Forest Residues as a Renewable Source of Energy: Elemental Composition and Physical Properties

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Forest residues are a potentially important source of renewable energy. They are generated as a byproduct of timber harvesting around the world. To optimize the utilization of such biomass, one must know its physical and chemical properties. This paper presents an analysis of comminuted forest residues from *Pinus sylvestris* L. They were classified into four size fractions for which three density parameters were established pursuant to relevant standards. The mean bulk density of the fractions amounted to 110 to 190 kg/m^3, apparent density 725 to 908 kg/m^3, and specific density 1111 to 1350 kg/m^3. The findings were compared to the results of previous research on other forms of forest biomass. The measured apparent-to-specific density conversion coefficient was β = 0.64. The elementary composition of forest residues measured in this work differed from that of other biomass types described in literature. In terms of carbon, nitrogen, sulfur, oxygen, and ash content, statistical analysis showed that the two compared types of biomass (forest residues and energy wood chips) formed two separate homogeneous groups, while both of these materials constituted one homogeneous group in the case of hydrogen content. The calorific value of the forest residues was 15.78 ± 0.39 MJ/kg.

Keywords: Forest residues; Density; Chemical composition

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INTRODUCTION

Recent years have seen an increased demand for biomass used for the production of a variety of liquid and gaseous fuels, improved solid fuels, such as pellets and briquettes, and for direct combustion (Rosendahl 2013; Ociepa-Kubicka 2015; Uliasz-Bocheńczyk and Mokrzycki 2015). This is directly linked to climate change and the effects of acid rain, which motivate scientists to seek and develop new methods of heat and electricity production (Ghaly and Mansaray 1999; Jabłoński and Stempski 2015; Ociepa-Kubicka 2015). According to Cardoso *et al.* (2011), approximately 14% of the total demand for energy worldwide is covered by biomass. In turn, the International Energy Agency (2017) reports that biomass accounts for 10.3% of the world's energy production.

Forest residues and other logging byproducts do not seem to be utilized to their full capacity. For sanitary and fire protection reasons, these types of biomass must not be left in forest areas and must be removed before forest regeneration work can begin. Unfortunately, this practice also leads to the removal of mineral substances, which would otherwise enrich the soil and enhance tree growth in the future. According to Gornowicz *et al.* (2015), the removal of forest residues from 1 ha entails, on average, a loss of 125 kg of nitrogen, 19 kg of phosphorus, 45 kg of potassium, 75 kg of calcium, and 9 kg of magnesium. On the other hand, it should be remembered that over dozens of years of tree stand growth has enriched the soil by other kinds of dead plant matter.

The studied kind of biomass is variously termed in the literature as forest residues, logging residues, or forest harvesting residues. A characteristic feature of such material is its inhomogeneity. In addition to "pure" wood, it contains considerable amounts of bark, conifer needles, and non-lignified shoots (Gendek *et al.* 2018a). Forest residues are generated during the harvesting of timber, as well as during forest tending treatments such as cleanings and thinnings (Moskalik *et al.* 2013, 2016). While preparing a forest stand for regeneration, lying branches and tree tops should be removed and stored either on the cleared forest area or at the roadside for further processing (*e.g.*, chipping). They may also be comminuted and mixed with the topsoil using specialized mulching equipment.

The processing of forest residues and their utilization for energy purposes has been pioneered by the Scandinavian countries (Hakkila and Parikka 2002), where the most widely used technologies are terrain and roadside chipping (Stampfer and Kanzian 2006; Yoshioka *et al.* 2006; Eker 2011; Röser *et al.* 2012). Similar technologies are used in Polish forests; however, in Poland, forest residues are also sometimes compressed into bundles, which are subsequently comminuted at power plants (Moskalik *et al.* 2013; Gendek and Nurek 2016; Moskalik *et al.* 2016).

In the literature there are numerous reports concerning biomass of various origins that is produced for energy (*i.e.* "energy biomass") (Aniszewska *et al.* 2018), its parameters, chemical composition, processing (Väisänen 2016), including processing into improved solid fuels (Gendek *et al.* 2018b), and supply chain optimization (Dessbesell *et al.* 2016). Miranda *et al.* (2009) has determined the chemical composition and gross calorific value of pellets made of residues from Pyrenean oak. There are also reports concerning other kinds of biomass (Werther *et al.* 2000; Phanphanich and Mani 2011; Malat'ak *et al.* 2018). However, the physical and chemical properties of forest residues from the most popular species in Poland and Europe (Scots pine and Norway spruce) have not been elucidated to date.

In considering the use of forest residues, one needs to take into account their natural composition, which is inhomogeneous. Such material consists of different forms of biomass, including branches, treetops, and bole fragments containing not only wood, but also bark, large amounts of conifer needles, and mineral contaminants (Gendek and Zychowicz 2015). Therefore, it is necessary to elucidate the chemical and physical properties of forest residues as a potential energy feedstock or raw material for the production of improved fuels.

A review of the available literature shows that while energy biomass has been extensively studied in terms of its physical (bulk density, moisture content, and particle size), chemical (carbon (C), hydrogen (H), nitrogen (N), and sulfur (S), oxygen (O), and ash content), and energetic (net and gross calorific value) properties, most papers either deal with only a limited range of those parameters or with biomass of types other than forest residues.

The bulk density of forest wood chips ranges from approximately 110 kg/m^3 to 340 kg/m^3, depending on their moisture content, composition, and origin (Ragland *et al.* 1991; Gigler *et al.* 2000; Jensen *et al.* 2006; Phanphanich and Mani 2009; Sultana and Kumar 2011; Gendek *et al.* 2018). Of great importance to bulk density is the size and orientation of particles. The size distribution of particles is crucial (Asikainen and Pulkkinen 1998), as it influences effective combustion (Hartmann *et al.* 2006) and storage properties, affecting the calorific value and durability of the material. The size distribution of wood chips depends on the type and size of the chipper (Spinelli *et al.* 2005), tree species (Nati *et al.* 2010; Gendek and Zychowicz 2015), part of the tree (stem or branches), as well as knife wear and mounting (Friedl *et al.* 2005). According to Barontini *et al.* (2014) and Gendek and Nawrocka (2014), knife wear and sharpening angle have an effect on particle size variation and distribution. Chipping with a blunt knife leads to smaller chips and a greater proportion of finer particles. While it is the operator who decides on knife replacement, according to Facello *et al.* (2013) one should avoid a situation in which the knives can no longer produce chips of satisfactory quality.

Oxygen, CHNS, and ash content have been extensively studied in various types of biomass, including many tree species and wood wastes (Friedl *et al.* 2005; Munalula and Meincken 2009; Reva *et al.* 2012), as well as different tree parts (Zhao *et al.* 2014; Wielgosiński *et al.* 2017) found in forest wood chips (Chandrasekaran *et al.* 2012; Sulaiman *et al.* 2017), such as wood, stumps, roots (Uri *et al.* 2015), bark, conifer needles and cones (Brebu *et al.* 2010), and seeds (Aniszewska *et al.* 2017).

The objective of the present study is to determine the physical properties and chemical composition of comminuted forest residues in the aggregate, as a mixture of different parts of trees and types of plant tissue (wood, bark, conifer needles) and mineral matter. The authors' findings were compared with physical and chemical data for other types of biomass. To the best of the authors' knowledge, no other work to date has provided such a comprehensive characterization of forest residues. Research results may be the basis for the choice of method for forest residues management. Physical and chemical properties of the residues have an impact on the possibilities and parameters of pressure agglomeration of biomass, as well as on the parameters of the combustion process, which will be the subject of further research. The innovation and originality of this research result from the absence of characteristics of this type of biomass in literature. The obtained results will enable the management of forest residues – by facilitating decisions on whether to leave the comminuted residues on the forest floor or use them as a source of energy.

EXPERIMENTAL

Materials

Material consisted of forest residues generated in the process of timber harvesting from an 80-year-old Scots pine (*Pinus sylvestris* L.) stand on a lowland mesic dystrophic site (Chojnów Forest District, Żabieniec, Poland). Twenty 2 × 2 m sampling plots were established on the area from which forest residues were to be removed (GPS coordinates of the center of that area are WGS84: 52.0492 N; 21.0563 E). The forest residues collected from the sampling plots were comminuted using a hammer mill that produced wood chips less than 16 mm in size. This size was selected due to the fact that one of the prospective objectives of the study was to examine the process of briquetting the analyzed biomass in a 45-mm chamber. Prior to physical and chemical testing, the material was homogenized by mixing wood chips obtained from all the sampling plots.

Methods

The comminuted biomass was fractionated for 180 s in a screen classifier (Lisowski *et al.* 2008a,b) according to the procedure described by Rynkiewicz and Śnieg (2015), with the four fractions (size classes) being 0 mm to 1 mm (f_1), 1 mm to 4 mm (f_2), 4 mm to 8 mm (f_3), and 8 mm to 16 mm (f_4).

The moisture content of the studied material was determined by weight loss on drying. The weight of samples was measured with an accuracy of 0.01 g on a WSP 600/C laboratory balance (Radwag, Radom, Poland). Sample drying was conducted in accordance with the standard ISO 18134-3: 2015 in a Top+ SLW 115 laboratory oven (Pol-Eko-Aparatura, Wodzisław Śląski, Poland) at 105±1 °C until constant weight.

The bulk density of the comminuted pine forest residues was determined pursuant to the standard PN-EN 15103:2010E (2010), using a measuring container described therein. Bulk density was defined as the quotient of biomass weight (difference between the weights of empty and filled measuring containers) and its volume (including the volume of air inside particle pores and between particles).

Apparent density was calculated using a modified measuring container from the standard PN-EN 15103:2010E (2010) and chemically pure water, based on Eq. 1,

$$\rho_{\mathrm{a}} = \frac{m_2 - m_1}{V_{\mathrm{c}} - V_{\mathrm{w}}} \tag{1}$$

where ρ_a is apparent density (kg/m^3), V_w is the volume of water added to the measuring container filled with wood chips (m^3), V_c is the volume of the measuring container (m^3), m_1 is the weight of the measuring container (kg), and m_2 is the weight of the measuring container filled with wood chips (kg).

Material swelling or shrinking was not taken into account during measurement because, according to the literature (Hartmann *et al.* 2004), it amounted to 0.7%. Because the test lasted for a short time, water absorption by the wood chips was not taken into consideration either.

The specific density (ρ_s) of comminuted forest residues was determined using a helium pycnometer (Ultrapycnometer 1200e with an accuracy of 0.03%) (Quantachrome Instruments, Boynton Beach, USA) according to the methodology described by Lisowski *et al.* (2011) and Aniszewska and Gendek (2016).

The apparent-to-specific density conversion coefficient β, was calculated from the two values defined above, according to Eq. 2, which is shown below.

$$\beta = \frac{\rho_{\mathrm{a}}}{\rho_{\mathrm{s}}} \tag{2}$$

Specific and apparent density was determined for unfractionated biomass and for all four wood chip fractions individually. Bulk density was determined for each wood chip fraction. The moisture content of the material was approx. 15%.

Comparative chemical analysis encompassed energy wood chips. Carbon, hydrogen, nitrogen, and sulfur content were determined using an Elementar Vario Macro apparatus (Elementar Americas Inc., Ronkonkoma, USA) pursuant to the protocol given by Sadhukhan *et al.* (2009). Dried samples with a weight of 200 mg were prepared according to the requirements of the apparatus. Following determination of elemental carbon, hydrogen, sulfur, and nitrogen content, the samples were incinerated to measure the relative proportions of ash and oxygen. The latter was determined by subtracting the content of the other chemical elements and ash from the material analyzed.

The percentage shares of the chemical elements and ash represent the mean values obtained from the measurements on a dry basis (db).

The chemical composition results for the forest residues were compared with energy wood chips, which were collected from a container ready to be shipped to a power plant.

Ash content was determined by slow incineration in a muffle furnace at 815 °C ± 10 °C, according to the ISO standard ISO 1928 (2009). Samples with a weight of 2 g were weighed with an accuracy of 0.0001 g.

Gross calorific value measurement of fractions of chipped forest residues was conducted according to the standard PN-ISO 1928 (2009) using a KL-11 Mikado calorimeter (Precyzja-Bit, Bydgoszcz, Poland). Distilled water at 20 °C was used and the mass of a single sample was 1 g, weighed on a WPS 210S laboratory balance (Radwag, Radom, Poland) with an accuracy of 0.0001 g.

While there are many models for calculating calorific value (Zhu and Zhuang 2012), the present study employed the widely used formula specified in an international ISO standard. On the basis of obtained gross calorific value results, the net calorific value (Q_{net}) was determined using Eq. 3, according to ISO 1928 (2009),

$$Q_{\mathrm{net}} = \left(Q_{\mathrm{gross}} - 206 \cdot H\right) \cdot (1 - 0.01 \cdot RH) - 23.0 \cdot RH \tag{3}$$

where Q_{gross} is gross calorific value (kJ/kg), RH is relative humidity (%), and H is hydrogen content (%). Statistical analyses were performed using Statistica software (Dell Inc., v. 13, Landolock, TX, USA) at a significance level of $\alpha = 0.05$. The obtained results were analyzed statistically, and analysis of variance (ANOVA) was performed to determine the significance of the tested parameter.

RESULTS AND DISCUSSION

The applied hammer mill produced wood chips with a maximum size of less than 16 mm. According to the adopted methodology, the material was separated into four fractions (0 mm to 1 mm, 1 mm to 4 mm, 4 mm to 8 mm, and 8 mm to 16 mm), which were weighed (m_{fi}) to determine their mean percentage shares (α_{fi}). The results are given in Table 1.

Gendek and Nawrocka (2014) have reported that forest residues comminuted using a Bruks 805CT chipper had a mean geometric size of 10.8 mm to 14.4 mm for blunt knives and 15.3 mm to 17.3 mm for sharp knives. The maximum size of the obtained wood chips was 63 mm, with the largest share in the 6 mm to 23 mm fraction. In turn, Spinelli *et al.* (2005), who examined nine types of wood chippers, obtained a mean geometric particle size of 14 mm to 30 mm, with the most abundant fractions being 3 mm to 16 mm and 16 mm to 45 mm. These results are consistent with the studies of Barontini *et al.* (2014) and Nati *et al.* (2010), who reported the largest relative proportions of wood chips in the size classes of 3 mm to 8 mm, 8 mm to 16 mm, and 16 mm to 45 mm.

As shown in Table 1, the relative proportions of the finest f_1 (0 mm to 1 mm) and coarsest f_4 (8 mm to 16 mm) fractions were the lowest (at 6.32% and 25.02%, respectively). The largest mean percentage share by weight (36.1%) was found for f_3 (4 mm to 8 mm). This was consistent with the reports of other authors (Spinelli *et al.* 2005; Nati *et al.* 2010; Barontini *et al.* 2014; Gendek and Nawrocka 2014). However, one should take into account the type and size of the applied hammer mill and the maximum size of material that can be fed. It was noteworthy that almost 70% of the wood chips ranged from 1 mm to 8 mm.

The size and fraction structure of wood chips make it possible to produce briquettes with a diameter of >40 mm in further studies. In addition, the fraction structure may be modified with a view to optimizing the quality of the fuel.

Table 1. Mean Percentage (± SD) Shares of the Various Fractions in Forest Residue Samples

Fraction Size (mm)	**Mean Percentage Share (%)**	**Minimum (%)**	**Maximum (%)**
f_1 (0 to 1)	6.32 (± 1.01)	5.21	7.14
f_2 (1 to 4)	32.52 (± 2.28)	31.11	35.15
f_3 (4 to 8)	36.14 (± 4.98)	30.42	39.49
f_4 (8 to 16)	25.02 (± 1.99)	23.57	27.29
SD – standard deviation			

Biomass density measurements for the four fractions and unfractionated wood chips are given in Table 2. The mean apparent density of the unfractionated comminuted pine forest residues measured with water was 787.3 kg/m^3, while the specific density obtained using a helium pycnometer model Ultrapycnometer 1200e (Quantachrome Instruments, Boynton Beach, FL, USA) was 1234.0 kg/m^3. In turn, specific density for the various fractions ranged from 1111 to 1350 kg/m^3 and apparent density from 725 to 908 kg/m^3.

Table 2. Mean (± SD) Density of Comminuted Pine Forest Residues and the Apparent-to-Specific Density Conversion Coefficient (β)

Fraction (mm)	**Mean Specific Density (ρ_s) (kg/m^3)**	**Mean Apparent Density Measured with Water (ρ_a) (kg/m^3)**	**Conversion Coefficient (β) for Fractions**	**Mean Value**
Unfractionated Biomass	1234.05$^{a)}$ (± 23.20)	787.30$^{a)}$ (± 127.32)	0.64	0.62 (± 0.05)
f_1 (0 to 1)	1350.81$^{b)}$ (± 5.04)	908.97$^{b)}$ (± 36.62)	0.67	
f_2 (1 to 4)	1287.53$^{c)}$ (± 2.95)	774.89$^{a)}$ (± 67.85)	0.60	
f_3 (4 to 8)	1111.88$^{d)}$ (± 17.66)	725.75$^{a)}$ (± 132.70)	0.65	
f_4 (8 to 16)	1282.73$^{c)}$ (± 4.74)	699.58$^{a)}$ (± 121.87)	0.55	
SD – standard deviation; a, b, c, d – homogeneous groups for individual fractions				

Statistical analysis (ANOVA, $p<0.05$) showed that the densities obtained by the two methods applied were significantly different, with an average absolute difference of 474.3 kg/m^3. Similar differences were found for each of the designated fractions. In the measurements with water, apparent density decreased with fraction size, while in pycnometric measurements the lowest specific density was found for the 4 mm to 8 mm fraction. The individual fractions and unfractionated material were also assigned to homogeneous groups. Four such groups were found for specific density, with fractions f_2 (1 mm to 4 mm) and f_4 (8 mm to 16 mm) being classified in the same group. Apparent density measurements revealed two homogeneous groups, with the fraction f_1 (0 mm to 1 mm) forming a group of its own. This meant that there were no significant differences between the other three fractions and unfractionated biomass.

An analysis of the data given in Table 2 showed that differences between the specific and apparent density measurements of unfractionated wood chips and the four fractions were of similar magnitude. As shown in Fig. 1, both types of density measurements for the various fractions and unfractionated material followed a similar trend. The conversion coefficient ranged from 0.55 for fraction f_4 (8 mm to 16 mm) to 0.67 for fraction f_1 (0 mm to 1 mm), with that for unfractionated biomass being 0.64. These results indicate that it is possible to determine specific density on the basis of tests performed using water for preliminary measurements, while the coefficient defined in this paper allows for correcting the results of the "water" method.

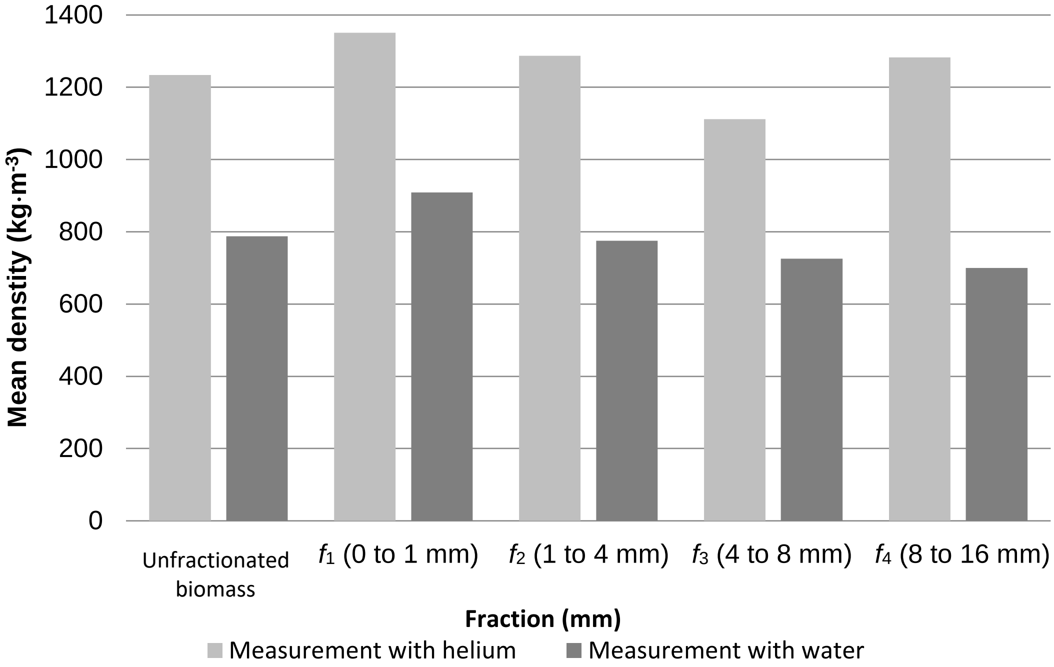

Fig. 1. Wood chip density obtained by different methods

The measured mean bulk density for the various fractions was as follows: 190 kg/m^3 for f_1 (0 mm to 1 mm), 170 kg/m^3 for f_2 (1 mm to 4 mm), 120 kg/m^3 for f_3 (4 mm to 8 mm), and 110 kg/m^3 for f_4 (8 mm to 16 mm).

The chemical composition of the studied biomass is given in Table 3. Energy wood chips were also tested according to the adopted methodology.

Table 3. Percentage Shares (± SD) of Chemical Elements and Ash in the Studied Forest Residues and Energy Wood Chips (db)

Material	**C**	**H**	**N**	**S**	**O**	**Ash**
	(%)					
Forest residues	50.84$^{a)}$ (± 0.07)	5.72$^{a)}$ (± 0.16)	0.66$^{a)}$ (± 0.06)	0.25$^{a)}$ (± 0.13)	41.46$^{a)}$ (± 0.07)	1.07$^{a)}$ (± 0.09)
Energy wood chips	49.95$^{b)}$ (± 0.08)	5.76$^{a)}$ (± 0.05)	0.27$^{b)}$ (± 0.02)	0.12$^{b)}$ (± 0.01)	41.99$^{b)}$ (± 0.05)	1.91$^{b)}$ (± 0.11)
SD – standard deviation; a, b – homogeneous groups for individual chemical elements						

The analyzed forms of raw material were characterized by remarkable differences in chemical compounds, which could be explained by the place of obtaining individual samples, as well as different compositions of the examined matter. The forest residues contained a large number of needles and a small number of branches and bark (non-lignified). For tests, they were manually collected directly from the forest surface onto the transport means. This noticeably reduced biomass contamination with the mineral fraction. The energy wood chips, in addition to pure wood, also contained various types of contamination, but in a much smaller amount than logging residues. They were characterized by high shares of mineral compounds. This was related to the technology of obtaining them, given that the residues were taken from the ground with a hydraulic crane grab, loaded onto the forest tractor, and then moved from the stack prepared for chipping to the wood chipper chute, also with a crane. During both operations, a large amount of soil and sand was collected along with the biomass.

According to the results of the tests conducted, the carbon content in the chipped logging residues was 50.8%. Thus, ANOVA indicated major differences between the studied biomass types, and the Duncan test was used to assign the materials to homogeneous groups. Each of the materials formed a separate homogeneous group, which confirmed considerable differences in carbon content between the tested materials. The significance level ($p < 0.0001$) for carbon content was much lower than the empirical statistic $F_{(1, 7)} = 310.99$.

The percentage share of hydrogen in the chemical structure of the analyzed materials was much lower (approximately 6%). Its content was within the upper limit given by Friedl *et al.* (2005) for wood and wood wastes (5.7% to 6%) and at the same time within the lower limits reported by Munalula and Meincken (2009) as well as Reva *et al.* (2012) (6.0% to 6.9%). It was slightly higher than the hydrogen content in conifer seeds (5.6% to 5.8%) determined by Aniszewska *et al.* (2017) or that in pine cones (5.56%) studied by Brebu *et al.* (2010) (it should be noted that cones are part of forest residues).

Statistical analysis revealed that the observed differences in oxygen content between the various biomass types were not significant at $p = 0.6595$, which was higher than the statistic $F_{(1, 7)} = 0.21$. This meant that all the materials belonged to one homogeneous group.

The percentage shares of nitrogen and sulfur in the structure of the analyzed material might have been influenced by silvicultural practices, site conditions, soil quality, and other environmental parameters.

According to the available literature (Friedl *et al.* 2005; Munalula and Meincken 2009; Reva *et al.* 2012), nitrogen and sulfur content in the wood and wood wastes ranges from 0.07% to 3.02% and from 0.0% to 0.22%, respectively. Similarly, Brebu *et al.* (2010) have reported the percentage share of nitrogen and sulfur in pine cones at 0.8% and 0.05%, respectively. Aniszewska *et al.* (2017), who studied the elemental composition of conifer seeds, found that they contain 0.6% to 2.6% of nitrogen and 0.2% to 0.3% of sulfur. In the forest residues examined herein, nitrogen and sulfur content was 0.66% and 0.25%, respectively, which was consistent with the literature data. However, those values deviated from those reported for other types of biomass, such as pine cones or conifer seeds (it should be noted that forest residues consist mostly of wood, bark, and needles, along with small amounts of cones and seeds).

All the types of biomass considered in this paper revealed low levels of sulfur and nitrogen, which indicated good environmental properties of those materials. Statistical analysis revealed that the significance level for nitrogen was very low ($p < 0.0001$) compared to the empirical statistic $F_{(1, 7)} = 215.10$, while that level for sulfur was $p = 0.0455$ compared to the empirical statistic $F_{(1, 7)} = 5.90$. Because the calculated significance levels for nitrogen and sulfur content in the various materials were less than 0.05, the Duncan test was performed to determine the homogeneous groups (Table 3).

In the case of ash content, statistical analysis revealed significant differences between the various biomass types, with $p < 0.0001$ and $F_{(1,7)} = 158.42$. Due to the obtained differences for the materials, further statistical analysis was conducted and two distinct homogeneous groups were determined (Table 3). According to Friedl *et al.* (2005), ash content in wood and wood waste amounts to 2.9% and 1.5%, respectively, while Font *et al.* (2009) found 4.5% and 0.8% of ash in pine needles and cones, respectively. Munalula and Meincken (2009) have reported that the ash content in several tree species ranges from 0.34% to 2.79%. The ash content found in the present study (1.07%) differed from the literature data for pine needles and cones, but remained within the cited range for wood and wood wastes.

The relatively low ash content in the examined forest residues was probably attributable to the high percentage share of bark and non-lignified shoots. As shown in Table 3, the differences in ash content between the two studied types of biomass were statistically significant, with the highest value found for energy wood chips (1.91%). This fact might have been due to the high degree of biomass contamination during storage in forest areas, transportation, and comminution. These results are consistent with the findings of Gendek *et al.* (2018b), who reported that mean ash content (1.4–5.9%) depends on the composition of forest residues and on the impurities that they contain. It should be noted that the studied forest residues fall within the maximum ash content threshold allowed by Polish energy companies for this kind of fuel, which is 5% (Gendek and Nurek 2016).

The percentage share of ash in the examined forest residues was consistent with the data for Scots pine (*Pinus sylvestris*) and Norway spruce (*Picea abies*) branches (Moriana *et al.* 2016). The results for energy chips did not correspond to any literature values. It should be remembered that the analyzed materials were collected from different locations and tree stands, and so the identified differences were difficult to explain.

The mean oxygen content (41.46%) was calculated by subtracting the percentage shares of the other chemical elements and ash. For all of the studied types of biomass, oxygen content was slightly lower that that reported for spruce wood (43.6% to 45.6% (Bach *et al.* 2016) and 43.2% (Kajda-Szcześniak 2013)). The percentage share of oxygen found herein for the forest residues was within the range reported for wood and wood wastes by Friedl *et al.* (2005) (41.0% to 41.9%) and Munalula and Meincken (2009) (39.7% to 41.8%), but at the same time it was higher than the values given by Font *et al.* (2009) for pine cones (38.7%) and needles (37.9%). Statistical analysis revealed significant differences in oxygen content between the various types of materials, which were classified into distinct homogeneous groups (Table 3). Oxygen was the second most abundant element in the studied samples.

The significance level for oxygen content was very low ($p < 0.0001$) with the empirical statistic amounting to $F_{(1,7)} = 186.19$, which indicated significant differences between the compared types of biomass. The results of gross and net calorific values of chipped logging residues are presented in Table 4.

Table 4. Gross and Net Calorific Values of Logging (Unfractionated Biomass)

Parameters	Mean (± SD)	Minimum	Maximum
	(MJ/kg)		
Gross calorific value	18.75 (± 0.43)	18.22	19.34
Net calorific value	15.78 (± 0.39)	15.30	16.32

As reported by Stolarski *et al.* (2007), the net calorific value of wood materials ranges from 19.12 MJ/kg to 20.08 MJ/kg, while the tested logging residues are characterized by a lower net calorific value (15.78 MJ/kg), which is affected by the biomass composition. The value obtained in the present study is similar to that reported by Barontini *et al*. (2014) for comminuted wood after a period of storage (approximately 16 MJ/kg). Ingredients, such as pine needles, bark, and minerals, reduce the net calorific value. According to Zhao *et al.* (2014), calorific value varies among stem wood, bark, branch, and foliage components, ranging from 18.9 to 20.6 MJ/kg. In turn, the study of Gendek *et al.* (2018b) shows that the calorific value of wood chips is affected not only by their composition, but also by harvesting technology and the presence of impurities. Nevertheless, the obtained results indicate the possibility of using logging residues as a solid fuel. It should also be remembered that this biomass could be further aggregated to obtain more favorable energy parameters.

CONCLUSIONS

1. Density measurement of comminuted forest residues with water may be deemed a good and economical preliminary method, for it does not require a specialized apparatus. The conversion coefficient defined and determined in this study makes it possible to estimate the specific density of wood chips.
2. The composition of the studied wood chips was compared with data for other types of biomass and considerable differences were identified. Those differences are attributable to the inhomogeneity of the studied wood chips, which contained a substantial amount of conifer needles, bark, and mineral matter.
3. The studied material is characterized by lower net and gross calorific values (15.78 MJ/kg and 18.75 MJ/kg, respectively) as compared to other wood materials.
4. The results of the present study indicate that it is advisable to collect forest residues for energy purposes. Irrespective of the logging technique applied, considerable amounts of forest residues remain on cleared forest areas. In addition to wood, those residues contain a substantial proportion of bark, conifer needles, and mineral matter. The present findings show that forest residues may be used as a source of thermal energy due to a high content of carbon and a low content of nitrogen and sulfur. However, given the low density of the studied material both before and after comminution, pressure aggregation of wood chips should be considered as an option.

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