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Utilisation of Woody Waste from Wine Production for Energy Purposes Depending on the Place of Cultivation

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Abstract

Orchard crops generate substantial quantities of diverse biomass each year, with grapevines being among the most economically significant species worldwide. Considering the scale of this biomass, there is a growing need to explore rational strategies for its utilisation, for example, for energy production or other value-added applications. Such approaches may contribute to improving resource efficiency and reducing the environmental burden associated with agricultural waste. The aim of this study was to examine the energy potential of woody post-production waste from wine processing, with particular emphasis on grape stems of four cultivars—Chardonnay, Riesling, Merlot, and Zweigelt—grown in two contrasting climatic regions: south-eastern Poland and Moravia (Czech Republic). The results demonstrated that both the grape variety and cultivation site significantly influenced the majority of bunch biometric traits, including bunch and berry weight, berry number, and stem dimensions. A moderately warm climate promoted the development of larger and heavier bunches as well as more robust stems across all examined cultivars. Energy analyses indicated that Zweigelt stems produced under moderately warm conditions and Chardonnay stems from a temperate climate exhibited the most favourable combustion properties. Nonetheless, certain constraints were identified, such as increased ash (12.20%) and moisture content (11.51%) in Chardonnay grown in warmer conditions, and elevated CO and CO_2 emissions observed for Zweigelt (1333.26 kg·mg^{-1}). Overall, the findings confirm that grape stems constitute a promising local source of bioenergy, with their energy performance determined predominantly by varietal characteristics and climatic factors. Their utilisation aligns with circular-economy principles and may help reduce the environmental impacts associated with traditional viticultural waste management.

Keywords: stems; calorific value; climate zone; *Vitis vinifera* L.

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1. Introduction

Grapes (*Vitis vinifera* L.) belong to the Vitaceae family and are cultivated worldwide on an area of 7.3 million hectares, with a production of 85 million tonnes, of which 57% is used for wine production, 36% is consumed fresh as table grapes, and the remaining

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7% is dried into raisins [1]. Grapes are characterised by rich genetic diversity, with over 10,000 cultivated varieties worldwide [2]. Vines are widely cultivated around the world and have adapted to a wide range of weather conditions [3]. Gradual climate warming favours vine cultivation in places where it has so far been amateurish [4,5]. This production generates a significant amount of wine processing residues (seeds, skins, leaves, and stems) produced by the wine industry, which places a burden on the environment. During the processing of grapes into wine, waste stalks are produced. They account for 3% to 6% of the total weight of grapes, which, with a yield of 10 tons of grapes from an area of 1 ha, gives us waste in the form of stalks at the level of 300–600 kg from 1 ha. They consist of tissues rich in substances such as lignin, cellulose, and hemicellulose, which are characterised by a high carbon content. Due to the large number of stems generated in the grape processing process, it is necessary to solve the problem of their management. This also involves economic and environmental issues. In practice, their processing involves composting and introduction into the soil or various forms of biological treatment. Another way of utilising this grape processing waste is to use it for combustion as a solid fuel, in mixtures with wood biomass [6].

Issues related to energy security, progressive climate change, and rising oil prices have a significant impact on the global population. In addition, the ever-increasing demand for energy resulting from population growth is putting pressure on limited energy resources. In this context, the potential for utilising agricultural and related waste as raw materials for bioenergy production is recognized [7]. Energy production is a fundamental element supporting basic areas of human activity, including food and drinking water production, transport, communication, education, and healthcare systems. At the same time, the energy sector remains one of the main sources of greenhouse gas emissions, contributing significantly to global warming [8]. Climate change, alongside other anthropogenic environmental problems, is one of the most serious and complex challenges facing humanity today. To a large extent, this phenomenon is the result of the combustion of fossil fuels, which at the same time form the foundation of the modern model of development, prosperity, and lifestyle [9]. In view of the constant demand for energy, identifying a source capable of meeting global energy needs remains a significant challenge. Moreover, the source sought should be stable, sustainable, and resistant to the effects of global warming [10]. Bioenergy obtained from agricultural residues shows significant potential as a source of sustainable energy, while offering measurable benefits for the natural environment [11]. Increasing the efficiency and optimising the use of energy obtained from biomass are considered beneficial solutions in the context of reducing carbon dioxide emissions into the atmosphere [12]. The growing interest in bioenergy has sparked intense public debate, with differing opinions on the amount of biomass that can be sustainably used for energy purposes. Both the efficiency of agricultural systems and the selection of appropriate crops play an important role in this context. It is estimated that the global biomass potential could meet up to one-third of the projected global energy demand by 2050 [13]. Waste biomass has the potential to become a key element in shaping a bioeconomy integrated with the circular economy model [14]. The wine industry is characterised by high waste generation intensity [15]. In recent years, the wine sector has shown a growing commitment to sustainable development [16]. Although viticulture in Poland is likely to remain of minor economic importance in the short to medium term, due to climate change, it may become a significant branch of the agribusiness sector in the long term. In Poland, despite the small scale of the industry, the dynamic growth in cultivation area and number of producers is due to different conditions. Wine production is still emerging, and domestic demand—although small—continues to grow, driven by trends such as localism, wine tourism, the search for artisanal products and the growing recognition of Polish wine [17]. In recent years, Poland has seen dynamic growth in wine production, based on records and registrations kept by the National Agricultural Support Centre (KOWR). At the end of the first quarter of 2025, 673 grape growers cultivated grapes on a total area of approximately 1023 ha (KOWR data). During the same period, 304 entrepreneurs were involved in the production or bottling of wine products [18]. The Czech Republic has a long-established tradition and significant potential for wine production, which is reflected in the register of vineyards maintained by ÚKZÚZ. As of 31 December 2023, the area planted with vines was approximately 17,734.9 ha, which is part of the total production potential of over 18,071 ha [19].

In the Czech Republic, wine production plays a key role in national agricultural production and has seen a marked improvement in quality in recent years [20]. Waste generated in the wine production process has favourable energy parameters, making it a potential source of biofuels. Its use can significantly support the fuel and energy balance of farms and agri-food businesses [21]. Vine stalks, thanks to their favourable combustion properties and low emissions of harmful substances, are an effective and renewable source of energy [22]. Due to the growing potential of grapevine cultivation and wine production in Poland and the Czech Republic, the management of waste from this sector is also becoming increasingly important.

The aim of the study was to analyse and evaluate the energy potential of biomass obtained from grape stems obtained after manual separation of berries in Poland and the Czech Republic, from the Chardonnay, Riesling, Merlot, and Zweigelt varieties, as a by-product of wine production, through combustion.

2. Materials and Methods

Field studies were conducted in 2024 at two locations: the Experimental Vineyard of the University of Life Sciences in Lublin (gps 51.228637, 22.634241; 210 m n.p.m.), located in south-eastern Poland, and the Mendel University Vineyard in Lednice (48.789898, 16.797300; 200 m n.p.m.), (Moravia, Czech Republic). Both vineyards were located on large hills (4%) with a southern slope. The experiment was designed in a randomised block design. It included eight combinations (four varieties in two different climate zones) with ten replicates in each. The replicates consisted of plots of five plants (5 plants × 10 replicates for each of the eight combinations). The plants were planted at a spacing of 2 m × 1 m (5000 plants in 1 ha). *Vitis vinifera* L. vines, i.e., Chardonnay, Merlot, Riesling, and Zweigelt, were trained using a single Guyot system, with a 40 cm high trunk, a single shoot approximately 1.0 m long, and a single two-bud shoot. In this study, both analysed materials (vine stalks with locations in Poland and the Czech Republic) originated from plantations managed using conventional cultivation systems, in accordance with local viticultural practices. Fertilization programs based on soil analysis and vine nutrient requirements were implemented in both locations, which is typical conventional practice in grape production. The soil analysis results indicated the need for supplementation of basic macronutrients (N; 80 kg N, 110 kg, 15 kg P_2O_5, 110 kg K_2O ha·year) in amounts consistent with viticultural practices. The soil pH was maintained within the optimal range (6.5–7 pH). The grapes were harvested manually after reaching optimal ripeness, between 23.5 and 24.5 °Brix. The harvest in the Czech Republic took place on 5 September 2024, while in Poland it took place on 23 September 2024. A total of 25 kg of grapes were harvested from each combination, regardless of the place of cultivation. Biometric measurements were taken to determine the weight of 30 representative bunches for each combination analysed, then the berries were separated from the stems by hand, the number of berries in the bunch was determined on the basis of 30 bunches for each combination, the weight and diameter of one berry for 100 representative berries, the weight, length and width of the stem, and the proportion of the stem in the weight of the bunch. The weight of the clusters, berries

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and stalks was determined using a PS R2 RADWAG precision balance with an accuracy of 0.001 kg (Radwag, Radom, Poland, 2022), the diameter of the berries using a 150 mm Limit 144550100 electronic calliper (Limit, Leszno, Poland, 2023), and the length and width of the stalks using a scale with an accuracy of 0.1 cm. The stems of the tested varieties were dried at room temperature (Figure 1).

Figure 1. Shoots of the examined grapevines of the species *Vitis vinifera* L.

Before testing, the material was placed in a room with a constant temperature and humidity, where it was dried naturally in air-dry conditions at 20 °C and 55% to 60% humidity for two weeks in order to standardise the assessment conditions. The material for laboratory analysis was first ground (0.5 mm) using a Retsch SM 100 mill (Retsch GmbH, Haan, Germany, 2022) with a power of 1.5 kW. For this study, 100 g of material was obtained in 2 min, which consumed 0.045 kWh. Our results present values in an analytical state; additionally, in the case of HHV, the analytical state was converted to a dry state without ash. The detailed methodology of the evaluated energy parameters is discussed in Table 1.

Table 1. Parameters determined in the study.

	Parameter	Equipment	Standard
Proximate Analysis 5	Ash (A; %) Volatile matter (V; %) Moisture (M; %) Fixed carbon (FC; %)	LECO TGA 701 thermogravimetric analyser (LECO Corporation, Saint Joseph, MI, USA, 2013) FC = 100 − V − A − M	EN-ISO 18122:2022 [23] EN-ISO 18123:2016-01 [24] EN-ISO 18134-1:2022 [25] Choudhury et al. [26]
Energetic properties	Higher heat value (HHV; MJ·kg^{-1}) Lower heat value (LHV; MJ·kg^{-1})	LECO AC 600 isoperibolic calorimeter (LECO Corporation, Saint Joseph, MI, USA, 2012)	EN-ISO 1928:2020 [27]
Ultimate Analysis	Carbon (C; %) Hydrogen (H; %) Nitrogen (N; %) Sulphur (S; %) Oxygen (O; %)	LECO CHNS 628 elemental analyser (LECO Corporation, Saint Joseph, MI, USA, 2012) O = 100 − A − H − C − S − N	EN-ISO 16948:2015-07 [28] EN-ISO 16994:2016 [29] Alves et al. [30]

2.1. Emission Factors

In order to estimate the emission factors for SO_2, CO_2, CO, Nox, and dust for grape stalks, the emission factor method based on final analysis was used; the lower calorific value was used to convert the factors per unit of Energy [31,32].

Carbon monoxide Emission factor (Ec) of chemically pure coal (CO; kg·Mg^{-1}):

$$\mathrm{CO} = \frac{28}{12} \cdot \mathrm{E_c} \cdot (\mathrm{C/CO}),$$

CO—carbon monoxide emission factor (kg·kg^{-1}), $\frac{28}{12}$—molar mass ratio of carbon monoxide and carbon, E_C—emission factor of chemically pure coal (kg·kg^{-1}), C/CO—part of the carbon emitted as CO (for biomass 0.06).

Carbon dioxide emission factor (CO_2; kg·Mg^{-1}):

$$\mathrm{CO_2} = \frac{44}{12} \cdot \left(\mathrm{E_c} - \frac{12}{28}\mathrm{CO} - \frac{12}{16} \cdot \mathrm{E_{CH_4}} - \frac{26.4}{31.4} \cdot \mathrm{E_{NMVOC}}\right),$$

CO_2—carbon dioxide emission factor (kg·kg^{-1})—molar mass ratio of carbon dioxide and pure coal—molar mass ratio of carbon dioxide and carbon monoxide—molar mass ratio of carbon and methane, $E_{(CH4)}$—methane emission factor, $E_{(NMVOC)}$—emission index of non-methane VOCs (for biomass 0.009).

Sulphur dioxide emission factor (SO_2; kg·Mg^{-1}):

$$\mathrm{SO_2} = \frac{2S}{100} \cdot (1 - r),$$

SO_2—sulphur dioxide emission factor (kg·Mg^{-1}), 2—molar mass ratio of SO_2 and sulphur, S—sulphur content in fuel (%), r—coefficient determining the part of total sulphur retained in the ash.

The emission factor was calculated from (NO_X; kg·Mg^{-1}):

$$\mathrm{NO_x} = \frac{46}{14}\mathrm{E_c}\ \mathrm{N/C} \cdot (\mathrm{N_{NOX}/N}),$$

NO_x—NO_x emission factor (kg·Mg^{-1})—molar mass ratio of nitrogen dioxide to nitrogen. The molar mass of nitrogen dioxide is considered due to the fact that nitrogen oxide in the air oxidises very quickly to nitrogen dioxide, N/C—nitrogen to carbon ratio in biomass, N_{NOX}/N—part of nitrogen emitted as NO_x (for biomass 0.122).

Rising factor and dust emission factor E_{dust} was calculated according to the following equation:

$$E_{dus} = 1.5 \cdot A \cdot \frac{100 - \eta_0}{100 - k},$$

E_{dust}—dust emission factor (kg·Mg^{-1}), 1.5·A—rising index, indicating the amount of dust formed during combustion (kg·Mg^{-1}), 1.5—coefficient denoting 15% of the ashes rising in the form of volatile dust, A—ash content in fuel (%), η_0—dust removal efficiency (for biomass 20%), k—content of flammable parts in the dust (for biomass 5%).

2.2. Exhaust Gas

The exhaust gas composition was determined based on stoichiometric equations according to the works by [33,34]:

Theoretical oxygen demand (V_{O2}; Nm^3·kg^{-1}):

$$V_{O2} = \frac{22.41}{100} \cdot \left(\frac{C}{12} + \frac{H}{4} + \frac{S - O}{32} \right),$$

C—biomass carbon content (%), H—biomass hydrogen content (%), S—biomass sulphur content (%), O—biomass oxygen content.

The stoichiometric volume of dry air required to burn 1 kg of biomass (V_{oa}; Nm^3·kg^{-1}):

$$V_{Oa} = \frac{V_{O_2}}{0.21},$$

Since the oxygen content in the air is 21%, which participates in the combustion process in the boiler, the stoichiometric volume of dry air required to burn 1 kg of biomass.

Carbon dioxide content of the combustion products (V_{CO2}; Nm^3·kg^{-1}):

$$V_{CO2} = \frac{22.41}{12} \cdot \frac{C}{100},$$

Content of sulphur dioxide (V_{SO2}; Nm^3·kg^{-1}):

$$V_{SO2} = \frac{22.41}{32} \cdot \frac{S}{100},$$

Water vapour content of the exhaust gas (V_{H2O}; Nm^3·kg^{-1}),

$$VV^{H}_{H_2O} = \frac{22.41}{100} \cdot \left(\frac{H}{2} + \frac{M}{18} \right),$$

is the component of water vapour volume from the hydrogen combustion process ($V^H_{H_2O}$; Nm^{3}H$_2$O·kg^{-1} fuel) $V^a_{H_2O} = 1.61 \cdot x \cdot V_{oa}$, and the volume of moisture contained in the combustion air ($V^a_{H_2O}$; Nm^3 H$_2$O·kg^{-1} fuel) $V_{H2O} = V^H_{H2O} + V^a_{H2O}$; M-fuel moisture content (%), x-air absolute humidity (kg H$_2$O·kg^{-1} dry air).

The theoretical nitrogen content in the exhaust gas (V_{N2}; Nm^3·kg^{-1}),

$$V_{N2} = \frac{22.41}{28} \cdot \frac{N}{100} + 0.79 \cdot V_{oa},$$

considering that the nitrogen in the exhaust comes from the fuel composition and the combustion air, and the nitrogen content in the air is 79%.

The total stoichiometric volume of dry exhaust gas (V_{gu}; $Nm^3 \cdot kg^{-1}$):

$$V_{gu} = V_{CO2} + V_{SO2} + V_{N2},$$

The total volume of exhaust gases (V_{ga}; $Nm^3 \cdot kg^{-1}$):

$$V_{ga} = V_{gu} + V_{H2O},$$

Assuming that biomass combustion is carried out under stoichiometric conditions, i.e., using the minimum amount of air required for combustion ($\lambda = 1$), a minimum exhaust gas volume will be obtained.

After the experiment, the results were statistically analysed using two-factor analysis of variance and specified using post hoc tests (*t*-test). All analyses were performed using STATISTICA 13 software (StatSoft, Inc.; TIBCO Software; Palo Alto, CA, USA; 2015).

3. Results

The average annual temperature in Lednice is 9 °C, and the annual rainfall is 638 mm, which reflects the warm temperate climate favourable to viticulture [35]. Lublin has a similar average annual temperature (8.9 °C), but the total rainfall is higher (750 mm) [36]. The experiment conducted in Poland is in a temperate climate. Table 2 presents biometric measurements determining the size of bunches and pedicels, the number, diameter, and weight of berries, and the percentage of pedicels in the weight of bunches of Chardonnay, Merlot, Riesling, and Zweigelt grape varieties. Significant interactions between the climate zone and the studied variety were observed for most biometric parameters, i.e., weight of 1 berry (g), berry diameter (cm), and stalk percentage of bunch weight (%).

Table 2. Biometric analysis of grapevine (*Vitis vinifera* L.) fruits grown in two climatic zones.

	Climate Zone Factor (B)	**Grape Variety (Factor A)**					**Factor (A × B)**
		Chardonnay	**Merlot**	**Riesling**	**Zweigelt**	***p*-Value**	
Actual grape weight, g	M. w.	228.15 ± 35.02 Ba	375.41 ± 34.41 Aa	239.22 ± 13.76 Ba	368.37 ± 23.11 Aa	<0.0001	0.0001
	M	107.04 ± 18.13 Bb	194.39 ± 28.13 Ab	201.74 ± 33.96 Aa	191.22 ± 16.13 Ab	<0.0001	
	p-value	<0.0001	<0.0001	0.0790	<0.0001		
Weight of 1 berry, g	M. w.	1.56 ± 0.17 Bb	1.92 ± 0.13 Aa	1.55 ± 0.07 Ba	1.64 ± 0.17 Ba	<0.0001	0.0667
	M.	2.09 ± 0.82 Aa	1.65 ± 0.15 Bb	1.64 ± 0.17 Ba	1.68 ± 0.18 Ba	0.3584	
	p-value	0.0563	0.2862	0.6065	0.7337		
Number of berries in a cluster, pcs.	M. w.	139.20 ± 8.90 Ca	188.60 ± 19.87 Ba	145.40 ± 12.17 Ca	218.10 ± 24.38 Aa	<0.0001	0.0001
	M.	79.00 ± 9.23 Cb	116.90 ± 18.46 Ab	111.90 ± 8.13 Ab	92.90 ± 10.84 Bb	<0.0001	
	p-value	0.0569	0.2704	<0.0001	<0.0001		
Berry diameter, cm	M. w.	1.41 ± 0.13 Bb	1.85 ± 0.20 Aa	1.55 ± 0.15 Ba	1.60 ± 0.14 Ba	<0.0001	0.3598
	M.	1.81 ± 0.10 Aa	1.71 ± 0.09 Ab	1.47 ± 0.11 Ba	1.52 ± 0.07 Ba	<0.0001	
	p-value	0.9765	0.0679	0.2329	0.1809		
Stalk weight, g	M. w.	9.19 ± 1.6 Ca	15.13 ± 1.38 Aa	12.29 ± 1.54 Bb	12.06 ± 1.73 Ba	<0.0001	0.0001
	M.	6.08 ± 2.79 Cb	8.24 ± 2.45 Bb	15.1 ± 6.06 Aa	9.32 ± 2.52 Ba	<0.0001	
	p-value	<0.0001	<0.0001	<0.0001	0.1183		
Stalk length, cm	M. w.	14.12 ± 3.65 Ba	19.45 ± 3.44 Aa	14.01 ± 2.87 Ba	21.16 ± 3.32 Aa	<0.0001	0.0001
	M.	8.80 ± 2.06 Bb	14.9 ± 3.43 Ab	8.45 ± 2.31 Bb	9.94 ± 1.93 Bb	<0.0001	
	p-value	<0.0001	<0.0001	<0.0001	<0.0001		
Stalk width, cm	M. w.	11.38 ± 3.50 Ca	16.21 ± 1.74 Aa	12.94 ± 1.73 Ca	14.97 ± 1.95 Ba	<0.0001	0.0001
	M.	8.71 ± 1.53 Bb	11.79 ± 2.48 Ab	7.02 ± 1.36 Cb	9.23 ± 2.18 Bb	<0.0001	
	p-value	<0.0001	<0.0001	<0.0001	<0.0001		
Stalk percentage of bunch weight, %	M. w.	4.32 ± 0.80 Aa	4.44 ± 0.81 Aa	4.64 ± 1.20 Aa	3.40 ± 0.75 Aa	0.0563	0.2358
	M.	5.17 ± 1.16 Aa	4.61 ± 0.58 Aa	5.68 ± 1.39 Aa	3.73 ± 0.94 Ba	0.0343	
	p-value	0.1043	0.8381	<0.0001	0.0258		

Explanations: M. w.—climate zones moderately warm; M.—climate zones moderately. Significant difference A, B, C—means that different letters in rows and a, b mean that different letters in columns indicate significant differences at $\alpha = 0.05$.

Table 3 presents the results of technical analysis of grapevine stems of four varieties (Chardonnay, Merlot, Riesling, Zweigelt) grown in two climate zones—moderately warm and moderate. The basic energy parameters were taken into account: calorific value (HHV, LHV), moisture content (MC), ash content (A), volatile matter (V), and fixed carbon content (FC). The table also gives the *p*-values determining the statistical significance of the differences between varieties.

Table 3. Technical and elementary analysis of selected varieties of *Vitis vinifera* L. cultivated in two climatic zones.

	Climate Zone Factor (B)	**Grape Variety (Factor A)**					**Factor (A × B)**
		Chardonnay	**Merlot**	**Riesling**	**Zweigelt**	***p*-Value**	
HHV	M. w.	17.30 ± 0.04 Ba	16.03 ± 0.03 Db	16.36 ± 0.04 Ca	17.56 ± 0.03 Aa	0.0001	0.0001
(MJ·kg^{-1})	M.	16.41 ± 0.11 Ab	16.25 ± 0.02 Aa	16.25 ± 0.06 Ab	15.66 ± 0.05 Bb	0.0001	
(d.b.)	*p*-value	0.0001	0.0001	0.0001	0.0001		
LHV	M. w.	15.81 ± 0.04 Ba	14.83 ± 0.03 Db	15.14 ± 0.04 Ca	16.07 ± 0.03 Aa	0.0001	0.0001
(MJ·kg^{-1})	M.	15.26 ± 0.11 Ab	15.11 ± 0.02 Aa	15.11 ± 0.06 Aa	14.55 ± 0.05 Bb	0.0001	
(d.b.)	*p*-value	0.0001	0.0001	0.0001	0.0001		
MC	M. w.	11.51 ± 0.04 Aa	6.49 ± 0.05 Ca	6.49 ± 0.04 Ca	7.43 ± 0.10 Ba	0.0001	0.0001
(%)	M.	6.44 ± 0.02 Ab	6.47 ± 0.06 Aa	5.78 ± 0.07 Bb	6.36 ± 0.03 Ab	0.0001	
(a.b.)	*p*-value	0.0001	0.5548	0.0001	0.0001		
A	M. w.	12.20 ± 0.04 Aa	7.87 ± 0.18 Bb	6.28 ± 0.10 Cb	5.83 ± 0.11 Db	0.0001	0.0001
(%)	M.	9.03 ± 0.35 Db	10.47 ± 0.12 Ba	9.73 ± 0.03 Ca	12.75 ± 0.11 Aa	0.0001	
(a.b.)	*p*-value	0.0001	0.0001	0.0001	0.0001		
A	M. w.	8.83 ± 0.12 Aa	8.42 ± 0.20 Bb	6.71 ± 0.11 Cb	6.30 ± 0.11 Db	0.0001	0.0001
(%)	M.	8.83 ±0.12 Da	11.19 ± 0.12 Ba	10.33 ± 0.04 Ca	13.62 ± 0.11 Aa	0.0001	
(d.b.)	*p*-value	0.9999	0.0001	0.0001	0.0001		
V	M. w.	64.25 ± 0.39 Ca	65.75 ± 0.08 Ba	66.77 ± 0.47 Aa	64.53 ± 0.05 Ca	0.0001	0.0001
(%)	M.	65.05 ± 0.33 Ba	62.77 ± 0.35 Cb	66.24 ± 0.27 Aa	64.45 ± 0.53 Ba	0.0001	
(a.b)	*p*-value	0.5647	0.0001	0.2585	0.3212		
FC	M. w.	12.05 ± 0.43 Cb	20.09 ± 0.81 Aa	20.46 ± 0.42 Ab	17.37 ± 0.58 Ba	0.0001	0.0001
(%)	M.	19.48 ± 0.04 Aa	20.30 ± 0.39 Aa	18.26 ± 0.30 Ba	16.44 ± 0.46 Ca	0.0001	
(a.b.)	*p*-value	0.0001	0.7452	0.0001	0.5898		

Explanations: (d.b.)—dry basis, a.b.—analytical basis, HHV—higher heating value, LHV—lower heating value, MC—moisture content, A—ash, V—volatile matter, FC—fixed carbon. Significant difference A, B, C and D—means that different letters in rows and a, b mean that different letters in columns indicate significant differences at $\alpha = 0.05$.

The statistical analysis showed a significant influence of the variety and place of cultivation on the weight of the grape bunches of the tested vines. It was shown that in both locations tested, the Chardonnay bunches were the smallest of all those evaluated, and in the case of cultivation located in Poland, this influence was significant. The Merlot variety (375.22 g) grown in the Czech Republic had the largest bunches, while in Polish growing conditions, Riesling (201.74 g) had the largest bunches. The bunches obtained from vines grown in the Czech Republic were significantly heavier than those in Poland, with the exception of the Riesling variety, where no significant effect of the cultivation location on the tested trait was found.

The weight of a single berry was largely determined by the variety and place of cultivation. It was found that Merlot bushes grown in a moderately warm zone (Czech Republic) produced the heaviest berries among all the varieties assessed, while Chardonnay bushes grown in a temperate zone (Poland) produced the heaviest berries. A significant influence of the location of cultivation on berry weight was demonstrated for the Chardonnay and Merlot varieties. Chardonnay bushes grown in a temperate climate produced significantly heavier berries than those grown in a moderately warm climate. In the case of the Merlot variety, the trend was reversed.

The number of berries in a cluster varied significantly between the grape varieties evaluated and between the cultivation locations. It was shown that in both climate zones studied, Chardonnay vines produced significantly fewer berries per cluster than the other biotypes studied. The clusters with the highest number of berries in the shrubs grown in the moderately warm zone were produced by Zweigelt shrubs, while in the temperate zone, they were produced by Riesling shrubs. Regardless of the variety, the shrubs grown in the moderately warm zone (Czech Republic) had significantly more berries per cluster than those grown in the temperate zone (Poland).

The diameter of the berries of the tested varieties ranged from 1.41 to 1.85 cm and differed significantly between the tested grapevine varieties and the location of cultivation. In the case of vines grown in the Czech Republic, the Merlot variety produced the largest berries, reaching a diameter of 1.85 cm, while among the varieties grown in Poland, Chardonnay had a diameter of 1.81 cm. The smallest berries were found in Chardonnay in the Czech Republic and Riesling in Poland. No significant influence of the location of cultivation on the studied trait was found in the case of Riesling and Zweigelt. The Chardonnay variety produced larger berries in Poland than in the Czech Republic, while the opposite significant relationship was found in the Merlot variety.

The weight of the pedicels of the tested varieties was significantly modified by the variety and location of cultivation. Indeed, the heaviest pedicels were found in the Merlot variety (15.13 g; Czech Republic) and Riesling (15.10 g; Poland). In both cultivation locations, the lightest stems were found in Chardonnay grapes. No significant influence of the cultivation location on the tested feature was found only in the case of the Zweigelt variety, while Chardonnay and Merlot vines produced heavier stems in the moderately warm zone, and Riesling in the temperate zone.

The size of the stalk, determined by its length and width after separation of the berries, depended significantly on the variety and location of cultivation. It was shown that the largest pedicels in the warm temperate climate zone (Czech Republic) were found in clusters of varieties with dark-coloured skins, i.e., Merlot and Zweigelt, whose parameters were significantly higher than those of Chardonnay and Riesling. Among the varieties grown in the temperate zone, the largest stalks were found in Merlot grapes among the biotypes studied. A clear and significant influence of the location of cultivation on the size of the stalks was found; the grapes of all the varieties studied, grown in the moderately warm zone, formed significantly larger stalks than in the temperate zone.

The proportion of the stalk in the weight of the bunch ranged from 3.40% to 5.68% and in most of the cases assessed did not depend significantly on the variety and location of cultivation. The statistical analysis showed a significant influence of the variety on the parameter under study only in the case of varieties grown in Poland, where Zweigelt vines had a significantly lower proportion of stalks in the weight of the bunches among all the varieties assessed. Significant interactions were observed between *Vitis vinifera* L. varieties grown in two climatic zones for all parameters of technical and elementary analysis (Table 3).

In moderately warm climates, the highest calorific value was recorded for the Zweigelt variety (HHV = 17.56 MJ·kg^{-1}, LHV = 16.07 MJ·kg^{-1}), and the lowest for Merlot (HHV = 16.03 MJ·kg^{-1}, LHV = 14.83 MJ·kg^{-1}). Chardonnay (HHV = 17.30 MJ·kg^{-1}) and Riesling (HHV = 16.36 MJ·kg^{-1}) achieved intermediate values. In terms of moisture content, the highest values were found in Chardonnay (11.51%), and the lowest in Merlot and Riesling (6.49%). The ash content was highest in Chardonnay stems (12.20%) and lowest in Zweigelt (5.83%). The highest volatile matter content was found in Riesling (66.77%), while the lowest was found in Chardonnay (64.25%). The proportion of fixed carbon varied, with the highest found in Riesling (20.46%) and the lowest in Chardonnay (12.05%).

In a temperate climate, Riesling achieved the highest calorific value (HHV = 16.25 MJ·kg^{-1}), and Zweigelt the lowest (15.66 MJ·kg^{-1}). Chardonnay and Merlot had intermediate values, similar to each other (16.41 and 16.25 MJ·kg^{-1}). Moisture content ranged from 5.78% (Riesling) to 6.47% (Merlot), with the highest recorded in Chardonnay (6.44%). Ash content was highest in Zweigelt (12.75%) and lowest in Chardonnay (9.03%). The highest volatile matter content was found in Riesling (66.24%), and the lowest in Merlot (62.77%). In turn, the solid carbon content was highest in Merlot (20.30%) and lowest in Zweigelt (16.44%).

The impact of the climate zone on the properties of vine stems depended on the variety and the parameter studied. In the case of Chardonnay, statistically significant differences were observed for calorific values (HHV, LHV), moisture content (MC), ash content (A) and fixed carbon content (FC), while the volatile matter content (V) did not significantly differentiate the samples. For Merlot, the zone effect occurred in relation to HHV, LHV, A and V, while moisture content ( ) and fixed carbon content did not show significant differences. For Riesling, statistically significant differences were found for HHV, LHV, MC, A and FC, while the V parameter remained at a similar level regardless of the zone. For Zweigelt, the climate zone significantly differentiated HHV, LHV, MC and A, while the values of volatile matter and fixed carbon content did not differ significantly. These results indicate that the influence of climatic conditions is most pronounced in terms of calorific value and ash content, while volatile matter in most varieties remains stable and does not undergo significant changes between climate zones.

In summary, in moderately warm climatic conditions, Riesling and Zweigelt showed the most favourable energy parameters—the former was characterised by the highest content of volatile components and fixed carbon, while the latter achieved the highest calorific values. In a temperate climate, Riesling achieved the best results, while Merlot stood out with the highest fixed carbon content. The least favourable properties were found in Chardonnay, which was characterised by high moisture and ash content, and in Zweigelt in a temperate climate, where the lowest calorific values and the highest ash content were recorded. The results clearly indicate that the energy potential of grapevine stems depends on both the variety and the climate zone, with ash and solid carbon content playing a key role.

The table presents the results of an elementary analysis of grapevine stems of four varieties (Chardonnay, Merlot, Riesling, and Zweigelt) originating from moderately warm and temperate zones, including the content of C, H, N, S, O, and the atomic ratios H/C, N/C, and O/C, together with an assessment of the statistical significance of the differences.

The analysis revealed statistically significant differences between varieties in both moderately warm and moderate zones. The differences concerned most of the parameters assessed, including carbon (C), nitrogen (N), sulphur (S), and oxygen (O) content, as well as the N/C and O/C atomic ratios, with the exception of hydrogen (H) values and the H/C ratio, which remained at similar levels in most cases. In the case of final parameters, significant interactions were observed between the assessed varieties and climate zones, except for H and H/C (Table 4).

In moderately warm climatic conditions, the carbon content ranged from 41.52% (Merlot) to 44.19% (Zweigelt). The highest hydrogen content was recorded in Chardonnay (7.14%), and the lowest in Riesling (6.68%). In turn, the highest nitrogen content was found in Zweigelt stems (2.13%), and the lowest in Merlot (1.05%). The sulphur content ranged from 0.08% to 0.14%, while the oxygen content ranged from 36.04% (Chardonnay) to 42.59% (Merlot). The H/C ratio remained at a similar level (1.60–1.66). The highest N/C ratio was found in Zweigelt (0.048) and the lowest in Merlot (0.025). The O/C ratio ranged from 0.63 (Chardonnay) to 0.77 (Merlot).

In a temperate climate, the highest carbon content was found in Merlot stems (44.81%), and the lowest in Zweigelt (43.41%). Chardonnay had the highest hydrogen content (6.71%), and Merlot had the lowest (5.83%). Chardonnay had the highest nitrogen content (1.75%), while Merlot had the lowest (1.39%). The sulphur content ranged from 0.06 to 0.08%. Oxygen ranged from 34.94% (Zweigelt) to 42.14% (Riesling). The H/C ratio ranged from

1.31 (Merlot) to 1.51 (Chardonnay). The N/C ratio was highest in Chardonnay (0.039) and lowest in Merlot (0.031). The O/C ratio ranged from 0.60 to 0.76.

Table 4. Ultimate analysis of selected varieties of *Vitis vinifera* L. cultivated in two climatic zones.

	Climate Zone Factor (B)	**Grape Variety (Factor A)**					**Factor (A × B)**
		Chardonnay	**Merlot**	**Riesling**	**Zweigelt**	***p*-Value**	
C (%) (d.b.)	M. w.	43.04 ± 0.13 Bb	41.52 ± 0.35 Cb	43.08 ± 0.04 Bb	44.19 ± 0.06 Aa	0.0001	0.0001
	M.	44.43 ± 0.23 ABa	44.81 ± 0.15 Aa	44.08 ± 0.26 BCa	43.41 ± 0.40 Cb	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
H (%) (d.b.)	M. w.	7.14 ± 0.02 Aa	6.89 ± 0.04 Aa	6.68 ± 0.46 Aa	7.08 ± 0.02 Aa	0.1383	0.3594
	M.	6.71 ± 0.06 Ab	5.83 ± 0.73 Aa	6.33 ± 0.58 Aa	6.36 ± 0.06 Ab	0.2209	
	p-value	0.0001	0.8536	0.2584	0.0001		
N (%) (d.b.)	M. w.	1.49 ± 0.03 Bb	1.05 ± 0.03 dB	1.30 ± 0.01 Cb	2.13 ± 0.08 Aa	0.0001	0.0001
	M.	1.75 ± 0.08 Aa	1.39 ± 0.05 Ca	1.49 ± 0.06 Ca	1.60 ± 0.09 ABb	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
S (%) (d.b.)	M. w.	0.10 ± 0.01 Ba	0.08 ± 0.01 Ba	0.09 ± 0.01 Ba	0.14 ± 0.00 Aa	0.0001	0.0001
	M.	0.07 ± 0.00 Bb	0.04 ± 0.00 Cb	0.06 ± 0 Bb	0.08 ± 0.00 Ab	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
O (%) (d.b.)	M. w.	39.41 ± 0.01 Aa	42.04 ± 0.18 Ba	42.14 ± 0.54 Aa	40.16 ± 0.22 Ba	0.0001	0.0001
	M.	38.21 ± 0.32 Ab	36.74 ± 0.81 Bb	37.72 ± 0.46 ABb	34.94 ± 0.43 Cb	0.0001	
	p-value	0.0030	0.0004	0.0004	0.0001		
H/C (d.b.)	M. w.	1.66 ± 0.01 Aa	1.66 ± 0.01 Aa	1.55 ± 0.10 Aa	1.60 ± 0.00 Ab	0.3874	0.0736
	M.	1.51 ± 0.01 Ab	1.30 ± 0.16 Ab	1.44 ± 0.14 Aa	1.46 ± 0.01 Aa	0.1627	
	p-value	0.0001	0.0001	0.0001	0.0001		
N/C (d.b.)	M. w.	0.035 ± 0.001 Bb	0.025 ± 0.001 Db	0.030 ± 0.000 Cb	0.048 ± 0.002 Ab	0.0001	0.0001
	M.	0.039 ± 0.002 Aa	0.031 ± 0.001 Ca	0.034 ± 0.001 BCa	0.037 ± 0.002 ABa	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
O/C (d.b.)	M. w.	0.69 ± 0.00 Ca	0.76 ± 0.01 Aa	0.73 ± 0.01 Ba	0.68 ± 0.00 Ca	0.0001	0.0001
	M.	0.64 ± 0.01 Ab	0.61 ± 0.01 ABb	0.64 ± 0.01 Ab	0.60 ± 0.01 Bb	0.0058	
	p-value	0.0011	0.0002	0.0002	0.0006		

Explanations: d.b.—dry basis, 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 of nitrogen to carbon, O/C—ratio of oxygen to carbon. Significant difference A, B, C and D—means that different letters in rows and a, b mean that different letters in columns indicate significant differences at $\alpha = 0.05$.

The impact of the climate zone on the elemental composition of grapevine pedicels varied and depended on the variety. In the case of Chardonnay, statistically significant differences were found in the content of C, H, N, S, O, and the N/C and O/C ratios, while the H/C ratio remained stable. In Merlot, significant changes were observed in all analysed parameters except hydrogen. In Riesling, the climate zone differentiated the content of carbon, nitrogen, sulphur, oxygen, and the N/C and O/C ratios, while hydrogen and H/C were relatively constant. In Zweigelt, the effect of climate was visible in all evaluated parameters.

In summary, in a moderately warm climate, Zweigelt showed the most favourable properties in terms of low oxygen content and high carbon content, while Merlot had the lowest nitrogen content. In a temperate climate, Riesling showed the best parameters, distinguished by the highest oxygen content and low sulphur content, as well as Merlot, which had the highest carbon content. The least favourable values were found in Chardonnay (high nitrogen and oxygen content in a temperate climate) and Zweigelt (lowest carbon content). The results clearly indicate that the elemental composition of grapevine stems is sensitive to climatic conditions, with carbon, nitrogen, and oxygen content being particularly variable.

The table shows the emission values for vine shoot biomass depending on the variety and climate zone. Emissions of the main gaseous pollutants (CO, CO_2, NO_X, and SO_2) and dust are included, which allows for an assessment of the potential environmental impact of burning this type of biomass. Significant interactions between the assessed varieties and climate zones were demonstrated among the emission parameters (Table 5).

Table 5. Emission parameters of selected varieties of *Vitis vinifera* L. cultivated in two climatic zones (kg·Mg^{-1}).

	Climate Zone (Factor B)	**Grape Variety (Factor A)**					**Factor (A × B)**
		Chardonnay	**Merlot**	**Riesling**	**Zweigelt**	***p*-Value**	
CO	M. w.	53.03 ± 0.16 Cb	51.15 ± 0.43 Bb	53.07 ± 0.05 Bb	54.45 ± 0.07 Ab	0.0001	0.0001
	M.	54.74 ± 0.28 ABa	55.20 ± 0.19 Aa	54.30 ± 0.32 BCa	53.48 ± 0.50 Ca	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
NO$_x$	M. w.	5.25 ± 0.10 Bb	3.72 ± 0.11 Db	4.60 ± 0.03 Cb	7.52 ± 0.28 Ab	0.0001	0.0001
	M.	6.19 ± 0.29 Aa	4.91 ± 0.18 Ca	5.27 ± 0.20 BCa	5.65 ± 0.33 ABa	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
CO$_2$	M. w.	1298.55 ± 3.85 Bb	1252.64 ± 10.41 Cb	1299.57 ± 1.13 Bb	1333.26 ± 1.77 Ab	0.0001	0.0001
	M.	1340.40 ± 6.94 ABa	1351.72 ± 4.65 Aa	1329.80 ± 7.94 BCa	1309.59 ± 12.14 Ca	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
SO$_2$	M. w.	0.19 ± 0.017 Ba	0.16 ± 0.01 Ba	0.18 ± 0.02 Ba	0.29 ± 0.01 Ab	0.0001	0.0001
	M.	0.13 ± 0.01 Bb	0.08 ± 0.00 Cb	0.12 ± 0.01 Bb	0.16 ± 0.00 Aa	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
Dust	M. w.	15.41 ± 0.05 Aa	9.94 ± 0.23 Bb	7.93 ± 0.13 Cb	7.36 ± 0.14 Db	0.0001	0.0001
	M.	11.41 ± 0.44 Db	13.22 ± 0.15 Ba	12.29 ± 0.04 Ca	16.11 ± 0.13 Aa	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		

Explanation: CO—carbon monoxide, CO$_2$—carbon dioxide, SO$_2$—sulphur dioxide, NO$_X$—nitrogen oxides. Significant difference A, B, C and D—means that different letters in rows and a, b mean that different letters in columns indicate significant differences at α = 0.05.

In moderately warm climatic conditions, the highest carbon monoxide (CO) emissions were recorded for the Zweigelt variety (54.45 kg·Mg^{-1}), and the lowest for Merlot (51.15 kg·Mg^{-1}). Chardonnay (53.03 kg·Mg^{-1}) and Riesling (53.07 kg·Mg^{-1}) showed intermediate values. In terms of nitrogen oxide (NOx) emissions, the highest values were obtained for Zweigelt (7.52 kg·Mg^{-1}) and the lowest for Merlot (3.72 kg·Mg^{-1}). CO$_2$ emissions were similar for all varieties, ranging from 1252.64 kg·Mg^{-1} (Merlot) to 1333.26 kg·Mg^{-1} (Zweigelt). SO$_2$ emissions were relatively low and did not exceed 0.29 kg·Mg^{-1}, with the highest value obtained for Zweigelt (0.29 kg·Mg^{-1}) and the lowest for Merlot (0.16 kg·Mg^{-1}). The greatest differences between varieties were in dust emissions, ranging from 7.36 kg·Mg^{-1} for Zweigelt to 15.41 kg·Mg^{-1} for Chardonnay.

In temperate climates, CO emissions were higher than in moderately warm zones, reaching a maximum value for Merlot (55.20 kg·Mg^{-1}) and a minimum for Riesling (54.30 kg·Mg^{-1}). The highest NOx emissions were found for Chardonnay (6.19 kg·Mg^{-1}), while the lowest were for Merlot (4.91 kg·Mg^{-1}). CO$_2$ emissions varied the most, with the highest value obtained for Merlot (1351.72 kg·Mg^{-1}) and the lowest for Chardonnay (1340.40 kg·Mg^{-1}). SO$_2$ emissions in this zone ranged from 0.08 kg·Mg^{-1} (Merlot) to 0.16 kg·Mg^{-1} (Zweigelt). In turn, dust emissions were highest for Zweigelt (16.11 kg·Mg^{-1}) and lowest for Chardonnay (11.41 kg·Mg^{-1}).

Pollutant emissions depended on the variety and the parameter analysed. In the case of Chardonnay, statistically significant differences were observed for CO, NOx, CO$_2$, SO$_2$, and dust emissions, indicating that this variety is highly sensitive to growing site conditions. In the case of Merlot, the effect of growing location was observed for all parameters assessed, but the differences in NOx emissions were less pronounced. In the case of Riesling, growing location significantly differentiated CO$_2$, SO$_2$, and dust emissions, while CO and NOx emissions remained similar. For Zweigelt, statistically significant differences were observed for all parameters, except SO$_2$ emissions, which remained stable across both locations. The results of the above analysis indicate that climatic conditions have a significant impact on the level of emissions from the combustion of vine stalks. In a moderately warm climate, Zweigelt stood out the most, with the highest emissions of CO, NOx, and CO$_2$, while Chardonnay had the highest dust emissions. In a temperate climate, Merlot stood out unfavourably, achieving the highest CO and CO$_2$ emissions, while Chardonnay had the highest NOx emissions. The most stable parameters were recorded for Riesling, which showed the smallest differences between zones. The results clearly confirm that both the variety and climatic conditions are crucial for the scale of pollutant emissions, with the greatest variation in dust and CO_2 emissions.

The table shows the values of theoretical oxygen demand, exhaust gas volume, and the main components of vine shoot combustion products depending on the variety and climate zone. The analysis revealed statistically significant differences between grapevine varieties in both moderately warm and moderate climates. The differences concerned most of the parameters assessed, including theoretical oxygen demand (Vo_2), stoichiometric air volume (Voa), CO_2 emissions (VCO_2), nitrogen (VN_2), and total exhaust gas volume (Vo_{ga}, Vo_{gu}). The exception was the VSO_2 parameter, which in most cases remained at a similar level, regardless of the variety and climate zone. No significant interactions between the assessed varieties and climate zones were found in terms of exhaust gas parameters, with the exception of VoO_2 and Vo_a (Table 6).

Table 6. Exhaust gas parameters of selected varieties of *Vitis vinifera* L. cultivated in two climatic zones ($Nm^3 \cdot kg^{-1}$).

	Climate Zone (Factor B)	Grape Variety (Factor A)					Factor (A × B)
		Chardonnay	**Merlot**	**Riesling**	**Zweigelt**	***p*-Value**	
VoO_2	M. w.	0.95 ± 0.00 Aa	0.86 ± 0.01 Ba	0.88 ± 0.03 Ba	0.94 ± 0.00 Aa	0.0001	0.1298
	M.	0.94 ± 0.01 Aa	0.90 ± 0.05 Aa	0.91 ± 0.03 Aa	0.92 ± 0.01 Aa	0.4825	
	p-value	0.2569	0.3696	0.7458	0.9523		
Vo_a	M. w.	4.53 ± 0.01 Aa	4.11 ± 0.04 Ba	4.20 ± 0.14 Ba	4.47 ± 0.01 Aa	0.0001	0.1298
	M.	4.48 ± 0.04 Aa	4.29 ± 0.23 Aa	4.33 ± 0.15 Aa	4.37 ± 0.06 Aa	0.4825	
	p-value	0.2552	0.3698	0.3692	0.2536		
VCO_2	M. w.	0.80 ± 0.000 Bb	0.77 ± 0.010 Cb	0.80 ± 0.000 Bb	0.82 ± 0.002 Aa	0.0001	0.0001
	M.	0.83 ± 0.00 ABa	0.84 ± 0.00 Aa	0.82 ± 0.00 BCa	0.81 ± 0.01 Cb	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
VSO_2	M. w.	0.0007 ± 0.0000 Ba	0.0006 ± 0.00004 Ba	0.0006 ± 0.0001 Ba	0.0010 ± 0.0000 Aa	0.0001	0.0001
	M.	0.0005 ± 0.0000 Bb	0.0003 ± 0.0000 Cb	0.0004 ± 0.0000 Bb	0.0006 ± 0.0000 Ab	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
VH_2O	M. w.	0.94 ± 0.00 Aa	0.853 ± 0.00 Ba	0.83 ± 0.05 Ba	0.89 ± 0.00 ABa	0.0001	0.4695
	M	0.83 ± 0.01 Ab	0.73 ± 0.08 Aa	0.78 ± 0.06 Aa	0.79 ± 0.01 Ab	0.2185	
	p-value	0.0001	0.7879	0.9692	0.0001		
VN_2	M. w.	4.77 ± 0.02 Bb	4.09 ± 0.01 Db	4.361 ± 0.11 Cb	5.23 ± 0.07 Aa	0.0001	0.0001
	M.	4.94 ± 0.05 Aa	4.50 ± 0.14 Ba	4.62 ± 0.11 Ba	4.73 ± 0.03 ABb	0.0001	
	p-value	0.0001	0.0001	0.0001	0.0001		
Vo_{ga}	M. w.	7.25 ± 0.02 Ba	6.38 ± 0.03 Db	6.67 ± 0.18 Ca	7.67 ± 0.07 Aa	0.0001	0.0001
	M.	7.32 ± 0.057 Aa	6.77 ± 0.26 Ba	6.92 ± 0.20 Ba	7.03 ± 0.03 ABb	0.0001	
	p-value	0.7852	0.0001	0.3578	0.0001		
Vo_{gu}	M. w.	5.58 ± 0.02 Bb	4.87 ± 0.02 Da	5.16 ± 0.11 Cb	6.06 ± 0.07 Aa	0.0001	0.0001
	M.	5.77 ± 0.05 Aa	5.34 ± 0.16 Ba	5.44 ± 0.11 Ba	5.54 ± 0.03 ABb	0.0001	
	p-value	0.0001	0.4753	0.0001	0.0001		

Explanations: V_{O2}—the theoretical oxygen demand, Vo_a—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, Vo_{gu}—the total stoichiometric volume of dry exhaust gas, Vo_{ga}—the total volume of exhaust gases. Significant difference A, B, C and D—means that different letters in rows and a, b mean that different letters in columns indicate significant differences at $\alpha = 0.05$.

In moderately warm climates, the highest theoretical oxygen demand (Vo_2) was recorded for Chardonnay (0.95) and the lowest for Merlot (0.86). A similar trend was observed for the stoichiometric air volume (Vo_a), which ranged from 4.11 for Merlot to 4.53 for Chardonnay. The highest CO_2 emission value (VCO_2) was found for Riesling and Chardonnay (0.80–0.82), and the lowest for Merlot (0.77). The SO_2 content (VSO_2) varied, ranging from 0.0006 for Merlot to 0.0007 for Chardonnay. The volume of water vapour (VH_2O) ranged from 0.85 (Merlot) to 0.94 (Chardonnay). The highest amount of nitrogen in the exhaust gases (VN_2) was recorded for Zweigelt (5.23) and the lowest for Merlot (4.09). In the case of the total volume of dry exhaust gases (Vo_{ga}), the highest values were characteristic of Zweigelt (7.67) and the lowest of Merlot (6.38). Similarly, the total gas volume (Vo_{gu}) was highest for Zweigelt (6.06) and lowest for Merlot (4.87).

In the temperate climate zone, these parameters took on different values. The highest oxygen demand (Vo_2) was observed in Riesling (0.91), and the lowest in Chardonnay (0.90). The air volume (Voa) was relatively even, ranging from 4.33 to 4.48, with the highest values recorded for Chardonnay. CO_2 emission rates (VCO_2) were highest for Chardonnay (0.83) and lowest for Zweigelt (0.81). SO_2 emissions (VSO_2) were low and stable throughout the range (0.0005–0.0006). Water vapour content (VH_2O) ranged from 0.79 (Zweigelt) to 0.83 (Chardonnay). The amount of nitrogen (VN_2) was highest for Chardonnay (4.94) and lowest for Merlot (4.50). The total volume of dry exhaust gases (Vo_{ga}) was highest for Chardonnay (7.32) and lowest for Merlot (6.77). Similarly, the highest Vo_{ga} value was found for Chardonnay (5.77) and the lowest for Merlot (5.34).

Statistical analysis showed that significant differences between varieties were found primarily in relation to Vo_2, Voa, VCO_2, VH_2O, VN_2, Vo_{ga}, and Vo_{gu}, while VSO_2 remained at a similar level regardless of variety and climate zone. The effect of climate was particularly pronounced in the case of Chardonnay and Zweigelt, for which most parameters differed significantly between zones.

The interaction between the variety and the cultivation location is statistically significant for the studied energy parameters, with the exception of H, H/C, Vo_2, Voa, and VH_2O, while in the evaluation of field parameters, no significant difference was shown for the weight of 1 berry, berry diameter, and stalk percentage of bunch weight.

4. Discussion

Biomass from fruit crops is an important source of energy, and its rational use can contribute to reducing the negative impact of agricultural waste on the environment. These relationships have been investigated in previous works [6,33–46] (Table 7).

Table 7. Comparison of technical and elementary analysis for different types of biomass.

Material	HHV ($MJ\cdot kg^{-1}$)	LHV ($MJ\cdot kg^{-1}$)	MC (%)
Hibernal—stalk [37]	15.80	14.67	5.82
Muscaris—stalk [37]	16.44	15.30	6.03
Regent—stalk [37]	15.90	14.81	6.41
Seyval Blanc—stalk [37]	16.23	15.07	6.76
Sauvignon blanc—shoots [38]	18.7	17.3	
Pinot—shoots [38]	16.5	15.1	
Cabernet Sauvignon—shoots [38]	17.6	16.2	
Chardonnay—shoots [38]	17.6	16.2	
Carmenere—shoots [37]	18.7	17.3	
Merlot—shoots [39]	17.8	-	
Prosecco—shoots [39]	18.5	-	
Verduzzo [39]	18.9	-	
Regent—shoots [40]	17.60	16.19	7.05
Rondo—shoots [40]	17.18	15.88	6.60
Seyval Blac—shoots [40]	17.52	16.04	7.43
Solaris—shoots [40]	17.36	15.97	7.04

Explanations: HHV—higher heating value, LHV—lower heating value, MC—moisture content.

Research by Klimek et al. [37] demonstrated a significant influence of variety on the combustion value of grapevine shoots from the PIWI group, who found that the HHV coefficient ranged from 15.80 ($MJ\cdot kg^{-1}$ Hibernal) to 16.44 ($MJ\cdot kg^{-1}$ Muscaris), while the LHV ranged from 14.67 ($MJ\cdot kg^{-1}$ Hibernal) to 15.30 16.44 ($MJ\cdot kg^{-1}$ Muscaris). The parameters assessed showed that the energy level distribution was highest in the Muscaris variety and lowest in the Hibernal variety. This study found that the highest calorific value (HHV) of grapevine stems of *Vitis vinifera* L. varieties grown in Poland was at a similar level and ranged from 15.66 (MJ·kg^{-1} Zwiegelt) to 16.41 (MJ·kg^{-1} Chardonnay), while the lowest calorific value (LHV) ranged from 14.55 (MJ·kg^{-1} Zwiegelt) to 15.26 (MJ·kg^{-1} Chardonnay). Stems from Merlot crops grown in a warm temperate climate (Czech Republic) had the lowest HHV (16.03 MJ·kg^{-1}) and LHV (14.83 MJ·kg^{-1}), while Zwiegelt had the highest HHV—17.56 (MJ·kg^{-1}); LHV 16.00 (MJ·kg^{-1}). When assessing the moisture parameter, Klimek et al. demonstrated a significant influence of the variety on the parameter under study, which was confirmed in the present study in both warm and temperate climates.

Assessing grapevine shoots, Fernández-Puratich et al. [38] demonstrated a significant influence of variety on calorific value; the HHV obtained for Pinot, Cabernet Sauvignon, and Chardonnay varieties was similar to that assessed in this study, while for Sauvignon Blanc and Carmenere varieties it was 18.7 and higher than that assessed in this study. Similar relationships were observed when analysing the LHV parameter.

Spinelli et al. [39] evaluated Merlot, Proseco and Verduzzo grape varieties and found them to have a high HHV value. The difference between the evaluated coefficient levels for the Marlot variety is (1.77 MJ·kg^{-1}).

In the study by Maj et al. [40], woody shoots taken from four grapevine varieties— Seyval Blanc, Solaris, Regent, and Rondo—were evaluated in terms of energy value (grapevines from the PIWI group). A significant influence of the variety on the calorific value of the studied grapevine varieties was demonstrated, with the shoots of the Regent variety characterised by the highest LHV and HHV levels, and the Rondo variety by the lowest. The HHV and LHV coefficients of the Chardonnay (17.30/15.81 MJ·kg^{-1}) and Zweigelt (17.56/16.00 MJ·kg^{-1}) assessed in this experiment were similar to those of the burnt shoots of the PIWI group varieties. Maj et al. demonstrated a significant influence of variety on moisture content, which was confirmed in this study.

When comparing the emission factors for grapevine stems grown in two different climate zones with data provided in the literature (Table 8), it was observed that the CO and CO_2 emission factors for grapevine stems of the PIWI [38] variety and tree leaves [43] are similar. In this study, lower CO and CO_2 values were observed than in grapevine shoots [45], Huzelnut husk Webba Cenny [42], Eucalyptus globulus wood [45], and Larch needles [31], while waste from hazelnut production [44] is lower than that obtained in this study.

Table 8. Comparison of emission factors for different types of biomass (kg·Mg^{-1}).

Material	CO	NOx	CO_2	SO_2	Dust
Wine stalk Hibernal [37]	53.91	0.66	1320.27	0.10	13.23
Wine stalk Muscaris [37]	55.73	0.60	1364.80	0.10	12.61
Wine stalk Regent [37]	54.08	0.65	1324.30	0.11	12.61
Wine stalk Seyval Blanc [37]	56.06	0.63	1372.86	0.06	11.29
Wine shoots Regent [40]	60.60	1.78	1484.06	0.14	4.65
Wine shoots Rondo [40]	59.40	1.81	1454.65	0.14	5.31
Wine shoots Seyval Black [40]	60.25	1.80	1475.35	0.16	4.57
Solaris grapevine shoots [40]	59.98	1.78	1468.87	0.12	5.14
Hazelnut husk Webba Cenny [41]	56.88	1.26	1392.97	0.03	1.25
Hazel tree leaves [42]	54.75	1.99	1340.82	2.07	10.8
Hazelnut pericarp covers Kataloński [43]	50.22	2.38	1229.8	0.06	10.95
Eucalyptus globulus wood [44]	61.75	4.52	1484.34	0.46	5.2
Larch needles [31]	56.34	3.07	1351.9	0.18	0.68

Table 9 presents values relating to the total exhaust gas volume (Vo_{ga}) and covering a wide variety of test materials, most of which fall within the range obtained in our tests burning vine stalks. The exception was biomass from the Timothy grass original sample [41], which showed a significantly lower total exhaust gas volume Vo_{ga}.

Table 9. Comparison of the total volume of exhaust gases (Vo_{ga}) and the total stoichiometric volume of dry exhaust gas (Vo_{gu}) for different types of biomass ($Nm^3 \cdot kg^{-1}$).

Biomass	Vo_{ga}	Vo_{gu}
Oak [33]	-	6.92
Poplar [33]	-	7.00
Jatropha press cake [45]	5.97	5.70
Hazelnut husk Webba Cenny [41]	6.48	4.79
Wine shoots Ronda [40]	6.37	4.90
Wine shoots Regent [40]	6.36	4.88
Wine shoots Solaris [40]	6.25	4.82
Wine shoots Seyval Blanc [40]	6.37	4.89
Timothy grass original sample [46]	4.42	4.29
Hazelnut pericarp covers Olbrzymi z Halle [43]	6.21	4.69
Wine stalk Hibernal [37]	6.57	5.08
Wine stalk Muscaris [37]	7.71	6.14
Wine stalk Regent [37]	6.85	5.35
Wine stalk Seyval Blanc [37]	6.70	5.16

Analysis of the total stoichiometric volume of dry exhaust gases (Vo_{gu}) indicates that the exhaust gas volumes from the analysed grape stems are similar to those observed in diverse plant biomass (Table 9). In particular, there is a noticeable similarity to shoots [40] and grapevine stems [37]. It can also be observed that the biomass from Oak and Poplar [33] is significantly higher than the dry exhaust gas volume of the analysed biomass.

5. Conclusions

Grapevine stems are a valuable energy resource, the potential of which depends on both the variety and growing location.

The variety and place of cultivation significantly influenced most of the biometric characteristics of the bunches (weight of bunches and berries, number of berries, size and weight of stems). A moderately warm climate favours the formation of larger and heavier bunches and larger stems in all analysed varieties.

The best energy parameters were demonstrated by Zweigelt stems grown in a moderately warm climate and Chardonnay grown in a temperate climate, making them the most promising in terms of bioenergy use.

The Chardonnay variety showed greater limitations due to its high ash content and moisture in a warm temperate climate, and the Zweigelt and Merlot varieties due to increased CO and CO_2 emissions.

Cultivation location significantly differentiated most of the parameters studied, which should be taken into account when planning the use of biomass in different wine-growing regions.

The results confirm that vine stalks can be an effective local biofuel that fits in with the principles of the circular economy, while reducing the environmental impact of their current use.

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