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ORIGINAL PAPER

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AUTHENTICITY OF WINES PRODUCED FROM 'FRANKOVKA' GRAPE VARIETY ORIGINATING IN THE MODRÉ HORY REGION (CZECH REPUBLIC)

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ABSTRACT

Background. The geographical authenticity of wine, often referred to as terroir, is crucial in determining its unique characteristics and quality. Terroir encompasses the environmental factors where the grapes are grown, including soil composition, climate, and topography. These factors influence the flavor, aroma, and overall profile of the wine, giving it characteristics that are unique to its region of origin. Establishing geographical authenticity helps protect wine heritage, ensures quality control, and enhances market value. This study analyzed the phenolic, volatile, and elemental composition of wines with original certification (WOC) from the Modré Hory region (MH) and compared them with wines from other Morava wine regions.
Materials and methods. The study analyzed 24 wines of the 'Frankovka' variety from the Morava wine region, with 12 of these wines originating from the MH region with WOC certification. The researchers used Solid-Phase Microextraction coupled with Gas Chromatography-Mass Spectrometry, High-Performance Liquid Chromatography, Inductively Coupled Plasma Optical Emission Spectroscopy, and Inductively Coupled Plasma Mass Spectrometry techniques for the analysis.
Results. Phenolic analysis revealed that MHWOC wines had significantly lower resveratrol levels, likely because of lower rainfall in the MH region. Volatile compound analysis reliably identified 38 substances, with MHWOC wines showing significant differences in the levels of ethyl octanoate, ethyl hexanoate, ethyl decanoate, and ethyl butyrate, attributed to unique production practices. Elemental analysis indicated higher Mg concentrations in MHWOC wines which were related to the region's clay and loess soils, whereas other wines from the Morava wine region exhibited higher levels of Sc, Ti, Fe, K, V, and Y due to different soil compositions.
Conclusion. This study highlights the influence of regional soil and climate on wine composition and the potential of these parameters for the geographical authentication of wine. Based on the analysis, principal component analysis (PCA) reliably distinguished MHWOC wines from other wines originating from the Morava wine region, thereby confirming their unique characteristics.

Keywords: terroir, geographical authentication, volatile compounds, phenolic compounds, elemental composition

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INTRODUCTION

The relationship between the area where the grapes are grown and the chemical composition of the wine is a subject of long-term interest for oenologists (Popîrdă et al., 2021; Koljančić et al., 2024). The factors that influence the quality of wine include not only the geological and geomorphological conditions but also the actions of the vintner, the agricultural techniques used in the vineyard, and the wine processing and production processes. The International Organization of Vine and Wine (OIV) defines these factors as terroir (Bonfante and Brillante, 2022). The same grape variety, when grown in two different viticultural regions with diverse terroirs, results in wines with different contents of phenolic and aromatic compounds in the same vintage (Di Paola-Naranjo et al., 2011; Lola et al., 2023).

The challenge of distinguishing wines from specific microregions from those produced in broader wine regions was solved by the introduction of wine appellation systems. Such systems lead to the production of distinctive, recognizable wines and contribute to rural development and tourism (Prokeš, 2013; Oltean and Gabor, 2022). France uses the designation Appellation d’Origine Contrôlée (AOC), Italy uses Denominazione di Origine Controllata (DOC), Austria has Districtus Austriae Controllatus (DAC), and Spain uses Denominación de Origen Calificada (DOC) to distinguish wines from specific regions from other wines on the market.

In the Czech Republic, the designation of Wines of Original Certification (WOC) was introduced for wines reflecting a characteristic terroir (Prokeš, 2019). There are currently 14 registered WOC associations in the Czech Republic. One of the oldest WOC associations in the Czech Republic is the Modré Hory WOC (MHWOC).

Located in the Morava wine region and the Velké Pavlovice subregion, the Modré Hory region lies between the municipalities of Velké Pavlovice, Kobylí, Němčičky, Vrbice, and Bořetice (Fig. 1).

The geological bedrock in this region mainly consists of calcareous clays and loess deposits. Soil profiles typically range from 30 cm to 50 cm in depth. The average soil skeleton content varies between 6% and 15%, rarely up to 25%. With 1,871 hours of long-term annual sunshine, this region receives approximately 580 mm of precipitation each year. In 2020, a total of 29,692 liters of wines with the MHWOC label were classified, with the majority being wines of the ‘Frankovka’ variety.

Fig. 1. Map of the Moravian wine region showing the boundaries of 4 sub-regions. An asterisk indicates the position of the MHWOC

The ‘Frankovka’ variety, also known as ‘Blaufränkisch’, ‘Lemberger’ or ‘Kékfrankos’, is an old blue grape variety probably originating in Austria (Vouillamoz, 2021). In the Czech Republic, it is among the most cultivated blue grape varieties. The bushes of this variety are lush, with upright growth and large dark green leaves. The grapes are large, with a short stalk and densely planted with medium-sized berries. The wine of the ‘Frankovka’ variety has a dark ruby color with purple undertones, and its taste and aroma are dominated by cherry and blackberry tones. To verify the authenticity of a wine and detect any instances of mislabeling, the application of analytical instrumental techniques is indispensable. Gas Chromatography (GC) is a powerful analytical technique used to analyze volatile compounds present in wine. It allows for the identification and quantification of these compounds, which are unique to different grape varieties, fermentation processes, and terroirs (Marengo et al., 2001; Câmara et al., 2006; Valls Fonayet et al., 2020; Zhang et al, 2023). High-Performance Liquid Chromatography (HPLC) is an essential analytical technique for detecting wine fraud and confirming geographical authenticity. It achieves this by analyzing non-volatile compounds present in the wine, such as phenolics, organic acids, and pigments. These compounds are indicative of the grape variety, winemaking processes, and regional characteristics (Kallithraka et al., 2006; Vergara et al., 2011; Ragone et al., 2015). In addition to these techniques, several others such as ICP-MS (Inductively Coupled Plasma Mass Spectrometry) and NMR (Nuclear Magnetic Resonance) are used to verify the geographical origin of a wine (Coetzee et al., 2005; Coetzee et al., 2014; Versari et al., 2014; Ragone et al., 2015; Pořízka et al., 2018; Valls Fonayet et al., 2020).

Only a few authors study the chemical composition of Moravian red wines (Papoušková et al., 2011; Slavíková et al., 2024). Moreover, no study has focused specifically on wines vinified from the 'Frankovka' grape variety, and available studies did not include wines produced in the MHWOC. Therefore, this work aims to study the content of phenolic substances, aromatic substances, and other substances in 'Frankovka' wines from the entire Morava wine region and to evaluate the impact of terroir on the wines produced at the MHWOC.

MATERIALS AND METHODS

Wine samples

24 samples of Moravian wines of the 'Frankovka' variety from the 2017 and 2018 vintages were examined. 12 samples bore the Modré Hory WOC designation, while the remaining twelve were selected to ensure representation from all four Moravian sub-regions, with three samples from each. The wines were stored in dark, cool areas before analysis, and individual bottles were opened just before the analysis began. The wine samples were filtered through a syringe filter with a pore size of 0.45 µm and were suitably diluted according to individual analyses. Ultrapure water with a resistivity of 18 MΩ·cm (Elga, Veolia, Paris, France) was used for the dilutions. A list of samples is provided in Table 1.

Table 1. List of the analysed samples

Subregion	Village	Vineyard track	Vintage	Alcohol $\%_{v/v}$	Residual sugar g/l
1	2	3	4	5	6
Velkopavlovická	Čejkovice	Novosády	2018	14.0	n.a.
Velkopavlovická	Velké Bílovice	Dlouhá hora	2018	14.0	0.8
Velkopavlovická	Velké Bílovice	Přední Hora	2017	13.5	n.a.
Mikulovská	Popice	Svidrunk	2017	13.0	0.3
Mikulovská	Dolní Dunajovice	Pod slunným vrchem	2017	12.5	0.5
Mikulovská	Novosedly	Kamenný vrch	2018	14.0	1.2
Znojemská	Dolní Kounice	Na nivách	2017	12.5	0.3
Znojemská	Dolní Kounice	Na nivách	2018	13.0	n.a.
Znojemská	Olbramovice	Na vyhlídce	2017	12.0	0.3
Slovácká	Svatobořice-Mistřín	Tabule	2018	13.0	n.a.
Slovácká	Hovorany	Podvinohradí	2018	12.7	0.6
Slovácká	Mařatice	Prostřední hora	2018	12.5	0.5
Velkopavlovická	Vrbice*	Krátký	2018	13.5	0.5
Velkopavlovická	Vrbice*	Krátký	2017	13.0	0.5

Table 1 cont.

1	2	3	4	5	6
Velkopavlovická	Vrbice*	Skale	2018	13.0	1.2
Velkopavlovická	Vrbice*	Skale	2017	13.0	1.7
Velkopavlovická	Vrbice*	Úlehle	2018	13.0	0.6
Velkopavlovická	Němčičky*	Růžený	2018	12.5	0.04
Velkopavlovická	Němčičky*	Růžený	2018	13.5	0.3
Velkopavlovická	Němčičky*	Soudná	2017	13.0	0.5
Velkopavlovická	Bořetice*	Terasy	2018	12.5	0.1
Velkopavlovická	Bořetice*	Terasy	2017	12.5	0.9
Velkopavlovická	Kobylí*	Nivky	2018	13.0	0.4
Velkopavlovická	Velké Pavlovice*	Nadzahrady	2017	12.5	0.2

Note: * means that wines are from MHWOC, n.a. = not available.

High-Performance Liquid Chromatography Analysis of Phenolic Compounds

A liquid chromatograph (Agilent 1260, Agilent, Santa Clara, USA) was used to analyze phenolics. A 2-fold dilution of the original samples with ultrapure water was used for the analysis. The mobile phase consisted of a mixture of 0.1% formic acid (component A) and methanol (component B). Methanol and formic acid were purchased from Avantor (Stříbrná Skalice, Czech Republic) The composition of the mobile phase transitioned from 90:10 (A: B) to 10:90 (A: B) over 20 minutes, starting at 2.5 minutes. From 20 to 30 minutes, the mobile phase returned to a ratio of 90:10 (A: B). The stationary phase used was a Kinetex EVO C18 column (Phenomenex, Torrance, USA). The injection volume was 5 µl, with a mobile phase flow rate of 1 mL/min. The detection of the analyzed substances was performed using a mass detector (MSDiQ, Agilent), with ionization conducted in negative electrospray ionization (ESI) mode.

Gas Chromatography Analysis of Volatile Compounds

Volatile compounds were analyzed using solid-phase microextraction coupled with gas chromatography-mass spectrometry (HS-SPME-GC-MS, Trace™1310 GC with ISQ™LT Single Quadrupole, Thermo Fisher Scientific Inc., Waltham, Massachusetts, USA). For SPME extraction, 1 mL of sample was transferred to a 10 mL screw cap glass vial and immediately analyzed. The operating conditions of HS-SPME-GC-MS were consistent with those described in a previous study (Trenzová et al., 2024). Chromatographic data were processed in Xcalibur™ software (version 2.2., Thermo Fisher Scientific) and all analytes were identified using the National Institute of Standards and Technology (NIST) mass spectral library (NIST23, Gaithersburg, Maryland, USA). Spectral similarity (peaks of the unknown mass spectrum versus peaks in the library spectra) was assessed using match factors. Only compounds with a match factor greater than 800 were included in this analysis. The GC-MS data were normalized using total sum normalization method (Noonan et al., 2018).

Spectroscopic Analysis of Mineral Compounds

For the analysis of macroelements (Ca, Na, K, Mg, Al, P), a 10-fold dilution with ultrapure water was used, while for the analysis of microelements (Li, Be, Sc, Ti, V, Cr, Mn, Fe, Co, Ni, Cu, Zn, Sr, Ba), the samples were diluted 2-fold. The content of macroelements in all samples was determined using Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) (Ultima 2, Horiba Jobin Yvon, France). The content of microelements was determined by ICP-MS (7900, Agilent). Operating parameters are presented in Table 2.

Table 2. Operating conditions for the analysis of selected elements in wines

	ICP-OES	ICP-MS
Sample uptake, mL/min	0.8	0.5
Nebuliser type	concentric	concentric
Spray chamber	cyclonic	cyclonic
RF power, W	1300	1500
Plasma gas	Ar	Ar
Plasma gas flow, L/min	13	15
Colision gas	---	He
Colision gas flow, mL/min	---	0.15
Wavelenghts/isotopes	214.914 nm (P) 285.213 nm (Mg) 317.933 nm (Ca) 396.153 nm (Al) 588.995 nm (Na) 766.490 nm (K)	^{7}Li, ^{11}B, ^{45}Sc, ^{47}Ti, ^{51}V, ^{52}Cr, ^{55}Mn, ^{56}Fe, ^{59}Co, ^{60}Ni, ^{63}Cu, ^{66}Zn, ^{88}Sr, ^{89}Y, ^{111}Cd, ^{137}Ba,
Internal standard	---	^{115}In

Quality Control and Statistical Analysis

For quality control, a synthetic wine containing 15 g/L glucose, 15 g/L fructose, 1,5 g/L tartaric acid, 1.5 g/L malic acid, 6 g/L glycerol, 1 g/L butane-2,3-diol and 95 g/L ethanol was prepared. From this wine, a control sample was created containing 100 mg/L Ca, 100 mg/L K, 100 mg/L Mg, 10 mg/L Cu, 1 mg/L Fe, 1 mg/L Zn, 0.1 mg/L Cd, 50 mg/L gallic acid, 10 mg/L catechine and 1 mg/L resveratrol. The control sample was analyzed after every fifth analysis of the wine sample using the partial analytical method. The recoveries of monitored analytes ranged from 85% to 97% throughout the experiment.

The Mann-Whitney U-test was used to assess statistically significant differences between the measured data obtained by the analysis of MHWOC wines and other wines from the Morava wine region. The confidence interval was set to 95% ($\alpha = 0.05$). The null hypothesis for this test (H0) states that the medians of a specific parameter do not differ significantly between the compared groups. The alternative hypothesis (H1) posits the opposite—that the medians of a particular parameter differ between the compared groups. Data identified as statistically significant using the Mann-Whitney U-test were further subjected to principal component analysis (PCA).

RESULTS AND DISCUSSION

Phenolic Compounds in Wines

A typical chromatogram from the analysis of the examined wines is depicted in the work of Diviš (2024). The content of individual phenolic compounds in the investigated wines is presented in Table 3. The concentrations of individual phenolic substances corresponded to those reported by other authors analyzing Italian and Spanish wines (Isabel Gil et al., 1995; Gambelli and Santaroni, 2004). A statistically significant difference ($p = 0.0141$) in the concentration of monitored phenolic substances was found only for resveratrol in wines from the MHWOC compared to those from other regions. Resveratrol content was nearly twice as high in other Moravian wines (average concentration 1.43 mg/L) compared to those from the MHWOC (average concentration 0.630 mg/L).

The lower average resveratrol content in MHWOC wines may be attributed to the region being one of the driest in the Morava wine area. During the two years of

Table 3. Concentration of analysed phenolic compounds in MHWOC wines and in other wines from Morava wine region

Phenolic compound		c (mg/L) other wines	c (mg/L) MHWOC wines
Gallic acid	min.–max.	10.2–125	37.1–97.4
	median	60.8	62.1
	average	68.3	63.3
Protocatechuic acid	min.–max.	1.58–4.65	2.75–4.62
	median	2.96	3.32
	average	2.79	3.46
Coumaric acid	min.–max.	2.25–21.1	0.782–7.34
	median	5.94	4.72
	average	7.47	8.34
Vanilic acid	min.–max.	2.50–7.47	4.08–8.34
	median	4.95	5.77
	average	4.90	5.82
Caffeic acid	min.–max.	3.68–31.7	1.02–20.1
	median	10.6	7.13
	average	13.8	7.64
Resveratrol	min.–max.	0.689–2.65	0.139–1.18
	median	1.32	0.627
	average	1.43	0.630
Catechin	min.–max.	22.4–65.1	31.7–79.8
	median	50.4	41.8
	average	45.5	46.1
Epicatechin	min.–max.	20.6–77.1	22.1–60.4
	median	38.1	42.5
	average	39.9	41.4
Kvercetin	min.–max.	0.385–7.50	0.142–6.88
	median	1.55	0.729
	average	2.28	1.49
Myricetin	min.–max.	0.707–4.38	0.118–3.44
	median	1.42	0.914
	average	1.81	1.28
Malvidine-3-glucoside	min.–max.	2.06–24.1	1.90–27.6
	median	10.5	11.3
	average	11.6	13.6

2017–2018, the average temperature in the MHWOC region, recorded at the Němčičky meteorological station, was 13.1°C, with an average annual rainfall of 433 mm. In contrast, the average temperature during this period in other Moravian wine regions varied between 10.5°C and 11.2°C, and the average annual rainfall ranged from 490 mm to 725 mm (ALA System, http://data.ala1.com). This difference in resveratrol content is consistent with findings by Rocchetti et al. (2021), who report a dependence of resveratrol content in wine on the Selianinov Index, indicating that wines with higher resveratrol content come from areas with higher rainfall. The higher resveratrol content in grapes from vines growing in more humid areas is attributed to the plant's need for protection against gray mold and downy mildew (Olivier et al., 2022).

Volatile Compounds in Wines

A typical chromatogram from the analysis of the examined wines is presented in Vítová's (2024) publication. In total, 38 substances were reliably identified in the wines analyzed, with 22 present in all samples. Eleven compounds were found in the group of esters, seven in the group of alcohols, and three in the group of carboxylic acids. Additionally, γ-butyrolactone was one of these identified substances (Table 4). The number and chemical structures of the identified substances align with findings from other studies analyzing red wines via HS-SPME-GC-MS (Ferreira et al., 2000; Marengo et al., 2001; Bonino et al., 2003; Stój et al., 2017; Zhang et al., 2023).Esters form during the fermentation process in wine through reactions between specific fatty acids and their corresponding alcohols, such as ethanol and isopentanol. The presence and concentration of esters in wine are significantly influenced by yeast metabolism and fermentation conditions (Antonelli et al., 1999; Lambrechts and Pretorius, 2000; Plata et al. 2003). Practices such as the type of fermentation vessel, aging method (e.g., stainless steel, oak barrels), and lees contact can also modify the ester profile of the wine. Statistical analysis revealed significant differences in the concentrations of ethyl octanoate (p = 0.0006), ethyl hexanoate (p = 0.0036), ethyl decanoate (p = 0.0166), and ethyl

Table 4. Identified volatile compounds in MHWOC wines and in other wines from Morava wine region and their average normalized peak area (avg. NPA)

Compound		RI_{exp}	RI_{lit}	Odor type	Avg. NPA other wines	Avg. NPA MHVOC wines
1	2	3	4	5	6	7
Esters	ethyl butyrate	1 040	1 048	sweet, fruity	0.0029 ±0.0004	0.0025 ±0.0007
	isoamyl acetete	1 149	1 143	sweet, banana	0.010 ±0.003	0.011 ±0.005
	ethyl hexanoate	1 252	1 258	sweet, pineapple	0.072 ±0.014	0.045 ±0.021
	ethyl lactate	1 350	1 342	sweet, acidic	0.034 ±0.007	0.044 ±0.016
	ethyl octanoate	1 445	1 438	musty, pineapple	0.18 ±0.02	0.10 ±0.06
	isoamyl lactate	1 584	1 570	creamy, nutty	0.005 ±0.001	0.004 ±0.003
	ethyl-2-hydroxy-4-methylvalerate	1 567	1 545	fresh, blackberry	0.003 ±0.001	0.004 ±0.002
	ethyl decanoate	1 650	1 648	waxy, apple	0.11 ±0.03	0.07 ±0.05
	diethyl succinate	1 658	1 690	fruity, apple	0.16 ±0.03	0.19 ±0.05
	ethyl dodecanoate	1 853	1 856	rummy, floral	0.006 ±0.004	0.012 ±0.008
	ethyl isopentyl succinate	1 910	1 901	fruity	0.003 ±0.001	0.004 ±0.002

Table 4 cont.

1	2	3	4	5	6	7
Alcohols	isobutanol	1 112	1 108	floral	0.022 ±0.006	0.032 ±0.012
	isoamyl alcohol	1 221	1 223	fruity, banana	0.198 ±0.025	0.246 ±0.021
	hexanol	1 360	1 354	herbal, grassy	0.019 ±0.009	0.024 ±0.008
	butane-2,3-diol	1 559	1 570	creamy	0.006 ±0.002	0.004 ±0.001
	octanol	1 571	1 574	floral, citrusy	0.005 ±0.001	0.004 ±0.001
	decanol	1 732	1 745	fatty, floral	0.019 ±0.012	0.011 ±0.009
	phenylethyl alcohol	1 934	1 944	rose-like	0.127 ±0.033	0.156 ±0.053
Carboxylic acids	acetic acid	1 471	1 484	pungent, sour	0.009 ±0.003	0.015 ±0.007
	hexanoic acid	1 872	1 873	sour, fatty	0.005 ±0.001	0.005 ±0.002
	octanoic acid	2 058	2 057	sour, vegetable, cheesy	0.012 ±0.004	0.011 ±0.003
Lactones	γ-butyrolactone	1 640	1 635	creamy	0.003 ±0.001	0.003 ±0.001

Note: RI_{exp} – retention indices on TG-WAX column; RI_{lit} – retention indices from the NIST WebBook open-access database.

butyrate (*p* = 0.0351) between wines from the MHWOC and other Moravian wine-growing sub-regions. These differences may stem from the controlled production conditions of MHWOC-produced wines. MHWOC winemakers use enological preparations in the form of enzymes and dried yeast to a lesser extent. Additionally, maturation in new barrique barrels or substitutes is prohibited, and carbonic maceration and thermovinification methods are not permitted. Higher alcohols, also known as fusel alcohols or fusel oils, are important compounds found in red wine. These alcohols primarily form during fermentation through the yeast's metabolism of amino acids (Hazelwood et al., 2018). Unique yeast populations in a vineyard contribute to the broader concept of terroir. Numerous studies indicate that microbial terroir can influence the wine's final expression, providing a signature linked to the vineyard's geography (Liu et al., 2019). All common higher alcohols, including 2-methyl-propane-1-ol, 3-methyl-butane-1-ol, hexane-1-ol, and 2-phenylethanol, were present in the investigated wines however, a statistically significant difference in higher alcohol content was found only for butane-2,3-diol (*p* = 0.0304) and decane-1-ol (*p* = 0.0351) between MHWOC wines and other Moravian wines. While butane-2,3-diol has a relatively neutral aroma and taste, it affects the mouthfeel of the wine, potentially contributing to a slightly viscous or smooth texture. Other studies addressing the geographical authenticity of wine have also used butane-2,3-diol and decane-1-ol as important parameters to distinguish the origins of French or Brazilian wines (Sivertsen et al., 1999; De Macêdo Morais et al., 2022)

Elemental Composition of Wines

The content of specific elements in the investigated wines is presented in Table 5 and Table 6. In general, the concentrations of elements in wines from MHWOC and other Moravian wines were within the range published by other authors who analyzed various European wines (Šperková and Suchánek, 2005; Gonzálvez et al., 2009; Fermo et al., 2021; Gajek et al., 2021; Slavíková et al., 2024). In viticulture, monitoring the copper content in wine is essential. The copper content in all analyzed wines was below the maximum acceptable limit set by the International Organisation of Vine and Wine (OIV)(1 mg/L). The elements with significantly different concentrations in MHWOC and other Moravian wines were Sc (*p* = 0.0036), Mg (*p* = 0.0226), Ti (*p* = 0.0404), Fe (*p* = 0.0405), K (*p* = 0.0446), V (*p* = 0.0464), and Y (*p* = 0.0466). Wines from the MHWOC region exhibited

Table 5. Elemental composition of MHWOC wines and other wines from Morava wine region determined by ICP-MS

Element		c (μg/L) other wines	c (μg/L) MHWOC wines
Li	min.–max.	11.4–39.7	9.87–112
	median	21.2	18.1
B	min.–max.	3.76–8.48*	4.04–9.10*
	median	6.52	5.80
Sc	min.–max.	0.377–0.852	0.232–0.872
	median	0.627	0.356
Ti	min.–max.	17.1–37.1	12.3–29.4
	median	27.1	18.9
V	min.–max.	0.531–37.0	0.317–4.56
	median	3.05	1.04
Cr	min.–max.	5.12–18.2	3.64–19.8
	median	13.6	12.2
Mn	min.–max.	0.590–1.62*	0.859–1.84*
	median	1.15	1.04
Fe	min.–max.	0.902–4.51*	0.422–2.41*
	median	1.82	1.37
Co	min.–max.	1.76–5.64	1.23–4.50
	median	3.23	2.70
Ni	min.–max.	18.5–39.5	12.7–63.0
	median	27.5	21.6
Cu	min.–max.	11.0–72.3	10.1–95.4
	median	23.1	23.5
Zn	min.–max.	0.342–2.11*	0.429–2.30*
	median	0.824	0.724
Sr	min.–max.	0.510–1.24*	0.850–1.38*
	median	0.938	1.05
Y	min.–max.	0.031–3.23	0.053–3.68
	median	0.786	0.181
Cd	min.–max.	0.222–0.454	0.162–0.533
	median	0.320	0.267
Ba	min.–max.	89.1–209	101–288
	median	177	143

Note: *concentration in mg/L.

Table 6. Elemental composition of MHWOC wines and other wines from Morava wine region determined by ICP-OES

Element		c (mg/L) other wines	c (mg/L) MHWOC wines
P	min.–max.	97.1–208	77.2–249
	median	140	147
Mg	min.–max.	91.0–127	97.9–141
	median	101	119
Ca	min.–max.	51.0–122	50.1–86.7
	median	58.8	57.4
Al	min.–max.	0.171–1.22	0.166–0.815
	median	0.439	0.346
Na	min.–max.	23.3–48.0	18.3–43.9
	median	3.05	24.8
K	min.–max.	0.629–1.53*	0.548–0.851*
	median	0.783	0.707

Note: *concentration in g/L.

higher concentrations of Mg compared to other Moravian wines. This likely occurs due to the prevalence of clay and loess soils rich in Mg in the MHWOC region. In contrast, concentrations of other elements (Sc, Ti, Fe, K, V, Y) were higher in wines from other Moravian regions. These regions have different soil compositions and, unlike MHWOC, contain rocks such as granodiorite, sandstone, travertine, or limestone. Sandstones and limestones can contain elements like Y and Sc, while other minerals in these soils contribute to higher levels of K, Fe, and Ti. Magnesium has already been identified as one of the most important parameters for distinguishing wines according to their geographical origin by Frías et al. (2001) and Thiel et al. (2004). Fabani et al. (2010) also evaluated potassium and iron as important discriminating parameters for determining the geographical authenticity of wine, while Kruzlicova et al. (2013) used the concentration of vanadium and titanium for this purpose.

Principal Component Analysis (PCA)

For 14 selected parameters, which were evaluated as statistically significant for differentiating the wines

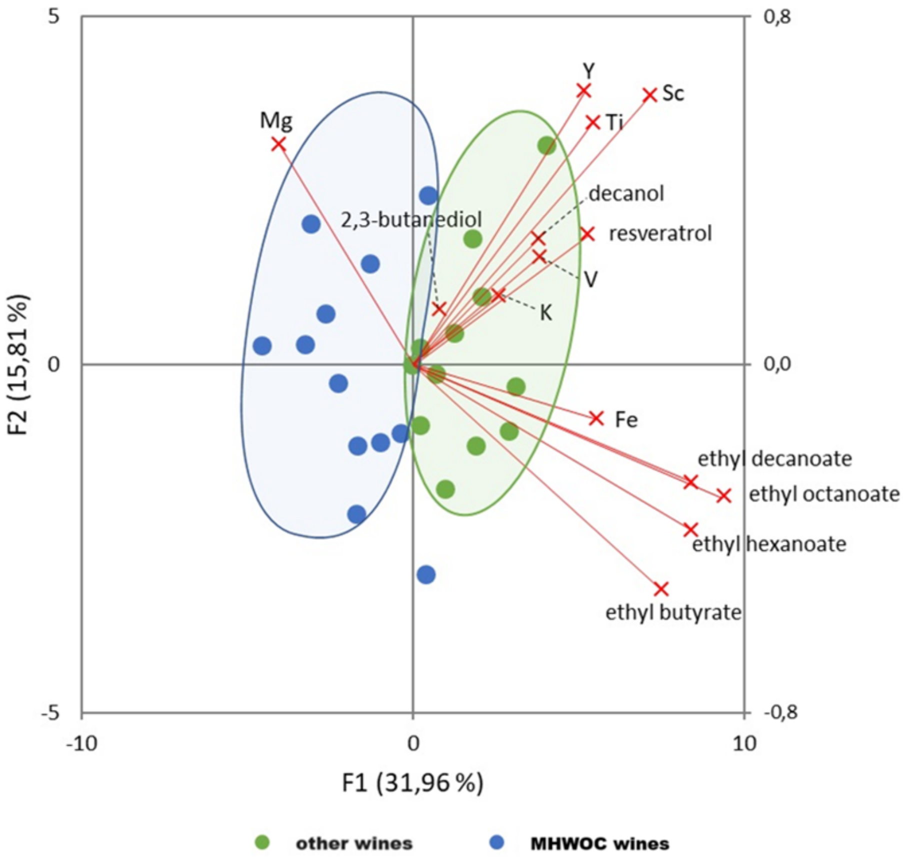

Fig. 2. Projection of the PCA score of analysed wines into a 2-D factor plane of principal components F1 and F2

into specific groups, a principal components analysis (PCA) was performed (Fig. 2). Except for two samples (sample no. 14 and sample no. 20), the wines from MHWOC were projected onto the left part of the graph with a negative score for component F1. In contrast, the other wines from the Morava wine region appeared in the right part of the graph (in the first and fourth quadrants) with a positive score for component F1. As discussed in previous chapters, MHWOC wines were characterized mainly by higher Mg content and lower levels of Fe, ethyl decanoate, ethyl octanoate, ethyl hexanoate, and ethyl butyrate in comparison to wines from other Moravian regions.

CONCLUSION

The study revealed significant differences in the phenolic, volatile, and elemental composition of wines with original certification from the Modré Hory region compared to other wines from the Morava wine subregions. Principal component analysis successfully differentiated MHWOC wines from other Moravian wines, emphasizing the influence of terroir on wine composition. These findings highlight the importance of geographical authenticity in winemaking, which preserves wine heritage, ensures quality control, and enhances market value. The distinct characteristics of MHWOC wines can serve as a powerful marketing tool to promote wine tourism in the region. Leveraging the unique composition and high quality of their wines, the MHWOC can attract wine enthusiasts and tourists, fostering economic development and cultural exchange. This, in turn, can stimulate increased investment in the region's wine industry, further improving production practices and supporting the local economy. Given that other microregions in the

Czech Republic also produce WOC wines, it would be valuable to verify the insights gained regarding the influence of terroir on wine composition by analyzing wines from these regions. Additionally, future studies could investigate the longer-term effects of terroir on the distinctiveness of WOC wines by analyzing wines from a wider range of vintages.

DECLARATIONS

Data statement

All data supporting this study has been included in this manuscript.

Ethical Approval

Not applicable.

Competing Interests

The authors declare that they have no conflicts of interest.

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