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Analysis of Selected Physical Properties of Conifer Cones with Relevance to Energy Production Efficiency

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Abstract: The paper presents gross and net calorific values, ash content, conversion factors, and bulk density for different-sized spent cones of Scots pine *Pinus sylvestris* L., Norway spruce *Picea abies* L., European larch *Larix decidua* Mill., and Silver fir *Abies alba* Mill. harvested from various sites. Gross and net calorific value and bulk density were measured in accordance with the relevant EN and ISO standards. The density conversion factors were determined based on free space measurement by means of water immersion. Gross calorific value for Scots pine, Norway spruce, European larch, and Silver fir was 19.04 ± 0.70 MJ·kg^{-1}, 20.08 ± 0.87 MJ·kg^{-1}, 20.37 ± 0.48 MJ·kg^{-1}, and 20.79 ± 0.61 MJ·kg^{-1}, respectively. The bulk density of larch cones was the highest at 223 kg·m^{-3}, which corresponds to 9%–18% of their specific density. The ANOVA test showed that the bulk density depends on the origin of the cones and is different for individual species. The conversion factors for the cones of Scots pine, Norway spruce, and Silver fir were similar and ranged from 0.18 to 0.26, while those for the European larch were much greater with a maximum of 0.55. All of the studied cones have shown a good potential as energy source, based on their physical characteristic and can be considered as a supplementary fuel. In the future, the study of chemical properties, such as the elemental composition and the ash melting temperature, will allow for a comprehensive characterization of the energy potential of the tested raw material.

Keywords: biomass; conifer cones; calorific value; bulk density; density conversion factor

1. Introduction

In face of the gradual depletion of fossil fuels, new renewable energy sources are sought, including medium- and small-diameter trees or branches and tops, which is mostly processed into pellets and chips to be burned in boiler stations or cogeneration plants [1–3]. The use of logging residues for energy purposes was pioneered in the Scandinavian countries [4], with the most popular technology being on-site or roadside wood chipping [5–8]. Further sources of forest biomass are sought; for example, forest undergrowth is harvested and processed into pellets [9]. An additional factor favoring various types of forest residue biomass for heat and electricity production is the opportunity to offset greenhouse gas emissions, which could make biomass use more economically viable [10].

Another interesting forest biomass alternative for both small- and large-scale consumers is offered by spent cones which are waste products of seed extraction facilities. Currently, there are 16 such facilities in Poland, including some dating to before the Second World War, some modernized ones, and some employing state-of-the art Swedish technologies [11,12].

Obviously, the seed extraction technologies largely affect the way in which the spent cones may be used. In some of the older facilities, cones are fed into boilers heating the extraction chambers or cabinets, while in modern electricity-powered facilities cones are treated as waste and usually sold in the local market.

Spent cones are a good energy source that may be directly burned in furnaces or boilers, or added to briquettes or pellets [13]. However, due to the relatively low availability of this material, cones may only be only used for heating purposes in the local market [12]. According to Kuszpit [14], in 2009–2012 in Poland an average of 35.8 Mg of cones were processed per seed extraction facility, resulting in approx. 27.0 Mg of spent cones which could be used for combustion purposes [15]. Dry pine cones can also be used as a component of biocomposites [16].

The parameters of cones presented in this publication will be used in the economic analysis of the possibility of offering cones as kindling in retail sales. Currently, people who have easy access to dry cones use them as ecological kindling, avoiding chemical ones.

Cones collected in forests can be an additional source of energy, especially in the case of increasing difficulties in acquiring energy from conventional sources. In Poland, the area of stands with the dominant share of pine is equal to 5 million hectares. Assuming that cones from 0.5 to 1 million hectares would be harvested annually, with an average yield of 1200 kg per hectare, the annual harvest would amount to 0.6 to 1.2 million tons of cones [15,17,18]. It should be remembered that the moisture content of open fallen cones in the summer is 10 to 15 percent, so they are very dry. The collection of cones in forests on a larger scale, can be introduced only in cases of recognition of small impacts on the nutrient and regeneration of stands.

In the literature, there is a considerable lack of information concerning the bulk density, calorific value and ash content of conifer cones in the context of transporting different forms of forest and agricultural biomass (timber, wood chips, branches, pellets, briquettes). A number of studies in this area have made considerable contributions to knowledge about biomass and its parameters [19–26]. In Poland, biomass parameters and processing has been studied by, amongst others, Frączek et al. [27], Gendek et al. [28], Konieczny [29], Niedziółka and Szpryngiel [30], Stolarski et al. [31], Tomczak et al. [32], Witkowska and Lachowicz [33], as well as Wojtan et al. [34]. Data are also available on density conversion factors, which serve as measures of material quality.

However, the available literature does not provide information on the physical properties of conifer cones which are critical to energetic and logistic evaluation of a material characterized by low weight and high volume. Therefore, the present study set out to determine the calorific values, ash content, bulk density, and conversion factors for cones of four tree species (Scots pine, Norway spruce, European larch, and Silver fir) harvested from different sites. The conversion factor may be of great importance in the case of settlements in the course of trade (as in the case of wood), due to the high variability of the moisture content of the cones.

2. Materials and Methods

2.1. Origin of Cones

The study material consisted of spent cones of Scots pine (*Pinus sylvestris* L.), Norway spruce (*Picea abies* L.), and European larch (*Larix decidua* Mill.), as well as Silver fir scales and rachises (*Abies alba* Mill.). The cones were obtained from seed extraction facilities in Czarna Białostocka (State Forests Regional Directorate in Białystok) and Grotniki (State Forests Regional Directorate in Łódź). Table 1 provides some basic information concerning the origin of the studied cones.

Pursuant to the Act on Forest Reproductive Material of 7 September 2001 [35], basic forest material (BFM) is understood as stock for the production of reproductive forest material (RFM—conifer cones, fruits, seeds, and plant parts for the production of planting stock). BFM includes seed source, tree stand, seed orchard, parent of family, and clone or clonal mixture. A tree stand is defined as a group of trees with similar morphological traits which grow in close proximity and influence one another. A seed orchard is a group of selected clones or families managed or isolated in such a way as to prevent pollination from external sources while providing an abundance of easily extractible seeds. RFM is material from identified sources, which is selected, qualified, and tested.

Table 1. Cone harvest sites—register number, basic forest material (BFM) category, reproductive forest material (RFM) category, and administrative forest district.

Species	Register Number	BFM Category	RFM Category	Forest District	GPS
Scots pine	MP/1/1694/05	Tree stand	From an identified source	Szczebra	53°55′ N, 22°57′ E
	MP/1/520/05	Tree stand	From an identified source	Czarna Białostocka	53°28′ N, 23°19′ E
	MP/1/647/05	Tree stand	From an identified source	Dojlidy	53°08′ N, 23°21′ E
	MP/2/31001/05	Tree stand	Selected	Płaska	53°57′ N, 23°15′ E
Norway spruce	MP/1/1817/05	Tree stand	From an identified source	Żednia	53°09′ N, 23°26′ E
	MP/1/46930/06	Tree stand	From an identified source	Głęboki Bród	53°58′ N, 23°12′ E
	MP/3/41002/05	Seed orchard	Classified	Bielsk(1)	52°41′ N, 23°06′ E
	MP/1/46911/06	Tree stand	From an identified source	Płaska(1)	53°00′ N, 23°14′ E
	MP/1/1894/05	Tree stand	From an identified source	Waliły	53°09′ N, 23°37′ E
European larch	MP/3/41001/05	Seed orchard	Qualified	Bielsk	52°41′ N, 23°06′ E
	MP/2/30988/05	Tree stand	Selected	Maskulińskie	53°39′ N, 21°32′ E
Silver fir	MP/1/8022/05	Tree stand	From an identified source	Poddębice	51°41′ N, 18°53′ E

2.2. Variability of Research Material

To characterize the studied material and its variability, the following parameters were measured: weight, length and width (greatest diameter) of 100 randomly selected open cones for each tree species and place of origin. Dimensions were measured using an electronic caliper with an accuracy of ±0.1 mm. Individual cones were weighed using a WPS 210S (RADWAG, Radom, Poland) moisture analyzer with an accuracy of 0.01 g. Gross and net calorific value determinations were performed at the laboratory of the Department of Agricultural and Forestry Machinery in Warsaw. These tests involved Scots pine cones from the Czarna Białostocka Forest District, Norway spruce cones from the Żednia Forest District, European larch cones from the Maskulińskie Forest district, and Silver fir cones from the Poddębice Forest District. The cones were ground to a particle size of less than 1 mm, and then dried in an SLW 115 TOP laboratory dryer (POL-EKO-APARATURA, Wodzisław Śląski, Poland) for 24 h at 103 ± 1 °C to constant weight. Gross calorific value measurements were conducted by the calorimetric method according to the standard ISO 1928:2009 [36].

2.3. Gross and Net Calorific Value

Analytical samples with a mass of 1 g were weighed with an accuracy of 0.0001 g using a WSP 210S (RADWAG, Radom, Poland) scale and burned in a KL 10 calorimeter (PRECYZJA-BIT, Bydgoszcz, Poland). Measurements were done in five or six replicates for each type of material. During the experiments, the temperature and humidity of the laboratory room was monitored and recorded using a Rotronik HygroPalm (Rotronic AG, Basserdorf, Switzerland) temperature and humidity meter with an accuracy of ±0.1 °C and ±0.1%, respectively. The ambient temperature was 22–23 °C and the humidity was 44%–46%.

Net calorific value Q_{net} (kJ·kg^{-1}) was calculated from the formula (ISO 1928:2002) [36]:

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

where: Q_{gross}—gross calorific values, kJ·kg^{-1}; RH—moisture content, %; H—hydrogen content, %.

According to the literature, hydrogen content of different types of biomass ranges from 5.5% to 7.0% [37–40]. The net calorific value of cones was calculated using the percentage content of hydrogen for softwood, which is 6.3% [13].

2.4. Ash Content

Ash content was determined by incineration at 550 °C in an LAC L 09/12 muffle furnace with an Ht 40 AL controller (LAC Ltd., Rajhrad, Czech Republic) pursuant to the standard ISO 18122:2015 [41]. The measurement method, including the thermal program, was described by Martinka et al. [42] and Gendek et al. [43]. For each type of material, 8 samples were prepared and weighed with an accuracy of 0.00001 g using a WPA 40/160/C/1 laboratory balance (RADWAG, Radom, Poland).

Representative samples of shredded cones were collected and prepared for each species, and then they were separated into three parts to measure moisture, ash content and colorific value.

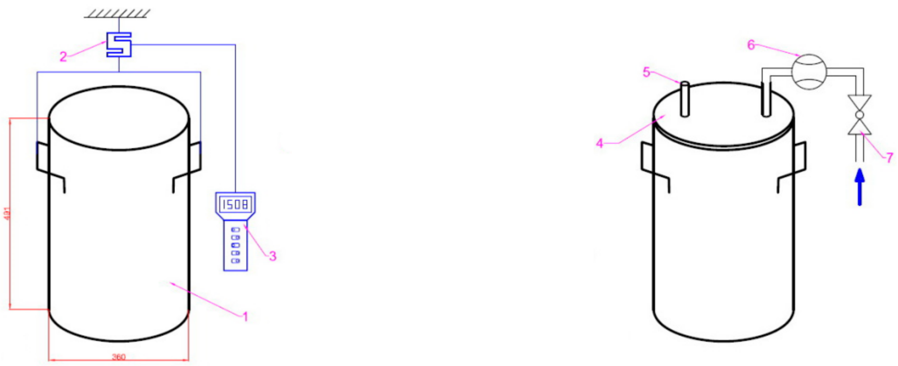
2.5. Bulk Density and Volume Conversion Factor

Bulk volume measurements, which served as a basis for determining conversion factors, were conducted at the seed extraction facilities in the Czarna Białostocka and Grotniki Forest Districts in December and January in the 2015/2016 extraction season. Extraction of seeds from cones of Scots pine, Norway spruce, and European larch was conducted at 40–65 °C for 16–54 h, depending on technology, until their full opening. In turn, Silver fir cones opened without any special treatment due to their morphological structure. Following seed extraction, the spent cones (rachises and scales in the case of Silver fir) were stored in well-ventilated areas.

The bulk density and conversion factors of Scots pine, Norway spruce, and European larch cones were determined in the Czarna Białostocka cone extraction facility, while the corresponding parameters for Silver fir were investigated in the Grotniki facility. Depending on the origin of the cones, experiments were done in five or six replicates.

Bulk density was determined pursuant to the PN-EN ISO 17828:2015 [44] procedure for bulk fuels with particle size larger than 12 mm, using a 0.05 m^3 measuring container consistent with the standard specifications. The measurement setup is presented in Figure 1a. Cones of the various conifer species were poured into the container from a height of 250 mm to obtain a geometric cone of maximum possible height above its upper rim. In order to compact and settle the material, the container was freely dropped twice from a height of 150 mm onto an even and rigid surface. Excess cones were removed with a strip of wood.

An empty, and then filled, container, was hung on a load cell integrated with a dynamometer with a measurement range of up to 1000 N and an accuracy of 0.1 N. The results were converted into kilograms by the internal calculator of the device.



(**a**) (**b**)

Figure 1. Scheme of the measurement setups: (**a**) for bulk density, (**b**) for the conversion factor: 1—measuring container, 2—load cell, 3—recorder, 4—lid, 5—air escape, 6—electronic flow meter, 7—valve.

The obtained data were used to calculate volume density as received (BD_{ar}), which was subsequently converted into bulk density dry weight (BD_d) according to the PN-EN ISO 17828:2015 [44] equations:

$$BD_{ar} = \frac{m_2 - m_1}{V} \quad (2)$$

$$BD_d = BD_{ar} \cdot \frac{(100 - M_{ar})}{100} \quad (3)$$

where: M_{ar}—moisture content, %; V—container volume, m^3; m_1—empty container weight, kg; m_2—filled container weight, kg.

After weighing the container (1) filled with cones, it was sealed with a lid (4) equipped with a liquid inlet with an air escape (5). Liquid flow was measured using an electronic meter (6) with an accuracy of 0.1 L. A stopwatch was used to measure the time of filling the container with water to the nearest second. The experimental setup is given in Figure 1b.

The conversion factor (K_z) for spent cones was calculated based on the volume of liquid in the measuring container and the volume of the container following the equation:

$$K_z = \frac{V_o - V_w}{V_o} \quad (4)$$

where: V_o—overall volume of the measuring container, m^3; V_w—volume of liquid in the measuring container, m^3.

As the porosity of a material may be determined using many different methods [45], the present authors, similarly to Igathinathane et al. [46] sought a simple and economical procedure that could be readily deployed during field studies. As a result, water was selected as the optimum medium for filling voids.

Cone dimensions, weight, gross and net calorific values, bulk density, and conversion factors were analyzed statistically using Statistica v.13 (Dell Inc., Landolock, TX, USA) software [47]. The Shapiro–Wilk test showed that the data had normal or near-normal distributions. The results were evaluated using variance analysis and Tukey's post-hoc test (RIR) for unequal sample sizes. All analyses were conducted at a significance level of $\alpha = 0.05$.

3. Results and Discussion

The moisture content of spent cones ranged from 8% to 11%, which is consistent with the information reported by Aniszewska [48]. The dimensions of open cones (length, width) and weight for the various tree species and harvesting sites are given in Table 2 (fir cones are not included as they disintegrated in the course of drying).

Table 2. Means, standard deviations, and factors of variation for the dimensions and weight of the studied cones.

Species	Forest District	Mean			Standard Deviation			Factor of Variation		
		Length	Width	Weight	Length	Width	Weight	Length	Width	Weight
		mm		g	mm		g	%		
Norway spruce	Głęboki Bród	118.6	54.5	33.3	13.6	5.1	9.2	11.5	9.3	27.7
	Bielsk(1)	145.9	62.4	52.6	19.5	6.6	14.5	13.4	10.5	27.6
	Płaska(1)	111.1	54.4	28.9	13.3	4.4	7.3	11.9	8.1	25.5
	Waliły	119.4	53.0	31.5	13.1	5.1	7.8	10.9	9.6	24.7
Scots pine	Szczebra	39.0	33.4	5.1	4.5	5.1	1.3	11.6	15.2	26.9
	Czarna Białostocka	41.4	36.3	6.3	5.2	5.9	1.9	12.6	16.1	30.8
	Dojlidy	37.6	31.7	4.8	5.4	5.4	1.6	14.3	17.0	34.1
	Płaska	41.8	35.6	5.9	4.2	4.4	1.5	10	12.3	25.5
European larch	Bielsk	25.8	20.9	1.9	4.6	3.4	0.8	18.0	16.2	41.1
	Maskulińskie	37.6	22.5	3.8	3.9	2.0	0.9	10.4	9.1	23.2

The mean length of the studied pine cones (37.6–41.8 mm) was within the 19–70 mm range reported by Białobok et al. [49]. Also the mean spruce cone length (111.1–145.9 mm) was consistent with the literature data (60–200 mm according to Chmielewski [50] and Białobok [51]). In turn, the mean larch cone length measured by Vîlcan et al. [52] in Romanian tree stands amounted to 25.2–36.9 mm. While the mean length of larch cones from the Bielsk Forest District was within that range (25.8 mm), larch cones from the Maskulińskie Forest District were slightly longer (37.6 mm). No literature data were found for the width of open cones of the studied species.

Analysis of variance revealed statistically significant differences in dimensions and weight between cones from different sites. The analysis of variance ($p < 0.0001$) showed statistically significant differences in the average length, thickness and mass of individual cones for different particular origins of investigated species.

Tukey's test showed significant differences in the mean size and weight of cones belonging to the same species harvested from different sites, but also some homogeneous groups of sites were revealed. The largest spruce cones were from the Bielsk(1) Forest District, and their dimensions and weight differed significantly from those of cones from the Głęboki Bród, Płaska(1), and Waliły Forest Districts ($p < 0.0001$). No significant differences in terms of length were observed between spruce cones from the Głęboki Bród and Płaska Forest Districts ($p = 0.0618$) or between those from the Głęboki Bród and Waliły Forest Districts ($p = 0.9905$). The other differences were statistically significant.

In terms of width and weight, only spruce cones from the Bielsk(1) Forest District were significantly different from cones from other Forest Districts ($p < 0.0001$). Spruce cone width did not differ significantly ($p > 0.3886$) as compared to other sites (Głęboki Bród, Płaska(1), Waliły), and therefore those sites may be considered a homogeneous group. The pairs of sites homogeneous in terms of cone weight were the Waliły and Głęboki Bród Forest Districts ($p = 0.7556$), the Waliły and Płaska(1) Forest Districts ($p = 0.5404$), as well as the Głęboki Bród and Płaska(1) Forest Districts ($p = 0.1132$). Cones from the Bielsk(1) Forest District were much wider than those from other sites probably due to the fact that at this particular site they were harvested from a seed orchard in contrast to the other forest districts, in which cones were collected from timber tree stands.

Homogeneous groups of sites in terms of pine cone length, width, and weight were the Płaska and Czarna Białostocka Forest Districts (length—$p = 0.9575$; width—$p = 0.38065$; weight—$p = 0.2127$) as well as the Dojlidy and Szczebra Forest Districts (length—$p = 0.1661$; width—$p = 0.0916$; weight—$p = 0.6190$), with the other sites being significantly different from each other (length $p < 0.002$; width—$p < 0.0113$;

weight—$p < 0.0025$). The differences and similarities between cone parameters are probably attributable to habitat characteristics, climate conditions, and tree stand age.

Significant differences in length, width, and weight were found for European larch cones from different sites ($p < 0.0001$), but, in contrast to spruce cones, larch cones collected from seed orchards were smaller than those harvested from timber tree stands.

Table 3 gives gross and net calorific values for spent cones of the studied species.

Table 3. Gross and net calorific values for spent cones of the studied tree species (dry bases), in MJ·kg^{-1}.

Species	Gross/Net Calorific Value			Standard Deviation	Factor of Variation
	Mean	Min	Max		
Norway spruce	20.08/18.78	18.49/17.19	21.05/19.75	0.87	4.66
Scots pine	19.04/17.74	17.74/16.44	19.86/18.56	0.70	3.94
European larch	20.37/19.07	19.38/18.08	20.96/19.66	0.48	2.54
Silver fir	20.79/19.49	19.81/18.51	21.85/20.55	0.61	3.14

The gross (19.04–20.79 MJ·kg^{-1}) and net (17.74–19.49 MJ·kg^{-1}) calorific values obtained in the present study are similar to the results reported by other authors for the timber of the various species (16–19 MJ·kg^{-1}). The mean net calorific values for Scots pine cones are consistent with the studies of Aniszewska and Gendek [53] and Gendek [13], that is, 18.11 MJ·kg^{-1} and 18.32 MJ·kg^{-1}, respectively.

The post-hoc test showed that the net calorific value of Scots pine cones differed significantly from that of the other species ($p < 0.004$), which in turn formed a homogeneous group ($p > 0.0795$).

The amount of ash remaining after fuel combustion is an important factor that largely determines the applicability of a given type of fuel. Ashes from the combustion of plant material may prove difficult to utilize especially those ashes that tend to slag [54,55]. Ash content in the studied cones is presented in Table 4.

Table 4. Ash content in cones from the studied tree species (dry bases), in %wt.

Species	Mean	Min	Max	Standard Deviation
Scots pine	0.33	0.29	0.38	0.03
Norway spruce	1.42	1.34	1.56	0.08
European larch	1.55	1.23	2.07	0.27
Silver fir	2.12	1.77	2.50	0.27

Analysis of variance ($F_{(3, 28)} = 341.57$; $p < 0.00$) revealed differences in ash content between the various cone species, which were confirmed to be statistically significant by a post-hoc multiple comparisons test. The lowest ash content was found for pine cones, which may be attributable to the fact that they contain much less resin than the other species.

Ash content in pine cones was similar to the results obtained for pine wood by Filbakk et al. [56], that is, 0.47%, but was much lower than the value found by Gendek et al. [43] for pine wood chips (0.86–3.94). All cone species were within the ash content range of 0.34%–2.79%, which was reported for various species by Munalula and Meicken [57]. In turn, spruce, larch, and fir cones were within the ash content range of 1.5%–2.9% reported for wood and wood waste by Friedl et al. [58]. An important issue regarding the process of burning cones will be further studies on the chemical composition of ashes and potential problems with ash slagging [54,55].

The lowest dry bulk density (110–122 kg·m^{-3}) was found for spruce cones, mostly due to their size, shape, and the fact that they have thin and widely spaced scales, making them bulky. Similar results (127.8 kg·m^{-3}) were obtained for Silver fir scales and rachises (Table 5).

Table 5. Bulk density of the studied conifer cones (dry 8%–11%), in kg·m$^{-3.}$

Species	Site	Mean	Min	Max	Standard Deviation	Factor of Variation
Norway spruce	Żednia	111.40	109.28	114.98	1.93	1.73
	Głęboki Bród	122.02	116.62	125.18	3.96	3.24
	Bielsk(1)	113.72	111.31	117.02	2.32	2.04
	Płaska(1)	109.99	108.87	112.95	1.98	1.80
	Waliły	118.27	113.00	125.00	3.28	2.78
Scots pine	Dojlidy	214.88	204.69	224.26	7.74	3.60
	Szczebra	195.96	190.01	203.47	4.95	2.53
	Czarna Białostocka	189.76	188.38	191.23	1.10	0.58
	Płaska	213.80	206.00	227.00	5.53	2.59
European larch	Maskulińskie	223.87	219.00	230.00	2.97	1.33
	Bielsk	195.77	186.54	204.69	7.43	3.79
Silver fir	Poddębice	127.8	125.00	129.00	1.79	1.40

The bulk density of Scots pine and European larch cones was almost twice as high (189–214 kg·m^{-3} and 195–223 kg·m^{-3}, respectively). The cones of those species are smaller and much more compact, and contain a greater proportion of woody tissue.

Analysis of variance revealed statistically significant differences in bulk density between cones from different harvesting sites with in individual species: pine $F_{(3, 26)} = 34.85$, spruce $F_{(4, 33)} = 18.37$, and larch $F_{(1, 17)} = 146.53$, with $p < 0.05$ in all cases.

A multiple comparison test showed two and three homogeneous groups in terms of bulk density for Scots pine and Norway spruce cones from different harvesting sites, respectively. In the case of Norway spruce, the cones from the Bielsk Forest District ($p = 0.1064$) did not differ significantly as compared to those from the Płaska(1), Waliły, and Żednia Forest Districts; the other homogeneous group consisted of the Waliły and Głęboki Bród Forest Districts ($p = 0.3506$), and the third one contained the Płaska(1) and Żednia ($p = 0.9547$) Forest Districts. The two homogeneous groups for pine cone bulk density consisted of the Płaska and Dojlidy Forest Districts ($p = 0.9890$) and of the Szczebra and Czarna Białostocka Forest Districts ($p = 0.2958$), respectively.

A good point of reference in terms of the bulk density of conifer cones is that of forest energy wood chips. Gendek et al. [25], who measured the bulk density of dry forest wood chips made with a Bruks wood chipper using different blade sharpness, reported figures ranging from 154 to 165 kg·m^{-3}, which is greater than the bulk density of spruce and fir cones, but smaller than that of pine and larch cones.

A comparison of results from the present study with data from other authors shows that the bulk density of pine and larch cones is satisfactory. Ragland et al. [59], who studied similar forest materials, reported the bulk density of wood chips to vary from 160 to 230 kg·m^{-3}, while Kofman [60] obtained 150 to 165 kg·m^{-3} for dry softwood chips.

In the current study, the bulk density of cones amounted to 9%–18% of the specific density of the ground material. European larch cones have the lowest mean specific density (1144.11 kg·m^{-3}), with the highest mean specific density found for Scots pine (1306.48 kg·m^{-3}) [11].

Conversion factors amount to 0.18–0.23 for Norway spruce cones, 0.24–0.27 for Scots pine cones, 0.22 for Silver fir cones, and 0.55 for European larch cones, which makes the last of these species most suitable for transportation purposes (Table 6). Comparing the obtained values to the conversion factors of other forest materials, e.g., wood chips (0.38–0.43) or branches (0.20–0.25), it can be concluded that pine and spruce cones have a coefficient similar to that for loose branches. Larch cones, on the other hand, have a conversion factor greater than for woodchips and similar to the coefficient of split timber in bulk (about 0.50–0.65).

Table 6. Conversion factors for the studied cone species.

Species	Site	Mean	Standard Deviation	Factor of Variation
Norway spruce	Żednia	0.20	0.01	6.99
	Głęboki Bród	0.19	0.01	2.60
	Bielsk(1)	0.18	<0.01	<0.01
	Płaska(1)	0.18	0.01	2.74
	Waliły	0.23	0.02	10.83
Scots pine	Dojlidy	0.27	0.01	3.12
	Szczebra	0.24	0.01	2.24
	Czarna Białostocka	0.24	<0.01	1.85
	Płaska	0.26	0.01	5.12
European larch	Maskulińskie	0.55	0.01	0.94
	Bielsk	0.32	0.01	2.55
Silver fir	Poddębice	0.22	0.02	9.60

Analysis of variance revealed statistically significant differences between conversion factors obtained for different cone harvesting sites within individual species: pine $F_{(3, 26)} = 8.01$, spruce $F_{(4, 33)} = 10.44$, and larch $F_{(1,17)} = 5010.90$; at $p < 0.05$.

A post-hoc test showed that the conversion factor for Scots pine cones from the Szczebra Forest District did not differ from those for the Płaska and Czarna Białostocka Forest Districts ($p > 0.0898$). The other homogeneous group consisted of the Płaska and Dojlidy Forest Districts ($p = 0.7020$). The mean conversion factor was statistically different from all the other cone harvesting sites ($p < 0.0483$).

In the case of Norway spruce, significant differences in mean conversion factors were found between the Bielsk(1) and Waliły ($p = 0.0017$), Płaska(1) and Waliły ($p = 0.0095$), as well as Żednia and Waliły ($p = 0.0334$) Forest Districts; the conversion factors for the remaining harvesting sites were not significantly different ($p > 0.0651$).

The conversion factors were found to be negatively correlated with the cone size (length $R = -0.7421$ and width $R = -0.9019$).

4. Conclusions

The studied spent cones of Scots pine, Norway spruce, and European larch from different sites differ in terms of length, width, and weight, except for Norway spruce cones from the Głęboki Bród and Waliły Forest Districts and Scots Pine cones from the Płaska and Czarna Białostocka Forest districts. A positive correlation was found between the mean width and length of cones and their weight. The coefficient of correlation between the length and the mass of cones was for pine $r = 0.2333$, for spruce $r = 0.6672$, and for larch $r = 0.9070$. In the case of the thickness of cones, the correlation coefficient with the cones mass was equal for pine $r = 0.5949$, for spruce $r = -2537$, and for larch $r = 0.6515$.

Gross calorific values were 19.04 MJ·kg^{-1}, 20.08 MJ·kg^{-1}, 20.37 MJ·kg^{-1}, and 20.79 MJ·kg^{-1} for Scots pine, Norway spruce, European larch, and Silver fir cones, respectively. The lowest dry bulk density (109–129 kg·m^{-3}) was recorded for Norway spruce cones and Silver fir scales and rachises. The bulk density of Scots pine and European larch cones was almost twice as large (188–227 kg·m^{-3} and 187–230 kg·m^{-3}).

The mean conversion factor amounts to 0.18–0.27 for Scots pine and Norway spruce cones, 0.22 for Silver fir scales and rachises, and 0.55 for European larch cones. The larger the cones, the lower the conversion factor.

The presented parameters may be used in the economic analysis of the possibility of offering cones as kindling in retail sales or (rather in the case of a drop in energy availability) as supplementary fuel. In subsequent studies, a chemical analysis of cones and ash, ash melting point and slag tendency should be carried out.

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References

1. Gendek, A.; Nurek, T. Variability of energy woodchips and their economic effects. *Folia For. Pol. Ser. A* **2016**, *58*, 62–71. [CrossRef]
2. Moskalik, T.; Sadowski, J.; Sarzyński, W.; Zastocki, D. Efficiency of slash bundling in mature coniferous stands. *Sci. Res. Essays* **2013**, *8*, 1478–1486.
3. Moskalik, T.; Sadowski, J.; Zastocki, D. Some technological and economic aspects of logging residues bundling. *Sylwan* **2016**, *160*, 31–39.
4. Hakkila, P.; Parikka, M. Fuel resources from the forest. In *Bioenergy from Sustainable Forestry: Guiding Principles and Practice*; Richardson, J., Björheden, R., Hakkila, P., Lowe, A.T., Smith, C.T., Eds.; Kluwer Academic Publishers: Dordrecht, The Netherlands, 2002; pp. 19–48.
5. Stampfer, K.; Kanzian, C. Current state and development possibilities of wood chip supply chains in Austria. *Croat. J. For. Eng.* **2006**, *27*, 135–145.
6. Yoshioka, T.; Aruga, K.; Nitami, T.; Sakai, H.; Kobayashi, H. A case study on the costs and the fuel consumption of harvesting, transporting, and chipping chains for logging residues in Japan. *Biomass Bioenergy* **2006**, *30*, 342–348. [CrossRef]
7. Eker, M. Assessment of procurement systems for unutilized logging residues for Brutian pine forest of Turkey. *Afr. J. Biotechnol.* **2011**, *10*, 2455–2468.
8. Röser, D.; Mola-Yudego, B.; Prinz, R.; Emer, B.; Sikanen, L. Chipping operations and efficiency in different operational environments. *Silva Fenn.* **2012**, *46*, 275–286. [CrossRef]
9. Mustelier, N.L.; Almeida, M.F.; Cavalheiro, J.; Castro, F. Evaluation of Pellets Produced with Undergrowth to be Used as Biofuel. *Waste Biomass Valoriz.* **2012**, *3*, 285–294. [CrossRef]
10. Yemshanov, D.; McKenney, D.W.; Hope, E.; Lempriere, T. Renewable Energy from Forest Residues—How Greenhouse Gas Emission Offsets Can Make Fossil Fuel Substitution More Attractive. *Forests* **2018**, *9*, 79. [CrossRef]
11. Aniszewska, M.; Gendek, A. Logistics of the supplies of selected forest tree species' cones. Part 1. Cone density and substitution coefficient. *Ann. Wars. Univ. Life Sci. SGGW Agric.* **2016**, *67*, 121–130.
12. Aniszewska, M.; Gendek, A. Logistics of delivery of cones of selected species of forest trees. Part 2: Cone transport. *Ann. Wars. Univ. Life Sci. SGGW Agric.* **2016**, *68*, 113–121.
13. Gendek, A. Combustion heat and calorific value of the mix of sawdust and cones of common pine (*Pinus sylvestris* L.). *Ann. Wars. Univ. Life Sci. SGGW Agric.* **2015**, *66*, 137–144.
14. Aniszewska, M.; Gendek, A. Porównanie ciepła spalania i wartości opałowej szyszek wybranych gatunków drzew leśnych. *Leśne Prace Badaw.* **2014**, *75*, 231–236.
15. Aniszewska, M.; Kuszpit, D. Analysis of acquisition and potential usage of conifer cones from Polish seed extraction houses between 2009–2012. *Ann. Wars. Univ. Life Sci. SGGW Agric.* **2015**, *65*, 93–101.
16. Gokdai, D.; Borazan, A.A.; Acikbas, G. Effect of Marble: Pine Cone Waste Ratios on Mechanical Properties of Polyester Matrix Composites. *Waste Biomass Valoriz.* **2017**, *8*, 1855–1862. [CrossRef]
17. Statistics Poland (Central Statistical Office). *Leśnictwo. Forestry 2016*; Główny Urząd Statystyczny: Warszawa, Poland, 2016.
18. Załęski, A. *Nasiennictwo Leśnych drzew i Krzewów Iglastych*; Oficyna Edytorska Wydawnictwo Świat: Warszawa, Poland, 1995; ISBN 978-83-85597-27-8.
19. Murphy, P.G.; Lugo, A.E. Structure and biomass of a subtropical dry forest in Puerto Rico. *Biotropica* **1986**, *18*, 89–96. [CrossRef]

20. Barszcz, A.; Rutkowska, L. Znaczenie współczynnika zmienności w określaniu jakości surowca drzewnego. *Sylwan* **1999**, *143*, 45–55.
21. Peters, S.; Boutin, S.; Macdonald, E. Pre-dispersal seed predation of white spruce cones in logged boreal mixedwood forest. *Can. J. For. Res.* **2003**, *33*, 33–40. [CrossRef]
22. Keane, R.E.; Reinhardt, E.D.; Scott, J.; Gray, K.; Reardon, J. Estimating forest canopy bulk density using six indirect methods. *Can. J. For. Res.* **2005**, *35*, 724–739. [CrossRef]
23. Phanphanich, M.; Mani, S. Impact of torrefaction on the grindability and fuel characteristics of forest biomass. *Bioresour. Technol.* **2011**, *102*, 1246–1253. [CrossRef] [PubMed]
24. Mikolajczak, E. The profitability of converting sawmill by-products into energy. *Drew. Pr. Nauk. Doniesienia Komun.* **2012**, *55*, 88–102.
25. Gendek, A.; Aniszewska, M.; Chwedoruk, K. Bulk density of forest energy chips. *Ann. Wars. Univ. Life Sci. SGGW Agric.* **2016**, *67*, 101–111.
26. Agar, D.A. A comparative economic analysis of torrefied pellet production based on state-of-the-art pellets. *Biomass Bioenergy* **2017**, *97*, 155–161. [CrossRef]
27. Frączek, J.; Kaczorowski, J.; Ślipek, Z.; Horabik, J.; Molenda, M. Standaryzacja metod pomiaru właściwości fizyczno-mechanicznych roślinnych materiałów ziarnistych. *Acta Agrophys.* **2003**, *92*, 7–158.
28. Gendek, A.; Nurek, T.; Zychowicz, W.; Moskalik, T. Effects of Intentional Reduction in Moisture Content of Forest Wood Chips during Transport on Truckload Price. *BioResources* **2018**, *13*, 4310–4322. [CrossRef]
29. Konieczny, S. Experience with the use of biomassin large conventional power. *Folia Pomeranae Univ. Technol. Stetin. Oecon.* **2011**, *65*, 81–87.
30. Niedziółka, I.; Szpryngiel, M. Ocena cech jakościowych peletów wytworzonych z biomasy roślinnej. *Inż. Rol.* **2012**, *2*, 267–276.
31. Stolarski, M.; Szczukowski, S.; Tworkowski, J.; Kwiatkowski, J.; Grzelczyk, M. Charakterystyka zrębków oraz peletów (granulatów) z biomasy wierzby i ślazowca jako paliwa. *Probl. Inż. Rol.* **2005**, *13*, 13–22.
32. Tomczak, A.; Jelonek, T.; Jakubowski, M. Density of Scots pine (*Pinus sylvestris* L.) wood as an indicator of tree resistance to strong winds. *Sylwan* **2013**, *157*, 539–545.
33. Witkowska, J.; Lachowicz, H. Variability of conventional wood density of Scots pine (*Pinus sylvestris* L.) depending on the selected factors. *Sylwan* **2013**, *157*, 336–347.
34. Wojtan, R.; Tomusiak, R.; Zasada, M.; Dudek, A.; Michalak, K.; Wroblewski, L.; Bijak, S.; Bronisz, K. Trees and their components biomass expansion factors for Scots pine (*Pinus sylvestris* L.) of western Poland. *Sylwan* **2011**, *155*, 236–243.
35. The Act od Parliament of Republic of Poland. Ustawa z dnia 7 Czerwca 2001 r. o Leśnym Materiale Rozmnożeniowym. Available online: http://prawo.sejm.gov.pl/isap.nsf/download.xsp/WDU20010730761/T/D20010761L.pdf (accessed on 4 July 2018).
36. *Solid Mineral Fuels—Determination of Gross Calorific Value by the Bomb Calorimetric Method and Calculation of Net Calorific Value*; ISO 1928:2009; International Organization for Standardization: Geneva, Switzerland, 2009.
37. Głodek, E. *Spalanie i Współspalanie Biomasy*; Instytut Ceramiki i Materiałów Budowlanych: Opole, Poland, 2010.
38. Skrifvars, B.-J.; Backman, R.; Hupa, M.; Sfiris, G.; Åbyhammar, T.; Lyngfelt, A. Ash behaviour in a CFB boiler during combustion of coal, peat or wood. *Fuel* **1998**, *77*, 65–70. [CrossRef]
39. Świeca, G. *Zawartość Wodoru w Różnych Rodzajach Biomasy*; Instytut Chemiczny Przeróbki Węgla: Zabrze, Poland, 2007.
40. Werther, J.; Saenger, M.; Hartge, E.-U.; Ogada, T.; Siagi, Z. Combustion of agricultural residues. *Prog. Energy Combust. Sci.* **2000**, *26*, 1–27. [CrossRef]
41. *Solid Biofuels—Determination of Ash Content*; ISO 18122:2015; International Organization for Standardization: Geneva, Switzerland, 2015.
42. Martinka, J.; Martinka, F.; Rantuch, P.; Hrušovský, I.; Blinová, L.; Balog, K. Calorific value and fire risk of selected fast-growing wood species. *J. Therm. Anal. Calorim.* **2018**, *131*, 899–906. [CrossRef]
43. Gendek, A.; Malaťák, J.; Velebil, J. Effect of harvest method and composition of wood chips on their caloric value and ash content. *Sylwan* **2018**, *162*, 248–257.
44. *Solid Biofuels—Determination of Bulk Density*; PN-EN ISO 17828:2015; Polish Committee for Standardization: Warsaw, Poland, 2015.

45. Anovitz, L.M.; Cole, D.R. Characterization and analysis of porosity and pore structures. *Rev. Mineral. Geochem.* **2015**, *80*, 61–164. [CrossRef]
46. Igathinathane, C.; Tumuluru, J.S.; Sokhansanj, S.; Bi, X.; Lim, C.J.; Melin, S.; Mohammad, E. Simple and inexpensive method of wood pellets macro-porosity measurement. *Bioresour. Technol.* **2010**, *101*, 6528–6537. [CrossRef] [PubMed]
47. Dell Inc. *Dell Statistica*, version 13; Data Analysis Software System; Dell Inc.: Landolock, TX, USA, 2016.
48. Aniszewska, M. *Dynamika Procesu Pozyskania Nasion w Jedno- i Dwuetapowych Procesach Łuszczenia Szyszek Sosny Zwyczajnej Pinus sylvestris L.*; Rozprawy Naukowe i Monografie; Wydawnictwo SGGW: Warszawa, Poland, 2012.
49. Białobok, S.; Boratyński, A.; Bugała, W. *Biologia Sosny Zwyczajnej*; Polska Akademia Nauk Instytut Dendrologii: Poznań-Kórnik, Poland, 1993; ISBN 978-83-85599-21-0.
50. Chmielewski, W. Study on cone variation in spruce in Poland. In *Population Studies of Norway Spruce in Poland*; Tyszkiewicz, S., Ed.; Forest Reaserch Institute: Warsaw, Poland, 1968.
51. Białobok, S. *Świerk Pospolity—Picea abies (L.) Karst. Nasze Drzewa Leśne*; Polska Akademia Nauk Instytut Dendrologii: Warszawa, Poland, 1999.
52. Vîlcan, A.; Holonec, L.; Tăut, I.; Sestras, R.E. Variability of the traits of cones and seeds in different larch clones I. The influence of the provenance. *Bull. Univ. Agric. Sci. Vet. Med. Cluj-Napoca Hortic.* **2011**, *68*, 474–480.
53. Aniszewska, M.; Gendek, A. Comparison of heat of combustion and calorific value of the cones and wood of selected forest trees species. *For. Res. Pap.* **2014**, *75*, 231–236. [CrossRef]
54. Gilbe, C.; Öhman, M.; Lindström, E.; Boström, D.; Backman, R.; Samuelsson, R.; Burvall, J. Slagging Characteristics during Residential Combustion of Biomass Pellets. *Energy Fuels* **2008**, *22*, 3536–3543. [CrossRef]
55. Vega-Nieva, D.J.; Ortiz Torres, L.; Míguez Tabares, J.L.; Morán, J. Measuring and Predicting the Slagging of Woody and Herbaceous Mediterranean Biomass Fuels on a Domestic Pellet Boiler. *Energy Fuels* **2016**, *30*, 1085–1095. [CrossRef]
56. Filbakk, T.; Jirjis, R.; Nurmi, J.; Høibø, O. The effect of bark content on quality parameters of Scots pine (*Pinus sylvestris* L.) pellets. *Biomass Bioenergy* **2011**, *35*, 3342–3349. [CrossRef]
57. Munalula, F.; Meincken, M. An evaluation of South African fuelwood with regards to calorific value and environmental impact. *Biomass Bioenergy* **2009**, *33*, 415–420. [CrossRef]
58. Friedl, A.; Padouvas, E.; Rotter, H.; Varmuza, K. Prediction of heating values of biomass fuel from elemental composition. *Anal. Chim. Acta* **2005**, *544*, 191–198. [CrossRef]
59. Ragland, K.W.; Aerts, D.J.; Baker, A.J. Properties of wood for combustion analysis. *Bioresour. Technol.* **1991**, *37*, 161–168. [CrossRef]
60. Kofman, P.D. Quality Wood Chip Fuel. 2006. Available online: http://biomasseastportmaine.com/Quality_wood_chip_fuel.pdf (accessed on 5 July 2018).