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Analysis of fuel parameters and emission characteristics of selected biomass fractions of common hazel (*Corylus avellana* L.)

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ABSTRACT

The aim of this study was to evaluate the fuel quality and emission characteristics of selected waste biomass fractions of common hazel (*Corylus avellana* L.) and to compare them independently of cultivar. Four biomass fractions were analysed: shells, shoots, leaves and husk, collected from a plantation located in south-eastern Poland. The analyses included proximate composition, elemental composition, higher heating value (HHV), lower heating value (LHV), estimated emission factors and the volumetric composition of flue gases. Significant differences were found among the analysed fractions. Shells showed the most favourable fuel profile, with the highest HHV and LHV values, 18.65 and 17.37 MJ·kg^{-1}, respectively, the highest carbon content (51.01%) and fixed carbon content (22.32%), and the lowest ash (0.82%), nitrogen (0.36%) and sulphur (0.01%) contents. Leaves were characterised by the highest ash (9.26%), nitrogen (2.12%) and sulphur (0.14%) contents, which resulted in the highest estimated emissions of NO_x, SO_2 and particulate matter, amounting to 7.48, 0.29 and 11.69 kg·Mg^{-1}, respectively. Shoots had the highest hydrogen (7.40%) and oxygen (47.11%) contents and generated the highest water vapour volume in the flue gas (1.03 Nm^3·kg^{-1}), whereas husk had the lowest HHV and LHV values, 15.94 and 14.76 MJ·kg^{-1}, respectively. In terms of flue gas parameters, shells were characterised by the highest theoretical oxygen demand (1.07 Nm^3·kg^{-1}) and the highest CO_2 volume in the flue gas (0.95 Nm^3·kg^{-1}), whereas leaves generated the highest total flue gas volume (7.59 Nm^3·kg^{-1}). The results confirm that common hazel waste biomass should not be treated as a homogeneous fuel. Separate assessment of individual fractions may support more efficient energy recovery and reduce the environmental impact of biomass combustion.

Keywords: hazelnut by-products, valorisation, biomass fraction, *Corylus avellana* L., energy properties, bioenergy, flue gas composition, emission factors.

INTRODUCTION

In the energy assessment of orchard biomass, the reference point is very often the plant species itself or the total mass of residues arising from harvesting and maintenance operations. However, this approach oversimplifies the actual characteristics of the material, as waste biomass does not form a homogeneous stream. Instead, waste biomass consists of fractions that differ in structure, degree of lignification, mineral content and elemental composition. These differences directly affect properties relevant to combustion (Casau et al., 2022; Cavalaglio et al., 2024; Picchio et al., 2023). The suitability of the raw material for energy purposes is therefore determined not only by its origin, but also by which part of the plant becomes fuel (Den Boer et al., 2020; Dyjakon et al., 2019; Pergola et al., 2024).

Modern low-carbon energy increasingly relies on renewable raw materials (Dybek et al., 2023; Gredka & Caban, 2024; Hawrot-Paw et al., 2019; Kapłan et al., 2025; Małuszyńska et al., 2013; Markandan & Chai, 2022; *The Global Energy Crisis – World Energy Outlook 2022 – Analysis*, n.d.), yet their use requires consideration not only of the energy balance but also of the broader environmental and material context. In the case of biomass, its management throughout the product life cycle is particularly important. This includes the generation of residues, their processing, and their final material or energy use. In an approach consistent with the principles of the circular economy, waste biomass is not treated solely as a fuel, but as a resource that can be directed towards various recovery pathways depending on its properties and utility potential (Iwaszczuk, 2019; Jankiewicz, 2025; Kulczycka & Pędziwiatr, 2019; Werle et al., 2021). The literature emphasises that such an approach, based on a full life-cycle assessment and the principle of cascading use of biomass, promotes more rational resource management and reduces the environmental impacts associated with the production of energy and bio-based products (Casau et al., 2022; Romero-Perdomo & González-Curbelo, 2023; Sherwood, 2020; Torreiro et al., 2020).

This is clearly evident in the case of common hazel (*Corylus avellana* L.), whose cultivation generates various by-products, including leaves, husk, shells and shoots.. Previous studies confirm that these wastes can be considered as an energy source, although their properties are not uniform. For leaves, significant differences have been demonstrated in terms of moisture content, ash content, volatile matter, elemental composition and calorific value, as well as the associated emission factors. With regard to husk, it has been shown that combustion parameters are linked to the elemental composition of the biomass and predicted emissions, particularly in terms of sulphur and nitrogen compounds. In contrast, hazelnut shells were found to have favourable fuel parameters, similar to those of woody biomass, although emission factors varied among the materials studied (Borkowska et al., 2025; Borkowska, et al., 2024a, 2024b; Klimek et al., 2025; Maj et al., 2025).

At the same time, lignocellulosic biomass from fruit crops can be processed in many ways. In addition to direct combustion, it can be used in gasification, pyrolysis, pelletisation and biochar production processes, as well as a feedstock for biorefinery processes aimed at recovering chemical compounds, materials or intermediates for other industries. In practice, the choice of utilisation pathway depends on the quality of the biomass, the costs of feedstock preparation, the scale of the process, and the expected value of the end product. In the case of fractions with a high ash content or a less favourable elemental composition, material applications or alternative conversion pathways may be more justified than conventional combustion, whereas fractions with high calorific value and low emissions may constitute a particularly attractive energy feedstock. For this reason, the assessment of biomass fuel properties is important not only for the energy sector, but also for the rational design of biomass utilisation pathways within the circular bioeconomy (Casau et al., 2022; Cavalaglio et al., 2024; Ciliberti et al., 2020; Picchio et al., 2023; Pokharel et al., 2025).

Previous research therefore suggests that hazel biomass should not be treated as a homogeneous fuel. Individual fractions differ not only in calorific value but also in characteristics that determine the combustion process and potential environmental impact. This has practical significance, as a material that is more advantageous in terms of energy does not necessarily have the most favourable emissions profile. Previous analyses of leaves, litter and husks have shown that differences in moisture content, ash content, volatile matter and elements such as nitrogen and sulphur can affect both the efficiency of the process and the levels of gaseous and particulate emissions (Borkowska et al., 2025; Klimek et al., 2025; Maj et al., 2025).

Therefore, the present study adopts an approach in which hazel biomass fractions are analysed as distinct fuel types rather than as a single waste stream defined only by variety or total mass. Such an approach allows us to answer a question that is more useful from a practical standpoint than merely confirming that crop residues can be used for energy. It is crucial to determine whether all hazel biomass fractions exhibit similar fuel quality or whether some fractions should be prioritised for thermal conversion because of a more favourable combination of fuel and environmental characteristics (Borkowska, et al., 2024a; Borkowska et al., 2025; Maj et al., 2025; Pergola et al., 2024).

The assessment of this type of material cannot be limited solely to the determination of the heat of combustion and calorific value. Equally important are technical and elemental parameters, i.e. moisture content, ash content, volatile matter and elemental composition, as these factors determine the intensity of the combustion process, the amount of mineral residue, the quality of the flue gas and potential operational difficulties. In this context, the comparison of hazel biomass fractions is important from both scientific and practical perspectives. It can support the selective allocation of specific plant parts to the most appropriate energy recovery pathway.Based on these assumptions, the present study was designed to verify whether individual waste biomass fractions of common hazel differ significantly in fuel quality and emission characteristics and therefore should be assessed separately rather than treated as a homogeneous biomass stream. It was assumed that fractions with lower ash, nitrogen and sulphur contents would exhibit a more favourable combustion profile and lower pollutant emissions, thereby supporting their greater suitability for energy recovery within a circular bioeconomy model.

MATERIALS AND METHODS

Field studies were conducted in 2024–2025 at a horticultural farm located in the municipality of Zawichost, in the Świętokrzyskie Voivodeship (50°49′20.5″ N; 21°44′35.0″ E), in south-eastern Poland. The study material consisted of ungrafted common hazel (*Corylus avellana* L.) shrubs, grown on their own roots and representing four varieties: Katalośki, Olbrzymi z Halle, Olga and Webba Cenny. The plants were planted in spring 2002 in loess soil classified as site classes II and II ab. The shrubs were cultivated in a row system, spaced 6 × 2.5 m apart, corresponding to a density of 666 plants·ha^{-1}.

Material for analysis was collected on two occasions. In autumn 2024, immediately after the fruit harvest, three biomass fractions were obtained: shells, husk, and leaves. Shoots, constituting the fourth biomass fraction, were collected in winter 2025 during the planned maintenance pruning of the shrubs. For each variety, plant material was collected from three randomly selected shrubs. The material within the same fractions was then grouped for comparative analyses conducted independently of the variety.

Composite samples were prepared separately for each biomass fraction. After collection, the material from the four cultivars was separated into shells, husk, leaves and shoots. For each biomass fraction, material collected from individual shrubs and cultivars was combined to obtain a representative composite sample. This approach was used because the aim of the study was to compare the fuel quality and emission characteristics of biomass fractions independently of cultivar and to assess the effect of the type of plant material rather than varietal variability. Before laboratory analyses, the composite samples were air-dried at 20°C and 55–60% relative humidity for two weeks to standardise moisture conditions. The dried material was then ground to a particle size of 0.5 mm using a Retsch SM 100 cutting mill (Retsch GmbH, Haan, Germany). The same preparation procedure was applied to all analysed fractions to ensure comparability of the results.

To clarify the practical context of the selected research material, it should be noted that regardless of theoretical possibilities, in everyday agricultural practice, these biomass fractions are currently treated primarily as troublesome waste and are either left in the orchards to decompose or open-burned on-site. However, they constitute a valuable raw material; therefore, the current management pathways and potential valorisation options reported in the scientific literature are summarised and compared in Table 1.

The study assessed the energy and emission properties of waste biomass from hazelnut cultivation, comparing its individual fractions. The quality of the material was determined on the basis of technical and elemental analysis, including the determination of moisture content, ash content, volatile matter and elemental composition. In addition, the heat of combustion and calorific value were determined. The methodological workflow for sample collection, composite sample preparation and analytical procedures is presented in Figure 1, while detailed information on the analytical methods, standards and equipment used in the study is provided in Figure 2.

The results were statistically analysed using Statistica 13.1 software. The normality of distribution was verified using the Shapiro–Wilk test. Differences between biomass fractions were assessed using one-way analysis of variance (ANOVA). Significant differences between means were determined using Tukey's HSD post-hoc test at a significance level of $\alpha = 0.05$.

Table 1. Current and potential management pathways of selected common hazel biomass fractions based on the scientific literature

Biomass fraction	Current/practical management in hazelnut production	Potential or validated valorisation pathways	Supporting literature
Shoots	Chipping, baling, local use as biomass fuel, and the production of wood chips or pellets	Shoots and branches from orchard pruning are treated as a lignocellulosic raw material suitable for energy use; research into hazel pruning residues indicates the potential for pellet production, whilst studies on orchard pruning biomass confirm its suitability for combustion in wood chip-fired plants, subject to the need to monitor its chemical composition and ash content.	(Bianchini et al., 2021)
Shells	Direct combustion, production of pellets and briquettes, pyrolysis, production of bio-oil, biochar, activated carbon, sorbents and composite materials	Shells are one of the best-known waste fractions from hazelnuts; the literature highlights their favourable fuel properties, high calorific value and low ash content; furthermore, research confirms that they can be processed via pyrolysis into bio-oil, wood vinegar and tar, as well as used as a raw material for the production of activated carbon and adsorbents for water treatment.	(Ceraulo et al., 2022; Chen et al., 2021; Klimek et al., 2025; Maj et al., 2025; Stjepanović et al., 2022)
Leaves	Leaving on the plantation, composting, contributing to the organic matter cycle, potential use as a source of bioactive compounds.	Leaves constitute an organic fraction that can support the circulation of organic matter within the plantation system; however, their direct use for energy production may be limited by their higher ash, nitrogen and sulphur content; research on *Corylus avellana* l. Leaves also indicates the presence of phenolic compounds and antioxidant activity, which justifies considering non-fuel applications for their valorisation.	(Borkowska et al., 2025; Maj & Piekut, 2018; Rusu et al., 2019; Wąsik & Klimowicz, 2022; Zhao et al., 2023)
Husk	Composting, mulching, soil improvement, production of horticultural growing media, anaerobic digestion and biogas production.	Husk is a lignocellulosic by-product produced during the harvesting and processing of nuts; research indicates that composts made from hazelnut waste can partially replace peat in horticultural substrates and improve selected soil properties; the potential for using husks in anaerobic digestion has also been demonstrated; following alkaline treatment, methane yield may increase compared to the control sample.	(Bignami et al., 2023; Ceylan, 2024; Dede & Ozdemir, 2018; Şenol, 2020)

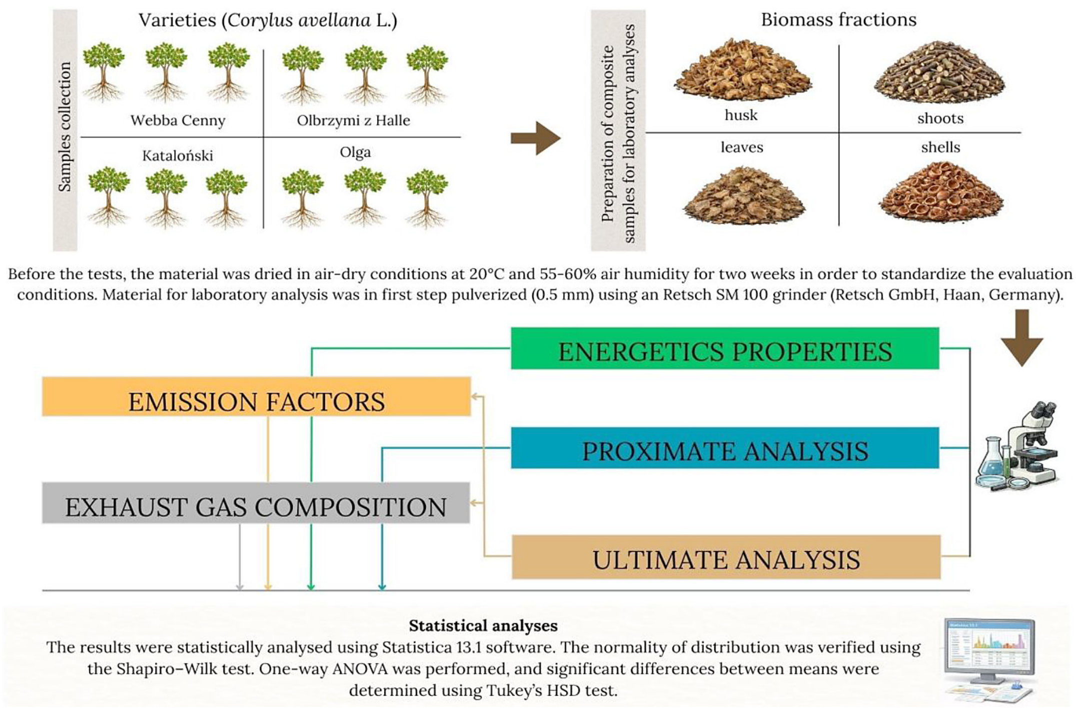

Figure 1. Methodological workflow for sample collection, composite sample preparation and analytical procedures

Parameter	Method	Equipment
ENERGETIC PROPERTIES		
Higher Heating Value (HHV; $MJ \cdot kg^{-1}$)	EN-ISO 1928:2009	isoperibolic calorimeter LECO AC 600
Lower Heating Value (LHV; $MJ \cdot kg^{-1}$)	EN-ISO 1928:2009	isoperibolic calorimeter LECO AC 600
PROXIMATE ANALYSIS		
Ash (A; %)	EN-ISO 18122-01	thermogravimetric analyser LECO TGA 701
Volatile matter (V; %)	EN-ISO 18123-01	thermogravimetric analyser LECO TGA 701
Moisture (M; %)	EN-ISO 18134-3	thermogravimetric analyser LECO TGA 701
Fixed carbon (FC; %)	FC = 100 − V − A − M (Choudhury et al., 2021)	
ULTIMATE ANALYSIS		
Carbon (C; %)	EN-ISO 16948:2015-07	elemental analyser LECO CHNS 628
Hydrogen (H;%)	EN-ISO 16948:2015-07	elemental analyser LECO CHNS 628
Nitrogen (N; %)	EN-ISO 16948:2015-07	elemental analyser LECO CHNS 628
Sulphur (S; %)	EN-ISO 16994:2016-10	elemental analyser LECO CHNS 628
Oxygen (O; %)	O = 100 − A − H − C − S − N (Alves et al., 2020)	
Emission factors calculated according to studies (Maj, 2018)		
EMISSION FACTORS		
Carbon monoxide emission factor (Ec) of chemically pure coal (CO; $kg \cdot Mg^{-1}$)	$CO = \frac{28}{12} \cdot Ec \cdot (C/CO)$, CO – carbon monoxide emission factor ($kg \cdot kg^{-1}$), $\frac{28}{12}$ – molar mass ratio of carbon monoxide to carbon, Ec – emission factor of chemically pure coal ($kg \cdot kg^{-1}$), C/CO – proportion of carbon emitted as CO (for biomass 0.06).	
Carbon dioxid emission factor (CO_2; $kg \cdot Mg^{-1}$)	$CO_2 = \frac{44}{12} \cdot (E_c - \frac{12}{28} \cdot CO - \frac{12}{16} \cdot E_{CH4} - \frac{26.4}{31.4} 26.4/31.4 \cdot E_{NMVOC})$, 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, E_{CH4} - methane emission factor, E_{NMVOC} - emission index of non-methane VOCs (for biomass 0.009).	
Sulphur dioxide emission factor (SO_2; $kg \cdot Mg^{-1}$)	$SO_2 = \frac{25}{100} \cdot (1 - r)$ 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 proportion of total sulphur retained in the ash.	
The emission factor was calculated from (NO_x; $kg \cdot Mg^{-1}$)	$NO_x = \frac{46}{14} \cdot Ec \cdot N/C \cdot (NNO_x / N)$, 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 taken into account because nitrogen oxide in the air oxidises very quickly to form nitrogen dioxide; N/C is the nitrogen-to-carbon ratio in biomass; N/NO_x is the proportion of nitrogen emitted as NO_x (for biomass, 0.122).	
The exhaust gas composition was calculated according to (Paraschivet al., 2020; Kovacs,2016)		
Theoretical oxygen demand (V_{O2}; $Nm^3 \cdot kg^{-1}$)	$V_{O2} = \frac{22.41}{100} \cdot (\frac{C}{12} + \frac{H}{14} + \frac{S-O}{32})$, C - biomass carbon content (%), H - biomass hydrogen content (%), S - biomass sulphur content (%), O - biomass oxygen content).	
The stoichiometric volume of dry air required to burn 1 kg of biomass (V_{Oa}; $Nm^3 \cdot kg^{-1}$)	$V_{Oa} = \frac{VO_2}{0.21}$, 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}; $Nm^3 \cdot kg^{-1}$)	$V_{CO_2} = \frac{22.41}{12} \cdot \frac{C}{100}$	
Sulphur dioxide content (V_{SO2}; $Nm^3 \cdot kg^{-1}$)	$V_{SO2} = \frac{22.41}{32} \cdot \frac{S}{100}$	
EXHAUST GAS COMPOSITION		
Water vapour content of the exhaust gas (V_{H_2O}; $Nm^3 \cdot kg^{-1}$)	$V^H_{H2o} = \frac{22.41}{100} \cdot (\frac{H}{2} + \frac{M}{18})$, is the component of water vapour volume from the hydrogen combustion process (V^H_{H2O}; $Nm^3H_2O \cdot kg^{-1}$ fuel) $V^a_{H2O} = 1.61 \cdot x \cdot V_{Oa}$ and the volume of moisture contained in the combustion air (V^a_{H2O}; $Nm^3H_2O \cdot kg^{-1}$ fuel) $V_{H_2O} = V^H_{H2O} + V^a_{H2O}$; M – fuel moisture content (%), x – absolute humidity of the air (kg $H_2O \cdot kg^{-1}$ dry air).	
The theoretical nitrogen content in the exhaust gas (V_{N2}; $Nm^3 \cdot kg^{-1}$)	$V_{N_2} = \frac{22.41}{28} \cdot \frac{N}{100} + 0.79 \cdot V_{Oa}$, 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}; $Nm^3 \cdot kg^{-1}$)	$V_{gu} = V_{CO2} + V_{SO2} + V_{N2}$	
The total volume of exhaust gases (V_{ga}; $Nm^3 \cdot kg^{-1}$)	$V_{ga} = V_{gu} + V_{H2O}$ Assuming that biomass combustion is carried out under stoichiometric conditions, i.e., using the minimum amount of air required for combustion ($\lambda = 1$), a minimum exhaust gas volume will be obtained.	

Figure 2. A summary of the methods and apparatus used for the energy and carbon analysis of the raw materials studied

RESULTS AND DISCUSSION

Fuel quality and elemental composition of biomass fractions

The study focused in particular on the energy properties of various types of waste biomass derived from common hazel, namely shells, husks, leaves and shoots. Based on technical and elemental analysis, the energy parameters and chemical composition of the four biomass fractions were compared, regardless of variety. The results obtained showed clear differences between the materials studied, related to their different anatomical structure, physiological function and elemental composition. Detailed data are summarised in Table 2.

The highest HHV and LHV values were recorded for the shells, 18.65 and 17.37 MJ·kg^{-1} respectively, confirming their highest energy potential among the analysed fractions. The lowest values were obtained for the husk (15.94 and 14.76 MJ·kg^{-1}). The results for the shells are consistent with the data from Borkowska et al. (2024b), who reported a range of HHV 18.61–18.68 MJ·kg^{-1} and LHV 17.33–17.40 MJ·kg^{-1} for hazelnut shells. Similar values were also obtained by Noszczyk et al. (2021) for hazelnut shells (HHV 18.887 MJ·kg^{-1}; LHV 17.078 MJ·kg^{-1}). It was also demonstrated that hazelnut shells have lower energy parameters than walnut and peanut shells, but higher than pistachio shells. More broadly, the hazelnut shells studied exhibited higher energy values than many types of agricultural biomass (Torreiro et al., 2020; Vassilev et al., 2017), whilst remaining comparable to woody biomass (Mitchell et al., 2020; Solarte-Toro et al., 2021). For husks, Borkowska et al. (2024a) reported a range of HHV 15.77–16.03 MJ·kg^{-1} and LHV 14.60–14.85 MJ·kg^{-1}, which is consistent with the results obtained in this study.

In terms of carbon (C) content, the highest proportion of this element was found in the shells (51.01%), whilst the lowest was in the leaves (42.84%). The value obtained for leaves is consistent with earlier studies, in which a range of 42.57–43.46% was reported for hazel leaf biomass depending on the variety (Borkowska et al., 2025). Maj and Piekut (2018) reported a slightly higher value for hazel leaves (44.45%), and for oak, maple and walnut leaves 47.66%, 44.34% and 43.07% respectively, which confirms the variation in carbon content between tree species. In contrast, for hazelnut shells, Borkowska et al. (2024b) reported lower C values, ranging from 46.17% to 47.03%, whilst Noszczyk et al. (2021) reported a level of approximately 49% for

Table 2. Comparison of the results of technical and elemental analysis of different types of hazel biomass, regardless of variety

Parameters	Type of waste biomass				p-value
	husks	leaves	shoots	shells	
HHV (MJ·kg^{-1})	15.94 ± 0.12 C	17.30 ± 0.25 B	17.13 ± 0.59 B	18.65 ± 0.06 A	<0.0001
LHV (MJ·kg^{-1})	14.76 ± 0.12 C	16.14 ± 0.25 B	15.79 ± 0.66 B	17.37 ± 0.06 A	<0.0001
C%	44.33 ± 0.38 B	42.84 ± 0.51 C	42.85 ± 1.63 C	51.01 ± 0.47 A	<0.0001
H%	6.42 ± 0.29 C	7.09 ± 0.25 B	7.40 ± 0.39 A	7.10 ± 0.21 AB	<0.0001
N%	0.78 ± 0.10 C	2.12 ± 0.06 A	0.88 ± 0.11 B	0.36 ± 0.06 D	<0.0001
S%	0.04 ± 0.01 C	0.14 ± 0.01 A	0.05 ± 0.01 B	0.01 ± 0.00 D	<0.0001
M%	7.60 ± 0.42 C	7.38 ± 1.02 C	16.45 ± 1.84 B	8.85 ± 0.16 A	<0.0001
O%	39.92 ± 0.58 B	38.55 ± 0.66 C	47.11 ± 1.49 A	40.69 ± 0.44 B	<0.0001
A%	8.50 ± 0.19 B	9.26 ± 0.30 A	1.73 ± 0.46 C	0.82 ± 0.11 D	<0.0001
V%	66.43 ± 1.16 B	66.40 ± 0.63 B	66.08 ± 1.43 B	68.01 ± 0.64 A	<0.0001
FC%	17.47 ± 0.89 B	16.97 ± 0.79 B	15.75 ± 0.74 C	22.32 ± 0.48 A	<0.0001
H/C	1.45 ± 0.07 B	1.65 ± 0.05 A	1.73 ± 0.14 A	1.39 ± 0.05 B	<0.0001
N/C	0.02 ± 0.00 C	0.05 ± 0.00 A	0.02 ± 0.00 B	0.01 ± 0.00 D	<0.0001
O/C	0.68 ± 0.01 B	0.68 ± 0.02 B	0.83 ± 0.06 A	0.60 ± 0.01 C	<0.0001

Note: HHV – higher heating value; LHV – lower heating value; C – carbon; H – hydrogen; N – nitrogen; S – sulphur; M – moisture; O – oxygen; A – ash; V – volatile matter; FC – fixed carbon; H/C, N/C and O/C – molar ratios. Values are presented as mean ± standard deviation. Significant difference: A, B, C, D — means denoted by the same letter in a row do not differ significantly, whilst means denoted by different letters differ significantly at α = 0.05.

this fraction. In the study by Matin et al.(2023), even higher carbon content values in the shells were reported, ranging from 57.60–57.95%, which indicates significant variability in this parameter depending on the origin of the material and the conditions of its preparation. This means that the shells analysed in this study were characterised by a higher carbon concentration than the values reported in most previous studies. The higher carbon content in the shells may be one of the reasons for their more favourable combustion parameters compared to the leaves.

The hydrogen (H) content was highest in the shoots (7.40%) and lowest in the husk (6.42%). The value obtained for shoots is consistent with earlier studies by Borkowska et al. (2024b), in which a range of 7.09–7.78% was recorded for annual shoots and 7.34–8.05% for perennial shoots. For husks, the same authors reported higher hydrogen values, ranging from 6.71–6.88% (Borkowska, et al., 2024b). In the literature, lower or similar hydrogen contents have also been reported for hazel biomass, including 6.40% according to Stolarski et al.(2021), 6.57% according to Bilandžija (2012) and 6.10% according to Cavalaglio et al. (2024). This means that the shoots analysed in this study were characterised by a relatively high hydrogen content, whilst the husk had a lower content than previously reported for this biomass fraction.

In terms of the elemental composition of the biomass, the highest nitrogen (N) content was recorded in the leaves (2.12%), whilst the lowest was in the shells (0.36%). The value obtained for the leaves is consistent with the results of Borkowska et al. (2024b), who reported a range of 2.10–2.66% for hazel leaves depending on the variety. Güleç et al. (2022) reported a slightly lower nitrogen content (2.05%) for this fraction, whilst similar or higher values were reported for the leaves of other tree and shrub species. In turn, the nitrogen content determined in the shells corresponds to the range of 0.29–0.36% previously reported for hazelnut shells by Borkowska et al. (2024b). The low nitrogen content in the shells is also confirmed by earlier analyses of this biomass fraction, indicating its more favourable emission profile compared to the more nitrogen-rich leaves. Compared to other tree leaves, for which Maj and Piekut (2018) reported lower nitrogen values, the leaves analysed in this study can be considered a fraction particularly rich in this element. This may indicate a greater emission potential of leaves in terms of NO_x compared to husk.

The sulphur (S) content was highest in the leaves (0.14%) and lowest in the shells (0.01%). The value obtained for the leaves falls within the range of 0.13–0.16% previously reported for hazel leaves by Borkowska et al. (2025), although it remains significantly lower than the 0.33% reported by Güleç et al. (2022) for the same fraction. In turn, the sulphur content determined in the shells corresponds to literature data for hazelnut shells, for which a very low level of this element was reported, ranging from 0.01–0.02% (Borkowska, et al., 2024b). Such a marked variation between fractions may partly explain their differing emission potentials for SO_2.

As regards oxygen (O) content, the highest values were found in shoots (47.11%), and the lowest in leaves (38.55%). These results are consistent with earlier studies by Borkowska et al. (2024b), in which a range of 45.12–48.62% was recorded for one-year-old shoots and 46.68–50.32% for multi-year-old shoots of hazel, whilst for leaves the range was 38.07–39.40% depending on the variety. Similar observations regarding the low variability in oxygen content were also noted for grapevine shoots, which may indicate that the shoot biomass of various species is characterised by a relatively stable proportion of this element. At the same time, Güleç et al. (2022) reported higher oxygen content values in the leaves of hazel and other tree species, confirming that this parameter may vary significantly depending on the type of plant material.

The ash content (A) was significantly highest in the leaves (9.26%), whilst the lowest values for this parameter were found in the shells (0.82%). The value obtained for leaves is similar to the data reported by Maj and Piekut (2018), who reported 8.55% for hazel leaves, whilst for oak, maple and walnut leaves they recorded 21.98%, 12.75% and 12.95% respectively, confirming the significant variation in this parameter between species. In contrast, the ash content determined in the shells was lower than in studies on Turkish hazelnut varieties, for which a range of 1.00–1. 2% (Maj et al., 2025), and also lower than the values reported for hazelnut, almond and chestnut shells by Güleç et al. (2022), amounting to 2.20%, 2.20% and 3.90% respectively. At the same time, the result obtained for shells remains significantly lower than for many other types of agrobiomass, i.e. bean hulls (8.00%), cocoa husk (9.96%), rice husk (13.70%) (Güleç et al., 2022) or data for hazelnut shells (Mladenovic et al., 2024). A similarly low ash content was found in woody biomass, including in the case of beech (Nunes, Loureiro, et al., 2021). The results obtained confirm that hazelnut shells belong to a fraction that is particularly advantageous from an energy perspective, whilst leaves, due to their high ash content, may exhibit less favourable fuel properties.

The highest proportion of volatile matter (V) was recorded in the shells (68.01%), whilst the lowest was in the shoots (66.08%). The result obtained for shoots is consistent with earlier studies by Borkowska et al. (2024b), in which a range of 64.93–68.22% was recorded for annual shoots and 67.20–70.61% for perennial shoots. In turn, for hazelnut shells, Borkowska et al. (2024b) reported values in the range of 67.20–68.54%, which are thus similar to those obtained in the present study. The results obtained are also consistent with the data for hazelnut shells presented by Mladenovic et al. (2024), as well as with results obtained for other lignocellulosic materials with low ash content, i.e. oak branches, pine chips, rye straw or miscanthus (Güleç et al., 2022; Matin et al., 2023). Higher values for volatile matter, however, were reported by Cavalaglio et al. (2024), citing 77.4% for hazel biomass, which indicates that the proportion of this fraction may vary significantly depending on the type of material and its origin. The results obtained confirm that shells belong to the more volatile fraction, which may facilitate easier ignition and a more favourable combustion process compared to shoots.

In turn, the highest fixed carbon (FC) content was found in the shells (22.32%), and the lowest in the shoots (15.75%). The low value obtained for shoots is consistent with observations regarding shoot biomass, in which the fixed carbon content shows relatively little variation. Similar relationships were noted by Kapłan et al. (2025) for grapevine shoots, indicating that rootstock selection influenced FC only to a limited extent, and the results obtained were similar to the data presented by Nunes et al. (2021a; 2021b). In contrast, for hazelnut shells, the value obtained in this study was similar to the range of 22.01–22.89% reported for Turkish varieties of hazel (Klimek et al., 2025), whilst being higher than in studies where values of 17.73–18.06% and 16.34–18.37% (Marcantonio et al., 2020; Matin et al., 2023; Smith et al., 2019). A significantly lower fixed carbon content for hazelnut shells was also reported by Noszczyk et al. (2021), obtaining a value of 11.39%. The results obtained indicate that hazelnut shells belong to a fraction that is particularly advantageous in terms of bound carbon content, which may contribute to a higher calorific value and a more stable combustion process compared to shoots.

The H/C, N/C and O/C molar ratios indicate chemical variation within the fractions. The highest H/C ratio was found in the shoots (1.73), and the lowest in the shells (1.39). The N/C ratio was highest in the leaves (0.05) and lowest, again, in the shells (0.01). The highest O/C ratio was found in the shoots (0.83) and the lowest in the shells (0.60).

Emission factors of biomass combustion

Table 3 presents the results of estimated emissions of the main gaseous and particulate pollutants generated by the combustion of various types of hazel biomass. The assessment covered emissions of carbon monoxide (CO), nitrogen oxides (NO_x), carbon dioxide (CO_2), sulphur dioxide (SO_2) and dust, expressed per unit of dry biomass mass ($kg \cdot Mg^{-1}$). The results obtained showed significant differences in all parameters studied.

The highest CO_2 emission values were obtained for shells (1539.00 $kg \cdot Mg^{-1}$), which can be attributed to their highest carbon content and calorific value, whilst the lowest CO_2 emissions were recorded for leaves (1292.42 $kg \cdot Mg^{-1}$). In the case of carbon monoxide (CO), the highest emissions were also estimated for shells (62.85 $kg \cdot Mg^{-1}$), and the lowest for leaves (52.78 $kg \cdot Mg^{-1}$). Significant differences were also observed in nitrogen oxide (NO_x) emissions. The highest values were found for leaves (7.48 $kg \cdot Mg^{-1}$), which is consistent with their highest nitrogen content in the elemental analysis, whilst the lowest NO_x emissions were recorded for shells (1.26 $kg \cdot Mg^{-1}$). In terms of sulphur dioxide (SO_2) emissions, the highest values were also recorded for leaves (0.29 $kg \cdot Mg^{-1}$), and the lowest for shells (0.03 $kg \cdot Mg^{-1}$), which correlates with the sulphur content in these fractions. Total dust emissions were highest for leaves (11.69 $kg \cdot Mg^{-1}$) and lowest for shells (1.04 $kg \cdot Mg^{-1}$), which may be attributed to the high ash content in leaves and the low proportion of mineral matter in shells (Table 3).

The results obtained for leaves are consistent with earlier observations (Maj & Piekut, 2018), who demonstrated significant variations in CO, NO_x, CO_2, SO_2 and particulate matter emissions between the leaves of hazel, oak, maple and walnut trees. High particulate matter emissions from leaf biomass are further confirmed by studies on emissions of particles generated during

Table 3. Emission parameters for various types of hazel biomass, regardless of variety

Parameters (kg·Mg^{-1})	Biomass fraction				p-value
	husks	leaves	shoots	shells	
CO	54.61 ± 0.47 B	52.78 ± 0.62 C	52.79 ± 2.01 C	62.85 ± 0.58 A	<0.0001
NOx	2.77 ± 0.34 C	7.48 ± 0.22 A	3.10 ± 0.37 B	1.26 ± 0.21 D	<0.0001
CO_2	1337.31 ± 11.46 B	1292.42 ± 15.24 C	1292.69 ± 49.19 C	1539.00 ± 14.26 A	<0.0001
SO_2	0.07 ± 0.01 C	0.29 ± 0.02 A	0.10 ± 0.02 B	0.03 ± 0.00 D	<0.0001
Dust	10.74 ± 0.24 B	11.69 ± 0.38 A	2.19 ± 0.58 C	1.04 ± 0.14 D	<0.0001

Note: CO – carbon monoxide; NO_x – nitrogen oxides; CO_2 – carbon dioxide; SO_2 – sulphur dioxide. Values are presented as mean ± standard deviation. Significant difference: A, B, C, D — means denoted by the same letter in a row do not differ significantly, whilst means denoted by different letters differ significantly at α = 0.05.

leaf combustion (Schmidl et al., 2008). In turn, studies on the leaves of selected hazel varieties have shown that high emissions of NO_x, SO_2 and particulate matter are associated with increased nitrogen, sulphur and ash content in leaf biomass (Borkowska et al., 2025).

The more favourable emission profile of the shells, characterised by the lowest emissions of NO_x, SO_2 and particulate matter, is consistent with earlier studies on hazelnut shell biomass, which highlighted their low ash, nitrogen and sulphur content and good suitability for energy use (Borkowska, et al., 2024b; Maj et al., 2025). With regard to CO_2 emissions, it should also be noted that the volume of this gas emitted during biomass combustion is closely linked to the elemental composition of the fuel, as also emphasised by Paraschiv et al. (2020). The results obtained therefore indicate that, among the fractions analysed, leaves exhibit the least favourable emission profile, whilst shells combine a high calorific value with relatively low emissions of acidifying pollutants and particulate matter (Table 3).

Flue gas composition and combustion-related parameters

Table 4 presents the volumetric composition of the main gases emitted during the combustion of individual types of hazel waste biomass, expressed per unit of dry mass (Nm³·kg^{-1}). The analysed parameters include, among others, the theoretical oxygen demand (V_{O2}), dry air volume (V_a), carbon dioxide volume (V_{CO2}), sulphur oxides (V_{SO2}) and nitrogen oxides (V_{N2}), the volume of water vapour (V_{H2O}) and the total volume of flue gas (V_{gu}, V_{ga}). The results obtained showed significant differences in all the parameters studied.

Among the analysed biomass fractions, the shells were characterised by the highest values of

Table 4. Composition of gases emitted from the combustion of various types of waste biomass

Parameters (Nm³·kg^{-1})	Type of waste biomass				p-value
	husks	leaves	shoots	shells	
V_{O2}	0.91 ± 0.02 BC	0.93 ± 0.02 B	0.89 ± 0.04 C	1.07 ± 0.01 A	<0.0001
V_a	4.33 ± 0.10 BC	4.42 ± 0.11 B	4.22 ± 0.17 C	5.07 ± 0.07 A	<0.0001
V_{CO2}	0.83 ± 0.01 B	0.80 ± 0.01 C	0.80 ± 0.03 C	0.95 ± 0.01 A	<0.0001
V_{SO2}	0.00 ± 0.00 C	0.00 ± 0.00 A	0.00 ± 0.00 B	0.00 ± 0.00 D	<0.0001
V_{H_2O}	0.81 ± 0.03 C	0.89 ± 0.03 B	1.03 ± 0.06 A	0.91 ± 0.02 B	<0.0001
V_{N_2}	4.05 ± 0.13 C	5.19 ± 0.13 A	4.03 ± 0.20 C	4.29 ± 0.07 B	<0.0001
V_{ga}	6.38 ± 0.17 C	7.59 ± 0.16 A	6.55 ± 0.24 C	6.97 ± 0.09 B	<0.0001
V_{gu}	4.87 ± 0.14 C	5.99 ± 0.13 A	4.83 ± 0.22 C	5.25 ± 0.08 B	<0.0001

Note: V_{O2} – theoretical oxygen demand; V_{Oa} – stoichiometric volume of dry air required for combustion; V_{CO_2} – volume of carbon dioxide in the flue gases; V_{SO_2} – volume of sulphur dioxide in the flue gases; V_{H_2O} – volume of water vapour in flue gases; V_{N_2} – volume of nitrogen in flue gases; V_{ga} – total volume of flue gases; V_{gu} – total volume of dry flue gases. Values are presented as mean ± standard deviation. Significant difference: A, B, C, D — means denoted by the same letter in a row do not differ significantly, whilst means denoted by different letters differ significantly at α = 0.05.

V_{O2} (1.07 Nm³·kg⁻¹), V_a (5.07 Nm³·kg⁻¹) and V_{CO2} (0.95 Nm³·kg⁻¹), which is consistent with their highest carbon content and favourable combustion parameters. In turn, the shoots were distinguished by the highest volume of water vapour in the flue gas (V_{H2O} – 1.03 Nm³·kg⁻¹), whilst the leaves generated the largest total volume of flue gases (V_{ga} – 7.59 Nm³·kg⁻¹; V_{gu} – 5.99 Nm³·kg⁻¹). The results obtained confirm that the elemental composition of biomass directly influences the theoretical oxygen demand, the amount of air required for combustion, and the volume of the main exhaust gas components, as also emphasised by Paraschiv et al. (2020) and Lala et al. (2022). Similar relationships for leaf biomass were demonstrated by Maj and Piekut (2018), pointing to a clear differentiation in emission and fuel parameters between the leaves of hazel, oak, maple and walnut. In turn, earlier studies by Borkowska et al.(2024b, 2024a; 2025) confirm that shells have a more favourable fuel profile than leaves and fruit husks, which is also reflected in a more favourable volumetric composition of flue gases. At the same time, the literature indicates that the final composition of the flue gas depends not only on the properties of the fuel itself, but also on the air supply conditions and the organisation of the combustion process (Caposciutti et al., 2018).

Environmental implications and circular management of hazel biomass fractions

The environmental assessment of common hazel biomass combustion should include not only fuel quality and emission parameters, but also the potential use of combustion by-products. Borkowska et al. (2026), in a study on the chemical composition of ash from the combustion of common hazel biomass, demonstrated that ash composition depends on both biomass fraction and cultivar. The same study showed that leaves and husk were characterised by the highest content of mineral components of fertilising importance, whereas shells exhibited the lowest values for most macronutrients. The content of potentially toxic elements, including ZnO, TiO_2 and Cr_2O_3, was low, which indicates a limited environmental risk and supports the potential secondary use of selected ash fractions, provided that environmental safety requirements are met.

These results are consistent with the general concept of biomass ash recycling. Biomass ash may contain relevant amounts of macronutrients, particularly calcium, potassium and phosphorus, and can therefore partially replace mineral fertilisers or improve selected soil properties. Similar relationships have been reported for other plant materials. Kapłan et al. (2025), analysing post-production waste from winemaking, showed that the plant fraction affected the chemical and energy properties of biomass, confirming that leaves and woody parts should not be treated as equivalent materials. Zając et al. (2018) demonstrated that biomass ashes differ considerably in chemical composition depending on the type and origin of plant material, and that their composition is dominated by macroelements such as Ca, K, P and S, which indicates their possible agricultural use. Zając et al. (2020), in a study on ashes from biomass used in the corn grain drying process, also confirmed that the chemical composition and fertiliser usefulness of ash depend on the type of biomass fraction. These findings confirm that the mineral value of biomass ash is strongly dependent on the botanical origin and anatomical part of the plant material.

However, combustion should not be considered the only management pathway for all hazel biomass fractions. In the present study, shells showed the most favourable fuel and emission profile, while shoots, as a woody lignocellulosic fraction, may also be directed towards energy recovery after appropriate preparation. This is supported by Bianchini et al. (2021), who demonstrated that a two-stage dry milling and fractionation process applied to hazelnut and olive pruning residues improved solid fuel quality. In the case of hazelnut pruning, the coarser fractions obtained after processing showed reduced ash and nitrogen contents and met the EN ISO 17225-2 requirements for both industrial and residential pellets. The same study also showed that the finest hazelnut fraction reached a methane yield of 118.1 Nm³·tVS⁻¹, corresponding to a 70.1% increase compared with the untreated substrate, indicating that mechanical processing may support both pellet production and anaerobic conversion of pruning residues.

In contrast, leaves were characterised by higher ash, nitrogen and sulphur contents and generated the highest estimated emissions of NO_x, SO_2 and particulate matter. Therefore, leaves may be more appropriate for non-combustion pathways, such as composting or biological recycling, especially when the objective is to return organic matter and nutrients to the soil. Studies by Bignami et al. (2023) showed that composts from grapevine and hazelnut by-products can partially replace peat in nursery substrates, up to 20% in hazelnut and 40% in raspberry cultivation. Ceylan (2024) also demonstrated that composts obtained from hazelnut wastes can be used in the cultivation of pepper seedlings, which supports the use of these residues in horticultural production. Dede and Özdemir (2018) showed that mixtures of hazelnut husk and municipal sewage sludge can be used to develop nutrient-rich growing media; the addition of sewage sludge enriched the media with plant nutrients, and the mixture containing 75% hazelnut husk and 25% sewage sludge was identified as the most suitable variant for ornamental plant production. In addition, Şenol et al. (2020) investigated anaerobic digestion of hazelnut husks and found that alkaline pretreatment with 4% NaOH increased methane yield to 278.45 ± 7.85 $mL \cdot g^{-1}$ VS. This indicates that selective management of common hazel biomass fractions is more justified than treating all residues as a single waste stream. Shells and shoots may be prioritised for energy recovery, whereas leaves and husk may be considered for composting, biological conversion or ash-based nutrient recycling, depending on their fuel quality, mineral composition and environmental performance.

CONCLUSIONS

The analysed fractions of common hazel biomass, i.e. shells, husk, leaves and shoots, differed significantly in terms of fuel quality, elemental composition, emission parameters and calculated flue gas characteristics. This confirms that common hazel waste biomass should not be treated as a homogeneous fuel, but as a set of fractions with different technological and environmental properties.

Shells showed the most favourable fuel profile, with the highest HHV and LHV values, the highest carbon and fixed carbon contents, and the lowest ash, nitrogen and sulphur contents. Husk had the lowest HHV and LHV values, which indicates the lowest fuel quality among the analysed fractions. Shoots, as a woody lignocellulosic fraction, showed fuel properties suitable for energy use, although their combustion profile was associated with the highest hydrogen and oxygen contents and the highest water vapour volume in the flue gas. Leaves showed the least favourable profile for direct combustion, mainly due to the highest ash, nitrogen and sulphur contents and the highest estimated emissions of NO_x, SO_2 and particulate matter.

The calculated emission factors and flue gas composition confirmed that the elemental and proximate composition of each fraction directly affects oxygen demand, combustion air requirement, pollutant formation and flue gas volume. Therefore, selective management of individual hazel biomass fractions is more appropriate than their collective treatment as a single waste stream.

From a practical perspective, shells and shoots may be directed primarily towards energy recovery, provided that appropriate fuel preparation methods are applied. Husk, due to its lower calorific value, may be considered for use in biomass blends or alternative valorisation pathways. Leaves, due to their higher ash, nitrogen and sulphur contents, may be more suitable for non-combustion management options, such as composting or biological conversion.

Future research should include pilot-scale combustion tests, assessment of ash behaviour and slagging tendency, and verification of actual emissions under real operating conditions. Further studies should also compare direct combustion with alternative valorisation pathways, including pelletisation, gasification, composting and life-cycle assessment, in order to determine the most appropriate management strategy for each common hazel biomass fraction.

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