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Comparison of physicochemical properties and waste biomass emission coefficients of leaves of selected hazel cultivars

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ABSTRACT

The purpose of this study was to evaluate the suitability of leaves of four hazel (*Corylus avellana* L.) cultivars – 'Kataloński', 'Olbrzymi z Halle', 'Olga' and 'Webba Cenny' – as waste biomass for energy purposes. A comprehensive morphometric and biometric analysis of the leaves, as well as physicochemical tests including calorific value, elemental composition, ash and moisture content, were conducted. In addition, emission factors for gaseous pollutants (CO, NO_x, CO_2, SO_2) and dust, as well as flue gas composition parameters, were determined to characterize the effect of variety on energy and environmental efficiency of biomass. The results showed significant differences between varieties – especially in terms of calorific value and pollutant emissions. The 'Kataloński' variety had the highest calorific value (17.63 $MJ \cdot kg^{-1}$), carbon content (43.46%) and lowest moisture content (6.24%), making it the most energy-efficient feedstock, but with the highest flue gas emissions. In contrast, 'Olga' showed the lowest emissions, with a slightly lower calorific value and higher moisture content. A dendrogram analysis confirmed the energy differentiation of varieties, indicating a significant influence of varietal characteristics on the energy potential of leaves. The results confirm the possibility of using hazel leaf biomass as a renewable resource, in accordance with the principles of a circular economy.

Keywords: *Corylus avellana*, leaves, multifunctional plant, waste biomass, physicochemical properties, sustainability, circular economy.

INTRODUCTION

A closed-loop economy (CLE) involves maximizing the use of available resources by reprocessing waste and minimizing its negative impact on the environment [1–4]. In the context of waste biomass, it is important to manage it properly, i.e. for energy purposes, which allows efficient use of renewable resources and reduction of organic waste [5–8]. The changes taking place in the way the orchard sector operates are due, among other things, to technological advances, for which innovation is responsible, currently considered the most important factor in long-term competition. The introduction of modern technologies for the processing of agricultural waste and its use for energy purposes is an important part of efforts to improve energy efficiency and sustainable resource management. Agriculture and the food industry provide numerous waste biomass streams [9] that can be converted into energy [10–12]. *Corylus avellana* L. is one of the most widely grown nut species in the world [13], used mainly in the food, confectionery or cosmetic industries [14–17]. Hazelnut cultivation generates significant amounts of organic waste, i.e., shoots obtained from agronomic pruning [18, 19], woody nut shells formed after hulling the edible kernel, and pericarp surrounding the nut, which are also widely used in other branches of the economy

[20]. The possibility of using different parts of the hazelnut for many purposes is due to its multifunctional properties and versatile applications [7]. Previous studies have shown that the waste can be effectively used as an energy resource. Hazel shoots have favorable fuel properties [21, 22], the woody shells have a high calorific value [23–27], and the fruiting bodies can be used as a fuel with rapid combustion [28]. Thus, the by-products of hazelnut cultivation fit into the model of a closed-loop economy, finding use as biofuel instead of lingering as waste [7, 29].

The many possible uses of hazelnut would lead to alternative uses than just nut production, avoiding significant economic losses, reducing the cost of organic waste disposal, and increasing agricultural sustainability [30–32]. Despite a wide range of studies on the management of branches and hard waste of the hazelnut, relatively little attention has been paid to the leaves. Given the size of the bush and their number per hectare, it can be estimated that this is a sizable green biomass, which is widely considered to be a waste with no economic value. In commodity cultivation, the most common form of hazel leaf management is leaving them under the bushes, where they decompose naturally [33] or are blown away by the wind over the surrounding fields. Meanwhile, the management of hazel leaves for energy purposes may be an additional use to those already in use, i.e. leaving them in the orchard [34]. Given that, previous studies suggest that leaves can have a calorific value in the range of 12–18 MJ/kg, which depends primarily on their species, fineness and moisture content [35–39].

The purpose of this study was to analyze the physicochemical properties of the leaves of four selected hazelnut (*Corylus avellana* L.) cultivars: ‘Kataloński’, ‘Olbrzymi z Halle’, ‘Olga’ and ‘Webba Cenny’, treated as waste biomass, in terms of their suitability for energy purposes. In particular, the calorific value, elemental composition, ash and moisture content, as well as the emission factors of gaseous pollutants (CO, NO_x, CO_2, SO_2) and dust were determined in order to assess the ecological effects of their combustion. In addition, morphometric and biometric analyses of the leaves were carried out to study their impact on energy potential. Particular attention was paid to variation among varieties to determine the extent to which varietal characteristics affect energy and environmental parameters of leaf biomass.

MATERIALS AND METHODS

The field research was carried out under moderate climate conditions, at a Horticultural Farm located in the Sandomierska Upland (50°4920.5 “N, 21°4435.0 “E) in the Zawichost municipality (Świętokrzyskie province). The study material consisted of four varieties of hazel (Corylus avellana L.): ‘Katalоński’, ‘Olbrzymi z Halle’, ‘Olga’ and ‘Webba Cenny’ growing on their own roots. The shrubs were planted in the spring of 2002 in a system of row cultivation, at a spacing of 6 × 2.5 m (666 pcs/ha) on loessy soils, belonging to bonitation classes II and IIab. The plants were managed in the form of a multi-stemmed, open vase, adapted to the natural bushy habit of the species.

The leaf samples for analysis were taken in autumn, after the fruit harvest. The material came from three randomly selected bushes of each cultivar, with three samples for each cultivar, which made it possible to determine the average values of the studied parameters. Each sample included 100 leaves. Immediately after harvesting, the samples were weighed to the nearest 0.001 kg using a PS R2 RADWAG precision balance. After weighing, the leaves were dried in a laboratory dryer at 105 °C to a moisture content of no more than 10%. The dried material was then ground. For laboratory testing, a bulk sample was prepared for each variety, obtained from three samples from randomly selected shrubs.

The study evaluated leaf weight (100 pieces for each variety), energy parameters and emission parameters for the tested material. The quality parameters of the biofuel were estimated by performing technical and elemental analyses, and the heat of combustion as well as calorific value were determined. The methodology of the procedures is shown in Table 1.

The experiment was designed in a randomized block layout, comprising 4 combinations with 5 replications. The replications consisted of plots, each containing 3 plants. After the experiment was completed, the obtained results were subjected to statistical analysis using one-way analysis of variance (ANOVA). Additionally, the results were presented in graphical form. Statistical inferences were made at a significance level of $p < 0.05$. Multidimensional data analysis techniques were employed, including cluster analysis. The results of the cluster analysis were presented using a dendrogram. All analyses were performed using STATISTICA 13 software.

PROXIMATE ANALYSIS	
• Higher Heating Value (HHV; MJ·kg^{-1}) • Lower Heating Value (LHV; MJ·kg^{-1})	• EN-ISO 1928:2020; Equipment LECO AC 600 [40]
• Ash (A; %)	• EN-ISO 18122-01; Equipment LECO TGA 701 [41]
• Volatile matter (V; %)	• EN-ISO 18123-01; Equipment LECO TGA 701 [42]
• Moisture content (M; %)	• EN-ISO 18134-3; Equipment LECO TGA 701 [43]
• Fixed carbon (FC; %) [44]	• FC=100-V-A-M

ULTIMATE ANALYSIS EMISSION FACTORS CALCULATED CCORDING STUDIES	
• Carbon (C; %) • Hydrogen (H;%) • Nitrogen (N; %)	• EN-ISO 16948:2015-07, Equipment LECO CHNS 628 [45]
• Sulfur (S; %)	• EN-ISO 16994:2016-10; Equipment LECO CHNS 628 [46]
• Oxygen (O; %) [29]	• O=100-A-H-C-S-N [47]

EMISSION FACTORS WAS CALCULATED ACCORDING TO [48]	
Carbon monoxide Emission factor (E_C) 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; 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})	$CO_2 = \frac{44}{12} \cdot (E_c - \frac{12}{28} \cdot CO - \frac{12}{16} \cdot E_{CH4} - \frac{26.4}{31.4} \cdot E_{NMVOC})$ 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 VsOC (for biomass 0.009)
Sulfur dioxide emission factor (SO_2; kg·Mg^{-1})	$SO_2 = \frac{2S}{100} \cdot (1 - r)$ SO_2 – sulfur dioxide emission factor (kg · kg^{-1}), 2 – molar mass ratio of SO_2 and sulfur, S – sulfur content in fuel (%), r – coefficient determining the part of total sulfur retained in the ash.
Emission factor was calculated from (NO_x; kg·Mg^{-1})	$NO_x = \frac{46}{14} \cdot E_C \cdot N/C \cdot (N_{NOx} / N)$ 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 [49,50]	
Theoretical oxygen demand (V_{02}; Nm^3· kg^{-1})	$V_{02} = \frac{22.41}{100} \cdot (\frac{C}{12} + \frac{H}{4} + \frac{S-0}{32})$, 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})	$V_{oa} = \frac{V_{oa}}{0.21}$ 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 sulfur dioxide (V_{SO2}; Nm^3·kg^{-1})	$V_{SO2} = \frac{22.41}{32} \cdot \frac{S}{100}$
Water vapor content of the exhaust gas (V_{H2O}; Nm^3·kg^{-1})	$V^H_{H2O} = \frac{22.41}{100} \cdot (\frac{H}{2} + \frac{M}{8})$ is the component of water vapor volume from the hydrogen combustion process (V^H_{H2O}; Nm^3 H_2O·kg^{-1} fuel) $V^a_{H2O} = 1.61 \cdot x \cdot V_{oa}$ and the volume of moisture contained in the combustion air (V^a_{H2O}; Nm^3H_2O·kg^{-1}fuel) $V_{H2O} = V^a_{H2O} + V^H_{H2O}$; M-fuel moisture content (%), -air absolute humidity (kg H_2O·kg^{-1} dry air).
The total stoichiometric volume of dry 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 theoretical nitrogen content in the exhaust gas (V_{ga}; Nm^3·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 (λ = 1), a minimum exhaust gas volume will be obtained.
The total volume of exhaust gases (V_{gu}; Nm^3·kg^{-1})	$V_{gu} = V_{CO2} + V_{SO2} + V_{N2}$

Figure 1. Methods and apparatus used for energy and carbon analysis of the raw material under study

RESULTS

Morphometric and biometric studies of leaves of hazel cultivars in the context of their use as biomass. The characteristics of the leaves of four selected varieties taking into account their shape, size and surface characteristics are presented in Table 2. These data are part of the morphometric studies, describing the qualitative characteristics of the leaves, in addition, they take into account the basic differences between varieties, highlighting the key morphological characteristics of the leaves.

As part of the biometric study, a leaf weight analysis (100 pieces) was also performed, the results of which are shown in Figure 1. This analysis provides quantitative data on leaf biomass potential depending on the variety.

The graph illustrates that leaf weight differs by variety. The highest leaf weight was recorded for the cultivar 'Webba Cenny', exceeding 130 g, while the lowest for the cultivar 'Kataloński', with a value oscillating around 80 g. The varieties 'Olbrzymi z Halle' and 'Olga' reached intermediate values, slightly exceeding 90 g. In comparison, Montiel-Bohórquez and Pérez [51] showed that some 2300 trees that overgrow the campus of the University of Antioquia (UdeA, Medellín-Colombia) produce an average of~ 2.8 tons of fallen leaves per month. In contrast, a study by Klimek et al. [52] found that grape leaf weight varies depending on the variety used in grape growing. Meanwhile, the observations by Kaplan et al. [53] indicated the influence of rootstock on grapevine leaf weight. They showed that vines grafted on the 161-49 rootstock produced significantly the lowest leaf weight, while those on the SO_4 rootstock produced significantly the highest leaf weight among the combinations evaluated (Figure 1).

Table 2 presents the results of technical and elemental analyses of hazel leaf biomass depending on the variety used in hazelnut

Table 1. Morphological characteristics of leaves of selected hazel cultivars

Variety name	Description of the leaves
'Kataloński'	Elliptical leaves, medium-sized (up to 10 cm long), with a slightly heart-shaped base and pointed apex. the surface is dull, slightly rough, the innervation is clear. the edges are doubly sawn. the color is green, in autumn they turn yellow.
'Olbrzymi z Halle'	Leaves broadly oval, large (up to 12 cm), with clearly serrated edges. surface dull, slightly hairy underneath. deep innervation, giving a wrinkled appearance. green color, in autumn they turn yellow.
'Olga'	Leaves large (up to 12 cm), elliptical, with slightly serrated edges. young leaves purple, later dark green with carmine tinge. surface dull, thick, slightly stiff, innervation strong. in autumn do not show intense discoloration.
'Webba Cenny'	Oval leaves, medium to large in size (8–12 cm), with double-sawn edges. surface rough, rough, with well visible innervation. color green, they turn yellow in autumn. leaves of medium thickness, but relatively stiff.

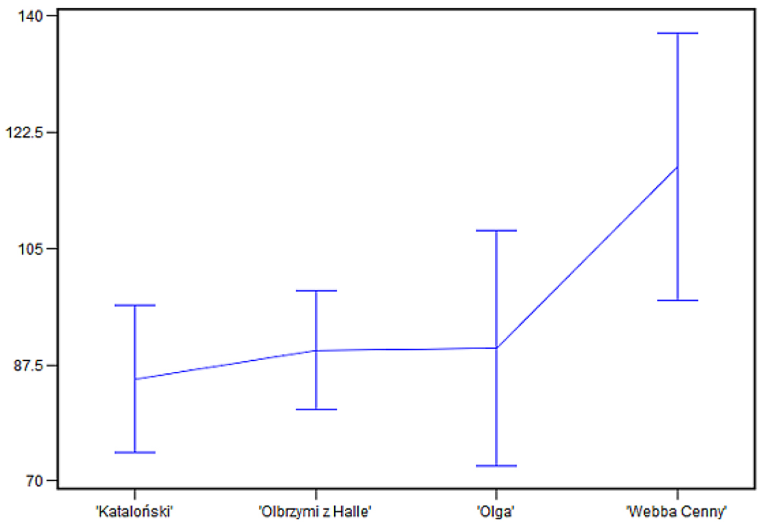

Figure 2. Average weight of 100 leaves for 4 hazel varieties expressed in grams

Table 2. Technical and elemental analyses of hazel leaf biomass according to the cultivar chosen in hazelnut cultivation

Parameter	Hazel variety				*p-value*
	'Kataloński'	'Olbrzymi z Halle'	'Olga'	'Webba Cenny'	
HHV (MJ·kg^{-1})	17.63 ± 0.04 a*	17.36 ± 0.02 b	17.01 ± 0.15 c	17.22 ± 0.04 bc	0.0001
LHV (MJ·kg^{-1})	16.48 ± 0.04 a	16.19 ± 0.02 b	15.83 ± 0.15 c	16.06 ± 0.04 b	0.0001
C (%)	43.46 ± 0.18 a	43.03 ± 0.12 b	42.17 ± 0.05 d	42.69 ± 0.09 c	0.0001
H (%)	7.12 ± 0.02 a	7.26 ± 0.02 a	6.93 ± 0.50 a	7.03 ± 0.01 a	0.4675
N (%)	2.18 ± 0.09 a	2.11 ± 0.00 ab	2.06 ± 0.01 b	2.13 ± 0.02 ab	0.0593
S (%)	0.16 ± 0.00 a	0.15 ± 0.00 ab	0.13 ± 0.00 c	0.15 ± 0.01 b	0.0001
MC (%)	6.24 ± 0.04 d	7.78 ± 0.09 b	8.76 ± 0.02 a	6.74 ± 0.04 c	0.0001
O (%)	38.07 ± 0.26 b	38.12 ± 0.23 b	39.40 ± 0.51 a	38.62 ± 0.53 ab	0.013
A (%)	9.00 ± 0.06 a	9.33 ± 0.25 a	9.32 ± 0.02 a	9.38 ± 0.56 a	0.4550
V (%)	67.23 ± 0.20 a	66.30 ± 0.31 ab	65.93 ± 0.31 b	66.13 ± 0.65 b	0.0179
FC (%)	17.53 ± 0.18 a	16.59 ± 0.37 b	15.99 ± 0.35 b	17.75 ± 0.34 a	0.0004
H/C	1.64 ± 0.00 a	1.69 ± 0.00 a	1.64 ± 0.12 a	1.65 ± 0.01 a	0.7456
N/C	0.05 ± 0.00 a	0.05 ± 0.00 a	0.05 ± 0.00 a	0.05 ± 0.00 a	0.3126
O/C	0.66 ± 0.01 c	0.66 ± 0.01 bc	0.70 ± 0.01 a	0.68 ± 0.01 b	0.0006

Note: HHV – higher heating value, LHV – lower heating value, C – carbon content, H – hydrogen content, N – nitrogen content, S – sulfur content, MC – moisture content, O – oxygen content, A – ash content, V – volatile matter content, FC – fixed carbon, ratio of hydrogen to carbon (H/C), ratio nitrogen to carbon (N/C), ratio oxygen to carbon (O/C).; * Significant difference means that different letters in the column indicate significant differences at α – 0.05.

cultivation. The analyses showed significant differences for most parameters, with the exception of A, H/C and N/C, indicating that the proportions of these elements remain relatively constant between varieties.

The highest calorific value of HHV was recorded for the 'Kataloński' variety (17.63 MJ·kg^{-1}), while the lowest for 'Olga' (17.01 MJ·kg^{-1}), giving a difference of 0.62 MJ·kg^{-1}. A similar relationship was noted for LHV, where the difference was 0.65 MJ·kg^{-1}, with the highest value for 'Kataloński' (16.48 MJ·kg^{-1}) and the lowest for 'Olga' (15.83 MJ·kg^{-1}). A study by Kaplan et al. [53] showed the influence of rootstock, while the observations by Klimek et al. [52] of the variety used in grape growing on the energy potential of grape leaves. In contrast, other studies have shown that leaves have a higher energy potential than pericarp by 8.5% for HHV and 11% for LHV [28], but lower than woody skins by 5.6% for HHV and 5.3% for LHV [27]. Alves et al. [54], on the other hand, showed that torrefaction-treated banana leaves achieved significantly higher HHV values (up to 20 MJ·kg^{-1}) compared to fresh weight. In turn, Wieczorek [55] obtained for Calamagrostis epigejos LHV of 17.5 MJ·kg^{-1}, while HHV was 16.6 MJ·kg^{-1}.

In terms of elemental composition, the highest C content was recorded for the 'Kataloński' variety (43.46%), while the lowest for the 'Olga' variety (42.57%), a difference of 0.89%. For comparison, Maj and Piekut [38] obtained 44.45% for hazel leaves, 47.66% for oak, and 44.34% for maple leaves not depending on the variety. In a study by Alves et al. [54], processed banana leaves were found to contain more concentrated fixed carbon than fresh pulp. This is confirmed by the results of Güleç et al. [56] obtained for hazel leaves, in a similar range of 43.25–45.52% was found for almond, apple and cherry tree leaves.

The H content was similar in all varieties, ranging from 7.03% ('Olbrzymi z Halle') to 7.12% ('Kataloński'). Studies conducted on other hazelnut waste fractions showed that the hydrogen content of the leaves was lower than that of the hazelnut shells (7.52–7.25%) by 0.37% [27], while higher than that of the pericarp (6.88–6.71%) about 0.30% [28].

The highest nitrogen content was found in 'Olga' (2.66%), and the lowest in 'Olbrzymi z Halle' (2.10%), giving a difference of 0.56%. Güleç et al. [54] for hazel leaves obtained a lower nitrogen concentration of 2.05%. Similar nitrogen concentration values were also shown for leaves of other species, i.e. chestnut (2.21%), orange (2.59%) and almond (2.85%). Significantly lower concentrations were recorded for pineapple (0.40%) and feijoa (1.23%) leaves.

For sulfur (S), the highest content was found in the 'Kataloński' variety (0.16%), while the lowest content was found for the 'Olga' variety (0.13%), a difference of 0.03%. Higher S values of 0.33% for hazel leaves were obtained by Güleç et al. [54]. Significant differences were observed for moisture content (M), with the 'Olga' variety showing the highest value (8.76%) and the 'Kataloński' variety the lowest (6.24%), a difference of 2.52%. These results are consistent with the literature – Maj and Piekut [38] reported hazel leaf moisture content of 8.70%, and Vargas-Soplín et al. [57] indicated that leaf moisture content ranges from 6–12%, which is consistent with the results obtained in this study.

Similar results were recorded for the oxygen (O) content, the most of which was in the leaves of the 'Olga' variety (39.40%), and the least in 'Kataloński' (38.07%) – a difference of 1.33%. The results of the study by Borkowska et al. [22] indicate that hazel shoots contain significantly more oxygen than leaves – the difference between these types of biomass ranges from 6.72% to 10.92%. Higher values of the oxygen content in hazel leaves (up to 45.71% – regardless of variety), as well as in the leaves of other trees, such as almond, apple and cherry, were also reported by Güleç et al. [54].

The ash content (A) did not show statistically significant differences between the analyzed varieties, remaining at similar levels – from 9.00% for 'Kataloński' to 9.38% for 'Webba Cenny'. Similar observations were made by Klimek et al. [52], who also found no statistically significant differences between grape varieties, although they recorded higher ash content levels, ranging from 10.79-12.12%. Higher ash values were recorded for leaves of other fruit tree and shrub species, i.e. apple, peach [54], grape, lemon, plum and raspberry [58]. Significantly higher ash content was also shown for other types of waste biomass, such as corn pomace, wheat husks [58] and artichoke biomass [59].

Significant differences were also noted for volatile substances (V), where the highest content was 67.23% ('Kataloński') and the lowest 65.93% ('Olga'), a difference of 1.30%. Similar results were obtained for hazelnut pericarp

(65.1–68.01%) [28], while 1.60% higher values were obtained for the woody shell [27].

On the other hand, the solid carbon (FC) content differed significantly between varieties. The highest value was recorded for the 'Kataloński' variety (17.53%), while the lowest for 'Olga' (15.99%), a difference of 1.54%.

The elemental ratios showed only significant differences for O/C, where 'Olga' had the highest value (0.70%) and 'Kataloński' the lowest (0.66%), a difference of 0.04%. In contrast, the H/C and N/C ratios showed no significant differences between varieties, keeping relatively constant values in the range of 1.64–1.69 for H/C and 0.05 for N/C, respectively.

Figures 2 and 3 (dendrograms) show a hierarchical cluster analysis of the four hazel cultivars in relation to their energy properties. The first dendrogram considers only calorific value (LHV and HHV), while the second includes other biomass elemental parameters (Table 2).

The division of varieties in the analysis of calorific value shows clear differences between them. The 'Kataloński' variety forms a separate group, which is due to its highest HHV and LHV. 'Olbrzymi z Halle' and 'Webbs Cenny' form a common cluster, indicating their similar calorific properties. In contrast, the 'Olga' variety is the outermost unit, which confirms its lowest calorific value and different combustion properties (Figure 3).

In the analysis of elementary parameters, the cluster structure is more elaborate, but similar relationships are still evident. 'Kataloński' again stands out from the other varieties, suggesting that its high calorific value is due to its high C and F/C content. The 'Olbrzymi z Halle' and 'Webb Cenny' again show similar properties, especially in terms of H, N and O content, while 'Olga' is the most distinct variety, as a result of its highest O and moisture content and lower C and F/C content, which negatively affects its energy properties. A comparison of the two dendrograms shows that calorific values are strongly correlated with C and F/C content, while high O and moisture content leads to lower biomass energy values. In both analyses, the 'Kataloński' variety stands out with the best energy properties, while 'Olga' shows the lowest combustion efficiency. The 'Olga', 'Olbrzymi z Halle' and 'Webba Cenny' varieties remain similar to each other in both calorific value and chemical composition (Figure 4). Table 3 shows the results of emission analyses for leaf biomass of four hazel varieties.

The highest CO emission was recorded for the 'Katalonski' variety, where it amounted to 53.55 $kg\cdot Mg^{-1}$, while the lowest value was recorded for the 'Olga' variety (51.95 $kg\cdot Mg^{-1}$). The difference of 1.60 $kg\cdot Mg^{-1}$ may be due to the slightly higher carbon content and lower moisture content in the biomass of the 'Katalonski' variety, which confirms previous studies indicating that biomass with a higher content of organic parts and less moisture can generate higher CO emissions [61, 62].

In terms of NO_x, the highest values were also recorded for 'Katalonski' (7.71 $kg\cdot Mg^{-1}$) and the lowest for 'Olga' (7.26 $kg\cdot Mg^{-1}$). The difference of 0.45 $kg\cdot Mg^{-1}$ may be related to the differences in leaf nitrogen content. These results are consistent with the observations of Malaťák et al. [62] and Fang et al. [61], who showed a significant correlation between the nitrogen content of biomass and NO_x emissions. The biomass with higher

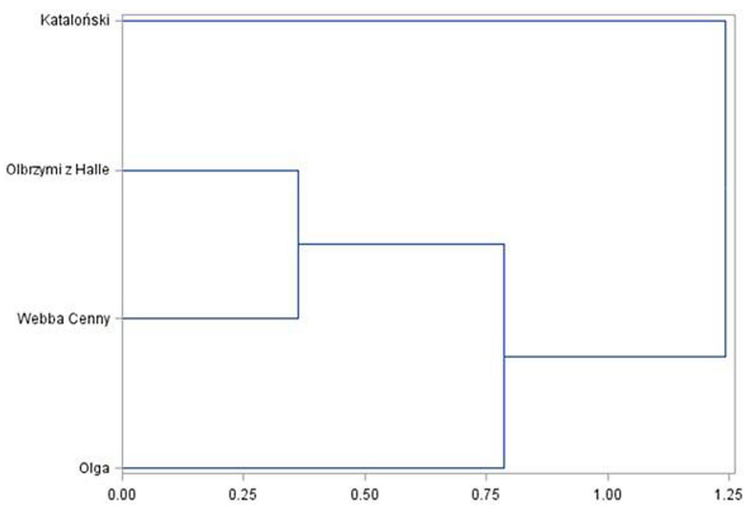

Figure 3. Comparative analysis of leaves energy production (LHV; HHV) of selected hazelnut varieties

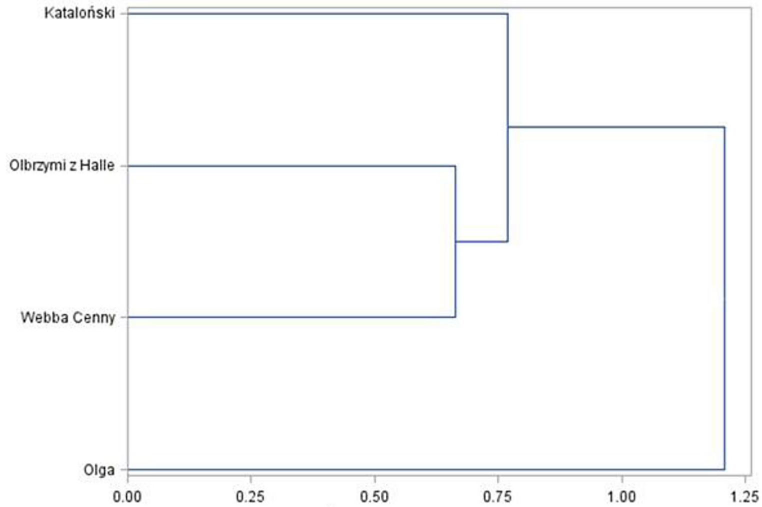

Figure 4. Comparative analysis of elemental parameters in the leaves of selected hazelnut varieties

Table 3. Emission parameters for hazelnut leaf biomass depending on the variety used in hazelnut cultivation

Parameter		Hazel variety				*p-value*
		'Kataloński'	'Olbrzymi z Halle'	'Olga'	'Webba Cenny'	
($kg \cdot Mg^{-1}$)	CO	53.55 ± 0.23 a*	53.02 ± 0.14 b	51.95 ± 0.06 d	52.60 ± 0.10 c	0.0001
	NO_x	7.71 ± 0.32 a	7.46 ± 0.01 ab	7.26 ± 0.02 b	7.51 ± 0.06 ab	0.0053
	CO_2	1311.21 ± 5.52 a	1298.29 ± 3.51 b	1272.18 ± 1.42 d	1287.99 ± 2.57 c	0.0001
	SO_2	0.31 ± 0.01 a	0.30 ± 0.00 ab	0.25 ± 0.01 c	0.29 ± 0.01 b	0.0001
	dust	11.37 ± 0.08 a	11.78 ± 0.31 a	11.77 ± 0.03 a	11.85 ± 0.70 a	0.4550

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

nitrogen content (e.g., grasses, leaves) generates higher emissions of these compounds compared to typical firewood.

The highest amount of CO_2 was emitted during the combustion of the 'Kataloński' variety (1311.21 $kg \cdot Mg^{-1}$), and the lowest for 'Olga' (1272.18 $kg \cdot Mg^{-1}$), a difference of 39.03 $kg \cdot Mg^{-1}$. CO_2 is the primary product of the total combustion of carbon contained in biomass, and its level depends directly on its content. According to Filipowicz et al. [63], the combustion of dry biomass can generate as much as 1500–1800 kg $CO_2 \cdot Mg^{-1}$, which means that the values obtained in the study are lower than the theoretical ones.

For sulfur dioxide emissions (SO_2), the highest value was also obtained for 'Kataloński' (0.31 $kg \cdot Mg^{-1}$) and the lowest for 'Olga' (0.25 $kg \cdot Mg^{-1}$). These values are similar to the literature data for biomass with low sulfur content, i.e. straw or leaves [61, 63].

Total dust emissions ranged from 11.37 $kg \cdot Mg^{-1}$ (variety 'Kataloński') to 11.85 $kg \cdot Mg^{-1}$ (variety 'Webba Cenny'). These values did not show significant statistical differences, but their absolute level was higher than in the case of woody biomass or grain straw, where typically 3–6 $kg \cdot Mg^{-1}$ are reported [61, 65].

The highest emissions of most of the analyzed gases were recorded for the 'Kataloński' variety, which may indicate a more intensive combustion process for this biomass. The 'Olga' variety, on the other hand, showed the lowest emissions of CO, NO_x, CO_2 and SO_2, suggesting that its combustion is less emissive. Dust emissions did not differ significantly between varieties, indicating that the amount of dust remains at a similar level regardless of hazel leaf variety.

The table shows the parameters of the composition of the exhaust gases produced during the combustion of leaf biomass of four hazel varieties. The results showed significant differences in the amount of emitted gases depending on the variety. These differences may be due to varying chemical composition of biomass and combustion conditions (Table 3). The highest oxygen content in the flue gas (VoO_2) was recorded for

Table 4. Composition of hazel leaf biomass exhaust depending on the variety used in hazelnut cultivation

Parameter		Hazel variety				*p-value*
		'Kataloński'	'Olbrzymi z Halle'	'Olga'	'Webba Cenny'	
$(Nm^3 \cdot kg^{-1})$	Vo_{O2}	0.95 ± 0.01 a*	0.94 ± 0.00 a	0.90 ± 0.03 b	0.92 ± 0.00 ab	0.0306
	Vo_a	4.50 ± 0.03 a	4.50 ± 0.02 a	4.29 ± 0.15 b	4.39 ± 0.02 ab	0.0306
	V_{CO2}	0.81 ± 0.00 a	0.80 ± 0.00 b	0.79 ± 0.00 d	0.80 ± 0.00 c	0.0001
	V_{SO2}	0.00 ± 0.00 a	0.00 ± 0.00 ab	0.00 ± 0.00 c	0.00 ± 0.00 b	0.0001
	V_{H2O}	1.60 ± 0.01 a	1.63 ± 0.01 a	1.58 ± 0.08 a	1.58 ± 0.03 a	0.3297
	V_{N2}	5.30 ± 0.10 a	5.25 ± 0.01 a	5.04 ± 0.13 b	5.17 ± 0.02 ab	0.0164
	Vo_{ga}	7.72 ± 0.11 a	7.68 ± 0.02 ab	7.40 ± 0.21 b	7.55 ± 0.02 ab	0.0369
	Vo_{gu}	6.12 ± 0.10 a	6.05 ± 0.02 a	5.82 ± 0.13 b	5.97 ± 0.02 ab	0.0112

Note: Vo_{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 sulfur dioxide, V_{H2O} – the water vapor 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 means that different letters in the column indicate significant differences at $\alpha = 0.05$.

the 'Kataloński' variety (0.95 $Nm^3 \cdot kg^{-1}$), while the lowest for 'Olga' (0.90 $Nm^3 \cdot kg^{-1}$), a difference of 0.05 $Nm^3 \cdot kg^{-1}$. Total oxygen content (Voa) was highest for the 'Kataloński' and 'Olbrzymi z Halle' (4.5 $Nm^3 \cdot kg^{-1}$) and the lowest for 'Olga' (4.29 $Nm^3 \cdot kg^{-1}$), a difference of 0.21 $Nm^3 \cdot kg^{-1}$. The highest amount of carbon dioxide (VCO_2) in the exhaust gas was shown for the 'Kataloński' variety (0.81 $Nm^3 \cdot kg^{-1}$), and the lowest for 'Olga' (0.79 $Nm^3 \cdot kg^{-1}$), a difference of 0.02 $Nm^3 \cdot kg^{-1}$. For sulfur dioxide (V_{SO_2}), the values for all varieties were 0.00 $Nm^3 \cdot kg^{-1}$. The moisture content (V_{H_2O}) present in the biomass, ranged from 1.58 $Nm^3 \cdot kg^{-1}$ ('Olga', 'Webba Cenny') to 1.60 $Nm^3 \cdot kg^{-1}$ ('Kataloński'), a difference of 0.02 $Nm^3 \cdot kg^{-1}$. The highest nitrogen content in the flue gas (V_{N_2}) was recorded for the 'Olga' variety from 'Halle' (5.25 $Nm^3 \cdot kg^{-1}$), while the lowest for 'Olga' (5.04 $Nm^3 \cdot kg^{-1}$), a difference of 0.21 $Nm^3 \cdot kg^{-1}$.

Total exhaust gas volume (Vo_{ga}) was highest for the 'Kataloński' variety (7.72 $Nm^3 \cdot kg^{-1}$) and lowest for 'Olga' (7.40 $Nm^3 \cdot kg^{-1}$), a difference of 0.32 $Nm^3 \cdot kg^{-1}$. In contrast, the volume of dry exhaust gas (Vo_{gu}) ranged from 5.82 $Nm^3 \cdot kg^{-1}$ ('Olga') to 6.12 $Nm^3 \cdot kg^{-1}$ ('Kataloński'), a difference of 0.30 $Nm^3 \cdot kg^{-1}$ (Table 4).

CONCLUSIONS

The analyses carried out showed that hazel leaf biomass can be a valuable renewable resource for energy purposes. Differences between varieties in terms of elemental composition, physicochemical properties and emission levels confirm that varietal characteristics have a significant impact on the energy potential of leaves. The most recommended variety for energy purposes is 'Kataloński', as it showed the highest calorific value and the most favorable elemental composition in terms of carbon content. The low moisture content of this variety minimizes energy loss for water evaporation, which increases combustion efficiency. In addition, 'Kataloński' has the highest volume of combustion gases, suggesting a more intense combustion process and higher energy efficiency. Although its leaf weight is lower compared to other varieties, its better energy properties make it the most efficient combustion resource.

However, some limitations must be taken into account. The 'Kataloński' variety generates the highest values of CO, NO_x, CO_2 and SO_2, which may pose an environmental problem and require additional mitigation measures.

If the key criterion is more available biomass and moderate emissions, the 'Webba Cenny' variety may be a better choice, because it:

- generates the highest leaf mass, which translates into higher biomass potential,
- has medium energy parameters that allow it to be used effectively as a biofuel,
- has a more balanced emissions balance compared to 'Kataloński'.

Alternatively, if the priority is to reduce emissions and burn ecologically, the 'Olga' variety may be the best choice, because it:

- shows the lowest exhaust gas emissions, which can be beneficial to the environment,

- burns more efficiently in terms of flue gas volume,
- its higher moisture content can reduce energy efficiency, but at the same time can reduce emissions.

Studies have shown that the morphological characteristics and chemical composition of leaf biomass of individual varieties can affect energy values and emissions. This can be important in the selection of biomass for energy applications and in assessing their environmental impact.

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