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Assessment of the energy potential and combustion characteristics of green biomass from selected varieties of *Vitis vinifera* L. grown in Central Europe

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ABSTRACT

Sustainable management of crop residues is a key element of the circular economy in the wine sector. This study evaluated the energy potential and combustion efficiency of green biomass waste (leaves) from four *Vitis vinifera* L. grape varieties (*Chardonnay, Merlot, Riesling, Zweigelt*) grown using the Guyot system in two different climatic regions: warm temperate and temperate. A comprehensive technical analysis, elemental composition analysis, and analysis of gaseous and particulate emissions were conducted. A highly significant effect ($p < 0.0001$) of both the variety factor and climatic conditions on the studied parameters was demonstrated. In the warm temperate climate, the *Chardonnay* variety exhibited the highest calorific value (HHV – 18.04 MJ/kg), which was correlated with the highest carbon content (C – 44.22%). In combustion tests, *Riesling* from a warm temperate climate stood out with the lowest particulate emissions (7.93 kg/Mg), while *Merlot* from the same region generated the lowest emissions of CO, NO_x, and SO_2. An analysis of *Merlot* cultivation in a temperate climate showed a significant increase in NO_x emissions (9.27 kg/t) and SO_2 (0.42 kg/t), which was directly attributable to higher concentrations of nitrogen (N – 2.63%) and sulfur (S – 0.21%) in leaf tissues. The results indicate that grapevine leaves are a valuable source of renewable energy, but their fuel and environmental parameters are strictly dependent on the interaction between the variety's genotype and habitat conditions.

Keywords: Guyot, grapevine, energy potential, combustion, calorific value.

INTRODUCTION

The common grapevine (Latin: *Vitis vinifera* L.) is one of the most important and highly valued fruit crops in the world (Güler and CandemiR, 2014). Grape production and agrotechnical practices in vineyards generate significant amounts of plant biomass, the potential uses of which are not always fully exploited. In addition to shoots, stems, pomace, skins, and seeds, grapevine leaves also constitute a significant stream of organic residues. This material is produced both as a result of the natural aging of plants at the end of the growing season and during agrotechnical practices carried out throughout the season. On many farms, the leaves are disposed of on the vineyard or treated as organic waste, even though their quantity, chemical composition, and physicochemical properties may indicate the possibility of further utilization. Grapevine leaves constitute a raw material with potential that goes beyond their treatment as agricultural waste. Due to the presence of bioactive compounds (Hefnawy et al., 2016; Moldovan et al., 2020), particularly polyphenols (Singh et al., 2023), flavonoids, and other secondary metabolites, they are considered a useful material in the food, pharmaceutical (Sharafan et al., 2023), nutraceutical, cosmetic (Bogdan et al., 2020), and feed (Abbas and Khayoon, 2021; Costa et al., 2022; Horaczek et al., 2025) sectors. In Mediterranean countries, grapevine leaves are also used directly in human nutrition, including as an ingredient in traditional dishes, which confirms their importance as a plant-based raw material with practical value. At the same time, extracts from grapevine leaves are being studied for their antioxidant activity and potential applications in functional and pharmaceutical products (Banjanin et al., 2020; Insanu et al., 2021; Li et al., 2022; Maia et al., 2019).

The importance of grapevine leaves as waste biomass stems not only from their availability but also from phytosanitary considerations. Leaving leaves and other plant debris on the vineyard may promote the persistence of pathogen inoculum (Jaspers et al., 2013) and increase the risk of disease spread in subsequent growing seasons. For this reason, removing this material from the vineyard can be a key element in reducing disease pressure and improving the phytosanitary condition of the vineyard (Hoffman et al., 2004). The question therefore arises as to whether biomass, which for agrotechnical and phytosanitary reasons should be removed from the plantation (Gramaje et al., 2018), can be treated not as problematic waste, but as a local raw material with specific utility value (Hoffman et al., 2004; Jaspers et al., 2013).

One possible use for grapevine leaves is energy production. Given the growing demand for renewable energy sources and the need to reduce organic waste, biomass from agricultural and horticultural production can be an important component of a circular economy. This approach allows for the integration of environmental, energy, and economic objectives, particularly in the case of materials that are produced locally and seasonally, and whose removal from plantations is justified by production practices (Díaz et al., 2024; Jesus et al., 2022; Kapłan et al., 2023, 2025; Maj et al., 2022a; Torreiro et al., 2020).

However, the possibility of using grapevine leaves as fuel biomass requires a detailed assessment of their properties. The mere availability of the raw material does not determine its energy suitability, as the fuel quality of biomass depends on its physicochemical parameters and chemical composition. Of key importance are the heat of combustion, calorific value, moisture content, ash content, volatile matter, and fixed carbon, which are among the basic indicators for evaluating solid fuels of biomass origin. High calorific value and low moisture content are desirable characteristics from a combustion standpoint, whereas excessive ash content can limit the fuel quality of biomass and increase the risk of operational issues. Equally important is the elemental composition, particularly the content of C, H, N, S, and O, as it affects both the material's energy potential and potential emission rates (Demirbas, 2002, 2004; Esteves et al., 2023; Mitchell et al., 2016; Sheng and Azevedo, 2005).

From an environmental impact perspective, nitrogen and sulfur content are of particular importance, as they may be linked to emissions of nitrogen and sulfur oxides. The proportion of volatile matter and fixed carbon, meanwhile, influences the combustion process, and moisture content can affect both energy efficiency and the emission profile. Therefore, the assessment of grapevine leaf biomass should include not only basic fuel parameters but also elemental composition, molar ratios, theoretical combustion parameters, and emission factors (Chen et al., 2010; Giuntoli et al., 2010; Mitchell et al., 2016; Moroń, 2015; Ren et al., 2017).

The properties of grapevine leaves may vary depending on the variety and the climatic conditions of the growing site. Grapevine varieties differ in morphological characteristics, growth rate, tissue structure, and the ability to accumulate mineral and organic compounds. At the same time, climatic conditions, including temperature, water availability, growing season length, and the intensity of physiological processes, can influence the chemical composition of the leaves and their fuel parameters. For this reason, the energy potential of grapevine leaves should be considered in the context of the interaction between the variety and the growing environment.

This study adopts a comprehensive approach to evaluating grapevine leaves as a potential energy biomass. Of particular importance is the simultaneous consideration of fuel properties, elemental composition, emission factors, combustion parameters, and multidimensional variety similarity. This approach allows not only for determining the basic energy potential of the analyzed material but also for assessing the extent to which the fuel and emission profiles differ between varieties and climatic zones.

The aim of this study was to evaluate the energy and emission properties of leaf biomass from four grapevine varieties: Chardonnay, Merlot, Riesling, and Zweigelt, originating from two climate zones: warm temperate and temperate. The scope of the research included an analysis of fuel parameters, elemental composition, molar ratios, emission factors, and theoretical combustion parameters. Additionally, correlation analysis and hierarchical cluster analysis were applied to determine the relationships between fuel properties and emission factors and to identify similarities among the varieties. The results obtained may serve as a basis for assessing the potential for the energy use of grapevine leaves as a local waste material, the removal of which from vineyards is justified by both production and phytosanitary considerations.

MATERIALS AND METHODS

The field studies were conducted in the fall, immediately after the fruit harvest, at two commercial vineyards located in different climate zones. The first, representing a temperate climate zone (Poland), is the Experimental Vineyard of the University of Life Sciences in Lublin, located in the southeastern part of the country. The second location, representing a warm temperate climate zone (Czech Republic), is the experimental and production vineyard of Mendel University in Brno, situated in the Lednice wine region in Moravia.

The study included four varieties of grapevine (*Vitis vinifera* L.): Chardonnay, Merlot, Riesling, and Zweigelt. At both locations, the plants were trained using the Single Guyot system with a trunk height of 40–50 cm, a single horizontal fruiting cane approximately 0.9 m long, and a replacement spur.

As part of the biometric assessment, leaves were analyzed; these were randomly collected from fruiting shoots in three replicates for laboratory analysis, yielding a total of 30 leaves in each replicate for a given variety and location. Each sample consisted of one-third of leaves collected from the lower fruiting zone, one-third from the middle part of the vine, and one-third from the upper, apical part of the plant crown. After the experiment was completed, the results were subjected to statistical analysis using one-way analysis of variance. All analyses were performed using STATISTICA 13 software.

The methodology for the laboratory evaluation of the energy properties and elemental composition of the dried and compressed material is summarized in Table 1.

Emission factors and exhaust gas

In order to estimate the emission factors for SO_2, CO_2, CO, NO_x and dust for grape marc, the emission factor method based on final analysis was

Table 1. Determinations carried out in the study

Parameter	Parameter	Equipment	Standard
Proximate analysis	Ash (A; %)	LECO TGA 701 thermogravimetric analyser (LECO Corporation, Saint Joseph, MI, USA, 2013)	(EN-ISO 18122:2022, 2022)
	Volatile matter (V; %)		(EN-ISO 18123:2023, 2023)
	Moisture (M; %)		(EN-ISO 18134-1:2023, 2022)
	Fixed carbon (FC; %)	FC=100-V-A-M (1)	(Choudhury et al., 2021)
Energetic properties	Higher heat value (HHV; MJ·kg^{-1})	LECO AC 600 isoperibolic calorimeter (LECO Corporation, Saint Joseph, MI, USA, 2012)	(EN-ISO 1928:2020, 2020)
	Lower heat value (LHV; MJ·kg^{-1})		
Ultimate analysis	Carbon (C; %)	LECO CHNS 628 elemental analyser (LECO Corporation, Saint Joseph, MI, USA, 2012)	(EN-ISO 16948:2015-07, 2015)
	Hydrogen (H; %)		
	Nitrogen (N; %)		
	Sulfur (S; %)		(EN-ISO 16994:2016, 2016)
	Oxygen (O; %)	O = 100 – A – H − C − S − N (2)	(Alves et al., 2020)

used (Maj, 2018). The exhaust gas composition was determined based on stoichiometric equations according to the works by (Kovacs et al., 2016; Paraschiv et al., 2020). The procedure for estimating the indicators is presented in Figure 1.

RESULTS

The results indicate that both the grapevine variety and the climate zone influenced the fuel properties, elemental composition, combustion parameters, and emission factors of the analyzed biomass. The comparison included four grapevine varieties: Chardonnay, Merlot, Riesling, and Zweigelt, originating from two climate zones: warm temperate and temperate. This approach allowed us to assess whether the energy and emission profile of grapevine biomass was primarily related to varietal characteristics, climatic conditions, or the combined effect of both factors.

In the first stage of the analysis, the basic fuel properties of the biomass were assessed, including HHV, LHV, M, A, V, and FC. These parameters are crucial for evaluating the suitability of biomass for energy purposes, as they determine both its calorific potential and selected technological limitations related to combustion. The results of this analysis are presented in Table 2. For all analyzed parameters, statistically significant variation in values was found depending on the combination of grapevine variety and climate zone ($p = 0.0001$). The distribution of values for individual varieties differed between climate zones, indicating that the direction of differences between zones was not uniform for all varieties.

The highest HHV value was recorded for the Chardonnay variety in the warm temperate climate, where it was 18.04 MJ/kg. The lowest value for this parameter was found for Merlot in the same climate zone, i.e., 16.07 MJ/kg. In the warm temperate climate, HHV values decreased in the following order: Chardonnay, Riesling, Zweigelt, and Merlot, whereas in the temperate climate, the highest value was obtained for Merlot, and the lowest for Chardonnay. A comparison of climate zones showed that Chardonnay and Riesling achieved higher HHV values in the warm temperate climate, while Merlot and Zweigelt were characterized by higher values in the temperate climate.

For the LHV parameter, the highest value was recorded for Chardonnay in a warm temperate climate, where it amounted to 16.27 MJ/kg. The lowest value was found for Merlot in the same climate zone, i.e., 13.94 MJ/kg. In the warm temperate climate, the Chardonnay variety had the highest LHV value, while Merlot had the lowest. In the temperate climate, the ranking of varieties

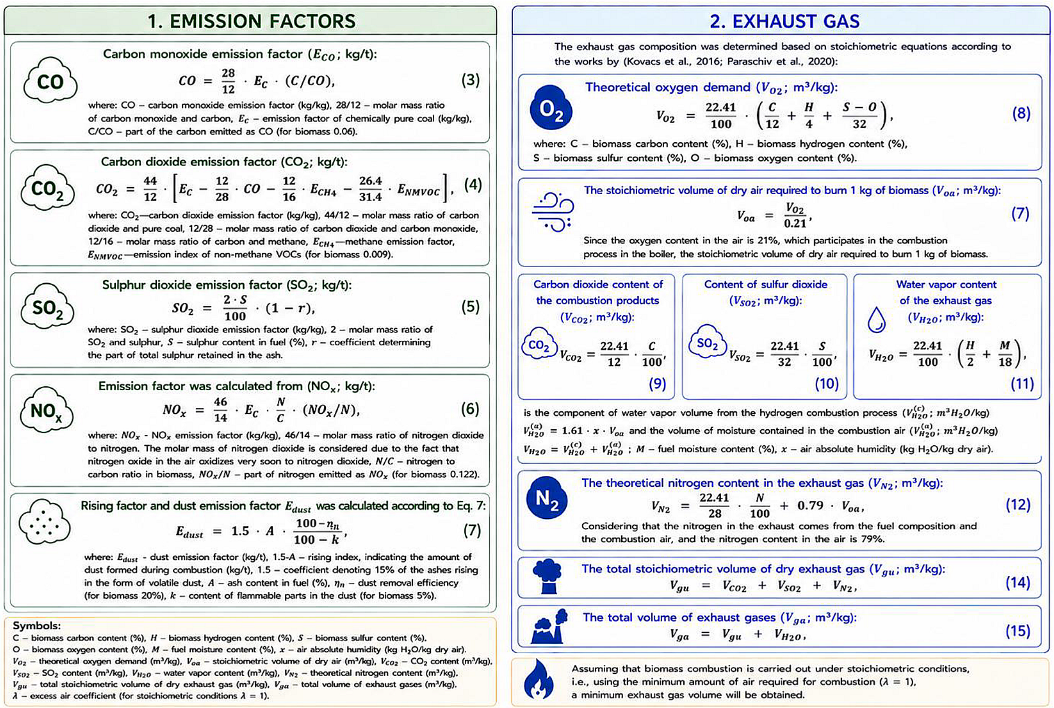

Figure 1. The procedure for estimating the indicators

Table 2. Calorific value and proximate analysis of the impact of grapevine biomass variety and climate zone on energy

Climate	Variety	HHV (MJ/kg)	LHV (MJ/kg)	M (%)	A (%)	V (%)	FC (%)
Moderately warm	Chardonnay	18.04 ± 0.05 Aa	16.27 ± 0.05 Aa	8.64 ± 0.03 Ca	11.35 ± 0.02 Cb	66.51 ± 0.16 Ab	13.50 ± 0.19 Ba
	Merlot	16.07 ± 0.05 Cb	13.94 ± 0.04 Db	11.51 ± 0.04 Aa	12.20 ± 0.04 Bb	64.25 ± 0.39 Bb	12.05 ± 0.43 Ca
	Resling	17.09 ± 0.10 Ba	14.94 ± 0.09 Bb	6.49 ± 0.04 Db	6.28 ± 0.10 Db	66.77 ± 0.47 Ab	20.46 ± 0.42 Aa
	Zweigelt	16.24 ± 0.09 Cb	14.47 ± 0.08 Cb	9.46 ± 0.01 Ba	13.78 ± 0.05 Aa	65.96 ± 0.38 Ab	10.81 ± 0.43 Da
	p-value	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Moderate	Chardonnay	16.33 ± 0.13 Cb	14.75 ± 0.12 Cb	8.43 ± 0.00 Ab	12.93 ± 0.10 Aa	72.50 ± 0.40 Ba	6.14 ± 0.33 Cb
	Merlot	17.29 ± 0.03 Aa	15.68 ± 0.03 Aa	8.16 ± 0.00Cb	12.47 ± 0.12 Ba	73.44 ± 0.28 Aa	5.93 ± 0.27 Cb
	Resling	16.71 ± 0.12 Bb	15.19 ± 0.11 Ba	7.89 ± 0.00 Da	11.81 ± 0.14 Ca	72.54 ± 0.16 Ba	7.76 ± 0.25 Bb
	Zweigelt	16.86 ± 0.04 Ba	15.27 ± 0.04 Ba	8.23 ± 0.00 Bb	9.44 ± 0.20 Db	71.94 ± 0.16 Ba	10.39 ± 0.30 Aa
	p-value	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
p-value	Chardonnay	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Merlot	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Resling	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Zweigelt	0.0001	0.0001	0.0001	0.0001	0.0001	0.9987

Note: HHV - high heating value, LHV - lower heating value, M - moisture content, A - ash content, V - volatile matter content, FC - fixed carbon. Significant difference means that different letters in the column indicate significant differences at $\alpha = 0.05$.

was different, as the highest value was obtained for Merlot, while the lowest was for Chardonnay. A comparison of climate zones showed that Chardonnay achieved a higher LHV value in the warm temperate climate, while Merlot, Riesling, and Zweigelt achieved higher values of this parameter in the temperate climate.

Moisture content (M) reached its highest value for Merlot in the warm temperate climate, at 11.51%. The lowest value for this parameter was found for Riesling in the same climate zone, i.e., 6.49%. In the warm temperate climate, Merlot had the highest moisture content, while Riesling had the lowest. In the temperate climate, the highest M value was recorded for Chardonnay, and the lowest also for Riesling. A comparison of climate zones indicates that Merlot and Zweigelt had higher moisture content in the warm temperate climate, while Chardonnay and Riesling achieved slightly higher M% values in the temperate climate.

The highest A value was recorded for Zweigelt in the warm temperate climate, where it was 13.78%. The lowest value was found for Riesling in the same climate zone, i.e., 6.28%. In the warm temperate climate, A values decreased in the following order: Zweigelt, Merlot, Chardonnay, and Riesling. In the temperate climate, the highest ash content was obtained for Chardonnay, while the lowest was for Zweigelt. A comparison of climate zones indicates that Chardonnay, Merlot, and Riesling achieved higher A values in the temperate climate, while Zweigelt was characterized by a significantly higher value of this parameter in the warm temperate climate.

For V, the highest value was recorded for Merlot in the temperate climate, where it was 73.44%. The lowest value of this parameter was found for Merlot in the warm temperate climate, i.e., 64.25%. In the warm temperate climate, Riesling had the highest V value, while Merlot had the lowest. In the temperate climate, the highest value was obtained for Merlot, and the lowest for Zweigelt. All analyzed varieties achieved higher V values in the temperate climate than in the warm temperate climate, indicating a consistent pattern of differences between climate zones for this parameter.

For the FC parameter, the highest value was recorded for Riesling in the warm temperate climate, where it was 20.46%. The lowest value was found for Merlot in the temperate climate, i.e., 5.93%. In the warm temperate climate, the highest FC value was obtained for Riesling, and the lowest for Zweigelt. In the temperate climate, Zweigelt had the highest value, while Merlot had the lowest. A comparison between climate zones showed that Chardonnay, Merlot, and Riesling achieved higher FC values in the warm temperate climate, while for Zweigelt, the values of this parameter were similar in both zones, with a slight advantage for the warm temperate climate.

In summary, the results indicate that none of the analyzed varieties nor any of the climatic zones exhibited a clearly most favorable profile for all parameters. The highest values of the energy parameters HHV and LHV were obtained for Chardonnay in the warm temperate climate, indicating a particularly favorable profile of this combination in terms of calorific value. In the temperate climate, Merlot exhibited the highest values of these parameters. The temperate climate was associated with a higher content of volatile components in all varieties, while higher FC values in the warm temperate climate were observed in most varieties, particularly in Riesling. From the perspective of fuel quality, lower M and A values were also advantageous; in this regard, Riesling stood out in the warm temperate climate for both parameters. At the same time, high M values for Merlot and A values for Zweigelt in the warm temperate climate indicate less favorable characteristics of these combinations.

The variation in energy parameters indicates that the fuel potential of grapevine biomass was not uniform across all varieties and climatic zones. Since HHV, LHV, volatile matter content, ash content, and fixed carbon content are related to the chemical composition of the material, the elemental composition and molar ratios of the tested samples were analyzed in the next stage. For all analyzed parameters of elemental composition and molar ratios, i.e., C, H, N, S, O, H/C, N/C, and O/C, statistically significant variation in values was found depending on the combination of grapevine variety and climate zone ($p = 0.0001$). The distribution of values for individual varieties differed between climate zones, indicating that the direction of differences between zones was not uniform for all varieties (Table 3).

The highest carbon (C) content was recorded for the Chardonnay variety in the warm temperate climate, where it was 44.22%. The lowest value for this parameter was found for Merlot in the same climate zone, i.e., 40.09%. In the warm temperate climate, carbon content decreased in the following order: Chardonnay, Zweigelt, Riesling, and Merlot, whereas in the temperate climate, the highest value was obtained for Zweigelt, and the lowest for Riesling. A comparison of climate zones

Table 3. An ultimate analysis of the impact of grapevine biomass variety and climate zone on energy properties

Climate	Variety	C (%)	H (%)	N (%)	S (%)	O (%)	H/C	N/C	O/C
Moderately warm	Chardonnay	44.22 ± 0.07 Aa	7.04 ± 0.39 Aa	2.22 ± 0.04 Aa	0.15 ± 0.00 Ba	35.02 ± 0.43 Db	1.59 ± 0.09 Ba	0.05 ± 0.001 Ba	0.59 ± 0.008 Db
	Merlot	40.09 ± 0.07 Cb	7.09 ± 0.01 Ab	1.14 ± 0.01 Cb	0.11 ± 0.01 Cb	39.37 ± 0.11 Ba	1.77 ± 0.00 Aa	0.03 ± 0.000Cb	0.737 ± 0.003 Ba
	Resling	41.09 ± 0.14 Ba	7.19 ± 0.01 Aa	2.21 ± 0.04 Aa	0.18 ± 0.01 Ab	43.04 ± 0.26 Aa	1.75 ± 0.01 Aa	0.05 ± 0.001 Aa	0.786 ± 0.007 Aa
	Zweigelt	41.14 ± 0.09 Bb	7.04 ± 0.03 Aa	2.13 ± 0.03 Ba	0.17 ± 0.01 ABa	35.75 ± 0.18 Cb	1.71 ± 0.00 Aa	0.05 ± 0.001 Ba	0.652 ± 0.005 Cb
	p-value	0.0001	0.9874	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Moderate	Chardonnay	41.27 ± 0.03 Bb	6.86 ± 0.27 Aa	2.14 ± 0.03 Bb	0.16 ± 0.01 Ba	36.64 ± 0.27 Ca	1.66 ± 0.06 Aa	0.05 ± 0.001 Ba	0.666 ± 0.005 Aa
	Merlot	41.86 ± 0.03 ABa	7.15 ± 0.01 Aa	2.63 ± 0.03 Aa	0.21 ± 0.01 Aa	35.69 ± 0.13 Db	1.71 ± 0.00 Ab	0.06 ± 0.001 Aa	0.639 ± 0.002 Bb
	Resling	41.19 ± 0.17 Ba	6.96 ± 0.02 Ab	2.16 ± 0.02 Ba	0.20 ± 0.01 Aa	37.68 ± 0.29 Bb	1.69 ± 0.00 Ab	0.05 ± 0.001 Ba	0.686 ± 0.008 Ab
	Zweigelt	42.52 ± 0.52 Aa	6.89 ± 0.26 Aa	2.01 ± 0.12 Ba	0.15 ± 0.00 Bb	39.00 ± 0.34 Aa	1.62 ± 0.08 Aa	0.05 ± 0.002 Ab	0.688 ± 0.014 Aa
	p-value	0.0001	0.8521	0.0001	0.0001	0.0001	0.7454	0.0001	0.0001
p-value	Chardonnay	0.0001	0.8412	0.0001	0.6632	0.0001	0.8585	0.8554	0.0001
	Merlot	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Resling	0.9632	0.0001	0.6514	0.0001	0.0001	0.0001	0.7412	0.0001
	Zweigelt	0.0001	0.7412	0.9514	0.0001	0.0001	0.1236	0.0001	0.0001

Note: C—carbon content, H—hydrogen content, N—nitrogen content, S—sulphur content, O—oxygen content, H/C—ratio of hydrogen to carbon, N/C—ratio nitrogen to carbon, O/C—ratio oxygen to carbon. Significant difference means that different letters in the column indicate significant differences at $\alpha = 0.05$.

showed that Chardonnay and Zweigelt achieved higher C values in the warm temperate climate, while Merlot was characterized by a higher carbon content in the temperate climate. In contrast, C values for Riesling were similar in both zones.

For hydrogen (H), the highest value was recorded for Riesling in a warm temperate climate, where it was 7.19%. The lowest value was found for Chardonnay in a temperate climate, i.e., 6.86%. In the warm temperate climate, H values were relatively even, with Riesling having the highest value, and Chardonnay and Zweigelt having the lowest. In the temperate climate, Merlot had the highest hydrogen content, while Chardonnay had the lowest. A comparison of climate zones indicates that Chardonnay, Riesling, and Zweigelt achieved higher H values in the warm temperate climate, while Merlot achieved a slightly higher value in the temperate climate.

The highest N content was recorded for Merlot in the temperate climate, where it was 2.63%. The lowest value of this parameter was found for Merlot in the warm temperate climate, i.e., 1.14%. In the warm temperate climate, Chardonnay and Riesling had the highest nitrogen content, while Merlot had the lowest. In the temperate climate, the highest N value was obtained for Merlot, and the lowest for Zweigelt. A comparison between zones indicates that Merlot achieved a significantly higher N content in the temperate climate, while Chardonnay achieved a higher value of this parameter in the warm temperate climate.

For the S parameter, the highest value was recorded for Merlot in the temperate climate, where it was 0.21%. The lowest value was found for Merlot in the warm temperate climate, i.e., 0.11%. In the warm temperate climate, sulfur content was highest for Riesling and lowest for Merlot. In the temperate climate, the highest S value was obtained for Merlot, while the lowest values were recorded for Chardonnay and Zweigelt. A comparison of climate zones indicates that Merlot and Riesling achieved higher S values in the temperate climate, while Zweigelt was characterized by a higher value of this parameter in the warm temperate climate. For Chardonnay, S values were similar in both zones.

The highest O content was recorded for Riesling in the warm temperate climate, where it was 43.04%. The lowest value of this parameter was found for Chardonnay in the warm temperate climate, i.e., 35.02%. In the warm temperate climate, O% values decreased in the following order: Riesling, Merlot, Zweigelt, and Chardonnay. In the temperate climate, the highest oxygen content was obtained for Zweigelt, while the lowest was for Merlot. A comparison between climate zones indicates that Chardonnay and Zweigelt achieved higher O values in the temperate climate, while Merlot and Riesling were characterized by a higher content of this element in the warm temperate climate.

For the H/C ratio, the highest value was recorded for Merlot in the warm temperate climate, where it was 1.77. The lowest value was found for Chardonnay in the same climate zone, i.e., 1.59. In the warm temperate climate, the highest H/C values were obtained for Merlot, Riesling, and Zweigelt, while the lowest were for Chardonnay. In the temperate climate, H/C values were more balanced; the highest value was recorded for Merlot, and the lowest for Zweigelt. A comparison of climate zones showed that Chardonnay achieved a higher H/C value in the temperate climate, while Merlot and Riesling achieved higher values in the warm temperate climate. For Zweigelt, the differences between zones were minor.

The highest N/C value was recorded for Merlot in the temperate climate, where it was 0.06. The lowest value was found for Merlot in the warm temperate climate, i.e., 0.03. In the warm temperate climate, the highest N/C values were obtained for Riesling, as well as for the Chardonnay and Zweigelt varieties, while the lowest was for Merlot. In the temperate climate, the highest N/C value was recorded for Merlot, while the lowest values were for Chardonnay, Riesling, and Zweigelt. A comparison of climate zones indicates that Merlot achieved a significantly higher N/C value in the temperate climate, whereas for the other varieties, the values of this index were similar across zones.

For the O/C index, the highest value was recorded for Riesling in the warm temperate climate, where it was 0.786. The lowest value was found for Chardonnay in the same climate zone, i.e., 0.59. In the warm temperate climate, O/C values decreased in the following order: Riesling, Merlot, Zweigelt, and Chardonnay. In the temperate climate, the highest O/C values were obtained for Zweigelt, Riesling, and Chardonnay, while the lowest was for Merlot. A comparison of climate zones showed that Chardonnay and Zweigelt achieved higher O/C values in the temperate climate, while Merlot and Riesling were characterized by higher values of this index in the warm temperate climate.

In summary, the results indicate that none of the analyzed varieties or climate zones was characterized by unequivocally the highest values for all elemental composition parameters. In the warm temperate climate, the Chardonnay variety stood out, achieving the highest C content, and Riesling, which was characterized by the highest values of H, O, and O/C. In the temperate climate, the highest C content was recorded for Zweigelt, while Merlot stood out with the highest values of N, S, H/C, and N/C. From the perspective of fuel quality, a high carbon content and relatively low content of heteroatomic elements are particularly important; therefore, a favorable C profile was obtained for Chardonnay in the warm temperate climate and for Zweigelt in the temperate climate. At the same time, elevated N and S values, particularly for Merlot in a temperate climate, may indicate less favorable characteristics of this combination in the context of potential energy use.

Variations in elemental composition, particularly the content of C, N, and S, are significant not only for fuel properties but also for potential emission indicators. Therefore, in the next stage, the values of CO, NO_x, CO_2, SO_2, and particulate matter were analyzed for individual grape varieties and climate zones (Table 4). For all analyzed emission indicators, statistically significant variation in values was found depending on the combination of grapevine variety and climate zone ($p = 0.0001$). The distribution of values for individual varieties differed across climate zones, indicating that the direction of differences between the warm temperate and temperate climates was not consistent across all varieties.

The highest CO value was recorded for the Chardonnay variety in the warm temperate climate, where it was 54.48 kg/t. The lowest value for this parameter was found for Merlot in the same climate zone, i.e., 49.39 kg/t. In the warm temperate climate, CO values decreased in the following order: Chardonnay, Zweigelt, Riesling, and Merlot. In the temperate climate, the highest CO value was obtained for Zweigelt, while the lowest was for Riesling. A comparison of climate zones showed that Chardonnay achieved a significantly higher CO value in the warm temperate climate, while Merlot, Riesling, and Zweigelt were characterized by higher values of this indicator in the temperate climate.

For NO_x, the highest value was recorded for Merlot in the temperate climate, where it was 9.27 kg/t. The lowest value was found for Merlot in the warm temperate climate, i.e., 4.03 kg/t. In the warm temperate climate, the highest NO_x values were obtained for Chardonnay and Riesling, while the lowest was for Merlot. In the temperate climate, Merlot had the highest NO_x value, while Zweigelt had the lowest. A comparison of climate zones indicates that Chardonnay, Riesling, and Zweigelt achieved higher NO_x values in the warm temperate climate, while Merlot had a

Table 4. Emission parameters for grapevine leaves by variety and growing location (kg/t)

Climate	Variety	CO	NO_x	CO_2	SO_2	Dust
Moderately warm	Chardonnay	54.48 ± 0.08 Aa	7.84 ± 0.13 Aa	1334.04 ± 2.03 Aa	0.31 ± 0.01 Ba	14.34 ± 0.02 Cb
	Merlot	49.39 ± 0.09 Bb	4.03 ± 0.03 Cb	1209.34 ± 2.18 Cb	0.22 ± 0.01 Cb	15.41 ± 0.05 Bb
	Resling	50.62 ± 0.17 Ca	7.81 ± 0.13 Aa	1239.66 ± 4.17 Ba	0.36 ± 0.01 Ab	7.93 ± 0.13 Db
	Zweigelt	50.69 ± 0.11 Bb	7.50 ± 0.12 Ba	1241.29 ± 2.81 Bb	0.34 ± 0.02 ABa	17.40 ± 0.06 Aa
	p-value	0.0001	0.0001	0.0001	0.0001	0.0001
Moderate	Chardonnay	50.84 ± 0.04 Bb	7.54 ± 0.11 Bb	1244.96 ± 0.89 Bb	0.32 ± 0.01 Ba	16.34 ± 0.12 Aa
	Merlot	51.57 ± 0.04 ABa	9.27 ± 0.11 Aa	1262.77 ± 1.04 ABa	0.42± 0.01 Aa	15.75 ± 0.16 Ba
	Resling	50.74 ± 0.20 Ba	7.63 ± 0.09 Ba	1242.52 ± 4.98 Ba	0.40 ± 0.01 Aa	14.92 ± 0.18 Ca
	Zweigelt	52.39 ± 0.64 Aa	7.08 ± 0.42 Ba	1282.93 ± 15.63 Aa	0.30 ± 0.01 Bb	11.92 ± 0.25 Db
	p-value	0.0001	0.0001	0.0001	0.0001	0.0001
p-value	Chardonnay	0.0001	0.0001	0.0001	0.9574	0.0001
	Merlot	0.0001	0.0001	0.0001	0.0001	0.0001
	Resling	0.8745	0.7532	0.7852	0.0001	0.0001
	Zweigelt	0.0001	0.6547	0.0001	0.0001	0.0001

Note: CO—carbon monoxide, CO_2—carbon dioxide, SO_2—sulphur dioxide, NO_x—nitrogen oxides. Significant difference means that different letters in the column indicate significant differences at $\alpha = 0.05$.

significantly higher value of this indicator in the temperate climate.

For the CO_2 index, the highest value was recorded for Chardonnay in the warm temperate climate, where it was 1334.04 kg/t. The lowest value was found for Merlot in the same climate zone, i.e., 1209.34 kg/t. In the warm temperate climate, CO_2 values decreased in the following order: Chardonnay, Zweigelt, Riesling, and Merlot. In the temperate climate, the highest CO_2 value was obtained for Zweigelt, while the lowest was for Riesling. A comparison of climate zones showed that Chardonnay achieved a higher CO_2 value in the warm temperate climate, while Merlot, Riesling, and Zweigelt were characterized by higher values of this parameter in the temperate climate.

The highest SO_2 value was recorded for Merlot in the temperate climate, where it was 0.42 kg/t. The lowest value of this parameter was found for Merlot in the warm temperate climate, i.e., 0.22 kg/t. In the warm temperate climate, the highest SO_2 value was obtained for Riesling, while the lowest was for Merlot. In the temperate climate, the highest SO_2 values were recorded for Merlot and Riesling, and the lowest for Zweigelt. A comparison of the two zones indicates that Merlot and Riesling achieved higher SO_2 values in the temperate climate, while Zweigelt had a higher value of this indicator in the warm temperate climate. For Chardonnay, SO_2 values were similar across the zones.

For dust emissions, the highest value was recorded for Zweigelt in the warm temperate climate, where it was 17.40 kg/t. The lowest value was found for Riesling in the same climate zone, i.e., 7.93 kg/t. In the warm temperate climate, dust values decreased in the following order: Zweigelt, Merlot, Chardonnay, and Riesling. In the temperate climate, the highest value was obtained for Chardonnay, while the lowest was for Zweigelt. A comparison of climate zones showed that Chardonnay, Merlot, and Riesling were characterized by higher dust values in the temperate climate, while Zweigelt achieved a higher value in the warm temperate climate.

Table 5. The composition of exhaust gases produced during the combustion of grapevine leaves, depending on the variety and climate zone (m^3/kg)

Climate	Variety	V_{O2}	V_{oa}	V_{CO2}	V_{SO2}	V_{N2}	V_{ga}	V_{gu}
Moderately warm	Chardonnay	0.98 ± 0.030 Aa	4.65 ± 0.12 Aa	0.83 ± 0.001 Aa	0.001 ± 0.000 Ba	5.45 ± 0.08 Aa	7.92 ± 0.14 Aa	6.23 ± 0.08 Aa
	Merlot	0.87 ± 0.002 Cb	4.15 ± 0.01 Cb	0.5 ± 0.001 Bb	0.001 ± 0.000Cb	4.19 ± 0.02Cb	6.55 ± 0.02Cb	4.94 ± 0.02 Cb
	Resling	0.87 ± 0.004 Cb	4.14 ± 0.02 Cb	0.77 ± 0.002 Ca	0.001 ± 0.000 Ab	5.05 ± 0.04 Ba	7.37 ± 0.05 Ba	5.81 ± 0.04 Ba
	Zweigelt	0.91 ± 0.004 Ba	4.35 ± 0.02 Ba	0.77 ± 0.002Bb	0.001 ± 0.000 ABa	5.14 ± 0.04 Ba	7.51 ± 0.05 Ba	5.91 ± 0.04 Ba
	p-value	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
Moderate	Chardonnay	0.90 ± 0.020Bb	4.28 ± 0.08Bb	0.77 ± 0.0001Bb	0.001 ± 0.000 Ba	5.094 ± 0.04Bb	7.43 ± 0.08 Bb	5.87 ± 0.03 Bb
	Merlot	0.93 ± 0.000 Aa	4.45 ± 0.00 Aa	0.78 ± 0.000 ABa	0.001± 0.000 Aa	5.61 ± 0.03 Aa	8.02 ± 0.03 Aa	6.40 ± 0.03 Aa
	Resling	0.90 ± 0.006 Ba	4.27 ± 0.03 Ba	0.77 ± 0.004 Ba	0.002 ± 0.000 Aa	5.107 ± 0.04 Ba	7.44 ± 0.04 Ba	5.87 ± 0.03 Ba
	Zweigelt	0.91 ± 0.010ABa	4.32 ± 0.04 ABa	0.80 ± 0.01 Aa	0.001 ± 0.000 Bb	5.02 ± 0.10 Ba	7.39 ± 0.10 Ba	5.82 ± 0.11 Ba
	p-value	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
p-value	Chardonnay	0.0001	0.0001	0.0001	0.7452	0.0001	0.0001	0.0001
	Merlot	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Resling	0.0001	0.0001	0.5654	0.0001	0.7453	0.3698	0.5654
	Zweigelt	0.7452	0.6569	0.0001	0.0001	0.7512	0.5889	0.4548

Note: V_{O2} – the theoretical oxygen demand, V_{oa} – stoichiometric volume of dry air required to burn 1 kg of biomass, V_{CO2} – the carbon dioxide content, V_{SO2} – the content of sulphur dioxide, V_{H2O} – the water vapour content of the exhaust gas, V_{N2} – the theoretical nitrogen content in the exhaust gas, V_{gu} – the total stoichiometric volume of dry exhaust gas, V_{ga} – the total volume of exhaust gases. Significant difference means that different letters in the column indicate significant differences at α = 0.05.

In summary, the results indicate that none of the analyzed varieties or climate zones was characterized by unambiguously the lowest values for all emission indicators. In the warm temperate climate, the lowest values for CO, NOx, CO_2, and SO_2 were recorded for Merlot, while Riesling had the lowest particulate matter emissions. In the temperate climate, the lowest CO and CO_2 values were obtained for Riesling, while the lowest NOx, SO_2, and particulate matter values were recorded for Zweigelt. From the perspective of emission reduction, Merlot exhibited a more favorable profile in the warm temperate climate for most gaseous emission indicators, while in the temperate climate, Riesling stood out in terms of CO and CO_2, and Zweigelt in terms of NOx, SO_2, and particulate matter.

The assessment of emission indicators was supplemented by an analysis of parameters related to the theoretical combustion process, including oxygen and air requirements as well as the volumes of gaseous combustion products. This allows for a more complete characterization of the properties of the studied biomass in the context of its potential energy use. For all analyzed parameters, statistically significant variation in values was found depending on the combination of grapevine variety and climate zone, at a significance level of $p = 0.0001$. The distribution of values for individual varieties differed between climate zones, indicating that the direction of differences between the warm temperate and temperate climates was not the same for all varieties (Table 5).

The highest V_{O_2} value was recorded for the Chardonnay variety in a warm temperate climate, where it was 0.98 ± 0.030. The lowest values for this parameter were found for Merlot and Riesling in the same climate zone, at 0.87 ± 0.02 m^3/kg and 0.87 ± 0.004 m^3/kg, respectively. In the warm temperate climate, V_{O_2} values decreased in the following order: Chardonnay, Zweigelt, Merlot, and Riesling. In the temperate climate, the highest value was obtained for Merlot, while the lowest values were recorded for Chardonnay and Riesling. A comparison of climate zones indicates that Chardonnay achieved a higher V_{O_2} value in the warm temperate climate, while Merlot and Riesling achieved higher values in the temperate climate. For Zweigelt, the values of this parameter were similar in both zones.

In the case of V_{oa}, the highest value was recorded for Chardonnay in the warm temperate climate, where it was 4.65 ± 0.12 m^3/kg. The lowest value was found for Riesling in the same climate zone, i.e., 4.14 ± 0.02 m^3/kg. In the warm temperate climate, Chardonnay had the highest V_{oa} value, while Merlot and Riesling had the lowest. In the temperate climate, the highest V_{oa} value was obtained for Merlot, and the lowest for Riesling. A comparison of both zones indicates that Chardonnay achieved a higher V_{oa} value in the warm temperate climate, while Merlot and Riesling were characterized by higher values in the temperate climate. For Zweigelt, the V_{oa} values were similar across the zones.

For the V_{CO_2} parameter, the highest value was recorded for Chardonnay in the warm temperate climate, where it was 0.83 ± 0.001 m^3/kg. The lowest value was found for Merlot in the same climate zone, i.e., 0.50 ± 0.001 m^3/kg. In the warm temperate climate, V_{CO_2} values were highest for Chardonnay and lowest for Merlot. In the temperate climate, the highest V_{CO_2} value was obtained for Zweigelt, while the lowest values were recorded for Chardonnay and Riesling. A comparison of climate zones showed that Chardonnay achieved a higher V_{CO_2} value in the warm temperate climate, while Merlot and Zweigelt were characterized by higher values in the temperate climate. For Riesling, V_{CO_2} values were similar in both zones.

For V_{SO_2}, values were low and generally ranged from 0.001 to 0.002 m^3/kg. The highest value of this parameter was recorded for Riesling in the temperate climate, where it was 0.002 ± 0.000 m^3/kg. The lowest values, amounting to 0.001 ± 0.000 m^3/kg, were found for most of the remaining combinations of variety and climate zone. In the warm temperate climate, all varieties were characterized by very similar V_{SO_2} levels. In the temperate climate, a higher value was obtained for Riesling, while for the other varieties the values remained at 0.001 ± 0.000 m^3/kg. A comparison of climate zones indicates that the greatest difference concerned Riesling, for which a higher V_{SO_2} value was recorded in the temperate climate.

For the V_{N_2} parameter, the highest value was recorded for Merlot in the temperate climate, where it was 5.61 ± 0.03 m^3/kg. The lowest value was found for Merlot in the warm temperate climate, i.e., 4.19 ± 0.02 m^3/kg. In the warm temperate climate, the highest V_{N_2} value was obtained for Chardonnay, while the lowest was for Merlot. In the temperate climate, Merlot had the highest value, while Zweigelt had the lowest. A comparison of climate zones showed that Chardonnay had a higher V_{N_2} value in the warm temperate climate, while Merlot achieved a significantly higher value of this parameter in the temperate climate. For Riesling and Zweigelt, VN_2 values were similar across zones.

For V_{ga}, the highest value was recorded for Merlot in the temperate climate, where it was 8.02 ± 0.03 m^3/kg. The lowest value was found for Merlot in the warm temperate climate, i.e., 6.55 ± 0.02 m^3/kg. In the warm temperate climate, Chardonnay had the highest V_{ga} value, while Merlot had the lowest. In the temperate climate, the highest value was obtained for Merlot, and the lowest for Zweigelt. A comparison of climate zones indicates that Chardonnay achieved a higher V_{ga} value in a warm temperate climate, while Merlot was characterized by a distinctly higher value in a temperate climate. For Riesling and Zweigelt, V_{ga} values were relatively similar across zones.

For the V_{gu} parameter, the highest value was recorded for Merlot in a temperate climate, where it was 6.40 ± 0.03 m^3/kg. The lowest value was also found for Merlot, but in a warm temperate climate, i.e., 4.94 ± 0.02 m^3/kg. In the warm temperate climate, Chardonnay had the highest V_{gu} value, while Merlot had the lowest. In the temperate climate, the highest value was obtained for Merlot, and the lowest for Zweigelt. A comparison of climate zones showed that Chardonnay achieved a higher V_{gu} value in the warm temperate climate, while Merlot achieved a significantly higher value in the temperate climate. For Riesling and Zweigelt, V_{gu} values were similar across zones.

In summary, the analyzed parameters related to oxygen and air demand, as well as the theoretical volumes of combustion products, varied both between varieties and between climate zones. In the warm temperate climate, Chardonnay exhibited the highest values for most parameters, i.e., $V_O{}^2$, V_{oa}, $V_{CO}{}^2$, $V_N{}^2$, V_{ga}, and V_{gu}. In the temperate climate, the highest values of $V_O{}^2$, V_{oa}, $V_N{}^2$, V_{ga}, and V_{gu} were recorded for Merlot, while the highest V_{CO_2} value was obtained for Zweigelt. The lowest values for many parameters in the warm temperate climate were recorded for Merlot, whereas in the temperate climate, lower values were more frequently observed for Riesling or Zweigelt. The results indicate that the combustion parameter profile depended on both the grapevine variety and the climate zone, with the ranking of varieties differing across the analyzed climates.

The Table 6 presented contains correlation coefficients between selected emission indicators and the fuel parameters of grapevine biomass analyzed in a warm temperate climate. The table allows for an assessment of the direction and strength of the relationship between emissions—i.e., $V_{CO}{}^2$, $V_{SO}{}^2$, V_{ga}, V_{gu}, CO, NO_x, and dust - and fuel properties, including LHV, elemental composition, ash content, volatile matter, fixed carbon, and moisture. Positive values of the coefficients indicate an increase in the emission index as a given fuel parameter increases, while negative values indicate an inverse relationship. Correlations marked with an asterisk were considered statistically significant.

In the warm temperate climate, an analysis of the correlations between emission indices and fuel parameters revealed a varied pattern of relationships. The strongest and most frequently statistically significant correlations primarily concerned LHV, C, N, S, V, and M. This indicates that in this climate zone, the variability of emission indices was most strongly associated with calorific value, carbon, nitrogen, and sulfur content, volatile matter content, and material moisture. Relationships with H, O, A, and FC were less clear-cut and, in most cases, did not reach statistical significance.

Table 6. Pearson/Spearman correlation coefficients between emission factors and fuel parameters of grapevine biomass in a warm temperate climate

Parameter	LHV (MJ/kg)	C (%)%	H (%)	N (%)	S (%)	O (%)	A (%)	V (%)	FC (%)	M (%)
V_{CO2}	0.97*	0.99*	-0.13	0.61*	0.27	-0.58	0.02	0.57	-0.01	-0.33
V_{SO2}	0.40	0.27	0.09	0.90*	0.98*	0.13	-0.46	0.86*	0.52	-0.87*
V_{ga}	0.85*	0.85*	0.01	0.91*	0.68*	-0.48	-0.07	0.82*	0.12	-0.60*
V_{gu}	0.84*	0.82*	-0.02	0.94*	0.73*	-0.43	-0.12	0.85*	0.17	-0.65*
CO	0.97*	0.99*	-0.13	0.61*	0.27	-0.58	0.02	0.57	-0.01	-0.33
NO_x	0.69*	0.61*	0.00	0.99*	0.90*	-0.17	-0.32	0.93*	0.38	-0.83*
Dust	-0.21	0.02	-0.34	-0.32	-0.46	-0.82	0.98	-0.50	-0.99*	0.79*

Note: * Statistically significant correlations are indicated. Positive correlation coefficients (+) indicate a positive correlation, while negative coefficients (-) indicate a negative correlation.

The V_{CO_2} index was very strongly positively correlated with C (0.99*) and LHV (0.97*). This indicates that an increase in carbon content and fuel calorific value was associated with an increase in the V_{CO_2} value. A statistically significant moderate positive correlation was also observed for N (0.61*). The relationship with V was moderately positive (0.57), but was not statistically significant. Negative but statistically insignificant correlations were observed for O (0.58) and M (-0.33). The correlations with A and FC were very weak, indicating a lack of a clear relationship between these parameters and V_{CO_2}.

For V_{SO_2}, the strongest positive correlation was found with S (0.98*), indicating a close relationship between this emission parameter and the sulfur content in the fuel. Strong positive and statistically significant correlations were also observed for N (0.90*) and V (0.86*). At the same time, V_{SO_2} showed a strong negative correlation with M (-0.87*), meaning that an increase in fuel moisture was associated with a decrease in this parameter's value. The correlations with LHV and FC were moderately positive, 0.40 and 0.52, respectively, but not statistically significant. Correlations with C, H, and O were weak or very weak, while the correlation with A was moderately negative (-0.46), without confirmation of statistical significance.

For the V_{ga} indicator, strong positive correlations were found with N (0.91*), LHV (0.85*), C (0.85*), and V (0.82*). A moderate positive and statistically significant relationship was also observed for S (0.68*). This indicates that an increase in calorific value, carbon, nitrogen, sulfur, and volatile matter content was associated with an increase in the V_{ga} index. At the same time, a statistically significant moderate negative correlation with M (-0.60*) was observed, meaning that higher fuel moisture was associated with lower values of this index. The relationships with H, A, and FC were very weak, while the correlation with O was moderately negative (-0.48) but not statistically significant.

A similar pattern of relationships was observed for V_{gu}. This index was strongly positively and statistically significantly correlated with N (0.94*), V (0.85*), LHV (0.84*), and C (0.82*). A strong positive correlation was also noted for S (0.73*). At the same time, V_{gu} showed a statistically significant moderate negative correlation with M (-0.65*). This means that higher V_{gu} values were primarily associated with higher calorific value, higher carbon, nitrogen, sulfur, and volatile matter content, and lower fuel moisture. Correlations with H, A, and FC were very weak, while the relationship with O was moderately negative but statistically insignificant.

In the case of CO, the relationship pattern was analogous to that of V_{CO_2}. Very strong positive correlations were found with C (0.99*) and LHV (0.97*), as well as a moderate positive correlation with N (0.61*). This indicates that the CO index was most strongly associated with the carbon content and calorific value of the fuel. The moderate positive correlation with V (0.57) was not statistically significant. Negative correlations with O (-0.58) and M (-0.33) also failed to reach significance. The parameters A and FC were practically unrelated to CO, as evidenced by correlation coefficients close to zero.

The most unambiguous correlation profile was obtained for NO_x. This parameter showed a very strong positive and statistically significant correlation with N (0.99*), indicating a particularly strong link between the nitrogen content in the fuel and NO_x. Strong positive correlations were also found with V (0.93*) and S (0.90*). Statistically significant positive correlations were also observed with LHV (0.69*) and C (0.61*), which, according to the adopted scale, were of moderate strength. At the same time, NO_x was strongly negatively correlated with M (-0.83*). These results indicate that higher NO_x values were mainly associated with higher nitrogen, volatile matter, and sulfur content, as well as lower fuel moisture. The relationships with H, O, A, and FC were weaker and statistically insignificant.

A different nature of the relationship was observed for the dust emission factor. Dust showed a strong negative and statistically significant correlation with FC (-0.99*) and a strong positive and statistically significant correlation with M (0.79*). This means that a higher fixed carbon content was associated with a decrease in the Dust value, while an increase in fuel moisture was associated with an increase in this parameter. A very strong positive correlation was also observed for A (0.98); however, the lack of statistical significance indicates that this relationship should be interpreted with caution. A strong negative correlation was also observed for O (-0.82), but again without statistical significance. The relationships with LHV, C, H, N, S, and V were weak or moderate and statistically insignificant, indicating that dust emissions exhibited a different relationship profile than gaseous emissions.

In summary, in the warm temperate climate, gaseous emissions showed the strongest associations with LHV, C, N, S, and V. The most consistent relationships were observed for N, which was positively and significantly correlated with most of the analyzed emission indicators, and most strongly with NO_x. Sulfur content was strongly associated with V_{SO_2} and significantly related to V_{ga}, V_{gu}, and NO_x. The proportion of volatile matter showed strong positive correlations with V_{SO_2}, V_{ga}, V_{gu}, and NO_x, while humidity was negatively correlated with these indicators but positively related to dust emissions. A different relationship profile was observed for Dust, for which the strongest statistically significant correlations were found with FC and M, while LHV, C, N, and S showed no significant correlations. The parameters H, O, and A were characterized by weaker or less clear relationships with most emission indicators, with the exception of strong but not statistically significant correlations between A and O and dust.

The final stage of the analysis was hierarchical cluster analysis, which enabled a synthetic assessment of the similarity of varieties based on the entire set of analyzed parameters (Figure 2). Dendrograms allow us to identify which varieties formed similar trait profiles and which exhibited distinct characteristics within a given climate zone.

The dendrogram identified a cluster comprising the Riesling and Zweigelt varieties, which were grouped together at the shortest agglomeration distance. This indicates that these varieties had the most similar energy parameter profile among all the varieties analyzed. In the next stage, the Merlot variety was added to this cluster, meaning that its energy profile was more similar to that of Riesling and Zweigelt than to Chardonnay, though it showed greater divergence than the relationship between Riesling and Zweigelt.

The Chardonnay variety formed a separate cluster and was combined with the other varieties only at the greatest agglomeration distance. This indicates the greatest distinctiveness of this variety in terms of the overall profile of energy parameters. This arrangement on the dendrogram suggests that Chardonnay differed most from the other varieties in the analyzed climate zone.

In summary, hierarchical cluster analysis allowed us to identify two main similarity patterns. The first included the Riesling–Zweigelt cluster, which was subsequently joined by Merlot. The second pattern was represented by Chardonnay, characterized by the most distinct energy profile. The clustering results indicate that the studied varieties did not form a homogeneous group in terms of energy parameters, and the greatest differentiation concerned the separation of Chardonnay from the other varieties.

In the temperate climate, the cluster arrangement differed from that in the previously analyzed zone (Figure 3).

A hierarchical cluster analysis based on all energy parameters showed that the greatest similarity was found between the Chardonnay and Riesling varieties. These varieties were grouped together with the smallest agglomeration distance, indicating the most similar energy profile within this climate zone.

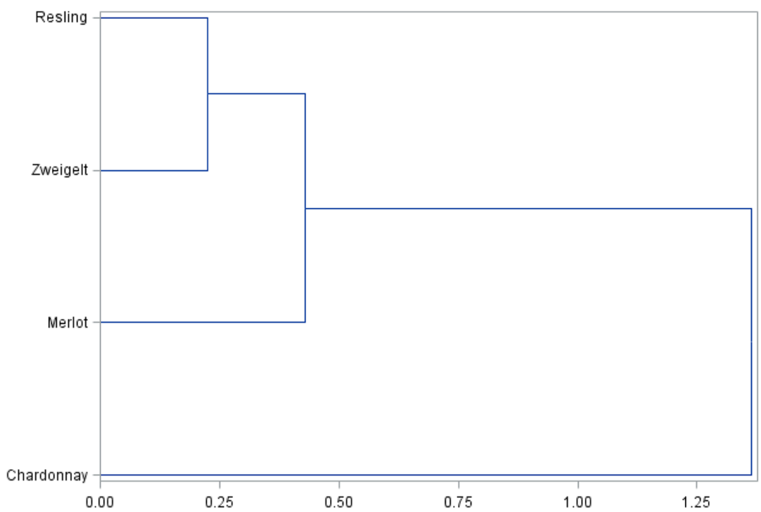

Figure 2. Hierarchical cluster analysis of grapevine varieties based on energy parameters in a moderately warm climate

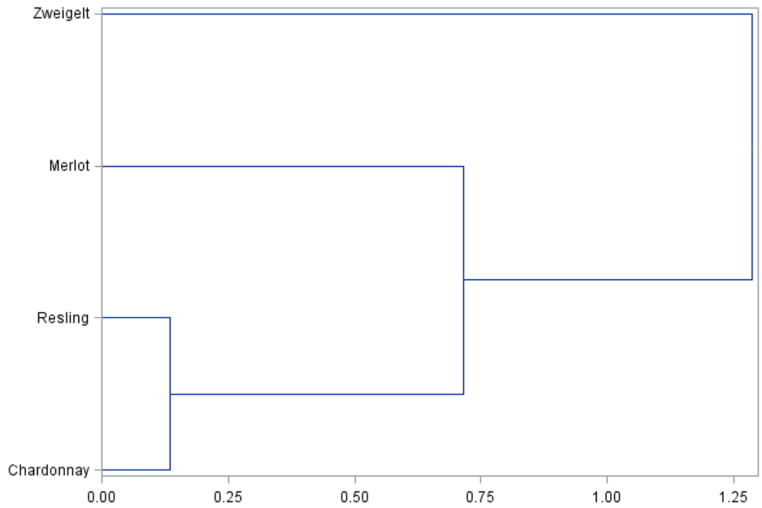

Figure 3. Hierarchical cluster analysis of grapevine varieties based on energy parameters in a temperate climate

In the next stage, the Merlot variety was added to the cluster comprising Chardonnay and Riesling. This means that Merlot showed partial similarity to this group, but its energy profile was more distinct than the relationship between Chardonnay and Riesling. Thus, in the temperate climate, a cluster comprising Chardonnay, Riesling, and Merlot can be distinguished, with the first two varieties forming the most compact cluster.

The most distinct variety was Zweigelt, which was grouped with the other varieties only at the greatest agglomeration distance. This indicates that Zweigelt was characterized by the most distinct energy parameter profile compared to the other varieties analyzed in the temperate climate.

In summary, in the temperate climate, the dendrogram indicates the formation of a single main cluster comprising Chardonnay, Riesling, and Merlot, as well as the separately located Zweigelt variety. The greatest energy similarity was found between Chardonnay and Riesling, while Zweigelt showed the greatest distinctiveness. Compared to the warm temperate climate, the clustering pattern was different, indicating that the similarity of varieties in terms of energy parameters depended on the analyzed climate zone.

In the next stage of the analysis, the relationships between emission factors and the fuel parameters of grapevine biomass in a temperate climate were evaluated (Table 7). The Pearson/Spearman correlation coefficients presented in the table allow for the determination of the direction and strength of the relationships between fuel properties and emission indicators. Statistically significant correlations are marked with an asterisk.

In temperate climates, an analysis of the correlations between emission indicators and fuel parameters revealed a varied pattern of relationships. The strongest and most frequently statistically significant correlations primarily concerned

Table 7. Pearson/Spearman correlation coefficients between emission indices and fuel parameters of four grape varieties in a temperate climate

Parameter	LHV (MJ/kg)	C (%)	H (%)	N (%)	S (%)	O (%)	A (%)	V (%)	FC (%)	M (%)
V_{CO2}	0.40	0.99*	-0.12	-0.01	-0.36	0.37	-0.75*	-0.28	0.64*	0.18
V_{SO2}	0.58	-0.36	0.48	0.77*	0.99*	-0.62*	0.50	0.76*	-0.55	-0.64*
V_{ga}	0.73*	0.13	0.61*	0.96*	0.70*	-0.77*	0.39	0.80*	-0.54	-0.07
V_{gu}	0.72*	0.13	0.54	0.98*	0.70*	-0.78*	0.40	0.81*	-0.56	-0.08
CO	0.40	0.99*	-0.12	-0.01	-0.36	0.37	-0.75*	-0.28	0.64*	0.18
NO_x	0.66*	-0.01	0.44	0.99*	0.77*	-0.84*	0.52	0.87*	-0.66*	-0.12
dust	-0.19	-0.75*	0.18	0.52	0.50	-0.87*	0.99*	0.64*	-0.97*	0.14

Note: * Statistically significant correlations are indicated. Positive correlation coefficients (+) indicate a positive correlation, while negative coefficients (-) indicate a negative correlation.

C, N, S, O, A, V, FC, and LHV. This means that in this climate zone, the variability of emission indices was particularly linked to the elemental composition of the fuel, the proportion of volatile matter, ash content, fixed carbon, and calorific value. The relationships with M were less clear-cut than in the warm temperate climate, and a statistically significant correlation with humidity was observed mainly for V_{SO_2}.

The V_{CO_2} index was very strongly positively correlated with C (0.99*), indicating a strong link between the carbon content in the fuel and the value of this emission index. Statistically significant correlations were also observed for A (-0.75*) and FC (0.64*). The relationship with A was strongly negative, while that with FC was moderately positive. This means that higher V_{CO_2} values were associated with higher carbon and fixed carbon content and lower ash content. Correlations with LHV, O, and M were weak or moderate but not statistically significant, while correlations with H, N, S, and V were very weak or weak.

For V_{SO_2}, the strongest positive correlation was found with S (0.99*), indicating a very strong relationship between this indicator and the sulfur content in the fuel. Statistically significant positive correlations were also observed for N (0.77*) and V (0.76*). At the same time, $_{VSO_2}$ was significantly negatively correlated with O (-0.62*) and M (-0.64*). This indicates that an increase in sulfur, nitrogen, and volatile content was associated with an increase in V_{SO_2}, while higher oxygen and moisture content was associated with lower values of this index. Correlations with LHV, H, A, and FC were moderate but were not statistically significant.

For the V_{ga} factor, a very strong positive correlation was found with N (0.96*) and strong positive correlations with V (0.80*), LHV (0.73*) and S (0.70*). A statistically significant moderate positive correlation was also observed for H (0.61*). At the same time, V_{ga} was strongly negatively correlated with O (-0.77*). These results indicate that higher V_{ga} values were mainly associated with higher nitrogen, volatile matter, sulfur, and hydrogen content, as well as higher calorific value, whereas lower values of this index were associated with higher oxygen content. The relationships with C, A, FC, and M were weak or moderate and statistically insignificant.

A similar pattern of relationships was observed for V_{ga}. This index was very strongly positively correlated with N (0.98*) and strongly positively correlated with V (0.81*), LHV (0.72*), and S (0.70*). A strong negative correlation was found with O (-0.78*). This means that an increase in V_{gu} was primarily associated with higher nitrogen, volatile matter, and sulfur content, as well as a higher calorific value, while showing a negative association with oxygen content. Correlations with C, H, A, FC, and M were not statistically significant, indicating their lesser importance in determining this index in the analyzed climate zone.

In the case of CO, the pattern of relationships was analogous to that of V_{CO_2}. The CO factor was very strongly positively correlated with C (0.99*) and significantly associated with A (-0.75*) and FC (0.64*). The relationship with A was strongly negative, while that with FC was moderately positive. This indicates that higher CO values were primarily associated with higher carbon and fixed carbon content, as well as lower ash content. Correlations with LHV, O, and M were weak or moderate but not statistically significant, while relationships with H, N, S, and V were very weak or weak.

The most unambiguous correlation profile was obtained for NO_x. This parameter showed a very strong positive and statistically significant correlation with N (0.99*) and strong positive correlations with V (0.87*) and S (0.77*). A statistically significant moderate positive correlation was also observed for LHV (0.66*). At the same time, NO_x was strongly negatively correlated with O (-0.84*) and moderately negatively correlated with FC (-0.66*). These results indicate that higher NO_x values were mainly associated with higher nitrogen, volatile matter, and sulfur content, as well as higher calorific value, whereas lower values of this indicator were associated with higher oxygen and fixed carbon content. The relationships with C, H, A, and M were not statistically significant.

A different nature of the relationship was found for the dust emission index. Dust showed a very strong positive correlation with A (0.99*) and a strong positive correlation with V (0.64*). At the same time, strong negative correlations were found with FC (-0.97*), O (-0.87*) and C (-0.75*). This means that higher Dust values were primarily associated with higher ash and volatile matter content, while lower values of this index were associated with higher fixed carbon, oxygen, and carbon content. Correlations with LHV, H, N, S, and M were not statistically significant, indicating that dust emissions in temperate climates exhibited a different relationship profile than most gaseous emission indicators.

In summary, in a temperate climate, gaseous emissions were most strongly associated with C, N, S, V, O, and LHV. C content was particularly strongly and positively correlated with V_{CO_2} and CO, while N showed very strong positive correlations with Voga, Vogu, and NOx. S content was most strongly associated with V_{SO_2}, but significant positive correlations were also observed for V_{ga}, V_{gu}, and NO_x. The proportion of volatile components was significantly positively correlated with V_{SO_2}, V_{ga}, V_{gu}, NO_x, and dust. In contrast, O showed mainly strong negative correlations with V_{SO_2}, V_{ga}, V_{gu}, NO_x, and dust. A different correlation profile was observed for Dust, for which key significant correlations were found with A, FC, O, C, and V. Moisture (M) had limited significance in this climate zone, and a significant correlation was noted only for V_{SO_2}.

DISCUSSION

An analysis of the energy properties of grape leaves from the Chardonnay, Merlot, Riesling, and Zweigelt varieties reveals significant differences resulting from both varietal characteristics and the climatic conditions of the temperate (Poland) and warm temperate (Czech Republic) zones.

Analysis of the obtained research results indicates that the higher heating value (HHV) of the tested leaves ranges from 16.07 to 18.04 MJ/kg. These values are similar to those of grapevine shoots 17.02 MJ/kg (Ayala et al., 2025), 17.49 MJ/kg (Malaťák et al., 2022)) (Table 8). It is worth noting that the highest HHV was recorded for the Chardonnay variety in the moderately warm climate (18.04 MJ/kg), while in the temperate climate this value was significantly lower (16.33 MJ/kg). This suggests that a warmer climate favors the accumulation of compounds with higher energy density in this particular variety. In contrast, the Merlot variety showed the opposite relationship, achieving a higher HHV value in Poland (17.29 MJ/kg) than in the Czech Republic (16.07 MJ/kg). These results are comparable to data for leaves of the Touriga Franca variety studied in Portugal (HHV 16.86 MJ/kg) (Oliveira et al., 2025).

One of the most problematic parameters for grape leaf biomass is the high ash content (A), which ranges from 6.28% to 13.78% in the tested samples. These values are significantly higher than those for Class A1 wood pellets, which is typical for herbaceous and deciduous biomass (EN-ISO 17225-2:2021, 2021). This value is significantly higher than that for shoots (3.70%) (Malaťák et al., 2022) or pine wood (Symanowicz et al., 2018), which is typical for herbaceous biomass. The lowest ash content (6.28%) was observed in the Riesling variety in a warm temperate climate, making it the most technologically advantageous (lower risk of slagging). Grape leaves in a temperate climate (Poland) tend to have a higher ash content (as high as 12.93% for Chardonnay) compared to a warm temperate climate (Czech Republic), which may result from more intensive mineral uptake under cooler conditions

The volatile matter content (V) was significantly higher in the temperate climate (71.94–73.44%) compared to the warm temperate climate (64.25–66.77%). The higher volatile matter content in the Polish samples indicates greater fuel reactivity and easier ignition, which is a characteristic feature of biomass from regions with a shorter growing season.

The carbon content (C) in leaves (40.09–44.22%) is consistent with literature data for

Table 8. Comparison of energy parameters for literature data

Material	HHV (MJ/kg)	LHV (MJ/kg)	A (%)	C (%)	N (%)
Red grape pomace (Malaťák et al., 2022)	22.17	20.84	5.24	53.18	2.13
Grape pomace (general) (Ayala et al., 2025)	20.74	19.20	7.36	49.32	3.54
Grape stems (Malaťák et al., 2022)	17.49	16.29	7.89	46.53	0.68
Vine prunings (Ayala et al., 2025)	17.02	17.59*	3.70	43.07	0.78
Grape leaves (Touriga Franca) (Oliveira et al., 2025)	16.86	16.85	8.20	43.20	5.37
Grape leaves (Regent) (Klimek et al., 2022)	-	-	12.30**	-	1.83
Hydrochar from wine waste (Barbanera et al., 2021)	24.10	22.26	3.58	60.86	2.14

Note: * Value reported by Ayala et al. (2025) for dry matter of shoots. ** Value estimated based on the organic dry matter (ODM) content provided in the source.

grapevine biomass (approx. 43–49%) (Ayala et al., 2025; Maj et al., 2022b; Malaťák et al., 2022; Vassilev et al., 2017). A key climatic difference is evident in the nitrogen (N) content, which in the temperate climate (Poland) was higher for most varieties, reaching 2.63% for the Merlot variety. By comparison, in the Czech Republic, the Merlot variety contained only 1.14% nitrogen. Such a high N content in Polish grape leaves (more than ten times higher than in wood) poses a significant emissions challenge, suggesting potentially higher nitrogen oxide (NOx) emissions during combustion, as confirmed by studies on agricultural biomass. The sulfur (S) content remained low (0.11–0.21%), making the leaves a safe fuel in terms of SO_2 emissions, similar to other vineyard waste (Ayala et al., 2025; Malaťák et al., 2022).

Particulate matter emissions showed high variability among varieties. The highest particulate matter levels were recorded for the Zweigelt variety (17.40 mg/m³) in a warm temperate climate and for Chardonnay in a temperate climate (16.34 mg/m³). Klimek et al. (2022) indicate that the combustion of vineyard waste without appropriate purification systems can lead to the emission of significant amounts of particulate matter into the atmosphere. Research data confirm that leaves from a cooler climate (Poland) tend to generate higher dust emissions for most varieties (except Zweigelt).

Studies show that grape leaves from a warm temperate climate have better energy parameters (higher HHV, lower ash content) than those from a temperate climate. The Chardonnay variety appears to be the most promising energy feedstock in both zones, although it requires exhaust gas treatment systems due to nitrogen and particulate emissions.

An analysis of emission parameters generated during the combustion of grape leaves of the Chardonnay, Merlot, Riesling, and Zweigelt varieties in two different climatic zones (warm temperate—Czech Republic, and temperate—Poland) reveals significant differences that are crucial for assessing the environmental aspects of using this biomass. Below is a discussion of the results based on raw data and their comparison with the literature.

The results show that CO emissions for the studied grape leaves range from 49.39 to 54.48 kg/t. The highest emissions were recorded for the Chardonnay variety in a warm temperate climate (54.48 kg/t), while in a temperate climate this value was lower (50.84 kg/t). When comparing these data with the results obtained by Malat’ák et al. (2022) (Table 9), who studied grape pomace and stems, the stability of the leaf combustion process is evident. The literature indicates that high CO emissions (often exceeding the standard of 2000 mg/m³) are a problem when burning pure grapevine biomass, suggesting the need to use mixtures with herbaceous biomass to optimize the process (Commission Regulation (EU) 2015/1185 of 24 April 2015 Implementing Directive 2009/125/EC of the European Parliament and of the Council with Regard to Ecodesign Requirements for Solid Fuel Local Space Heaters (Text with EEA Relevance), 2017; Malaťák et al., 2022).

The most drastic climatic differences were observed in terms of NO_x emissions. The Merlot variety stands out in particular, generating 9.27 kg/t of NOx in a temperate climate (Poland), while in a warm temperate climate (Czech Republic) this value was only 4.03 kg/t.

This represents an increase of over 100%, suggesting that a cooler climate promotes higher nitrogen accumulation in the tissues of this variety. The literature confirms that the nitrogen content in grapevine biomass (ranging from 2.13–3.54%) is directly correlated with NOx emissions (Malaťák et al., 2022; Toscano et al., 2013). Results for the remaining varieties in both zones were more consistent (7.08–7.84 kg/t).

CO_2 emissions were highest for the Chardonnay variety in the Czech Republic (1334.04 kg/t), which is associated with the high elemental carbon content in this raw material. In the temperate climate, the highest CO_2 value was recorded for the Zweigelt variety (1282.93 kg/t). In contrast, SO_2 emissions remained at a very low level (below 0.42 kg/t) in all samples. This is consistent with the elemental analyses by Ayala et al. (2025) and Malat’ák (2017, 2022), which show trace sulfur content (0.04–0.12%) in wine waste, making it a safe fuel in terms of sulfur compound emissions.

Particulate matter emissions showed high variability. The highest particulate matter levels were recorded for the Zweigelt variety in a warm temperate climate (17.40 kg/t) and for Chardonnay in a temperate climate (16.34 kg/t). The literature indicates that high ash content (which ranges from 5.24% to 7.89% for stems and pomace) is the main factor generating particulate matter emissions during combustion. Klimek et al. (2022) emphasize that the lack of adequate flue gas treatment systems during the combustion of

Table 9. Comparison of emissions for selected biomass

Material	CO [mg/m³]	NOx [mg/m³]	SO_2 [% or mg/m³]	Ash / Dust [% d.s.]
Red grape pomace (Malaťák et al., 2022)	7865.37	532.46	0.11–0.12*	5.24
White grape pomace (Malaťák et al., 2022)	10 270.74	572.99	0.06–0.07*	5.85
Grape stems (Malaťák et al., 2022)	9823.39	730.88	0.04*	7.89
Grapevine prunings (Barbanera et al., 2021)	high**	0.84*	0.05*	3.52
Pomace/Miscanthus mix (50/50) (Malaťák et al., 2022)	2023.81	496.43	trace	-
Miscanthus straw (MS-100) (Malaťák et al., 2022)	1365.00	473.51	0.08*	5.07
Grape leaves (biogas - H_2S) (Klimek et al., 2022)	-	-	82–193 ppm***	12.3–15.8

Note: * The value refers to the sulfur (S) or nitrogen (N) content in the dry matter (d.m.) of the fuel. ** The literature indicates significant pollutant emissions during open combustion of shoots. *** Hydrogen sulfide (H_2S) concentration in biogas obtained from leaves.

wine biomass leads to a significant burden on the atmosphere from particulate matter.

Analysis of the stoichiometric parameters of grape leaf combustion, such as the theoretical air requirement (V_{gu}) and the theoretical volume of dry exhaust gas (V_{ga}), allows for the assessment of energy efficiency and the design of exhaust gas discharge systems depending on the climate zone (Poland – temperate climate vs. Czech Republic – warm temperate climate). The data analysis shows that grape leaves are characterized by a high air demand for combustion, ranging from 4.94 to 6.40 m³/kg. A significant dependence on the climate zone is noticeable. For the Chardonnay variety, higher values were recorded in the warm temperate climate (6.28 m³/kg) than in the temperate climate (5.87 m³/kg). The opposite trend was observed for the Merlot variety, where biomass from Poland showed a significantly higher requirement (6.40 m³/kg) than that from the Czech Republic (4.94 m³/kg). When comparing these results with the literature, a clear advantage of leaves over other wine-making waste is evident. According to research by Malat'ák et al. (2022), the theoretical air demand for red grape pomace is 4.79 m³/kg, and for stems only 3.86 m³/kg.

The values obtained for leaves (up to 6.40 m³/kg) suggest a higher carbon and hydrogen content in the tested leafy biomass, which translates to the need to supply a greater amount of oxygen during the oxidation process (Ayala et al., 2025; Malaťák et al., 2017). The amount of dry flue gas generated for the tested leaves ranges from 6.55 to 8.02 m³/kg. The highest flue gas generation value was recorded for the Merlot variety in Poland (8.02 m³/kg) and Chardonnay in the Czech Republic (7.92 m³/kg). These parameters are significantly higher than those reported in the literature for white pomace (4.45 m³/kg) or red pomace (4.66 m³/kg) (Malaťák et al., 2022).

Such a large volume of flue gas generated by the leaves is of critical importance for the design of heating equipment—it requires the use of exhaust fans with higher capacity and appropriately sized flue cross-sections compared to the combustion of typical wood or pomace (Ahmed et al., 2024).

Differences between climatic zones indicate that growth conditions (temperature sum, humidity) significantly modify the elemental composition of leaves. The higher air demand and greater flue gas emissions in the Polish samples of the Merlot variety may result from different dynamics of organic compound accumulation in a temperate climate. At the same time, the low values for the Merlot variety in the Czech Republic suggest higher ash content or lower levels of combustible elements in the tissues from that region.

CONCLUSIONS

The grapevine variety (*Vitis vinifera* L.), the climate zone of the growing site, and their interaction significantly ($p = 0.0001$) determine the fuel properties, elemental composition, and emission profile of waste biomass in the form of leaves.

The energy value of the analyzed raw material shows strong variation by variety and growing site; the highest calorific potential (HHV – 18.04 MJ/kg and LHV – 16.27 MJ/kg) was found for the Chardonnay' in a warm temperate climate, whereas from a technological perspective (lowest ash content of 6.28% and low moisture content), the Riesling' variety stood out with the most favorable profile in the same zone.

Theoretical combustion process parameters, such as air demand and the volume of generated flue gases, are strictly dependent on the climate zone; in a warm temperate climate, the Chardonnay' variety generates the highest values of these indicators, while in a temperate climate, the Merlot' variety exhibits the highest combustion process parameters.

Correlation analysis confirmed that emissions of nitrogen oxides (NO_x) and sulfur (SO_2) are directly and most strongly determined in both zones by the nitrogen and sulfur content in the leaf structure, respectively, while particulate matter emissions exhibit a different mechanism of relationships, depending mainly on ash content in the temperate climate and fixed carbon (FC).

Multidimensional cluster analysis showed that the structure of technological similarity among varieties is reversed under the influence of the environment—in the warm temperate climate, the Riesling' and Zweigelt' varieties exhibit the most similar profile (with Chardonnay' being distinctly different), whereas in a temperate climate, Chardonnay' and Riesling' show the highest similarity, and Zweigelt' occupies an extremely distinct position.

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