

Article

Analysis of the Energy–Carbon Potential of the Pericarp Cover of Selected Hazelnut Varieties

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Abstract: The research presents weight estimation and analysis of the energy and carbon potential of the pericarp cover of four hazelnut varieties. A technical and elementary biofuel analysis was carried out for the biomass studied, as well as a correlation and principal component analysis to demonstrate the influence of individual characteristics on the parameters achieved. In addition, emission factors and the composition and volume of flue gases from the combustion of the material studied were estimated based on stoichiometric equations. The research showed that the highest calorific value (LHV) was characterised by the pericarp cover of the ‘Olga’ variety ($14.86 \text{ MJ} \cdot \text{kg}^{-1}$) and the lowest by the ‘Kataloński’ variety ($14.60 \text{ MJ} \cdot \text{kg}^{-1}$). In the case of exhaust volume, the highest volume was obtained from the ‘Olbrzymi z Halle’ variety ($250.06 \text{ Nm}^3 \cdot \text{kg}^{-1}$) and the lowest from the ‘Kataloński’ variety ($12.43 \text{ Nm}^3 \cdot \text{kg}^{-1}$). The correlation analysis carried out showed that the HHV and LHV parameters in the covers showed a very strong positive correlation with sulphur content and SO_2 emissions, and a moderate correlation with nitrogen content and its associated NO_x emissions, indicating their direct influence on the higher calorific value of biomass.

Keywords: horticultural waste; *Corylus avellana*; pericarp cover; energy potential; emissions



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1. Introduction

The changes taking place in the era of economic development and increasing economic requirements are forcing producers and distributors of energy resources to look for new, more environmentally friendly energy options as an alternative to traditional fossil fuels [1,2]. In the face of new legislative and environmental requirements, the management of the energy sector, requires them to take a fresh look and update the strategies covered [3,4]. The general challenge in bioenergy production is to effectively manage the supply chain at each stage, while taking into account economic, environmental and social aspects [5–7].

Biomass, as a renewable resource and alternative fuel, is expected to play a key role in achieving climate and energy neutrality [8]. Its role is multidimensional and is not limited to providing raw materials for economic use. It is responsible for energy diversity, carbon capture and storage, air quality, reducing greenhouse gas emissions and ensuring the continuity of ecosystems [9–11]. Given that the new scenario envisages an increase in the share of RES to 27% in Europe, as well as a 40% reduction in greenhouse gas emissions by 2030 [12], efforts are being made to improve technology and introduce innovations for biomass conversion in order to reduce the cost of bioenergy production [13]. The conversion and use of biomass are worth promoting, especially with an emphasis on less common, variable, random and often dispersed materials such as organic waste from agricultural production [14,15]. Their chemical composition, quantity, availability and properties predispose them to reuse through biochemical, chemical and thermochemical

processes and the creation of bioproducts, biomaterials and use through direct conversion to biofuels in gasification and pyrolysis processes, thus creating local industrial and energy value chains [15–17].

Hazelnut, which is the fruit of the hazelnut tree, is an excellent example of functional food due to its taste, nutritional and health-promoting qualities, and is a valuable raw material not only in the kitchen [18,19]. Less well-known but equally important is the use of the waste biomass that is generated during its production. Their quantity depends on the volume of production, as well as the way it is organised. Traditionally, this waste was seen as a problem, but modern technologies and innovative approaches to waste management make it possible to turn this ‘problem’ into ecological and economical solutions. In an era of sustainability and closed-loop economics, even waste can become a valuable resource. Transforming them into new products for energy production aims to add value to the by-product [20,21]. In addition, this approach makes it possible to reduce landfill and thus minimise the negative impact on the environment [14,15].

In the context of the use of hazelnut production residues, the pericarp cover also represents a valuable material that can be processed for energy recovery. It is formed from the fusion of three inflorescences with serrated edges. It is characterised by its green or red colour and the extent to which it covers the pericarp. When the nut ripens, the shell falls off, leaving a characteristic mark on the woody shell, known as the shield. Most of this waste decomposes on the farm. Although detailed research on pericarp casing is limited, the inclusion of this form of biomass in the energy cycle may contribute to the efficient and holistic management of waste biomass from hazelnut cultivation, regardless of its type.

The aim of the research was to estimate the weight of pericarp casings for a selected hazelnut variety and to define fuel quality parameters by performing technical and elemental analysis, as well as determining the combustion heat and calorific value. In addition, the study aimed to assess the emission factors of CO, CO₂, SO₂, NO_x and dust, in order to determine the degree of impact of potential bio-waste generated during the combustion process. An analysis of the flue gas composition based on estimation from stoichiometric equations was also carried out.

2. Materials and Methods

The study tested the influence of hazelnut cultivar on the parameters of the energy potential of waste biomass in the form of pericarp cover obtained during harvesting.

The field research was conducted in 2023 in south-eastern Poland (private Horticultural Farm; Zawichost municipality; Świętokrzyskie voivodeship; 50°49′20.5″ N, 21°44′35.0″ E) under temperate climate conditions. The study included ungrafted hazel shrubs growing on their own roots of the varieties: ‘Kataloński’, ‘Olbrzymi z Halle’, ‘Olga’ and ‘Webba Cenny’. The shrubs were planted in spring 2002 on loess soil (bonitation classes II and II ab) in a row system, with a spacing of 6 × 2.5 m applied (666 pcs·ha^{−1}). The following parameters were analysed: yield based on the weight of the whole hazelnut (husk + kernel) and the weight of 100 and 1 bush of pericarp cover (waste). The obtained parameters were converted to a unit area of 1 ha. Samples for analysis were taken at full harvest maturity from 3 randomly selected bushes, 4 samples for each cultivar, which made it possible to determine the average value for the parameters studied. Immediately after harvest, samples were weighed with an accuracy of 0.001 kg, and then their weight was determined on a RADWAG PS R2 precision balance (RADWAG, Radom 26-600, Poland).

The study evaluated the energy and emission parameters for the materials tested. Fuel quality parameters were estimated by performing technical and elemental analysis, and the heat of combustion and calorific value were determined. The methodology of the procedures is shown in Table 1.

Table 1. A summary of the methods and apparatuses used for the energy and carbon analysis of the raw materials studied.

	Parameter	Method	Equipment
Energetic properties	Higher Heating Value (HHV; MJ·kg ^{−1})	EN-ISO 1928:2009 [22]	isoperibolic calorimeter LECO AC 600
	Lower Heating Value (LHV; MJ·kg ^{−1})		
Proximate Analysis	Ash (A; %)	EN-ISO 18122-01 [23]	thermogravimetric analyser LECO TGA 701
	Volatile matter (V; %)	EN-ISO 18123-01 [24]	
	Moisture (M; %)	EN-ISO 18134-3 [25]	
	Fixed carbon (FC; %)	FC = 100 − V − A − M [26]	
Ultimate Analysis	Carbon (C; %)	EN-ISO 16948:2015-07 [27]	elemental analyser LECO CHNS 628
	Hydrogen (H; %)		
	Nitrogen (N; %)		
	Sulfur (S; %)	EN-ISO 16994:2016-10 [28]	
	Oxygen (O; %)	O = 100 − A − H − C − S − N [29]	
Emission factors calculated according studies [30]:			
Emission Factors	Carbon monoxide Emission factor (Ec) of chemically pure coal (CO; kg·Mg ^{−1})	$CO = \frac{28}{12} \cdot E_c \cdot (C/CO),$ CO—carbon monoxide emission factor (kg·kg ^{−1}), $\frac{28}{12}$ —molar mass ratio of carbon monoxide and carbon, Ec—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})	$CO_2 = \frac{44}{12} \cdot \left(E_c - \frac{12}{28} \cdot CO - \frac{12}{16} \cdot E_{CH_4} - \frac{26.4}{31.4} \cdot E_{NMVOC} \right),$ CO ₂ —carbon dioxide emission factor (kg·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})	$SO_2 = \frac{2S}{100} \cdot (1 - r),$ SO ₂ —sulphur dioxide emission factor (kg·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 was calculated from (NO _x ; kg·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·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).	
Exhaust gas composition was calculated according to [31,32]:			
Exhaust gas composition	Theoretical oxygen demand (V _{O₂} ; Nm ³ ·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 sulfur content (%), O—biomass oxygen content).	
	The stoichiometric volume of dry air required to burn 1 kg of biomass (V _{oa} ; Nm ³ ·kg ^{−1})	$V_{O_a} = \frac{V_{O_2}}{0.21},$ 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 ·kg ^{−1})	$V_{CO_2} = \frac{22.41}{12} \cdot \frac{C}{100},$	
	Content of sulfur dioxide (V _{SO₂} ; Nm ³ ·kg ^{−1})	$V_{SO_2} = \frac{22.41}{32} \cdot \frac{S}{100},$	

Table 1. Cont.

Parameter	Method	Equipment
Exhaust gas composition	Water vapor content of the exhaust gas (V_{H_2O} ; $Nm^3 \cdot kg^{-1}$)	$V_{H_2O}^H = \frac{22.41}{100} \cdot \left(\frac{H}{2} + \frac{M}{18} \right),$ is the component of water vapor volume from the hydrogen combustion process $(V_{H_2O}^H; Nm^3 H_2O \cdot kg^{-1} fuel)$ $V_{H_2O}^a = 1.61 \cdot x \cdot V_{oa}$ and the volume of moisture contained in the combustion air $(V_{H_2O}^a; Nm^3 H_2O \cdot kg^{-1} fuel)$ $V_{H_2O} = V_{H_2O}^H + V_{H_2O}^a$; M-fuel moisture content (%), -air absolute humidity ($kg H_2O \cdot kg^{-1}$ dry air).
	The theoretical nitrogen content in the exhaust gas (V_{N_2} ; $Nm^3 \cdot kg^{-1}$)	$V_{N_2} = \frac{22.41}{28} \cdot \frac{N}{100} + 0.79 \cdot V_{oa},$ 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} ; $Nm^3 \cdot kg^{-1}$)	$V_{gu} = V_{CO_2} + V_{SO_2} + V_{N_2}$
	The total volume of exhaust gases (V_{ga} ; $Nm^3 \cdot kg^{-1}$)	$V_{ga} = V_{gu} + V_{H_2O}$ 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.

Figure 1 shows the flow chart of the test rig.

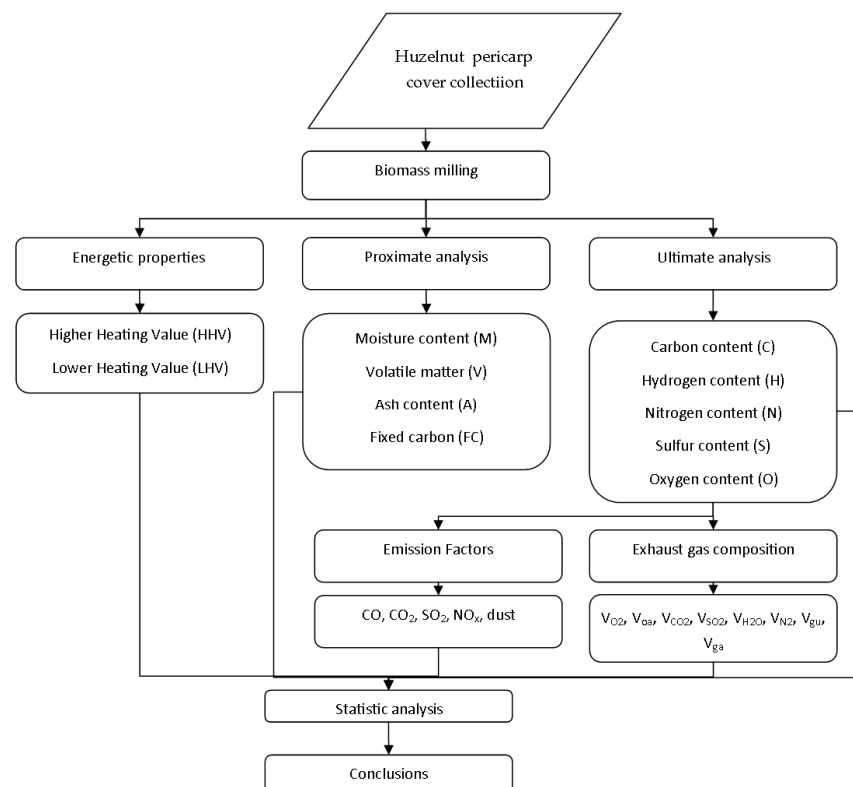


Figure 1. Flow chart of the test rig.

3. Results and Discussion

As part of the research, particular attention was paid to the differentiation of hazelnut varieties in terms of their energy properties and the productivity of waste biomass in the form of pericarp covers. The hazelnut, being not only a valuable source of nutrients but also a raw material for energy, is of interest in the context of sustainable agriculture and renewable energy.

Cultivars, i.e., ‘Kataloński’, ‘Olbrzymi z Halle’, ‘Olga’ and ‘Webba Cenny’, were analysed to determine the mass of hazelnut pericarp covers and their energy potential.

Table 2 shows the results of the comparisons of the hazelnut yield and the pericarp weight for four hazel cultivars: ‘Kataloński’, ‘Olbrzymi z Halle’, ‘Olga’ and ‘Webba Cenny’. The analysis was performed for the yield of whole hazelnuts and seed coats alone for 100 units (in g), per bush (in kg) and per unit area (in tons per ha). The study indicates that there are statistically significant differences between the varieties tested.

Table 2. Comparison of hazelnut yield and pericarp weight according to the cultivar used in the crop.

Parameter		Hazelnut Varieties				p-Value
		‘Kataloński’	‘Olbrzymi z Halle’	‘Olga’	‘Webba Cenny’	
100 pcs. (g)	yield	481.00 ± 12.29 ^c	599.33 ± 56.01 ^a	598.00 ± 7.21 ^a	502.33 ± 24.58 ^b	0.0026
	pericarp	76.00 ± 8.00 ^c	144.33 ± 26.08 ^{ab}	156.00 ± 4.36 ^{ab}	101.67 ± 20.82 ^{bc}	0.0015
1 bush (kg)	yield	5.70 ± 0.08 ^a	5.20 ± 0.35 ^{ab}	5.5 ± 0.1 ^a	4.80 ± 0.20 ^a	0.0039
	pericarp	1.07 ± 0.11 ^c	1.65 ± 0.3 ^{ab}	1.94 ± 0.05 ^a	1.22 ± 0.25 ^{bc}	0.0029
1 ha (t·ha ^{−1})	yield	3.80 ± 0.05 ^a	3.46 ± 0.23 ^{ab}	3.66 ± 0.07 ^a	3.19 ± 0.13 ^b	0.0032
	pericarp	0.71 ± 0.07 ^c	1.10 ± 0.20 ^{ab}	1.29 ± 0.04 ^a	0.81 ± 0.17 ^{bc}	0.0017

±standard deviation; a, b, c, ab, bc—means with the same letter in row show no significant difference and means with different letters with significant differences at $\alpha = 0.05$.

Biometric evaluation is important not only for distinguishing hazelnut varieties but also for determining their use and designing processing equipment. Analysing the data in Table 2 in the 100-unit category, ‘Olbrzymi z Halle’ shows the highest average weights for both whole nut and pith, 599.33 g and 144.33 g, respectively, while ‘Webba Cenny’ shows the lowest values for both parameters (502.33 g for whole nut and 101.67 g for pith). These differences are statistically significant, indicating a clear phenotypic diversity between varieties in the context of whole nut and pericarp weight.

A study by Król et al. [33], evaluating six hazelnut cultivars of *Coryllus avellana* L. produced in Poland, showed a significant effect of cultivar on nut weight. This relationship was also confirmed in the present study. The work by Cierniewska and Ratusz [34] also showed a significant effect of cultivar on hazelnut weight, with nuts of the ‘Kataloński’ cultivar being the heaviest and ‘Cosford’ the lightest; nuts of the ‘Webba Cenny’ cultivar ranked in the middle. Król et al. [33] found that indeed the ‘Nottinghamski’ (2.24 g) and ‘Cosford’ (2.41 g) varieties had the lightest nuts, while the ‘Webba Cenny’ variety had the heaviest (3.21 g). It was shown that the nuts of the ‘Olbrzymi z Halle’ variety were significantly heavier than ‘Kataloński’, a relationship that was fully confirmed in the present study. The study also showed that the nut weight of the ‘Webba Cenny’ cultivar ranked between ‘Olbrzymi z Halle’ and ‘Kataloński’, a finding that was not confirmed in the study by Król et al. [33], where ‘Webba’ produced significantly the heaviest nuts of those evaluated. Ferrão et al. [35] also observed significant differences between some hazelnut cultivars where, in terms of nut weight in the shell, Gunslebert cultivar fruit was heavier on average (3.89 ± 0.64 g), while the Negreta cultivar fruit was lighter on average (2.23 ± 0.37 g). A study by Lopes et al. [36] also found that varietal characteristics determined nut weight.

Habitat conditions [37,38], cultivar and harvest date may be important modifiers of hazelnut quality ratings [39–41]. Our observations and analytical results confirm these opinions. Immediately after harvest, the average weight of 100 nuts was 5.09 g (‘Olbrzymi z Halle’), 4.76 g (‘Kataloński’) and 4.63 g (‘Webba Cenny’). Morphological traits are often used to identify varieties. To be useful, traits must be consistent from year to year and from tree to tree. Solar and Stampar [42] showed that the nut weight of sixteen hazelnut varieties of different origins ranged from 2.36 g to 4.30 g, the present study results also confirm this.

Nuts of small to medium size, with weights up to 3.2 g and crunchy kernels, are preferred for the processing market. In contrast, in the direct sales market for shelled nuts, larger nuts are more sought after [43]. Although the hazelnut varieties studied had a higher average nut weight, the average kernel weight was quite similar to the results obtained by Ozdemir and Akinci [44], where this trait in Turkish hazelnut varieties ranged from 0.89 g to 1.33 g.

Similar trends are observed when analysing hazelnut yield and seed coat weight per bush and per unit area, where ‘Olbrzymi z Halle’ and ‘Olga’ present higher weights of both whole nut and seed coat compared to the cultivars ‘Kataloński’ and ‘Webba Cenny’.

The significant differences in the weights of whole nuts and their seed coats between the analysed varieties highlight the influence of genetics on these traits. This provides valuable information for variety selection to optimise production, where ‘Olbrzymi z Halle’ may be preferred for its higher hazelnut yield and seed coat weight, while ‘Webba Cenny’ may be less desirable in the context of commercial hazelnut production and waste biomass acquisition (Table 2).

The cluster analysis presented in the dendrogram (Figure 2) illustrates the classification of hazelnut cultivars in terms of the amount of waste seed coat biomass generated. The dendrogram distinguishes two main clusters, which allows an understanding of the differences in biomass productivity between varieties.

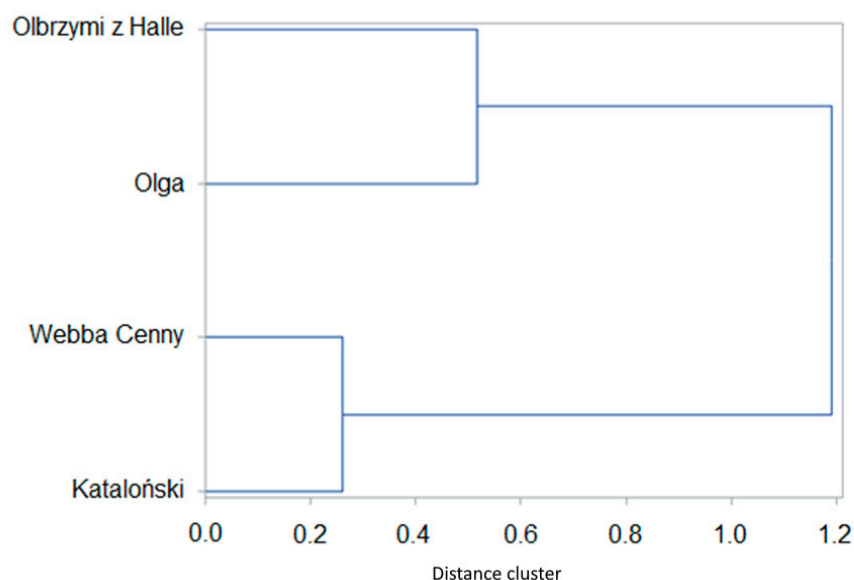


Figure 2. Comparative analysis of the pericarp cover of selected hazelnut cultivars in terms of the amount of waste biomass generated.

The first cluster includes the varieties ‘Webba Cenny’ and ‘Kataloński’. The proximity of these varieties on the dendrogram suggests that they are characterised by similar, lower waste biomass production. Such characteristics may be beneficial in terms of waste management and efficiency in smaller or intensively managed growing areas.

The second cluster is formed by the varieties ‘Olbrzymi z Halle’ and ‘Olga’, which show a higher amount of waste biomass generated. The higher productivity of these varieties may be more beneficial in energy applications, where more biomass translates into better energy yield, which is important in the context of biomass energy production.

The division of varieties into two main clusters provides information on the potential use of different hazelnut varieties depending on specific production and energy needs. Knowledge of the amount of waste biomass generated enables better planning and management of biomass resources in a sustainable manner.

The results of the technical and elemental analysis of hazelnut pericarp covers show the existence of statistically significant differences between varieties in many categories, suggesting the influence of genetic diversity on biomass properties (Table 3).

Table 3. Comparison of the results of the technical and elemental analysis of hazelnut seed coats according to the variety used in cultivation.

Parameter	Hazelnut Varieties				<i>p</i> -Value
	‘Kataloński’	‘Olbrzymi z Halle’	‘Olga’	‘Webba Cenny’	
LHV (MJ·kg ^{−1})	14.60 ± 0.02 ^b	14.85 ± 0.07 ^a	14.86 ± 0.02 ^a	14.75 ± 0.08 ^a	0.0014
HHV (MJ·kg ^{−1})	15.77 ± 0.02 ^b	16.02 ± 0.07 ^a	16.03 ± 0.02 ^a	15.94 ± 0.08 ^a	0.0014
M (%)	7.44 ± 0.02 ^c	7.59 ± 0.06 ^b	7.12 ± 0.02 ^d	8.23 ± 0.08 ^a	0.0001
V (%)	66.67 ± 0.29 ^b	66.33 ± 0.17 ^b	68.01 ± 0.7 ^a	65.1 ± 0.33 ^c	0.0002
A (%)	8.67 ± 0.16 ^a	8.55 ± 0.24 ^a	8.54 ± 0.04 ^a	8.31 ± 0.15 ^a	0.1175
FC (%)	17.66 ± 0.17 ^{ab}	17.54 ± 0.19 ^{ab}	16.34 ± 0.72 ^b	18.37 ± 0.35 ^a	0.0113
C (%)	40.76 ± 0.22 ^b	41.26 ± 0.06 ^a	40.82 ± 0.14 ^{ab}	40.99 ± 0.22 ^{ab}	0.0322
H (%)	6.72 ± 0.29 ^a	6.88 ± 0.32 ^a	6.83 ± 0.26 ^a	6.71 ± 0.30 ^a	0.8587
N (%)	0.67 ± 0.01 ^b	0.85 ± 0.06 ^a	0.72 ± 0.06 ^b	0.65 ± 0.02 ^b	0.0014
S (%)	0.03 ± 0.00 ^d	0.04 ± 0.00 ^a	0.04 ± 0.00 ^b	0.03 ± 0.00 ^c	0.0001
O (%)	43.14 ± 0.27 ^a	42.41 ± 0.05 ^a	43.05 ± 0.47 ^a	43.32 ± 0.66 ^a	0.1308
H/C	1.65 ± 0.07 ^a	1.67 ± 0.08 ^a	1.67 ± 0.06 ^a	1.64 ± 0.06 ^a	0.9068
N/C	0.02 ± 0.0002 ^b	0.02 ± 0.0014 ^a	0.02 ± 0.0013 ^b	0.02 ± 0.0005 ^b	0.0016
O/C	0.79 ± 0.0062 ^a	0.77 ± 0.0008 ^a	0.79 ± 0.0112 ^a	0.79 ± 0.0165 ^a	0.0847

±standard deviation; a, b, c, d, ab—means with the same letter in row show no significant difference and means with different letters with significant differences at $\alpha = 0.05$.

The heat of combustion for the pericarp covers tested, depending on the cultivar used, ranged from 15.77 to 16.03 MJ·kg^{−1} for HHV values and from 14.6 to 14.85 MJ·kg^{−1} for LHV. The cultivar ‘Olbrzymi z Halle’ shows the highest HHV (16.02 MJ·kg^{−1}) and LHV (14.85 MJ·kg^{−1}) values, indicating its energy potential as the highest among the cultivars tested. ‘Kataloński’ presents the lowest LHV values (14.06 MJ·kg^{−1}) and ‘Webba Cenny’ the lowest HHV (15.94 MJ·kg^{−1}). The differences for HHV and LHV are statistically significant, confirming the effect of cultivars on biomass energy efficiency. The LHV and HHV results for the pericarp covers tested are lower in relation to walnut shells, hazelnut shells, peanut shells, and pistachio shells [14,45]. The most similar LHV values are between the cultivars ‘Olga’ and ‘Olbrzymi z Halle’ and pistachio shells. The variety ‘Kataloński’ has the same LHV values as rice husk [29]. In the case of the ‘Kataloński’ and ‘Webba Cenny’ varieties, a higher level and heat of combustion was obtained for the shells of these varieties [46].

The volatile compound (V) content ranged from 65.1% for ‘Webba Cenny’, which is favourable for thermal processes, to 68.01% for ‘Olga’. It can be noted that for this trait the difference between the extreme results was more than 2.91%. The content of volatile parts obtained in the study is the same as the tested hazelnut shells for the cultivars Istarskiduguljasti and Rimskiokrugli [47]. Comparing the hazelnut shells of the cultivars ‘Webba Cenny’ and ‘Kataloński’ in the study of Hebda et. al. [46] an average of 4% higher content of volatile parts was obtained than in the tested pericarp shells.

On the other hand, analysis of the ash content (A) of the biomass tested showed significant differences between the varieties. The discrepancy between the extreme results was 0.36%. The pericarp covers of the ‘Kataloński’ variety had the highest ash content (8.67%), while the ‘Webba Cenny’ variety had the lowest (8.31%). Much lower ash content was found in the hazelnut husks of the cultivars ‘Webba Cenny’, ‘Kataloński’, ‘Casina’ or ‘Bergera’ (on average by 7%) [46] in relation to the tested pericarp covers of walnut shells (by 6%), almond shells (by 5%) or sunflower shells (by 4%) [45], or peanut shells (by 4.9%) [48]. Therefore, the tested material is characterized by a much higher ash content than other types of biomass. A comparable ash content was found for hazel tree leaves [49].

The lowest content of 40.76% for carbon (C) was recorded for the pericarp covers of the cultivar ‘Kataloński’, while the cultivar ‘Olbrzymi z Halle’ showed the highest estimated value of 41.26%. Considering the carbon content, the choice of the right variety in cultivation may result in a difference of not a whole percentage in the content of this element in the pericarp covers. A much higher (about 16%) carbon concentration was

recorded in the hazelnut shells of the Istarskiduguljasti and Rimskiokrugli cultivars in relation to the tested covers [47]. The results obtained for the carbon content of pericarp shells are lower by 7–10% on average in relation to hazelnut husks, walnut husks, almond husks [45] and are 3% lower for sunflower husk [50].

The atomic ratio indices, i.e., H/C, are higher for the ‘Olbrzymi z Halle’ and ‘Olga’ varieties, reaching 1.67%, indicating an increased hydrogen-to-carbon content and possibly affecting combustion properties. The lowest H/C ratio value is shown by the ‘Kataloński’ variety (1.65%), indicating a lower hydrogen-to-carbon ratio compared to the two previously mentioned varieties. The differences in N/C and O/C ratios are not statistically significant. However, it is worth noting that ‘Webba Cenny’ has the lowest N/C value of 0.02%. In addition, ‘Webba Cenny’ together with ‘Kataloński’ achieved the lowest O/C values of 0.79%. This indicates lower nitrogen and oxygen-to-carbon content in these varieties compared to the others.

In summary, the pericarp covers of the selected varieties differ significantly in terms of energy values, moisture, ash and carbon content, which may influence their use as biofuel (Table 3).

Figure 3 shows the result of the principal component analysis for the resulting heat of combustion for the tested shoots of the four hazelnut varieties.

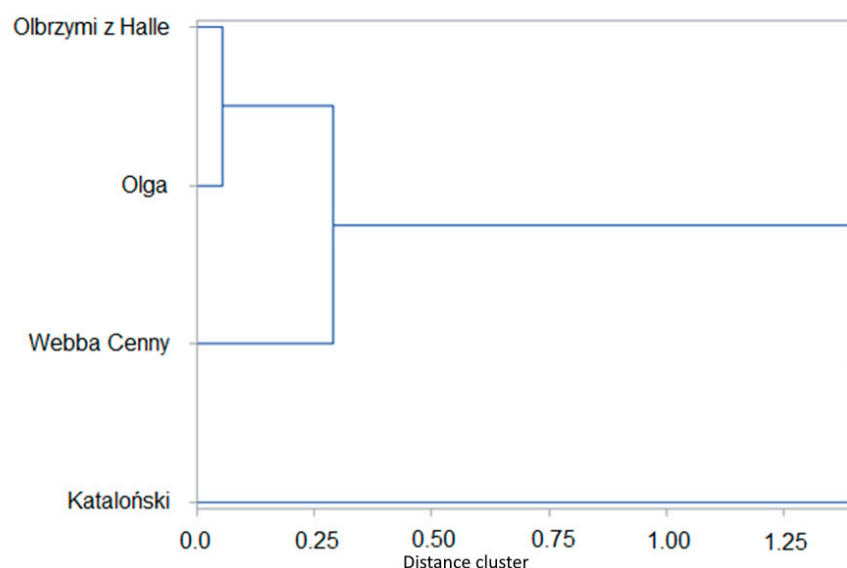


Figure 3. Comparative analysis of seed coats of selected hazelnut cultivars tested for energy production (HHV).

The cluster analysis on the presented dendrogram for hazelnut cultivars in terms of HHV values shows the formation of two main clusters. The first cluster is formed by the cultivars ‘Olbrzymi z Halle’ and ‘Olga’, which show higher HHV values, highlighting their greater potential for efficient use in energy production. The second cluster brings together the varieties ‘Kataloński’ and ‘Webba Cenny’, which show similar lower HHV values, which may suggest their similar energy potential and combustion properties. This analysis highlights the differences in energy potential between the different variety groups. Varieties in the first cluster may be more desirable in the context of applications where maximising the energy yield from the feedstock used is key, while varieties in the second cluster may be preferred for applications requiring lower energy biomass. With this knowledge, it is possible to better plan the use of different hazelnut varieties according to specific energy needs and processing needs (Figure 3).

Table 4 shows the estimated emission factors for the tested pericarp covers of the four hazelnut varieties.

Table 4. Emission parameters for hazelnut pericarp covers depending on the variety used in cultivation.

Parameter	Hazelnut Varieties				p-Value
	‘Kataloński’	‘Olbrzymi z Halle’	‘Olga’	‘Webba Cenny’	
CO (kg·Mg ^{−1})	50.22 ± 0.27 ^b	50.83 ± 0.08 ^a	50.29 ± 0.17 ^{ab}	50.5 ± 0.275 ^{ab}	0.0322
CO ₂ (kg·Mg ^{−1})	1229.80 ± 6.58 ^b	1244.72 ± 1.86 ^a	1231.61 ± 4.12 ^{ab}	1236.57 ± 6.74 ^{ab}	0.0322
NO _x (kg·Mg ^{−1})	2.38 ± 0.04 ^b	3.02 ± 0.21 ^a	2.56 ± 0.20 ^b	2.28 ± 0.07 ^b	0.0014
SO ₂ (kg·Mg ^{−1})	0.06 ± 0.00 ^d	0.09 ± 0.00 ^a	0.07 ± 0.00 ^b	0.07 ± 0.00 ^c	0.0001
Dust (kg·Mg ^{−1})	10.95 ± 0.19 ^a	10.8 ± 0.30 ^a	10.78 ± 0.04 ^a	10.49 ± 0.19 ^a	0.0175

±standard deviation; a, b, c, d, ab—means with the same letter in row show no significant difference and means with different letters with significant differences at $\alpha = 0.05$.

Pollutants analysed include carbon monoxide (CO), carbon dioxide (CO₂), nitrogen oxides (NO_x), sulphur oxide (SO₂) and dust. The differences in CO and CO₂ emissions between the varieties tested are not statistically significant, suggesting similar combustion performance in terms of these pollutants for all varieties. On the other hand, statistically significant differences were found for NO_x emission values, which draws attention to the variation between varieties in the context of nitrogen oxide emissions. The highest values were observed for the cultivar ‘Olbrzymi z Halle’ at 3.02 kg·Mg^{−1}, while the lowest values were recorded for ‘Webba Cenny’ at 2.28 kg·Mg^{−1}. Similar significance was shown for SO₂ emissions, where the highest emissions were recorded for ‘Olbrzymi z Halle’ at 0.09 kg·Mg^{−1} and the lowest for ‘Kataloński’ at 0.06 kg·Mg^{−1}. The differences in dust emissions are also statistically significant, with the highest value for ‘Kataloński’ 10.95 kg·Mg^{−1} and the lowest for ‘Webba Cenny’ 10.49 kg·Mg^{−1}.

Comparable CO results for the raw materials tested were shown for wheat straw [30] and *Pinusradiata* wood [51], Jackfruitpeel [29], and for CO₂ as for wheat straw and oat gran [30], *Jackfruitpeeli* Jackfruit seeds [29]. *Pinusradiata* (by 13 kg·Mg^{−1} on average), or *Eucalipthusglobulus* (by 11 kg·Mg^{−1} on average) have much higher CO [52]. Similar NO_x values for the cultivars ‘Kataloński’ and ‘WebbaCenny’ are shown by larch needles and rapeseed pods [30]. The examined pericarp covers for all varieties show significantly lower SO₂ emission (on average 0.1–0.7 kg·Mg^{−1}) in relation to wood biomass [51,52] and agrobiomass [30]. The pericarp covers of the cultivars ‘Olga’ and ‘Webba Cenny’ show identical SO₂ emissions to Jackfruit peel [29].

In summary, ‘Olbrzymi z Halle’ has higher NO_x and SO₂ emissions, which may have a negative impact on the environment, while ‘Webba Cenny’ shows lower values for dust emissions, which may be beneficial in terms of air quality protection. The differences in CO and CO₂ emissions are minimal which allows for greater flexibility in variety selection based on other criteria, i.e., crop performance or disease resistance.

Table 5 shows the estimated volumes of flue gas components and the volume of dry and moisture-containing flue gases. The parameters analysed include the theoretical oxygen demand (V_{oO2}), dry air volume (V_{oa}), carbon dioxide volume (V_{CO2}), sulphur oxides (V_{SO2}) and nitrogen oxides (V_{N2}), water vapour volume (V_{H2O}) and total flue gas volume (V_{gu}, V_{ga}), among others.

The analysed parameters in Table 5 show many similarities between the tested varieties. In the case of V_{oO2}, V_{oa}, V_{CO2} and V_{H2O}, their values are very similar and do not show statistically significant differences, suggesting uniform combustion conditions. The exceptions are the parameters V_{CO2}, V_{SO2}, V_{N2}, V_{gu} and V_{ga}, which showed statistically significant differences.

The largest fluctuations in parameter values can be seen for dry flue gas volume (V_{gu}) and wet flue gas volume (V_{ga}). The V_{gu} values for the analysed hazelnut varieties range from 4.43 Nm³·kg^{−1} for the ‘Webba Cenny’ variety to 4.69 Nm³·kg^{−1} for the ‘Olbrzymi z Halle’ variety. A similar variation can be observed for the volume of wet exhaust gas (V_{gu}). The lowest value is reached by the ‘Kataloński’ and ‘Webba Cenny’ variety (5.93 Nm³·kg^{−1}) while the highest value is reached by the ‘Olbrzymi z Halle’ variety (6.21 Nm³·kg^{−1}). These

variations also indicate differences in the amount of dry and wet flue gases generated during the combustion of the different varieties. All V_{SO_2} values are very low, suggesting that sulphur dioxide emissions from these varieties are minimal.

Table 5. Composition of hazelnut pericarp fumes according to the variety used in cultivation.

Parameter	Hazelnut Varieties				p-Value
	‘Kataloński’	‘Olbrzymi z Halle’	‘Olga’	‘Webba Cenny’	
V_{O_2} (Nm ³ ·kg ^{−1})	0.84 ± 0.02 ^a	0.86 ± 0.02 ^a	0.84 ± 0.02 ^a	0.84 ± 0.03 ^a	0.5264
V_{O_2} (Nm ³ ·kg ^{−1})	3.98 ± 0.08 ^a	4.09 ± 0.08 ^a	4.02 ± 0.10 ^a	3.99 ± 0.12 ^a	0.5264
V_{CO_2} (Nm ³ ·kg ^{−1})	0.76 ± 0.004 ^b	0.77 ± 0.001 ^a	0.76 ± 0.003 ^{ab}	0.77 ± 0.004 ^{ab}	0.0322
V_{SO_2} (Nm ³ ·kg ^{−1})	0.00020 ± 0 ^d	0.00029 ± 0 ^a	0.00026 ± 0 ^b	0.00023 ± 0 ^c	0.0001
V_{H_2O} (Nm ³ ·kg ^{−1})	0.84 ± 0.03 ^a	0.86 ± 0.04 ^a	0.85 ± 0.03 ^a	0.85 ± 0.03 ^a	0.9017
V_{N_2} (Nm ³ ·kg ^{−1})	3.68 ± 0.06 ^b	3.92 ± 0.06 ^a	3.75 ± 0.11 ^{ab}	3.67 ± 0.09 ^b	0.0234
V_{gu} (Nm ³ ·kg ^{−1})	4.44 ± 0.06 ^b	4.69 ± 0.06 ^a	4.51 ± 0.11 ^{ab}	4.43 ± 0.10 ^b	0.0225
V_{ga} (Nm ³ ·kg ^{−1})	5.93 ± 0.10 ^d	6.21 ± 0.10 ^a	6.02 ± 0.16 ^b	5.93 ± 0.15 ^c	0.0082

±standard deviation; ^{a, b, c, d, ab}—means with the same letter in row show no significant difference and means with different letters with significant differences at $\alpha = 0.05$.

When comparing the total volume of flue gases when burning the seed coats of all hazelnut varieties, a lower volume of 1 m³·kg^{−1} was found in relation to oak and poplar [31]. Comparing the dry flue gas volume, the raw materials tested showed a higher volume of 0.2 m³·kg^{−1} compared to Czech knotweed and 0.3 m³·kg^{−1} compared to meadow hay [53]. In contrast, the varieties ‘Webba Cenny’ and ‘Kataloński’ showed similar dry gas volumes to Timothy grass [53].

The results of the analyses in Table 5 show that different hazelnut varieties can differ significantly in terms of their flue gas composition, which should be taken into account when selecting them both in terms of energy efficiency and minimising negative environmental impacts.

The results in Table 6 highlight the influence of the selected parameters on the content of other compounds, combustion parameters or emission factors contained in hazelnut seed coats, regardless of cultivar. An analysis of the data shows that the parameters HHV and LHV in the covers show a very strong positive correlation with S and SO₂, and a moderate correlation with N and NO_x, indicating their direct influence on the higher calorific value of the biomass.

Correlations with carbon content (C) show its important role in increasing the energy value of biomass and CO₂, as evident in the very strong positive correlation with CO and CO₂. It is also moderately positively correlated with N, S, NO_x and SO₂, suggesting that higher carbon concentrations may slightly contribute to the increase in these compounds. In contrast, the negative correlation with O indicates that higher carbon content is associated with a significant decrease in the oxygen content of the biomass studied.

For hydrogen (H) content, a strong negative correlation with oxygen (O) content was observed, indicating that higher hydrogen concentration in the biomass is associated with lower oxygen content.

Nitrogen content (N) shows a strong positive correlation with sulphur content (S), oxides of nitrogen (NO_x) and sulphur dioxide (SO₂), suggesting that higher nitrogen concentrations may contribute to the increase in these components, which is important for exhaust emissions analysis. Additionally, N shows moderate positive correlations with values such as higher heating value (HHV), lower heating value (LHV), carbon content (C) and carbon monoxide (CO) and carbon dioxide (CO₂) emissions, indicating its effect on improving biomass energy properties and increasing greenhouse gas emissions.

Table 6. Analysis of significant multivariate correlations of combustion parameters, elements and emission factors independently of the hazelnut variety analysed.

	HHV	LHV	C	H	N	S	M	O	A	V	FC	CO	NO _x	CO ₂	SO ₂	Dust
HHV	1	0.98 *	0.4	0.03	0.54 *	0.79 *	−0.11	−0.19	−0.33	0.19	−0.29	0.4	0.54	0.4	0.79 *	−0.33
LHV	0.97 *	1	0.39	0.04	0.55 *	0.79 *	−0.16	−0.20	−0.30	0.24	−0.34	0.39	0.55 *	0.39	0.79 *	−0.3
C	0.40	0.39	1	0.32	0.61 *	0.68 *	0.27	−0.72 *	−0.12	−0.23	0.19	0.96 *	0.61 *	0.90 *	0.68 *	−0.12
H	0.03	0.04	0.32	1	0.21	0.27	−0.17	−0.73 *	0.04	0.25	−0.44	0.32	0.21	0.32	0.27	0.04
N	0.54 *	0.55 *	0.61 *	0.21	1	0.82 *	−0.31	−0.67 *	0.21	0.26	−0.28	0.61 *	0.88 *	0.61 *	0.82 *	0.21
S	0.79 *	0.79 *	0.68 *	0.27	0.82 *	1	−0.11	−0.59 *	−0.08	0.1	−0.23	0.68 *	0.82 *	0.68 *	0.94 *	−0.08
M	−0.11	−0.16	0.27	−0.17	−0.31	−0.11	1	0.21	−0.53 *	−0.93 *	* 0.78	0.27	−0.31	0.27	−0.11	−0.53 *
O	−0.19	−0.20	−0.72 *	−0.73 *	−0.67 *	−0.59 *	0.21	1	−0.38	−0.21	0.36	−0.72 *	−0.67 *	−0.72 *	−0.59 *	−0.38
A	−0.33	−0.30	−0.12	0.04	0.21	−0.08	−0.53 *	−0.38	1	0.39	−0.45	−0.12	0.21	−0.12	−0.08	0.87 *
V	0.19	0.24	−0.23	0.25	0.26	0.1	−0.93 *	−0.21	0.39	1	−0.87*	−0.23	0.26	−0.23	0.1	0.39
FC	−0.29	−0.34	0.19	−0.44	−0.28	−0.23	0.78*	0.36	−0.45	−0.87	1	0.19	−0.28	0.19	−0.23	−0.45
CO	0.41	0.39	0.94 *	0.32	0.61 *	0.68 *	0.27	−0.72 *	−0.12	−0.23	0.19	1	0.61 *	0.83 *	0.68 *	−0.12
NO _x	0.54 *	0.55 *	0.61 *	0.21	0.89 *	0.82 *	−0.31	−0.67 *	0.21	0.26	−0.28	0.61 *	1	0.61 *	0.82 *	0.21
CO ₂	0.40	0.39	0.89 *	0.32	0.61 *	0.68 *	0.27	−0.72 *	−0.12	−0.23	0.19	0.88 *	0.61 *	1	0.68 *	−0.12
SO ₂	0.79 *	0.79 *	0.68 *	0.27	0.82 *	0.89 *	−0.11	−0.59 *	−0.08	0.1	−0.23	0.68 *	0.82 *	0.68 *	1	−0.08
Dust	−0.33	−0.3	−0.12	0.04	0.21	−0.08	−0.53 *	−0.38	0.91 *	0.39	−0.45	−0.12	0.21	−0.12	−0.08	1

* Significant difference at $\alpha = 0.05$.

The analysis of sulphur (S) content showed a very strong and robust correlation related to SO_2 and NO_x emissions, suggesting its significant impact on these compounds during combustion. The strong correlations between the HHV and LHV values indicate that sulphur may improve the energy properties of biomass. S is also strongly correlated with nitrogen (N) content, which may indicate similar accumulation pathways for these elements. In addition, moderate positive correlations with carbon (C), CO and CO_2 highlight its role in combustion processes and its impact on gas emissions. In contrast, the moderate negative correlation with moisture (M) suggests that higher concentrations of sulphur may account for the lower moisture content of biomass.

Volatile matter concentration (V) shows very strong and strong negative correlations with moisture content (M) and fixed carbon content (FC). This means that higher volatile matter levels are associated with lower moisture content and lower fixed carbon content in the material, which may affect its combustion properties and overall quality as a fuel.

Solid carbon content (FC) shows a moderately positive correlation with moisture content (M). This means that higher moisture content levels are associated with slightly higher fixed carbon content in the material, which may affect its combustion properties and quality.

Carbon monoxide (CO) shows very strong positive correlations with carbon (C) and carbon dioxide (CO_2) content, indicating its intensive production in processes where these components are abundant. In addition, CO shows a strong positive correlation with nitrogen (N), sulphur (S), nitrogen oxides (NO_x) and sulphur dioxide (SO_2) content, suggesting that its presence is closely associated with combustion processes where these compounds are present in greater quantities.

For nitrogen oxides (NO_x), there were very strong positive correlations with nitrogen (N), sulphur (S) and sulphur dioxide (SO_2), suggesting intensive production when these components are present. In addition, NO_x moderately positively correlates with HHV, LHV, C, CO and CO_2 , indicating a link to combustion processes. In contrast, a moderate negative correlation with oxygen (O) content shows that a higher presence of oxygen can reduce NO_x emissions.

Carbon dioxide (CO_2) is strongly correlated with carbon content (C) and carbon monoxide (CO), indicating their main influence on its production. In addition, CO_2 correlates moderately with N, S, NO_x and SO_2 , showing their joint contribution to emissions during combustion. Also significant is the strong negative correlation with O, indicating a reduction in CO_2 emissions at higher oxygen levels.

Sulphur dioxide (SO_2), on the other hand, shows very strong positive correlations with nitrogen (N), sulphur (S) and nitrogen oxides (NO_x), highlighting their influence on its emissions. SO_2 also correlates strongly with the calorific values of HHV and LHV, and moderately with coal (C), CO and CO_2 , indicating their role in SO_2 production during combustion. In addition, the moderate negative correlation with oxygen (O) suggests that higher oxygen concentrations may reduce SO_2 emissions.

Dust content is strongly correlated with higher ash content (A) and shows a moderate negative correlation with moisture content (M), indicating that lower moisture content favours higher dust accumulation.

The correlation analysis for the seed coats of selected varieties shows the influence of varietal characteristics on the variation of these parameters (Table 7).

For the cultivar 'Kataloński', the morphological characteristics of the seed coats are very strongly negatively correlated with the values of HHV, LHV, carbon content (C) and volatile matter (V). In addition, a strong negative correlation is observed for carbon monoxide (WE_{CO}) and carbon dioxide (WE_{CO_2}) indices. On the other hand, there is a very strong positive correlation between morphological characteristics and ash content (A), moisture content (M) and dust emission (WE_{Dust}). The morphological traits of the seed covers of the cultivar 'Kataloński' tend to reduce the energy potential of this biomass, which can be an important factor in the selection of material for energy purposes.

Table 7. Analysis of the relationship of combustion parameter values, elements and emission factors to morphological characteristics of the pericarp cover for each variety evaluated.

Parameter	Hazelnut Varieties			
	‘Kataloński’	‘Olbrzymi z Halle’	‘Olga’	‘Webba Cenny’
HHV	−0.94722	0.40572	0.27486	0.83419
LHV	−0.94722	0.40572	0.27486	0.83419
C	−0.85314	−0.40643	−0.36927	−0.86005
H	−0.25539	0.63546	−0.70506	−0.93126
N	0.00049	0.30914	−0.99828	−0.12313
S	0.4123	0.3987	0.3552	0.4112
M	0.86603	−0.94111	0.30038	−0.30944
O	0.46946	0.39998	0.74641	0.91531
A	0.86603	−0.9165	−0.88189	−0.90154
V	−0.86603	0.54972	−0.99688	0.02934
FC	−0.14803	0.91473	0.99733	0.43725
WE _{co}	−0.85314	−0.40643	−0.56927	−0.86005
WE _{co2}	−0.800208	0.536112	0.10914	−0.78739
WE _{NOx}	0.00049	0.30914	−0.99828	−0.12313
WE _{CO2}	−0.85314	−0.40643	−0.56927	−0.86005
WE _{SO2}	0.2998	0.4012	0.3552	0.3112
WE _{Dust}	0.86603	−0.9165	−0.88189	−0.90154

In the case of the cultivar ‘Olbrzymi z Halle’, its varietal traits are very strongly positively correlated with fixed carbon content (FC) and moderately positively with H. An inverse relationship was observed for M and WE_{Dust}, where very strong negative correlations were shown. The morphological characteristics of the seed coats of the cultivar ‘Olbrzymi z Halle’ increase the biomass energy value through higher fixed carbon and hydrogen content, while reducing moisture and dust emission problems. These characteristics make this variety potentially more attractive for energy purposes, providing more efficient combustion and better emission Parameters.

The varietal traits of ‘Olga’, on the other hand, correlate very strongly positively with FC, which is beneficial for the energetic use of biomass, as carbon is the main energy component and also strongly positively with O, which can influence combustion processes by increasing the availability of oxygen necessary for efficient combustion. An inverse relationship was observed with N, A, V, WE_{Dust} and W_{NOx}, where a very strong negative relationship was shown and a strong negative relationship with H. Lower ash content and lower dust emissions are beneficial in terms of boiler operation and maintenance and reduced impact on air quality.

On the other hand, ‘Webba Cenny’ varietal traits correlate very strongly positively with HHV, LHV and O. In contrast, a very strong negative correlation was observed in relation to C, H, A, WE_{co}, WE_{co2} and WE_{Dust}. Morphological traits of the pericarp cover of the cultivar ‘Webba Cenny’ have a mixed effect on their energy and environmental potential. On the one hand, better energy properties indicated by higher HHV and LHV and higher oxygen content may improve combustion efficiency. On the other hand, the lower content of key energy components like carbon and hydrogen and emissions may limit the energy potential of biomass and its environmental impact.

The analysis highlights how different varietal characteristics of the seed coat affect key combustion-related parameters, which may be useful for further selection and breeding of hazelnut varieties with a view to optimising their energy use and reducing emissions of harmful components. In conclusion, different hazelnut cultivars show a variety of correlation profiles between the analysed parameters and their energy values and emissions, which is relevant for the selection of a cultivar for specific energy applications.

4. Conclusions

The study showed significant differences in yield and waste biomass, as well as in the calorific values of the pericarp shells of different hazelnut cultivars, which is important for the selection of suitable cultivars for biofuel production.

The cultivar ‘Olbrzymi z Halle’ had the highest values for both nut weight and pericarp weight, which may indicate its higher productivity and energy potential. This is in contrast to the cultivar ‘Webba Cenny’, which presented the lowest values for both these parameters, which may limit its usefulness in terms of energy production.

The ‘Olga’ variety had the highest calorific value ($14.86 \text{ MJ} \cdot \text{kg}^{-1}$), while the ‘Katański’ variety had the lowest value ($14.60 \text{ MJ} \cdot \text{kg}^{-1}$).

The ‘Olbrzymi z Halle’ variety generated the highest flue gas volume ($250.06 \text{ Nm}^3 \cdot \text{kg}^{-1}$), which can affect energy efficiency and emissions. In contrast, the lowest exhaust gas volume was obtained for the ‘Katański’ variety ($12.43 \text{ Nm}^3 \cdot \text{kg}^{-1}$). Correlation analyses showed strong positive correlations between calorific values and sulphur content and SO_2 emissions, and moderate ones with nitrogen content and NO_x emissions.

The HHV and LHV parameters of pericarp cover have strong positive correlations with sulphur content and SO_2 emissions, suggesting that higher sulphur content may raise the calorific value of biomass but increase emissions. Similar moderate correlations were found for nitrogen content and NO_x emissions.

The results highlight the potential of using hazelnut pericarp covers as biofuel, especially the varieties ‘Olga’ and ‘Olbrzymi z Halle’. Understanding the differences in emissions and energy values will help to optimise the selection of varieties for energy production and minimise negative environmental impacts. They also provide information on the use of hazelnut waste biomass, which is important for sustainable agriculture and renewable energy production.

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