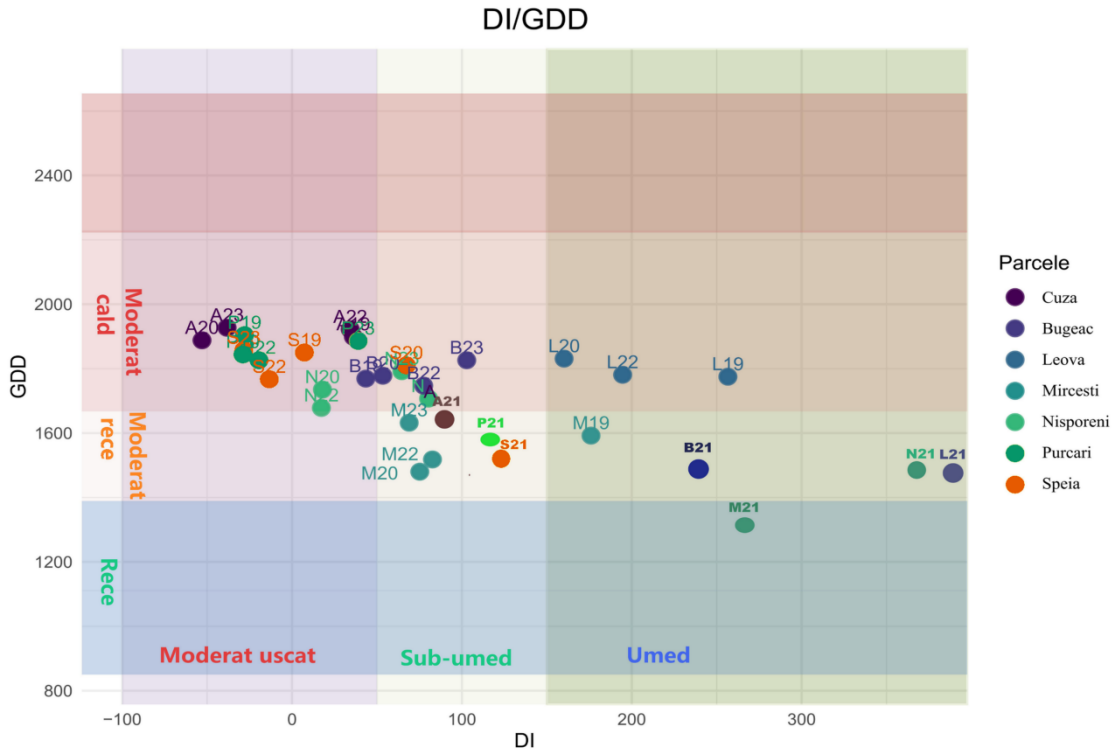

Figure 2.2. Particularities of the experimental plots according to bioclimatic indicators

The interaction between thermal accumulation, nocturnal regime, hydrothermal balance, and soil fertility directly influences the synthesis of aromatic precursors, the acidity/alcohol balance, and phenolic ripening [11,24]. The integration of these factors demonstrates the existence of a coherent and functional terroir gradient, which justifies a differentiated approach to technological strategies and confirms the first research hypothesis regarding the influence of pedoclimatic factors on the aromatic potential of the Fetească Neagră variety.

3. STUDY OF THE VOLATILE COMPOSITION AND SENSORY PROFILE OF FETEASCĂ NEAGRĂ WINES (DRY RED WINES, 2022 VINTAGE

The analysis of the volatile composition of dry red Fetească Neagră wines originating from seven representative terroirs of the Republic of Moldova revealed significant regional differences under a unified winemaking technology, allowing the observed variations to be attributed exclusively to the influence of pedoclimatic factors [25].

Using the GC-IMS technique, 44 signals corresponding to volatile organic compounds were detected, mainly belonging to the classes of esters, higher alcohols, aldehydes, ketones, sulfur compounds, and terpenes [26].

The variation in volatile compound concentrations among samples highlights parcel-level differences and confirms the influence of terroir on the aromatic profile of Fetească Neagră wines. Figures 3.1 A&B and table 3.1 present the quantitative differences in the main classes of volatile

compounds across the seven parcels, emphasizing significant regional variability.

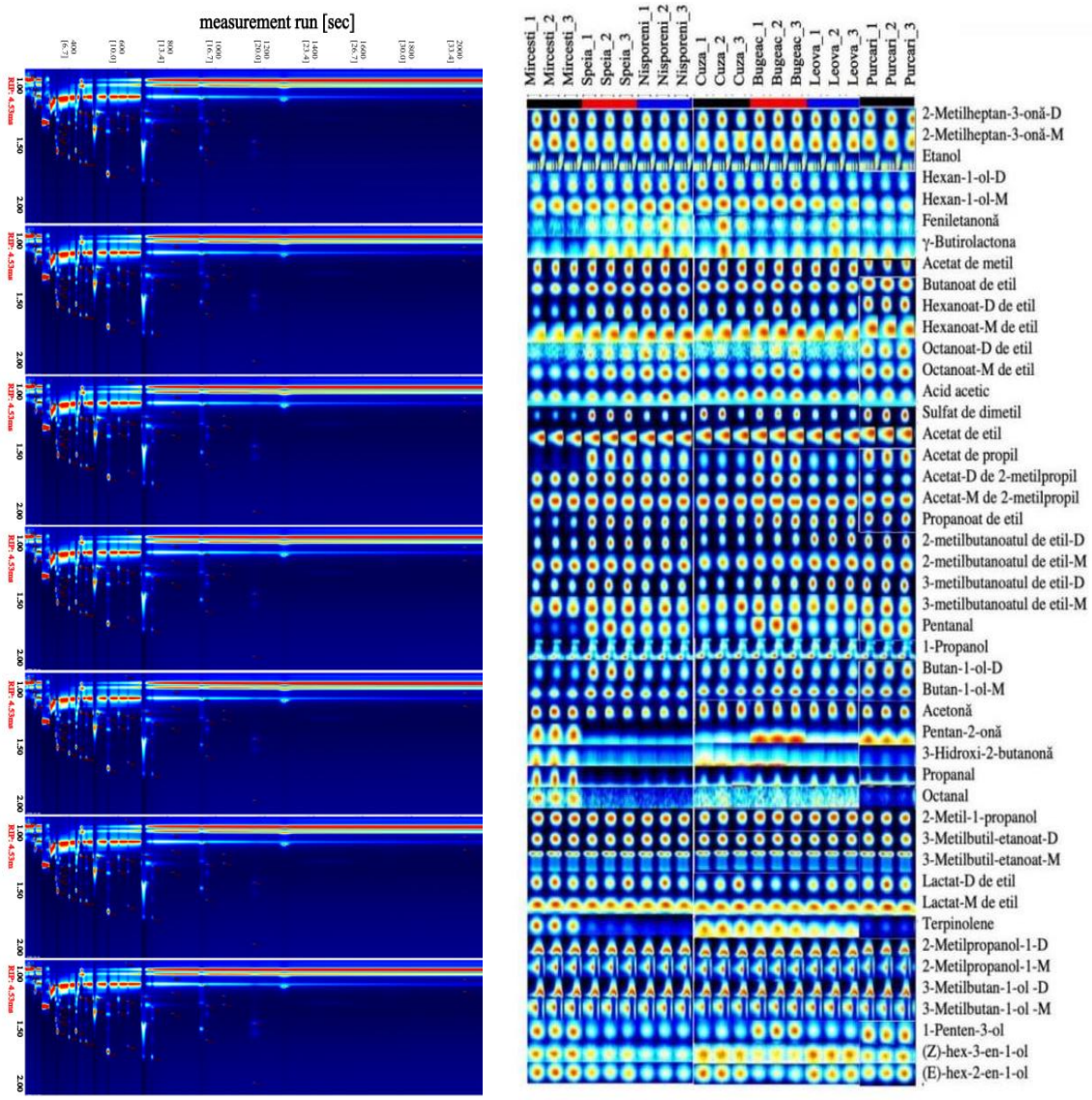

Figure 3.1. Volatile organic compound fingerprints of Fetească Neagră wines (A) Two-dimensional VOC spectrum, (B) Volatile organic compound fingerprint.

The total content of higher alcohols was relatively high in all samples, with a maximum in Bugeac and a minimum in Mircești, suggesting differences in aromatic intensity and structural complexity. Aldehydes and ketones showed moderate variation, with higher levels in Cuza and Leova, while esters primarily responsible for fruity notes reached maximum values in Cuza and Purcari [27] and minimum levels in Mircești.

Esters constituted the dominant fraction of the volatile profile, with total values ranging between approximately 62,600 and 78,500 µg/L. The highest concentrations were recorded in wines from Cuza and Purcari, while the lowest were observed in Mircești. Higher alcohols varied between 278,231 µg/L and 338,222 µg/L, with a maximum in Bugeac, suggesting a broader aromatic structure in areas with high thermal accumulation. Aldehydes showed pronounced differences,

particularly in the case of pentanal, while dimethyl sulfate varied more than threefold among terroirs, indicating a potential role in modulating fruity character. A noteworthy result is the identification of terpinolene as the only terpenic compound detected, with concentrations exceeding the sensory threshold in several samples, suggesting a distinctive aromatic feature of the variety under the studied pedoclimatic conditions.

The heatmap (figura 3.2) representation of volatile compound distribution highlights a clear separation of samples according to origin. Wines from Mircești form a distinct cluster, characterized by lower levels of esters and relatively higher concentrations of C6 alcohols and propanal, outlining a fresh, vegetal aromatic style with pronounced acidity.

In contrast, wines from Purcari and Cuza stand out due to high concentrations of ethyl esters and dimethyl sulfate, shaping an intensely fruity profile with broad structure and aging potential. Wines from Bugeac, Nisporeni, and Speia occupy an intermediate position, displaying similar volatile profiles and suggesting a coherent regional expression.

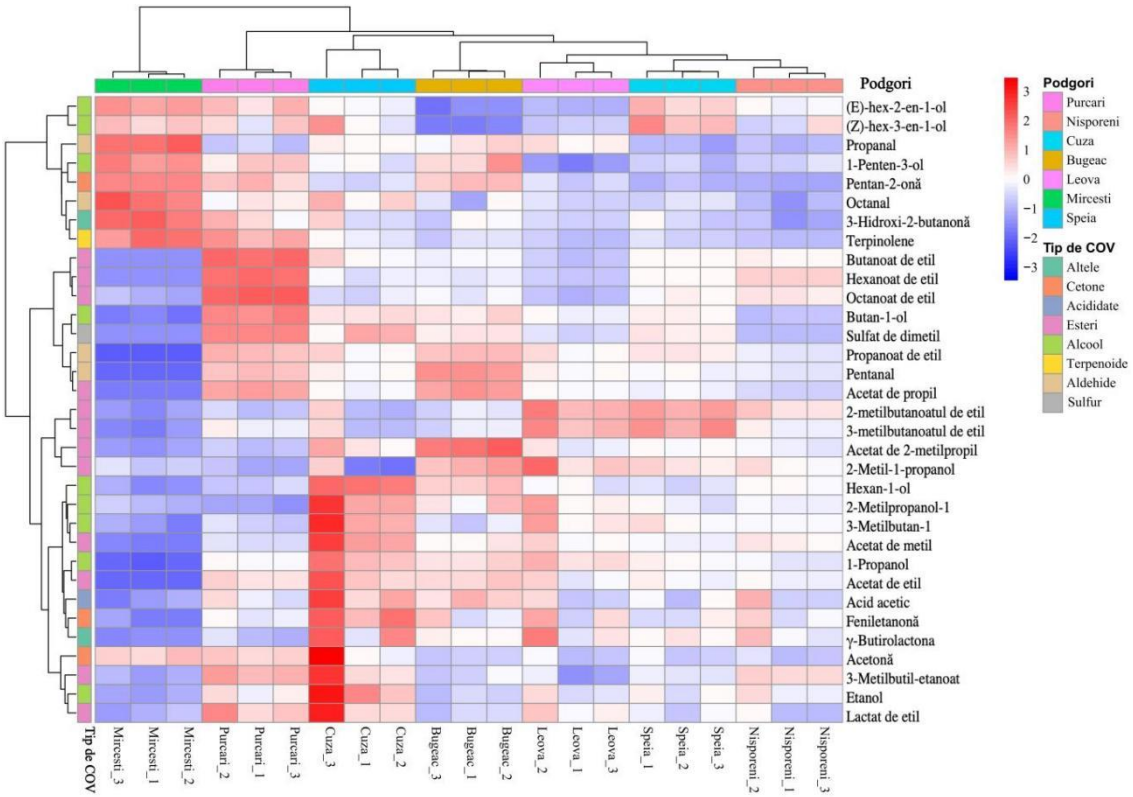

Figure 3.2. Heatmap analysis of volatile organic compounds

The analysis of volatile compounds confirms the existence of significant regional differences among parcels, highlighting the influence of terroir on the aromatic profile of Fetească Neagră wines through variations in volatile acidity, higher alcohols, aldehydes, esters, dimethyl sulfate, and the distinctive presence of terpinolene, which contributes to defining typicity and regional identity.

Table 3.1. Concentration of volatile organic compounds determined in dry red Fetească Neagră wines obtained from different terroirs of the Republic of Moldova.

Nr.	Description	Parcel						
	Volatile compounds,µg/L	**Mircești**	**Nisporeni**	**Speia**	**Cuza**	**Bugeac**	**Leova**	**Purcari**
1.	Acetic acid	6240.7±338.24b	7207.77±508.34ab	7416.91±895.43ab	7451.37±465.51ab	8792.02±1014.88a	8098.95±336.85a	7262.73±603.75ab
2.	**Total volatile acidity**	6240.7±338.24b	7207.77±508.34ab	7416.91±895.43ab	7451.37±465.51ab	8792.02±1014.88a	8098.95±336.85a	7262.73±603.75ab
3.	(E)-2-Hexenol	344.22±8a	312.95±17.58a	269.17±4.52b	313.27±19.27a	267.61±6.71b	185.49±10.78d	218.94±2.84c
4.	Z-3-Hexenol	354.57±5.68ab	365.51±13.28a	327.69±18.44ab	342.94±17.13ab	344.29±25.81ab	284.56±2.74c	313.97±0.7bc
5.	1-Hexanol	742.35±40.11e	851.98±14.3cd	904.27±8.93c	821.05±19.29d	1119.81±16.88a	984.98±24.98b	880.83±38.14cd
6.	3-Methyl-1-butanol	23848.41±493.76c	26006.53±438.83b	25724.42±82.35bc	25047.86±352.17bc	28334.9±1444.52a	25194.75±379.08bc	26723.57±1019.79ab
7.	1-Penten-3-ol	105.85±2.87a	79.92±2.84de	82.3±1.33d	94.96±3.1bc	85.81±3.32cd	98.06±5.97ab	71.07±3.31e
8.	1-Butanol	2543.99±49.75e	3793.06±51.43bc	3149.15±23.28d	4741.81±91.57a	3913.4±60.03b	3942.79±136.89b	3619.31±111.27c
9.	2-Methyl-1-propanol	26666.19±345.65bc	27544.12±425.45bc	27600.45±146.16bc	26047.42±225.15c	30387.18±1396.71a	28468.94±642.38ab	28675.44±981.23ab
10.	1-Propanol	8703.35±52.96d	11382.57±213.92bc	11002.05±137.93c	11315.28±135.68bc	12793.11±761.44a	11897.31±200.29abc	12057.17±445.23ab
11.	Ethanol	214922.3±1882.3b	232032.54±6058.37b	233573.75±6165.19b	235788.72±5465.51b	260976.21±18453.57a	222633.54±3134.57b	230722.5±8670.48b
12.	**Total higher alcohols**	278231.23±1483.73b	302369.16±6621.46b	302633.24±6507.46b	304513.31±5940.63b	338222.31±21854.68a	293690.42±3364.47b	303282.8±11239.23b
13.	Octanal	73.02±3.63a	48.27±1.41cd	41.22±3.45d	54.4±1.77bc	58.89±4.43b	48.15±6.1cd	47.13±1.72cd
14.	Pentanal	58.48±0.81e	212.18±8.51cd	192.42±4.36d	285.91±2.31b	227.89±13.07c	331.58±2.03a	224.94±9.63c
15.	Ethyl propanoate	1238.61±15.5d	2406.2±50.33b	2103.34±26.21c	2683.03±43.01a	2327.36±166.67bc	2674.37±28.3a	2333.03±116.63b
16.	Propanal	471.71±13.71a	204.59±18.91c	221.31±8.51c	237.02±15.74c	311.52±2.42b	326.58±26.16b	322.56±15.79b
17.	**Total aldehydes**	1841.82±15.62d	2871.24±77.01b	2558.29±40.76c	3260.36±54.94a	2925.66±185.23b	3380.68±52.43a	2927.66±141.51b
18.	Ethyl octanoate	1096.77±84.17e	1571.59±57.42bc	1670.05±30.86b	2422.21±47.13a	1311.57±86.68d	1460.57±50.79cd	1122.39±82.42e
19.	Ethyl lactate	5208.78±160.56c	5623.82±247.91abc	5511.45±370.74bc	6482.67±387.71ab	6711.65±902.02a	5474.84±164.34bc	6052.74±274.12abc
20.	Ethyl hexanoate	1306.3±1.84f	1980.53±12.54c	2215.21±9.76b	2800±17.55a	1823.25±75.67d	1821.62±53.55d	1602.47±55.99e

21.	Isoamyl acetate	11470.27±137.11b	12002.9±27.71ab	12601.91±64.86ab	12944.03±144.9a	13009.58±944.88a	11868.79±246.12ab	11543.74±461.48b
22.	Ethyl 3-methylbutanoate	1935.71±52.27c	2742.33±72.88a	2347.13±65.11b	2356.73±61.1b	2247.79±228.07b	2270.13±69.19b	2667.56±117.27a
23.	Ethyl 2-methylbutanoate	2201.72±41.14c	2917.84±58.93a	2714.88±72.51ab	2376.72±63.03c	2457.52±243.52bc	2478.77±55.87bc	2905.8±123.65a
24.	Ethyl butanoate	2140.65±34.3d	3105.73±38.7b	3123.93±39.87b	4331.05±67.68a	3190.11±244.94b	2987.39±60.35b	2577.23±105.63c
25.	2-Methylpropyl acetate	3114.8±53.8e	3651.84±44.38bc	3558.15±38.41cd	3331.31±46.75de	3889.65±238b	4439.7±72.57a	3614.15±148bcd
26.	Propyl acetate	55.43±1.4d	240.7±2.21b	188.92±4.86c	401.12±8.34a	251.91±11.51b	415.13±10.28a	257.88±10.44b
27.	Ethyl isobutyrate	6122.59±75.06ab	6411.87±66.26ab	6348.74±83.89ab	5961.75±74.82b	5989.34±434.43b	6645.66±87.76a	6630.39±278.06a
28.	Ethyl acetate	24360.81±101.75c	29325.3±427.18b	29107.01±370.02b	30481.29±322.74ab	32334.03±2491.84a	30873.9±399.91ab	29535.57±1159.86ab
29.	Methyl acetate	3584.75±29.11c	4362.61±53.34b	4568±43.78b	4239.25±34.03b	5349.06±407.9a	4556.22±48.61b	4591.7±178.21b
30.	**Total esters**	62598.56±462.52b	73937.07±751.35a	73955.38±1160.99a	78128.13±1130.8a	78565.46±6162.39a	75292.73±1162.15a	73101.64±2990.06a
31.	Acetophenone	426.38±31.6c	559.5±44.87bc	583.73±62.16abc	566.08±23.81bc	743.45±63.98a	587.17±62.58abc	615.57±88.94ab
32.	2-Pentanone	174.35±1.08a	86.88±4.92cd	77.8±2.44d	145.43±9.9b	101.21±5.31c	147.77±5.15b	100.63±5.91c
33.	Acetone	2749.65±61.36	2469.34±84.8	2414.26±74.8	2749.48±43.66	2870.16±496.12	2433.79±22.66	2455.67±107.26
34.	**Total ketones**	3350.38±59.94ab	3115.72±82.04ab	3075.79±139.01b	3460.99±64.67ab	3714.82±539.99a	3168.73±41.89ab	3171.87±193.76ab
35.	Dimethyl sulfide	549.28±9.27d	1172.28±22.58b	744.69±10.54cd	1684.67±17.56a	1365.62±218.36b	1205.42±38.05b	914.71±39.65c
36.	**Total sulfur compounds**	549.28±9.27d	1172.28±22.58b	744.69±10.54cd	1684.67±17.56a	1365.62±218.36b	1205.42±38.05b	914.71±39.65c
37.	Terpinolene	480.18±34.74a	237.49±21.79bc	202.74±8.45c	426.23±32.28a	278.11±24.76b	245.9±24.98bc	205.28±15.91c
38.	**Total terpenoids**	480.18±34.74a	237.49±21.79bc	202.74±8.45c	426.23±32.28a	278.11±24.76b	245.9±24.98bc	205.28±15.91c
39.	γ-Butyrolactone	606.8±15.35b	854.26±14.93ab	854.93±95.72ab	718.5±52.7ab	1000.68±193.91a	841.15±17.4ab	914.75±164.67a
40.	3-Hydroxy-2-butanone	124.72±3.31a	79.95±7.48bc	66.9±6.5c	97.39±10.67b	85.03±11.74bc	82.58±7.9bc	76.31±0.89bc
41.	**Total others**	731.51±15.97b	934.21±15.97ab	921.84±100.99ab	815.89±63.14ab	1085.71±201.27a	923.73±9.51ab	991.06±165.45ab

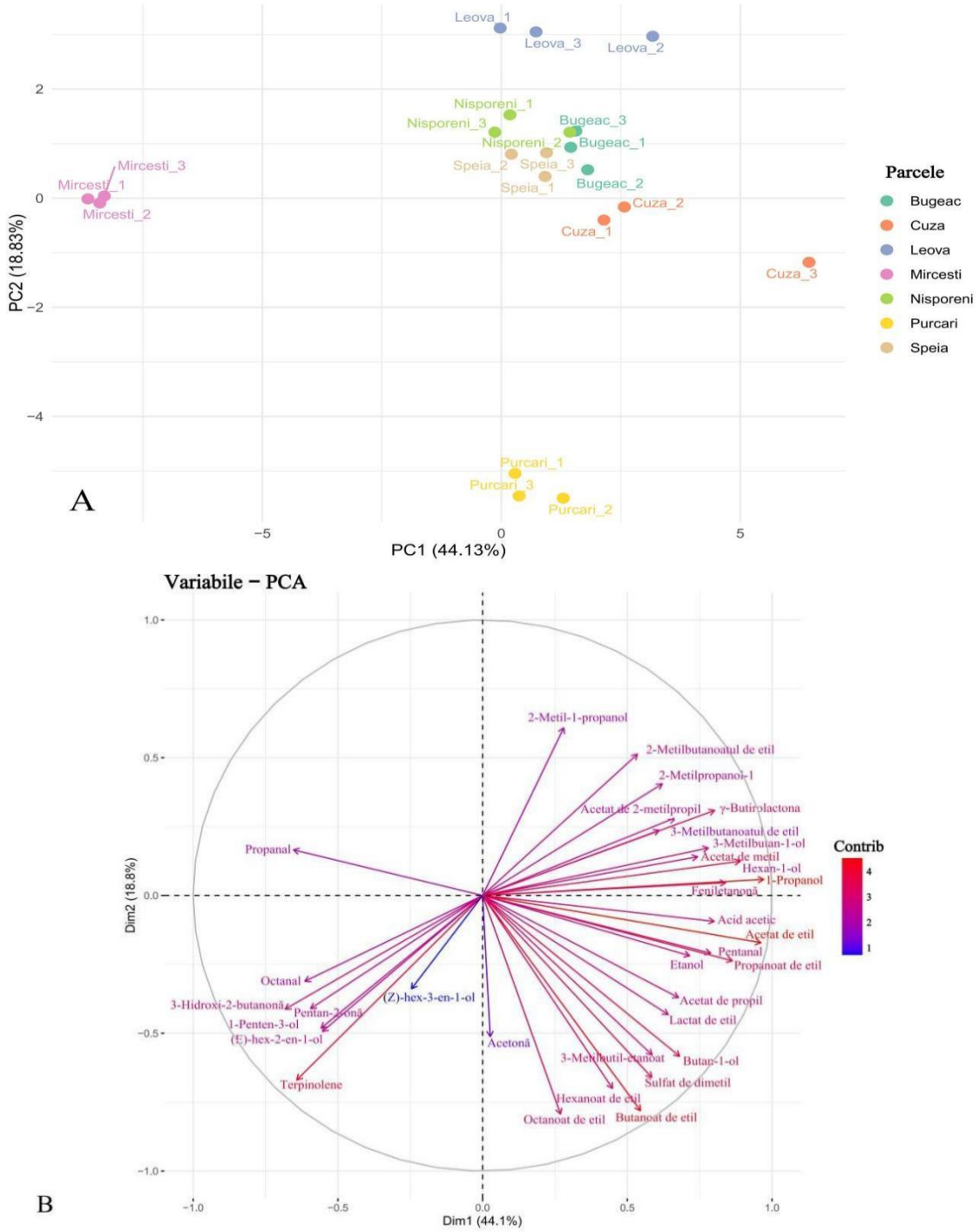

Figura 3.3(A). Componentelor principale ale compușilor organici volatili; (B). Proiecția variabilelor (compuși organici volatili) pe primele două componente principale.

Principal component analysis further confirms regional chemical differentiation, with the first two components explaining approximately 63% of the total variation (figure 3.3 A&B). Wines from the tarcels of Mircești and Purcari clearly separate from the other terroirs, the former through the contribution of C6 compounds and aldehydes, and the latter through elevated levels of esters and sulfur compounds.This statistical separation confirms the existence of distinct aromatic expression trajectories depending on terroir.

To assess the actual impact on aroma, odor activity values (OAVs) were calculated, identifying 15 compounds with OAV > 1. Ethyl esters dominated the aromatic contribution, particularly ethyl 3-methylbutanoate, ethyl hexanoate, and ethyl butanoate, which exhibited extremely high OAVs, confirming their central role in generating red and black fruit notes.

Dimethyl sulfate also showed significant OAV values, indicating a possible synergistic effect on fruity perception. The interactions between esters, sulfur compounds, and higher alcohols highlight the integrated nature of aromatic expression, which depends not only on concentration but also on matrix effects.

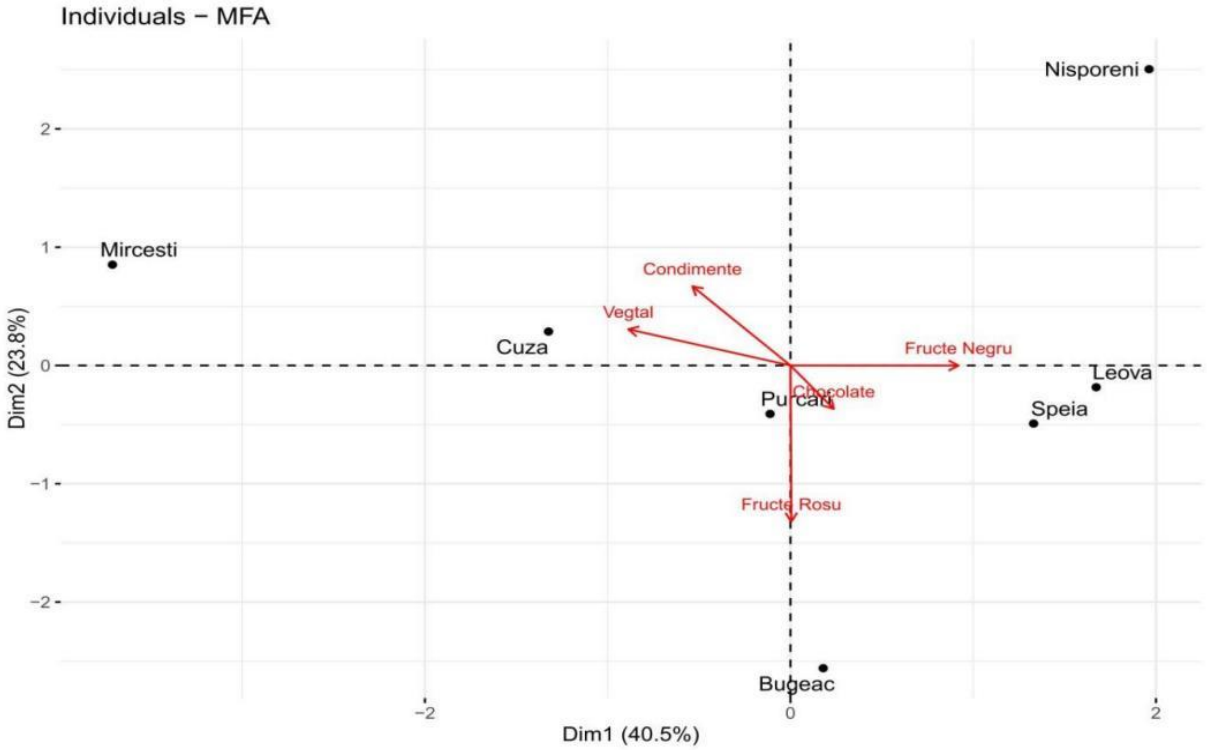

Figure 3.4. Multiple factor analysis of correlations among sensory descriptors

Sensory evaluation, analyzed using a multifactorial method (Figure 3.4), demonstrated a high level of coherence with the instrumental data. Wines from Nisporeni and Speia correlate with the descriptors “black fruits” and “chocolate,” Bugeac with “red fruits,” Cuza with “spicy” and “vegetal” notes, and Purcari with a balanced and complex profile. Mircești displays a distinct sensory profile, positioned separately from the other descriptors, confirming its specific aromatic identity.

Spearman correlation analysis (Figure 3.5) highlighted significant relationships between bioclimatic indices and key volatile compounds. The Huglin Index showed positive correlations with ethyl esters and dimethyl sulfate, while altitude and the hydrothermal coefficient influenced the concentration of higher alcohols and C6 compounds.

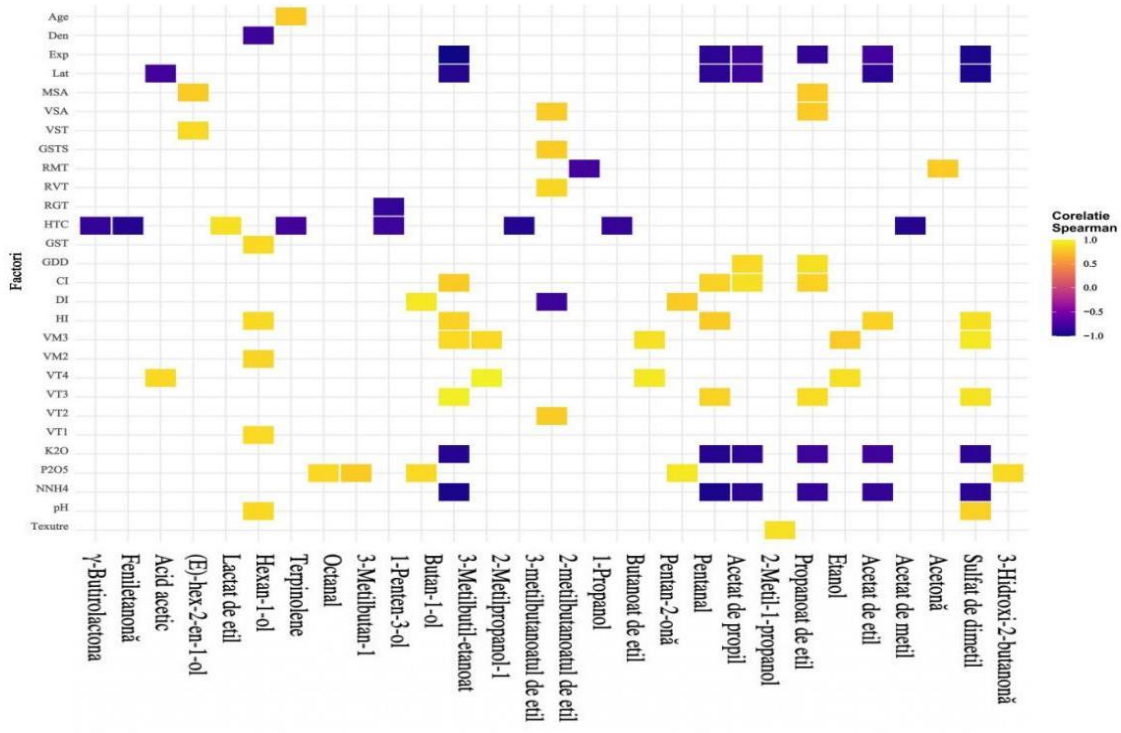

Figure 3.5. Spearman correlations between terroir factors and volatile organic compounds

Soil potassium and ammonium content exhibited negative correlations with several esters, confirming the role of mineral nutrition in regulating the biosynthesis of aromatic precursors.

Tabelul 3.2. Correlation of sensory expression, dominant volatile organic compounds, and recommended winemaking strategies for dry red Fetească Neagră wines

Parcel	Dominant climatic indicator	Pedological particularity	Dominant volatile profile	Recommended technological style	Market segment
Mircești	HI ≈ 2000; HTC > 1	Fertile soil, High nitrogen (N) content	C6↑; moderate esters	Short maceration, limited extraction	Fresh, acidic wine
Nisporeni	HI ≈ 2300	Balanced soil	Fruity esters↑	Medium maceration, controlled fermentation	Elegant fruity profile
Speia	HI ≈ 2400; DI moderate	Clay-loam texture	Alcohols+ Ester↑	Medium maceration, temperature control	Black fruit notes
Bugeac	HI ≈ 2450	High humus content	Esters↑; broad structure	Extended maceration	Concentrated style
Leova	HI ≈ 2400; HTC ≈ 1	Well-drained chernozem	Primary esters↑	4-5 days maceration	Rapid consumption
Cuza	HI > 2600; DI high	Arid soil	Esters↑; DMS↑	Phenolic extraction control	Round, fruity
Purcari	HI > 2500	Carbonatic chernozem	Ethyl esters↑; lactones	Amphora fermentation + oak aging	Premium, age-worthy

Based on the established correlations between bioclimatic indices, the volatile compound profile, and sensory evaluation, differentiated technological recommenddations were developed for each terroir unit, as summarized in table 3.2.

Overall, the results demonstrate that the volatile profile and sensory expression of Fetească Neagră wines are determined by the complex interaction between thermal accumulation, hydric regime, altitude, and soil characteristics.

The observed regional differences, confirmed both instrumentally and sensorially, validate the hypothesis regarding the pedoclimatic control of aromatic expression and provide a scientific basis for adapting winemaking strategies to the specific characteristics of each terroir.

4. RESULTS REGARDING THE PRACTICAL VALORISATION OF THE RESEARCH

The research results were capitalized through the direct implementation of differentiated technological models in two distinct contexts: one industrial premium and one educational-commercial, with the aim of applicatively validating the established correlations between terroir, volatile composition, and sensory expression of Fetească Neagră wines.

The first direction of implementation targeted the production of the iconic "Academia Fetească Neagră" series within Purcari Winery (Figure 4.1), primarily intended for the Chinese market. The technological foundation was established based on data regarding high thermal accumulation (HI > 2500°C), pedological composition, and the volatile profile characteristic of the Purcari terroir.

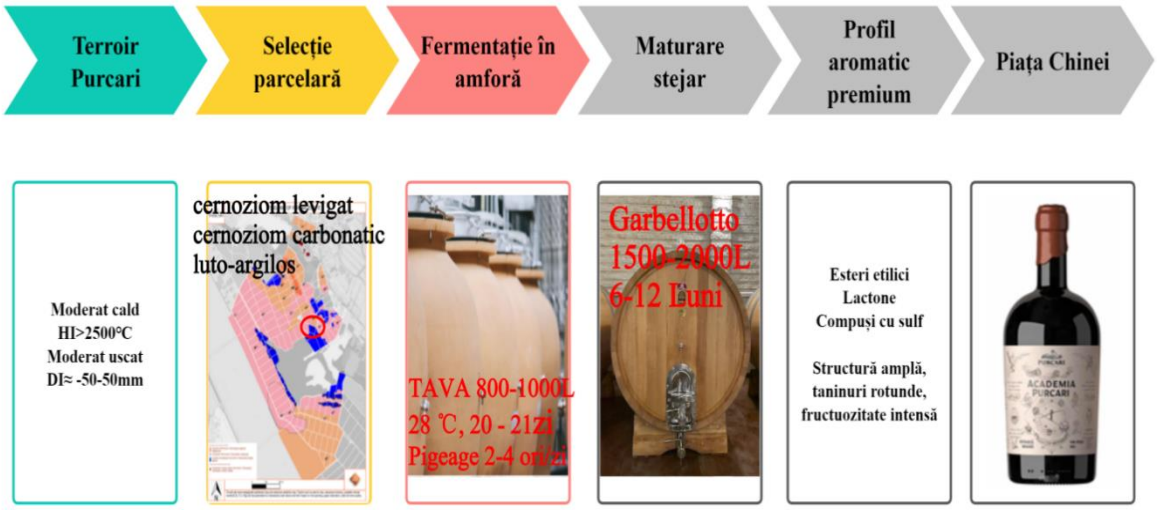

Figure 4.1. Production itinerary of the "Academia Fetească Neagră" wines

Parcel selection, strict monitoring of grape maturity (23.5-24.5 °Brix), controlled fermentation in clay amphorae at 28°C, extended maceration, and differentiated aging in oak vats enabled the production of a wine with stable polyphenolic structure and a distinctive aromatic signature.

The "Academia" wine exhibited an alcohol content of 14.5% vol., a non-reducing dry extract of

31 g/L, and an organoleptic score of 95 points (Table 4.1). It was produced in a batch of approximately 3,000 bottles intended for export to the Chinese market.

The aromatic profile, dominated by ethyl esters, lactones, and sulfur compounds, previously correlated through GC-IMS analysis and OAV calculations, confirmed the validity of the "aromatic fingerprint" concept applied in practice. The adaptation of the style to Asian consumer preferences, broad structure, rounded tannins, and intense fruitiness, demonstrates the direct translation of scientific results into commercial strategy.

Table 4.1. Results of comparative physico-chemical and organoleptic analyses of the experimental wines

Nr.	Physico-chemical indices	Direct implementation of technological models	
		Purcari	Leova
		Value	
1.	Alcohol content, % vol.	14,5 ± 0,1	13,0 ± 0,2
2.	Total acidity, g/L	5,5 ± 0,1	6,0 ± 0,1
3.	pH	3,72	3,62
4.	Non-reducing dry extract, g/L	31,0 ± 0,4	26,8 ± 0,3
5.	Residual sugars, g/L	< 2,5	< 3,0
6.	Organoleptic score, points	95	86
7.	Style	Structured, complex	Fruity, for rapid consumption
8.	Market	China (premium)	Canada (SAQ)

The second direction of valorization was implemented within the Teaching Winery of the Vocational School in Leova (Figure 4.2), through the development of a young wine intended for rapid consumption and the North American market.

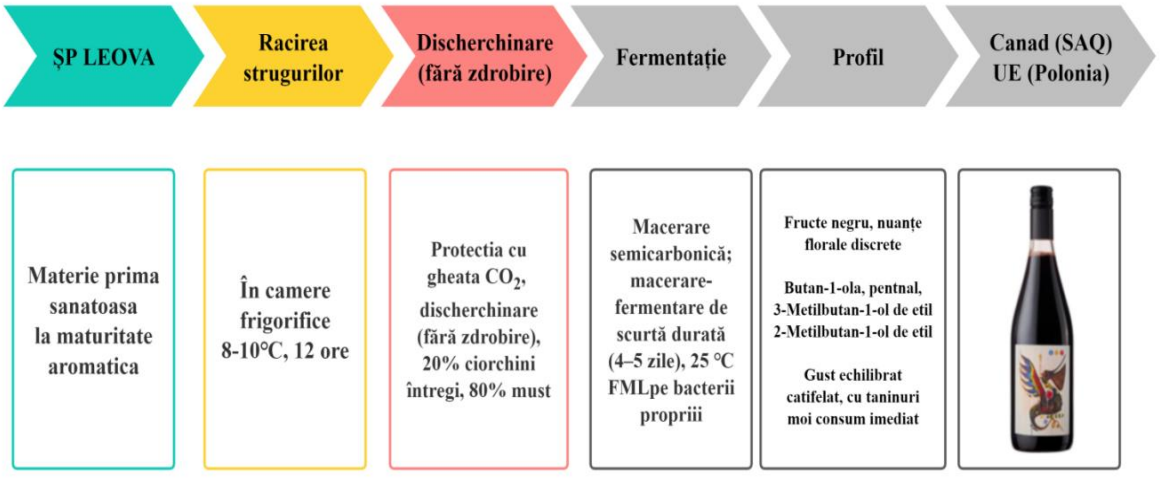

Figure 4.2. Implementation scheme of wine production within the Leova Teaching Winery - wine intended for rapid consumption

The application of a simplified technology short maceration (4-5 days), fermentation at 25°C, limited control of phenolic extraction, and partial malolactic fermentation enabled the production of a balanced wine with 13.0% vol. alcohol and a total acidity of 6.0 g/L (Table 4.1), characterized by a fruity profile and soft tannins.

The pilot batch of approximately 5,000 bottles was directed to the Canadian market through SAQ, representing external validation of both the technological quality and the product's market competitiveness.

The two applications represent complementary models of research valorization: a premium model, based on the profound expression of terroir and differentiated aging, and a reproducible model, intended for young wines oriented toward rapid consumption and professional training. In both cases, the technological parameters were directly derived from pedoclimatic analysis and the characterization of volatile organic compounds, demonstrating the effective transfer of knowledge from research to production.

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The practical impact of this chapter consists of:

- validating the applicability of the established correlations between bioclimatic indices and aromatic expression;
- developing two differentiated technological itineraries adapted to regional specificity;
- producing and commercially valorizing a total of 8,000 bottles;
- integrating research results into the professional training process of students (2023-2025);
- consolidating a data-driven winemaking model applicable to other autochthonous grape varieties.

Overall, the results demonstrate that terroir is not merely a descriptive concept, but an operational technological and economic tool capable of guiding winemaking decisions, optimizing aromatic expression, and supporting the strategic positioning of Moldovan wines on international markets.

GENERAL CONCLUSIONS

The present research aimed to systematically analyze the influence of terroir conditions on the composition of volatile organic compounds and the sensory expression of Fetească Neagră wines originating from seven representative parcels of the Republic of Moldova. By integrating GC-IMS analyses, OAV assessments, and sensory testing, the study clearly highlighted inter regional differences in terms of aromatic structure, wine body, and stylistic positioning potential on the market. The main pedoclimatic and nutritional factors controlling the aromatic expression of the variety were also identified.

1. The existence of a regional pedoclimatic gradient among the seven studied parcels was demonstrated, differentiated into moderately cool, moderately warm, and warm-arid typologies with distinct hydric regimes, forming the basis for modeling the aromatic expression of the Fetească Neagră variety (**Chapter 3, subsections 3.1-3.2**).

2. The analysis of volatile organic compounds using GC-IMS, correlated with sensory evaluation and multivariate analysis (PCA, MFA), revealed statistically significant differentiation of wines according to terroir, confirming the influence of pedoclimatic factors on the aromatic profile (**Chapter 4, subsections 4.1 and 4.1.2**).

3. Fifteen compounds with major sensory impact (OAV > 1) were identified, defining the regional aromatic fingerprint and serving as differentiating markers of terroir expression (**Chapter 4, subsection 4.1.3**).

4. Significant correlations between bioclimatic indices (HI, DI, HTC), soil parameters, and the distribution of esters, higher alcohols, and sulfur compounds demonstrate the possibility of integrating natural factors into a predictive model of aromatic expression (**Chapter 4, subsection 4.2**).

5. The integrated technological model "Terroir-Volatile Profile-Market" was developed and validated, demonstrating that aromatic markers can be enhanced or preserved by adapting maceration, fermentation, and aging parameters to the specific characteristics of each terroir unit (**Chapter 5, subsections 5.1 and 5.2**).

6. The practical implementation of the model in the production of 8,000 bottles intended for external markets (China and Canada), along with its integration into professional training processes, confirms the economic, technological, and educational impact of the research (**Chapter 5, subsection 5.3**).

Overall, the research demonstrates that terroir can be transformed from a descriptive concept into a predictive and reproducible technological tool, capable of supporting stylistic differentiation and the competitive positioning of Moldovan wines.

PRACTICAL RECOMMENDATIONS

1. Integration of bioclimatic classification (HI, DI, HTC) into vineyard management and parcel selection in order to optimize harvest timing (**Chapter 3**).

2. Implementation of the GC-IMS technique and OAV analysis in the quality and authenticity control of Fetească Neagră wines (**Chapters 4.1 and 4.1.3**).

3. Adaptation of maceration duration and fermentation regime to terroir typology in order to maximize specific aromatic expression (**Chapters 5.1 and 5.2**).

4. Extension of the integrated model to other autochthonous varieties and viticultural regions, using the same terroir-volatile profile-market correlation framework (**Chapter 4.2 and Chapter 5**).

5. Development of a national platform for correlating pedoclimatic and aromatic data to support terroir wines with demonstrable traceability (derived from **Chapters 3-5**).

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Categoria B+: **Wang, F.,** Yao, M., Arpentin, G. Exploring the Micro and Macro terroir of Feteasca Neagra wine from Moldova. In: *Journal of Engineering Sciences*, 2024, vol. 31, nr.1, pp. 97-111. ISSN 2587-3474. Disponibil: https://doi.org/10.52326/jes.utm.2024.31(1).08

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Yao M., **Wang F.**, Arpentin G., Xiao C. Volatile compounds as indicators of terroir differentiation in Moldovan Feteasca Neagra wines. In: *IVES Conference Series, 46th World Congress of Vine and Wine,Chișinău, Moldova. 2025.* Disponibil: https://doi.org/10.58233/XgY6a09Y

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WANG, F. Phenology of the native species Fetească Neagră in Moldova under the background of climate change. In: *Smart Life Sciences and Technology for Sustainable Development, Ed. Ediția 13*, 28 iunie 2023, Chișinău. Chișinău: „Tehnica-UTM”, 2023, Ediția 13, p. 61. ISBN 978-9975-64-363-4.

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ADNOTARE

Teza de doctorat elaborată de WANG Fei, cu tema „Argumentarea itinerariilor de producere struguri-vin adaptate la cerințele pieței de desfacere”, specialitatea 253.03 - Tehnologia băuturilor alcoolice și nealcoolice, este consacrată fundamentării științifice a unui model tehnologic integrat de valorificare a terroirului în vinificarea soiului autohton Fetească Neagră.

Teza este structurată în introducere, cinci capitole, concluzii și recomandări, bibliografie cu 221 de titluri și 6 anexe. Conținutul de bază însumează 121 pagini, incluzând 20 tabele și 17 figuri. Rezultatele cercetării au fost reflectate în 10 publicații științifice.

Cuvinte-cheie: Fetească Neagră, terroir, compuși organici volatili, GC-IMS.

Scopul lucrării constă în elaborarea și validarea unui model tehnologic bazat pe corelarea parametrilor agro-pedo-climatici cu profilul compușilor organici volatili și cu deciziile tehnologice de vinificare, în vederea optimizării expresiei aromatice și adaptării produsului la cerințele pieței.

Obiectivele cercetării au vizat: caracterizarea multicriterială a unităților de terroir din regiunile cu Indicație Geografică Protejată ale Republicii Moldova; determinarea profilului volatil prin tehnica GC-IMS și analiză statistică multivariată; identificarea markerilor aromatici regionali prin calculul valorilor activității olfactive (OAV); stabilirea corelațiilor dintre indicii bioclimatici și expresia aromatică; fundamentarea și validarea itinerariilor tehnologice diferențiate.

Noutatea și originalitatea științifică constau în elaborarea modelului integrat „Terroir-Profil volatil-Piață”, care transformă terroirul într-un instrument tehnologic predictiv. Cercetarea a demonstrat existența unui gradient pedoclimatic regional și influența acestuia asupra distribuției compușilor volatili, fiind identificați 44 compuși organici volatili și 15 markeri aromatici cu impact senzorial major (OAV > 1). Analiza multivariată a confirmat diferențierea statistică a vinurilor în funcție de origine.

Valoarea practică și aplicativă constă în dezvoltarea unor itinerarii tehnologice adaptate tipologiei terroirului, care permit optimizarea macerației, fermentației și maturării pentru obținerea unor stiluri diferențiate de vin. Metodologia elaborată poate fi extinsă la alte soiuri autohtone și constituie un instrument operațional pentru managementul vitivinicol bazat pe date științifice.

Implementarea rezultatelor a fost realizată prin producerea a aproximativ 8000 de butelii destinate piețelor externe (China și Canada), precum și prin integrarea modelului în procesul de formare profesională, confirmând aplicabilitatea tehnologică și impactul economic al cercetării.

АННОТАЦИЯ

Диссертационная работа WANG Fei на тему «Обоснование технологических маршрутов производства вин из винограда с учетом требований рынков сбыта», специальность 253.03 - Технология алкогольных и безалкогольных напитков, посвящена научному обоснованию интегрированной технологической модели использования терруара при производстве вин из автохтонного сорта Фетяска Нягрэ.

Диссертация состоит из введения, пяти глав, общих выводов и рекомендаций, библиографии, включающей 221 наименований, и 6 приложений. Основной текст изложен на 121 страницах и содержит 20 таблиц и 17 рисунков. Результаты исследования отражены в 10 научных публикациях.

Ключевые слова: Фетяска Нягрэ, терруар, летучие органические соединения, GC-IMS.

Цель работы заключалась в разработке и валидации технологической модели, основанной на корреляции агро-почвенно-климатических параметров с профилем летучих органических соединений и технологическими решениями в процессе виноделия, с целью оптимизации ароматического выражения и адаптации продукции к требованиям рынка.

В задачи исследования входили: мультикритериальная характеристика единиц терруара регионов с защищенным географическим указанием Республики Молдова; определение профиля летучих соединений методом GC-IMS с применением многомерного статистического анализа; идентификация региональных ароматических маркеров на основе показателя активности запаха (OAV); установление корреляций между биоклиматическими индексами и ароматическим профилем; обоснование и валидация дифференцированных технологических маршрутов.

Научная новизна и оригинальность заключаются в разработке интегрированной модели «Терруар-Профиль летучих соединений-Рынок», которая трансформирует понятие терруара в предиктивный технологический инструмент. В ходе исследования доказано существование регионального почвенно-климатического градиента и его влияние на распределение летучих соединений. Идентифицировано 44 летучих органических соединения, из которых 15 являются ключевыми ароматическими маркерами (OAV > 1). Многомерный анализ подтвердил статистически значимую дифференциацию вин в зависимости от их происхождения.

Практическая и прикладная ценность работы состоит в разработке технологических маршрутов, адаптированных к типологии терруара, что позволяет оптимизировать процессы мацерации, ферментации и выдержки для получения дифференцированных стилей вина. Предложенная методология может быть распространена на другие автохтонные сорта винограда и представляет собой операционный инструмент управления виноградарством и виноделием на основе научных данных.

Результаты исследования внедрены в промышленную и образовательную практику посредством производства около 8000 бутылок вина, предназначенных для рынков Китая и Канады, а также путем интеграции модели в процесс профессиональной подготовки, что подтверждает технологическую применимость и экономическую значимость выполненной работы.

ABSTRACT

The doctoral thesis authored by WANG Fei, entitled "Substantiation of Grape-to-Wine Production Itineraries Adapted to Market Requirements", specialty 253.03 - Technology of Alcoholic and Non-Alcoholic Beverages, is devoted to the scientific substantiation of an integrated technological model for valorizing terroir in the vinification of the autochthonous grape variety Fetească Neagră.

The thesis consists of an introduction, five chapters, general conclusions and recommendations, a bibliography comprising 221 references, and 6 appendices. The main body includes 121 pages, containing 20 tables and 17 figures. The research results have been published in 10 scientific papers.

Keywords: Fetească Neagră, terroir, volatile organic compounds, GC-IMS.

The aim of the research was to develop and validate a technological model based on the correlation between agro-pedo-climatic parameters and the profile of volatile organic compounds, as well as winemaking decisions, in order to optimize aromatic expression and adapt the final product to market requirements.

The research objectives included: multicriteria characterization of terroir units within the Protected Geographical Indication (PGI) regions of the Republic of Moldova; determination of the volatile profile using GC-IMS and multivariate statistical analysis; identification of regional aromatic markers through Odor Activity Values (OAV); establishment of correlations between bioclimatic indices and aromatic expression; and substantiation and validation of differentiated technological itineraries.

The scientific novelty and originality consist in the development of the integrated model "Terroir-Volatile Profile-Market", which transforms the concept of terroir into a predictive technological tool. The research demonstrated the existence of a regional pedoclimatic gradient and its influence on the distribution of volatile compounds. A total of 44 volatile organic compounds were identified, including 15 key aromatic markers with OAV > 1. Multivariate analysis confirmed the statistically significant differentiation of wines according to origin.

The practical and applied value of the research lies in the development of terroir-adapted technological itineraries enabling the optimization of maceration, fermentation, and maturation processes to obtain differentiated wine styles. The proposed methodology can be extended to other autochthonous grape varieties and represents an operational tool for data-driven viticultural management.

The scientific results were implemented through the production of approximately 8,000 bottles destined for external markets (China and Canada), as well as through integration into professional training processes, confirming the technological applicability and economic impact of the research.

WANG FEI

ARGUMENTATION OF GRAPE-WINE PRODUCTION PATHWAYS ADAPTED TO MARKET REQUIREMENTS

253.03 - TECHNOLOGY OF ALCOHOLIC AND NON-ALCOHOLIC BEVERAGES

Summary of the doctoral thesis in engineering sciences

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