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Evaluation and Analysis of the Energy Potential of Grapevine Peduncles of PIWI Group Varieties

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Abstract: This paper presents an analysis of the energy potential of grape stalk biomass from PIWI varieties, namely 'Seyval Blanc', 'Muscaris', 'Hibernal', and 'Regent', during the combustion process. Biometric, technical, and elemental analyses of the grape stalk biomass were conducted. We evaluated the mass, length, and width of the stalks and their contribution to the total cluster mass. The higher and lower heating values, moisture content, volatile compounds, ash, fixed carbon content, and elemental composition were analysed. Emissions of carbon monoxide, nitrogen oxides, carbon dioxide, sulphur, and particulates were also measured. A significant influence of the cultivar on the assessed biometric and technical parameters was found. 'Muscaris' exhibited the highest calorific value (HHV 16.44 MJ·kg^{-1}) and the lowest ash content (9.99%). The highest carbon content (45.51%) was recorded for 'Seyval Blanc', and the highest hydrogen content (6.74%) for 'Muscaris'. Nitrogen oxide emissions were the lowest for 'Seyval Blanc', making it more environmentally friendly. The biomass of grape stalks from PIWI varieties, particularly 'Muscaris' and 'Seyval Blanc', shows high energy potential and can be effectively utilised as a renewable energy source. Our results could be summarised as 'sustainable energy production and reduced greenhouse gas emissions from grape stalks'.

Keywords: combustion; grape stalks; PIWI; energy potential

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Citation: Klimek, K.E.; Kapłan, M.; Maj, G.; Borkowska, A.; Buczyński, K.; Sotolář, R.; Danko, R. Evaluation and Analysis of the Energy Potential of Grapevine Peduncles of PIWI Group Varieties. *Energies* **2024**, *17*, 6043. https://doi.org/10.3390/en17236043

Academic Editor: Albert Ratner

Received: 23 October 2024
Revised: 25 November 2024
Accepted: 27 November 2024
Published: 1 December 2024

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1. Introduction

The adverse effects of climate change, accelerated by fossil fuel combustion, urgently necessitate the development of sustainable energy sources [1]. Currently, environmental concerns and dependency on fossil resources drive the scientific community to seek renewable energy sources for product generation [2,3].

Energy security, climate change, and rising oil prices affect the global population. Additionally, the increasing demands of a growing population present challenges to energy resources. It is noteworthy that the use of agricultural and related waste can lead to the production of valuable products, such as bioenergy. These methods manage waste and potentially provide a more accessible, sustainable energy source [4]. Currently, there is a significantly increased interest in alternative energy sources. Numerous proposals exist for the utilisation of wastes from various sources in the energy systems [5]. A rapidly growing sector of the bioenergy industry is the field that aims to use organic matter, such as plants and waste, to produce renewable energy [6].

Renewable energy sources are valuable due to their versatile applications in various sectors, from solid fuels and biogas to liquid biofuels used in cars, boats, and aeroplanes [7,8]. One-third of the global greenhouse gas emissions caused by human activities come from the agriculture and agrifood sectors, mainly due to improper waste management [9]. The use of bioenergy in agriculture is based on both plant and animal production, promoting an integrated bioenergy production model that includes plants, animals, and breeding [10]. The utilisation of waste energy from production processes is one way to improve energy efficiency [11]. Issues concerning green energy are very important for humanity in the era of global warming. At present, the European Union legislation draws attention to the need for an efficient and economical use of waste in the form of biomass. These actions will be restrictive in the next stage, outside the European Union. Food waste can be processed through combustion, pyrolysis, composting, anaerobic fermentation, hydrothermal carbonisation, and landfilling [12]. The combustion of biomass aims to generate heat, which is then converted into electricity or used for heating [13]. It has been proven that maintaining a rise in global temperature below 2 °C relative to preindustrial levels is crucial for preserving life on Earth. The primary outcome of such actions is the reduction of greenhouse gas emissions. In this context, residual biomass is a valuable resource that can play a significant role in achieving this goal [14].

The use of the natural diversity of plant biomass to produce liquid fuels and valuable byproducts, which are both economically and environmentally sustainable, requires the strategic integration of various technologies, each precisely tailored to a specific type of biomass [15]. The fruit and vegetable industry generates larger amounts of waste compared to other food processing sectors, comprising 25% to 30% of skins, as well as seeds, shells, pods, cores, pulp, and pomace. The perishability of this waste, product characteristics, and logistical and disposal issues are among the main challenges that make the valorisation of this waste a difficult task [16]. The utilisation of biomass residues for energy production contributes to renewable energy sources and the overall energy balance [17]. Therefore, reducing the carbon footprint in the food chain is essential to counteract climate change, and proper waste management plays a crucial role in this [18].

The grapevine (*Vitis vinifera* L.) is one of the most valuable horticultural plants cultivated in the world [19]. The current grape growing areas are primarily located in temperate latitudes, including California in the USA, southern France, northern Spain and Italy, the Barossa region in Australia, Stellenbosch in South Africa, and Mendoza in Argentina [20]. In the crop structure, grapes are the third most commonly cultivated fruit in the world, valued for their taste and use as a raw material for wine production. Consequently, the production of grape juice and wine generates significant amounts of biomass waste, mainly grape seeds and skins [21].

The global wine sector plays a significant role in several national economies [22], but the resulting residues can have negative environmental impacts if not properly managed. Based on current knowledge about the value of these residues, effective and environmentally friendly strategies are necessary to extract value by utilising these residues as valuable raw materials in various processes [23]. Grapevine offers potential for the extraction of valuable phytochemicals and basic chemicals (mainly stilbene-based), as well as for bioenergy production from lignocellulosic residues [24]. The vigour of the rootstock and weather conditions can significantly modify the mass of grape stalks [25].

The aim of this study was to analyse and evaluate the energy potential of biomass obtained from the stalks of PIWI grape varieties, specifically 'Seyval Blanc', 'Muscaris', 'Hibernal', and 'Regent', during the combustion process. This research is innovative because the analysis and assessment of the energy potential of grapevine biomass in temperate climate conditions on the PIWI variety group has not been conducted so far. Taking up this subject has a very large practical aspect because such procedures are not used on wine farms.

2. Materials and Methods

Field research was conducted in 2023 in southeastern Poland, Lublin, at the Experimental Vineyard of the University of Life Sciences. The grapevines were planted in the spring of 2020 with a spacing of 2.5 × 1.2 m (3330 bushes × ha^{-1}) on loess soil. The vines of the studied grape varieties were trained using a single Guyot cord system. On each vine, regardless of the variety, ten fruiting shoots were left with 2 clusters on each shoot. In total, there were 20 clusters on each vine, which is equivalent to 20 stalks. Taking the above into account, 6.66 stalks can be obtained from 1 m^2 of crop. The grapevines were trained using the single Guyot system, with a trunk height of 40 cm, a single cane approximately 0.9 m long, and a single two-bud spur. Stalks from the PIWI varieties—'Seyval Blanc', 'Muscaris', 'Hibernal', and 'Regent'—were collected after a specified period following the separation of berries. Before the berries were separated from the stalks, a sample of 50 clusters was randomly selected for each variety to determine the average cluster weight. The stalks were then subjected to biometric measurements, including mass, length, and width, and the percentage contribution of the stalks to the total cluster mass was determined. The stalks were dried at a controlled temperature.

The experiment was designed in a randomised block design, including four combinations with five replicates. The replicates were plots, each containing three plants. The obtained results were statistically analysed using one-way analysis of variance (ANOVA). The results were additionally presented in graphical form. Statistical conclusions were performed at the significance level of $p < 0.05$. A principal component analysis (PCA) was used to determine the relationships between parameters defining the yield of the studied grape variety. Additionally, multivariate data analysis techniques were used, including cluster analysis, the aim of which was to group rootstock types into homogeneous clusters, ensuring that objects in each cluster were more similar to each other than to objects in other clusters. The results of the cluster analysis were presented using a dendrogram. All analyses were performed using STATISTICA 13 software. The detailed methodology of the measured parameters is discussed in Tables 1–3. Before the tests, the material was placed in a room with constant temperature and humidity conditions, where it was naturally dried in air-dry conditions at 20 °C and 55% to 60% air humidity for two weeks in order to standardise the evaluation conditions. The material for laboratory analysis was in the first step pulverised (0.5 mm) using a Retsch SM 100 grinder (Retsch GmbH, Haan, Germany, 2022) with a power of 1.5 kW. For the purposes of this research, 100 g of material was obtained in 2 min, which consumed 0.045 kWh. Our results present values in the analytical state; additionally, for HHV, the analytical state was recalculated to the dry ash-free state.

Table 1. Fuel characterisation analysis.

Parameter	Method	Equipment
Energetic properties		
Higher Heating Value (HHV; MJ·kg^{-1})	EN-ISO 1928:2020 [26]	Isoperibolic calorimeter LECO AC 600 (LECO Corporation, Saint Joseph, MI, USA, 2012)
Lower Heating Value (LHV; MJ·kg^{-1})		
Proximate Analysis		
Ash (A; %)	EN-ISO 18122:2022 [27]	Thermogravimetric analyser LECO TGA 701 (LECO Corporation, Saint Joseph, MI, USA, 2013)
Volatile matter (V; %)	EN-ISO 18123:2023 [28]	
Moisture (M; %)	EN-ISO 18134:2023 [29]	
Fixed carbon (FC; %)	FC = 100 − V − A − M [30]	

Table 1. *Cont.*

Parameter	Method	Equipment
Ultimate Analysis		
Carbon (C; %)	EN-ISO 16948:2015 [31]	Elemental analyser LECO CHNS 628 (LECO Corporation, Saint Joseph, MI, USA, 2012)
Hydrogen (H; %)		
Nitrogen (N; %)		
Sulphur (S; %)	EN-ISO 16994:2016 [32]	
Oxygen (O; %)	$O = 100 - A - H - C - S - N$ [33]	

Table 2. Emission factors.

Parameter	Method
Carbon monoxide Emission factor (EC) of chemically pure coal (CO; $kg \cdot Mg^{-1}$)	$CO = \frac{28}{12} \cdot E_c \cdot (C/CO)$, CO-carbon monoxide emission factor ($kg \cdot kg^{-1}$), $\frac{28}{12}$— molar mass ratio of carbon monoxide and carbon, EC—emission factor of chemically pure coal ($kg \cdot kg^{-1}$), C/CO—part of the carbon emitted as CO (for biomass 0.06).
Carbon dioxide emission factor (CO_2; $kg \cdot Mg^{-1}$)	$CO_2 = \frac{44}{12} \cdot \left(E_c - \frac{12}{28} \cdot CO - \frac{12}{16} \cdot E_{CH_4} - \frac{26.4}{31.4} \cdot E_{NMVOC}\right)$, CO_2—carbon dioxide emission factor ($kg \cdot kg^{-1}$)—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, ECH4—methane emission factor, ENMVOC—emission index of non-methane volatile organic compounds (for biomass 0.009).
Sulphur dioxide emission factor (SO_2; $kg \cdot Mg^{-1}$)	$SO_2 = \frac{2S}{100} \cdot (1 - r)$, SO_2–sulphur dioxide emission factor ($kg \cdot kg^{-1}$), 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.
Emission factor calculated from (NO_x; $kg \cdot Mg^{-1}$)	$NO_x = \frac{46}{14} \cdot E_c \cdot N/C \cdot (N_{NO_x}/N)$, NO_x—NO_x emission factor ($kg \cdot kg^{-1}$)—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 oxidizes very soon to nitrogen dioxide, N/C—nitrogen to carbon ratio in biomass, NO_x/N—part of nitrogen emitted as NO_x (for biomass 0.122).

Table 3. Exhaust gas composition (Exhaust gas composition was calculated according to [33,34]).

Parameter	Method
Theoretical oxygen demand (V_{O2}; $Nm^3 \cdot kg^{-1}$)	$V_{O_2} = \frac{22.41}{100} \cdot \left(\frac{C}{12} + \frac{H}{4} + \frac{S-O}{32}\right)$, C—biomass carbon content (%), H—biomass hydrogen content (%), S—biomass sulphur content (%), O—biomass oxygen content).
stoichiometric volume of dry air required to burn 1 kg of biomass (V_{oa}; $Nm^3 \cdot kg^{-1}$)	$V_{O_a} = \frac{V_{O_2}}{0.21}$, 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}; $Nm^3 \cdot kg^{-1}$)	$V_{CO_2} = \frac{22.41}{12} \cdot \frac{C}{100}$,
Content of sulphur dioxide (V_{SO2}; $Nm^3 \cdot kg^{-1}$)	$V_{SO_2} = \frac{22.41}{32} \cdot \frac{S}{100}$,

Table 3. *Cont.*

Parameter	Method
Water vapor content of the exhaust gas (V_{H2O}; $Nm^3 \cdot kg^{-1}$)	$V^H_{H_2O} = \frac{22.41}{100} \cdot \left(\frac{H}{2} + \frac{M}{18}\right)$, is the component of water vapor volume from the hydrogen combustion process $\left(V^H_{H_2O}\ ;\ Nm^3H_2O \cdot kg^{-1}\ \text{fuel}\right)$ $V^a_{H_2O} =$ $1.61 \cdot x \cdot V_{oa}$; where : x–air absolute humidity and the volume of moisture contained in the combustion air $\left(V^a_{H_2O}\ ;\ Nm^3H_2O \cdot kg^{-1}\text{fuel}\right)$ $V_{H2O} = V^H_{H2O} + V^a_{H2O}$; M—fuel moisture content (%), -air absolute humidity (kg $H_2O \cdot kg^{-1}$ dry air).
Theoretical nitrogen content in the exhaust gas (V_{N2} ; $Nm^3 \cdot kg^{-1}$)	$V_{N2} = \frac{22.41}{28} \cdot \frac{N}{100} + 0.79 \cdot V_{oa}$, 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%.
Total stoichiometric volume of dry exhaust gas (V_{gu}; $Nm^3 \cdot kg^{-1}$)	$V_{gu} = V_{CO2} + V_{SO2} + V_{N2}$
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.

3. Results and Discussion

Table 4 presents the biometric parameters of waste biomass for the four grapevine varieties 'Hibernal', 'Muscaris', 'Regent', and 'Seyval Blanc'. The analysis was conducted for the mass, length, and width of the stalks, as well as their contribution to the total cluster mass (g). The conducted analysis indicated the occurrence of statistically significant differences between the analysed varieties.

Table 4. Assessment of waste biomass in the form of peduncles of four grape varieties.

Variety	Mass of 1 Stalk (g)	Stalk Length (cm)	Stalk Width (cm)	Stalk Share in Bunch Mass (%)
'**H**ibernal'	8.98 ± 2.75 A *	10.53 ± 1.77 A	6.83 ± 1.48 A	4.98 ± 2.31 AB
'**M**uscaris'	8.90 ± 3.40 AB	10.63 ± 2.77 A	8.27 ± 2.68 A	6.28 ± 3.33 A
'**R**egent'	6.45 ± 0.71 BC	10.17 ± 0.71 A	6.77 ± 0.71 A	3.25 ± 0.51 B
'**S**eyval Blanc'	5.64 ± 2.59 C	10.72 ± 3.83 A	7.39 ± 3.59 A	4.88 ± 4.47 AB
p-value	0.0006	0.9654	0.2879	0.0679

* A significant difference means that different letters in the column and A–C—were significantly different from each other at $\alpha = 0.05$.

The data analysis from Table 4 revealed significant differences in stalk mass, with the highest mass observed in the 'Hibernal' variety (8.98 g) and the lowest in 'Seyval Blanc' (5.64 g). The stalk lengths were relatively similar, ranging from 10.17 cm in the 'Regent' variety to 10.72 cm in 'Seyval Blanc'. In contrast, stalk width varied, with 6.77 cm for the 'Regent' variety and 8.27 cm for 'Muscaris'. The highest contribution of stalks to the total cluster mass was observed in the 'Muscaris' variety (6.28 g), while the lowest was in 'Regent' (3.25 g). However, these differences are not statistically significant, indicating a lack of clear diversity among the varieties in the context of the parameters studied.

The cluster analysis presented in the dendrogram illustrates the classification of PIWI varieties based on stalk mass for 'Hibernal', 'Muscaris', 'Regent', and 'Seyval Blanc'. The dendrogram identified two main clusters, providing insights into the differences in stalk mass among the individual varieties (Figure 1).

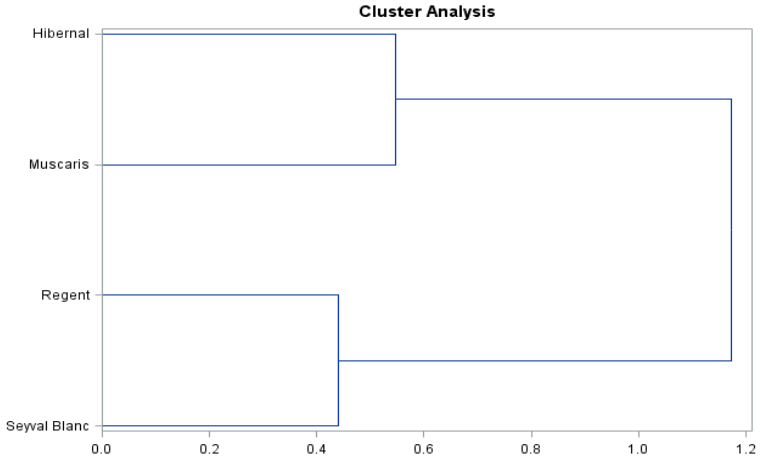


Figure 1. Comparative analysis of the stalk mass depending on the grape variety.

In the first cluster, the varieties 'Hibernal' and 'Muscaris' were grouped together. The proximity of these varieties on the dendrogram suggests that they have similar stalk mass, potentially improving yield uniformity and easing management during harvest.

The second cluster consists of the 'Regent' and 'Seyval Blanc' varieties, which exhibit greater differences in stalk mass compared to the first cluster. The higher stalk mass of these varieties may be more beneficial in the context of wine production, where the specific properties of the varieties can influence the quality and character of the wine.

The division of varieties into two main clusters provides insights into the potential use of different PIWI varieties depending on specific production and quality requirements. This knowledge allows for better planning and resource management in viticulture in a sustainable manner (Figure 1).

Table 5 presents the results of the technical and elemental analysis of waste biomass in the form of PIWI stalks, depending on the variety used in grape cultivation. The analysed parameters include lower heating value (LHV), higher heating value (HHV), moisture content (M), volatile matter content (V), ash content (A), fixed carbon content (FC), as well as elemental composition—carbon (C), hydrogen (H), nitrogen (N), sulphur (S), oxygen (O)—and the ratios of hydrogen to carbon (H/C), nitrogen to carbon (N/C), and oxygen to carbon (O/C).

Table 5. Proximate and ultimate analysis of PIWI stalks depending on the grape variety.

Parameter	'Hibernal'	'Muscaris'	'Regent'	'Seyval Blanc'	*p*-Value
HHV ($MJ \cdot kg^{-1}$)	15.80 ± 0.03 D *	16.44 ± 0.04 A	15.95 ± 0.02 C	16.23 ± 0.06 B	<0.0001
HHV ($MJ \cdot kg^{-1}$) dry ash free state	18.88 ± 0.06 C	19.57 ± 0.07 A	19.09 ± 0.04 B	19.25 ± 0.06 B	<0.0001
LHV ($MJ \cdot kg^{-1}$)	14.67 ± 0.03 D	15.30 ± 0.04 A	14.81 ± 0.02 C	15.07 ± 0.06 B	<0.0001
C%	43.76 ± 0.18 B	45.24 ± 0.59 A	43.90 ± 0.12 B	45.51 ± 0.07 A	0.0002
H%	6.41 ± 0.31 A	6.74 ± 0.03 A	6.44 ± 0.04 A	6.48 ± 0.03 A	0.1125
N%	1.05 ± 0.07 C	2.05 ± 0.14 A	1.36 ± 0.03 B	0.94 ± 0.03 C	<0.0001
S%	0.05 ± 0.01 A	0.05 ± 0.02 A	0.05 ± 0.01 A	0.03 ± 0.02 A	0.3531
M%	5.82 ± 0.08 D	6.03 ± 0.01 C	6.41 ± 0.04 B	6.76 ± 0.07 A	<0.0001
O%	38.24 ± 0.34 A	35.94 ± 0.76 B	38.26 ± 0.17 A	38.10 ± 0.19 A	0.0004
A%	10.48 ± 0.17 A	9.99 ± 0.13 B	9.99 ± 0.19 B	8.94 ± 0.17 C	<0.0001
V%	67.01 ± 1.51 A	64.92 ± 0.11 B	64.68 ± 0.16 B	63.97 ± 0.04 B	0.0065
FC	16.69 ± 1.31 B	19.07 ± 0.20 A	18.93 ± 0.08 A	20.34 ± 0.10 A	0.0011
H/C	53.92 ± 0.22 A	55.73 ± 0.73 A	54.08 ± 0.14 A	56.06 ± 0.08 A	0.2269
N/C	3.72 ± 0.24 C	7.22 ± 0.51 A	4.81 ± 0.09 B	3.33 ± 0.11 C	<0.0001
O/C	1.47 ± 0.07 A	1.49 ± 0.02 B	1.47 ± 0.01 A	1.42 ± 0.01 A	0.0006

* A significant difference means that different letters in the column and A–D—were significantly different from each other at $\alpha = 0.05$.

Our analysis revealed no significant difference in hydrogen content (H%), sulphur content (S%) and hydrogen to carbon ratio (H/C) between the tested varieties. The HHV values ranged from 15.80 MJ·kg^{-1} for the 'Hibernal' variety to 16.44 MJ·kg^{-1} for the 'Muscaris' variety. A similar trend was observed for the LHV values, which ranged from 14.67 to 15.30 MJ·kg^{-1} for these same varieties. The high HHV for 'Muscaris' suggests greater energy efficiency, making this variety more attractive for biomass energy production, while the lower HHV for 'Hibernal' may indicate reduced energy utility. Higher HHV values can indicate a greater amount of energy obtained per unit of mass. Considering that 6.66 peduncles can be obtained from 1 m^2 of vine cultivation, the energy potential from such an area is from 0.56 MJ (6.04 GJ·ha^{-1}) for the Seyval Blanc variety to 0.90 MJ (8.99 GJ·ha^{-1}) for the Muscaris variety. The similar LHV and HHV values for 'Hibernal' and 'Regent' were noted in comparison to the Rape Straw Pellets [35], Rice husk [36], wheat straw [37], while the values for 'Muscaris' and 'Seyval Blanc' were comparable to those of olive waste (Small Twigs) [38].

The carbon (C) content ranged from 43.76% for the 'Hibernal' variety to 45.51% for the 'Seyval Blanc' variety, resulting in a difference of 1.75%. A higher carbon content suggests a greater energy potential of the biomass, which can be important when considering its use as a renewable energy source. The carbon content in the stalks is consistent with that of general biomass. The carbon content for the 'Hibernal' and 'Regent' varieties is comparable to that found in pine and pineapple leaf pellets and thistle, while for the 'Muscaris' and 'Seyval Blanc' varieties, it is similar to coffee husk, olive tree pruning, or vine orujillo [39]. The highest hydrogen (H) content was recorded for the 'Muscaris' variety (6.74%), while the lowest was for the 'Hibernal' variety (6.41%), with a difference of 0.33%. The hydrogen content in these varieties is similar to that of peanut shells, plum stones, rye cereals, and thistles [40]. Regarding nitrogen (N), the highest values were observed for the 'Muscaris' variety (2.05%) and the lowest for 'Seyval Blanc' (0.94%), resulting in a difference of 1.11%. Higher nitrogen content can be undesirable, as it may lead to the formation of nitrogen oxides (NO_x) during combustion, which are harmful to the environment. Sulphur (S) content ranged from 0.54% to 0.56%, showing minimal differences between the varieties. Low sulphur content is beneficial, as it reduces the risk of emitting harmful gases such as sulphur dioxide (SO_2) during combustion. Oxygen (O) content ranged from 35.94% for the 'Muscaris' variety to 38.26% for the 'Regent' variety, with a difference of 2.32%.

Moisture content (M) was highest for the 'Seyval Blanc' variety (6.76%) and lowest for the 'Hibernal' variety (5.82%), indicating a difference of 0.94%. Biomass moisture affects its combustion properties, and lower moisture typically translates to better energy efficiency. Ash content (A) was highest in the 'Hibernal' variety (10.48%) and lowest in 'Muscaris' (9.88%), showing a difference of 0.60%. Ash content is crucial because it affects the amount of residue left after biomass combustion. Such high ash values are unfavourable from the point of view of using stalks as fuel in the combustion process. The obtained values were consistent with the values obtained for tree leaves [41,42]. Nevertheless, in the case of a positive assessment of the ash composition in terms of micro and macro elements, the obtained ash could be used as a fertiliser. In addition, further studies would be necessary to determine the levels of slagging and boiler fouling using this type of material.

Volatile matter (V) ranged from 63.97% for 'Seyval Blanc' to 67.01% for 'Hibernal', with a difference of 3.04%. Higher volatile matter content may indicate easier ignition and more intense combustion. Fixed carbon (FC) values varied from 16.69% for 'Hibernal' to 20.34% for 'Seyval Blanc', giving a difference of 3.65%. Higher fixed carbon content may indicate greater combustion stability and longer burn time.

The hydrogen to carbon ratio (H/C) was highest for 'Muscaris' (75.73%) and lowest for 'Hibernal' (55.77%), resulting in a difference of 19.96%. A higher H/C ratio can indicate a greater energy potential of the biomass. Meanwhile, the nitrogen to carbon ratio (N/C) ranged from 3.33% for 'Seyval Blanc' to 7.22% for 'Muscaris', indicating a difference of 3.89%. A higher N/C ratio may lead to increased nitrogen oxide emissions during combustion.

Lastly, the oxygen to carbon ratio (O/C) differed from 1.42% for 'Seyval Blanc' to 1.49% for 'Muscaris', with a difference of 0.07%. The O/C ratio affects combustion efficiency and the amount of heat generated.

The greatest variations were observed in the carbon content, nitrogen content, and volatile matter, indicating diversity in the energy potential and chemical composition of the biomass depending on the grapevine variety. These parameters demonstrate that grapevine stalk biomass has the potential for effective use as a renewable energy source. High values of HHV and LHV, appropriate carbon content, low ash content, and favourable elemental ratios suggest that varieties such as 'Muscaris' and 'Seyval Blanc' may be particularly valuable in an energy context.

Table 6 presents the results of the emission factor analysis for carbon monoxide, nitrogen oxides, carbon dioxide, sulphur dioxide, and particulate matter. The analysis revealed significant relationships between the grapevine varieties and the parameters studied, with the exception of sulphur dioxide.

Table 6. Analysis of PIWI stalk emission factors for selected grape varieties (kg·Mg^{-1}).

Parameter	'Hibernal'	'Muscaris'	'Regent'	'Seyval Blanc'	*p*-Value
CO	53.91 ± 0.22 B *	55.73 ± 0.73 A	54.08 ± 0.14 B	56.06 ± 0.08 A	0.0002
NO_x	0.66 ± 0.01 C	0.60 ± 0.02 A	0.65 ± 0.00 B	0.63 ± 0.00 C	<0.0001
CO_2	1320.27 ± 5.35 B	1364.80 ± 17.79 A	1324.30 ± 3.52 B	1372.86 ± 1.98 A	<0.0001
SO_2	0.10 ± 0.01 A	0.10 ± 0.05 A	0.11 ± 0.02 A	0.06 ± 0.03 A	0.3531
WE_{dust}	13.23 ± 0.21 A	12.61 ± 0.16 B	12.61 ± 0.24 B	11.29 ± 0.22 C	<0.0001

* A significant difference means that different letters in the column and A–C—were significantly different from each other at $\alpha = 0.05$.

CO values remained at a similar level, with the highest content recorded in the 'Seyval Blanc' variety (56.06 kg·Mg^{-1}) and the lowest in the 'Hibernal' variety (53.91 kg·Mg^{-1}). A similar trend was noted for NO_x, where the range varied between 0.60 kg·Mg^{-1} ('Muscaris') and 0.66 kg·Mg^{-1} ('Hibernal'). For the CO_2 emission factor, the highest values were recorded for 'Hibernal' (1320.27 kg·Mg^{-1}), while the lowest was for 'Seyval Blanc' (1372.86 kg·Mg^{-1}). In the case of SO_2, the values ranged from 0.06 for 'Seyval Blanc' to 0.11 for 'Regent'. WE_{dust} were highest for 'Hibernal' (13.23 kg·Mg^{-1}) and lowest for 'Seyval Blanc' (11.29 kg·Mg^{-1}).

In comparing the emission factors for grape stalks to those reported in the literature (Table 7), it was observed that the CO and CO_2 emission factors are similar to those for Larch needles, Hazelnut husk ('Webba Cenny' cultivar), and most closely to Hazel tree leaves. Our study indicated that stalks have significantly lower NO_x emissions compared to agroforestry biomass, particularly in comparison to *Eucalyptus globulus*. Apart from the 'Seyval Blanc' variety, the SO_2 emission levels are comparable to those observed for Wine shoots ('Ronda') [43]. However, stalks exhibit high particulate matter emissions, similar to those found in tree leaves [44] and hazelnut production waste [45]. Due to the high emission rates for dust related to the high ash content in the tested material, solutions leading to the reduction of this type of emission should be foreseen. A good solution would be to use fuel mixtures consisting of fuels with a low dust emission rate with the tested biomass. In addition, additional filters can be used to capture emitted dust without interfering with the process of exhaust gas release.

Table 8 presents the estimated volumes of exhaust gas components, including both dry and moisture containing exhaust gases. The analysed parameters include the theoretical oxygen demand (Vo_{O2}), the volume of dry air (V_{ogu}), the volume of carbon dioxide (V_{CO2}), sulphur oxides (V_{SO2}), and nitrogen oxides (V_{N2}), the volume of water vapour (V_{H2O}), as well as the total volume of exhaust gases (V_{gu} for dry gases and V_{ga} for gases containing moisture).

Our analysis revealed statistically significant differences for most parameters, except for Vo_{O2}, V_{C2}, V_{SO2}, and V_{H2O}. The oxygen demand (Vo_{O2}) showed similar values across

most varieties, with minor statistical differences ranging from 0.91 $Nm^3 \cdot kg^{-1}$ ('Hibernal' and 'Regent') to 0.97 $Nm^3 \cdot kg^{-1}$ ('Muscaris'), suggesting comparable combustion efficiency in terms of Vo_{O2} emissions. Carbon monoxide emissions (V_{C2}) exhibited a similar trend, with values ranging from 4.33 $Nm^3 \cdot kg^{-1}$ for the 'Hibernal' variety to 4.62 $Nm^3 \cdot kg^{-1}$ for 'Muscaris'.

Table 7. Comparison of emission factors for different types of biomasses ($kg \cdot Mg^{-1}$).

Biomass	CO	NO_x	CO_2	SO_2	Dust
Eucalyptus globulus wood [46]	61.75	4.52	1484.34	0.46	5.20
Larch needles [47]	56.34	3.07	1351.90	0.18	0.68
Huzelnut husk 'Webba Cenny' [48]	56.88	1.26	1392.97	0.03	1.25
Wine shoots 'Ronda' [43]	59.40	1.81	1454.65	0.14	5.31
Hazel tree leaves [44]	54.75	1.99	1340.82	2.07	10.80
Hazelnut pericarp covers 'Kataloński' [45]	50.22	2.38	1229.80	0.06	10.95
Hard coal [49]	82.01	4.09	1969	5.20	23.57

Table 8. Composition of exhaust gases for PIWI stalks depending on the grape variety ($Nm^3\ kg^{-1}$).

Parameter	'Hibernal'	'Muscaris'	'Regent'	'Seyval Blanc'	*p*-Value
Vo_{O2}	0.91 ± 0.02 C *	0.97 ± 0.02 A	0.91 ± 0.00 BC	0.95 ± 0.00 AB	0.0016
V_{CO}	4.33 ± 0.10 C	4.62 ± 0.08 A	4.35 ± 0.02 BC	4.51 ± 0.01 AB	0.0016
V_{CO2}	0.82 ± 0.00 B	0.84 ± 0.01 A	0.82 ± 0.00 B	0.85 ± 0.00 A	0.0002
V_{SO2}	0.00 ± 0.00 A	0.00 ± 0.00 A	0.00 ± 0.00 A	0.00 ± 0.00 A	0.3531
V_{H2O}	0.79 ± 0.03 A	0.83 ± 0.00 A	0.80 ± 0.00 A	0.81 ± 0.00 A	0.1113
V_{N2}	4.26 ± 0.08 C	5.29 ± 0.18 A	4.53 ± 0.01 B	4.31 ± 0.04 BC	<0.0001
Vo_{ga}	6.57 ± 0.13 B	7.71 ± 0.20 A	6.85 ± 0.01 B	6.70 ± 0.04 B	<0.0001
Vo_{gu}	5.08 ± 0.09 B	6.14 ± 0.19 A	5.35 ± 0.01 B	5.16 ± 0.04 B	<0.0001

* A significant difference means that different letters in the column and A–C—were significantly different from each other at $\alpha = 0.05$.

For sulphur dioxide emissions (V_{SO2}), zero emissions were recorded, which is key for assessing the environmental impact of burning this type of biomass. The similar water vapour volume across all varieties indicates comparable moisture content in the biomass, with the highest value observed for 'Muscaris' at 0.83 $Nm^3 \cdot kg^{-1}$ and the lowest for 'Hibernal' at 0.79 $Nm^3 \cdot kg^{-1}$.

In contrast, significant differences were observed in nitrogen oxide emissions, with the highest values recorded for the 'Muscaris' variety (5.29 $Nm^3 \cdot kg^{-1}$) and the lowest for 'Hibernal' (4.26 $Nm^3 \cdot kg^{-1}$). These differences in nitrogen emissions could affect the chemical composition of the exhaust gases and the energy efficiency of combustion.

The total volume of exhaust gases (V_{oga}) and dry exhaust gas (V_{ogu}) showed that the 'Muscaris' variety had the highest values for V_{oga} (7.71 $Nm^3 \cdot kg^{-1}$) and V_{ogu} (6.14 $Nm^3 \cdot kg^{-1}$), whereas 'Hibernal' had the lowest values (6.57 and 5.08 $Nm^3 \cdot kg^{-1}$, respectively). A higher total volume of exhaust gases may indicate greater energy efficiency, but it could also suggest a potentially larger environmental impact.

Table 9 presents a comparison of the total volume of exhaust gases (V_{oga}) and the total stoichiometric volume of dry exhaust gas (V_{ogu}) for different types of biomasses.

Our analysis of the total stoichiometric volume of dry exhaust gas (V_{ogu}) indicates that the exhaust gas volumes from the grape stalks studied are similar to those observed in agroforestry biomass (Table 9). Specifically, there is a noted similarity with wine shoots from the 'Ronda' cultivar [46]. It can also be clearly stated that the volume of dry exhaust gases falls within the medium range compared to other types of biomasses.

Regarding the total volume of exhaust gases (V_{oga}), the analysed stalks exhibit similar exhaust volumes to those of hazelnut husks from the 'Webba Cenny' cultivar [48]. However, it should be noted that the total volume of exhaust gases (V_{oga}) is higher in the analysed stalks compared to the other types of biomasses included in the comparison (Table 9).

Table 9. Comparison of the total volume of exhaust gases (V_{oga}) and the total stoichiometric volume of dry exhaust gas (V_{ogu}) for different types of biomasses ($Nm^3 \cdot kg^{-1}$).

Biomass	Vo_{ga}	Vo_{gu}
Oak [33]	-	6.92
Poplar [33]	-	7.00
Jatropha press cake [50]	5.97	5.70
Huzelnut husk 'Webba Cenny' [48]	6.48	4.79
Wine shoots 'Ronda' [43]	6.37	4.90
Timothy grass original sample [51]	4.42	4.29
Hazelnut pericarp covers 'Olbrzymi z Halle' [49]	6.21	4.69

4. Conclusions

1. The highest stem mass was shown in the 'Hibernal' variety, while the lowest was in 'Seyval Blanc'. The length and width of the peduncles of the tested varieties were similar and did not differ significantly.

2. Analysing the calorific value (HHV), it was observed that the 'Muscaris' variety was characterised by the highest level of 16.44 $MJ \cdot kg^{-1}$, which suggests that it has the highest energy potential among the tested varieties. Similar relationships were shown in the case of hydrogen and nitrogen levels.

3. The highest carbon content (45.51%) and the lowest emissions of nitrogen oxides (NO_x) and sulphur dioxide (SO_2) were recorded for the 'Seyval Blanc' variety, indicating more environmentally friendly parameters.

4. This study confirms that PIWI grape varieties, particularly 'Muscaris' and 'Seyval Blanc', can be effectively used as a renewable energy source due to their favourable combustion properties and low levels of harmful emissions. In further research directions, the influence of stalks on boiler slagging and fouling should be assessed. Additionally, the composition of ash should be studied to assess its fertilising potential. In addition, the creation of fuel mixtures with the inclusion of grape stalks would allow for the indication of directions for biomass use while achieving high energy parameters with a low impact on the environment.

Author Contributions: Conceptualisation, G.M., K.E.K. and M.K.; methodology, G.M. and M.K.; software, K.E.K.; validation, G.M., K.E.K. and M.K.; formal analysis, K.E.K.; investigation, G.M. and M.K.; resources, K.E.K., R.S. and R.D.; data acquisition, G.M. and M.K.; writing—original draft preparation, K.E.K., A.B. and K.B.; writing—reviewing and editing, A.B. and K.B.; visualisation, K.B.; supervision, K.E.K.; project administration, A.B.; funding acquisition, M.K., R.S. and R.D. All authors have read and agreed to the published version of the manuscript.

Funding: Statutory funds were provided by the University of Life Sciences in Lublin (TKZ/S/45/2024 and OIP/S/51/2024).

Data Availability Statement: The data presented in this study are available upon request from the corresponding author.

Conflicts of Interest: The authors declare no conflicts of interest.

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