

## Article

# Chemical Characteristics of Selected Grass Species from Polish Meadows and Their Potential Utilization for Energy Generation Purposes

Bogusława Waliszewska <sup>1,\*</sup>, Mieczysław Grzelak <sup>2</sup>, Eliza Gawel <sup>3</sup> , Agnieszka Spek-Dźwigala <sup>1</sup>, Agnieszka Sieradzka <sup>1</sup> and Wojciech Czekala <sup>4</sup>

<sup>1</sup> Department of Chemical Wood Technology, Poznan University of Life Sciences, Wojska Polskiego 38/42, 60-637 Poznań, Poland; agnieszka.spek-dzwigala@up.poznan.pl (A.S.-D.); agnieszka.sieradzka@up.poznan.pl (A.S.)

<sup>2</sup> Department of Grassland and Natural Landscape Sciences, Poznań University of Life Sciences, Dojazd 11, 60-632 Poznań, Poland; mieczyslaw.grzelak@up.poznan.pl

<sup>3</sup> Department of Forage Crop Production, Institute of Soil Science and Plant Cultivation—State Research Institute, Czartoryskich 8, 24-100 Puławy, Poland; eliza.gawel@iung.pulawy.pl

<sup>4</sup> Department of Biosystems Engineering, Poznań University of Life Sciences, Wojska Polskiego 50, 60-627 Poznań, Poland; wojciech.czekala@up.poznan.pl

\* Correspondence: boguslawa.waliszewska@up.poznan.pl

**Abstract:** Analyses were conducted on 10 grass species from permanent grasslands in the Noteć Leniwa and Noteć Bystra valley. Their chemical composition was assayed, and their heat of combustion and heating value were determined. The cellulose content ranged from 33.38% to 38.68%, while the content of lignin ranged from 15.42% to 21.99%, and that of hemicellulose from 30.27% to 34.31%. The heating value of grasses was comparable to that of wood from 2- to 3-year-old willows and other fast-growing energy crops. However, the calorific value of naturally dried grasses may be slightly lower. The quantities of minerals in these grasses, exceeding those in wood, did not result in a lowering of their heat of combustion. The analyses clearly showed that the investigated grass species may be successfully used for energy generation purposes.

**Keywords:** chemical composition of grass; cellulose; lignin; ash; calorific value



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## 1. Introduction

In view of the current search for energy materials providing an alternative to fossil fuels, plant biomass from annual grass species appears to be a promising source. According to the European Environment Agency [1], plant biomass for energy purposes shows the greatest potential among renewable energy sources in Poland. This is connected with its availability, its cost-effectiveness as a fuel, and the relatively low costs of the combustion system. Additionally, the rational utilization of renewable energy sources is an essential element of a sustainable economy. When conditions were adopted in 2020 to ensure a 15% share of renewable sources in energy generation, it was assumed that the increased contribution of renewable sources would be based on the utilization of plant biomass. At present, wood biomass (chips, pellets, briquettes and sawdust) is the plant biomass material used most commonly in Poland [2]. In turn, in agricultural biogas plants, frequently used substrates include by-products of agricultural production, i.e., plant waste biomass, as well as straw or sugar beet pulp [3,4]. In the case of the so-called dedicated energy crops (DEC) for biogas production, such as maize grown for silage [5], a potential conflict may arise between food production and cultivation for feedstocks [6]. An alternative in such cases may be provided by the cultivation of dedicated energy crops on poorer, frequently degraded soils [7,8], or barren lands.

Advantages of plant biomass over fossil fuels include the low contents of sulfur and nitrogen as well as its approximately fourfold greater oxygen content. Additionally, the

combustion of straw instead of wood produces lower emissions of polycyclic aromatic hydrocarbons (PAHs), such as naphthalene, phenanthrene, fluoranthene and pyrene [9].

It is also noteworthy that plant material from permanent grassland may be used as a biogas plant substrate and (particularly in the case of plants with high contents of lignocellulose compounds) as a structural material in the composting process [10,11]. The primary factor affecting the proper course of this process is the availability of oxygen [12]. Due to their porous structure, straw and grass provide adequate oxygen during composting [13].

Plant biomass with increased contents of lignocellulose compounds (i.e., grasses and straw) may also be used as a quality substrate for agricultural biogas plants [14]. Due to their lower water content, dried grasses or straw (e.g., maize straw, also called corn stover) may provide higher biogas yields than maize silage, the most popular substrate in European biogas plants [4]. An important aspect of the use of biomass of plant origin is the production of various types of chemical substances. This is an important process for the substitution of petrochemical products. Substances such as furfural, alcohols, levulinic acid, 5-hydroxymethylfurfural, lactic acid, succinic acid and phenols are valuable substrates in the chemical industry and can successfully replace petrochemical products [15].

Permanent grasslands in Poland cover 3.1 million ha, which accounts for 21.4% of the utilized agricultural area and 10.5% of the country's total area [16]. It includes both natural and semi-natural grassland (approx. 50% of the total area) as well as anthropogenic grassland, i.e., grassland subjected to periodical renovation using seeds of meadow plants for the undersowing and sowing of new meadows and pastures, treated as valuable pastures (approx. 50% of the total area). The basic function of grasslands in terms of their utilization is to provide feed for graminivorous animals. On organic farms, the biomass formed in the process of photosynthesis is used as a valuable energy material to produce pellets and briquettes. Among native grass species, those characterized by particularly high yields are recommended for the production of solid biomass. These species include reed canary grass (*Phalaris arundinacea*), common reed (*Phragmites australis*), awnless brome (*Bromus inermis*), cock's foot (*Dactylis glomerata*) and false oat-grass (*Arrhenatherum elatius*). Moreover, there has been increasing interest recently in introduced grass species, mainly from the genus *Miscanthus*, such as giant miscanthus (*Miscanthus x giganteus*), Amur silvergrass (*Miscanthus sacchariflorus*) and maiden silvergrass (*Miscanthus sinensis*), as well as other C4 grasses, such as prairie cordgrass (*Spartina pectinata*) and switchgrass (*Panicum virgatum*) [17]. An advantageous aspect of the utilization of such biomass for energy generation is the neutral effect of their combustion on greenhouse gas emissions to the atmosphere. The zero-carbon balance of plant biomass is commonly known and acknowledged [18]. The suitability of solid biofuels for energy generation is determined by many factors, including the heat of combustion parameters and the contents of cellulose, lignin and ash [19]. The literature sources present information on the chemical composition of native tree and shrub species as well as many introduced plants offering high biomass yields [20,21]. However, practically no data are available on the chemical composition and heating value of common grass species found in Polish meadows.

A characteristic property of plant biomass is the heterogeneity of its anatomical structure and differences in the chemical composition even within the same species. These depend on many factors, including location, plant age or even the part of the plant. These factors affect the potential industrial uses of the raw material. Thus, for the rational utilization of plant raw materials, it is essential to know the contents and quality of their individual components [22,23].

The utilization of grasses harvested from grassland for energy generation purposes is in line with the assumptions of the EU climate and energy policy aimed at reducing greenhouse gas emissions by 2030 and achieving the long-term low-emission strategy by 2050, which is an important element for the reduction in greenhouse gas emissions [14].

The aim of this study was to analyze the chemical composition of the aboveground parts of plants and to determine the heat of combustion and heating value of selected grass species, with a view to their utilization for energy generation purposes. Based on this

comprehensive analysis of biomass composition, an indication will be made of the possible end uses of each species.

**Hypothesis 1.** *The hypothesis of the present work is that the studied grass species are suitable for bioenergy conversion.*

## 2. Materials and Methods

Ten grass species commonly found on grassland in Poland were selected for this study. The species are reed canary grass (*Phalaris arundinacea* L.), wood small-reed (*Calamagrostis epigejos* L. Roth), common reed (*Phragmites australis* Cav.), couch grass (*Elymus repens* L. Gould.), downy brome (*Bromus tectorum* L.), false oat-grass (*Arrhenatherum elatius* (L.) P. Beauv. ex J. Presl & C. Presl), common bent (*Agrostis capillaris* L.), sweet vernal grass (*Anthoxanthum odoratum* L.), cock's foot (*Dactylis glomerata* L.) and velvet grass (*Holcus lanatus* L.). A composite material in the mature form (leaves and culms together with inflorescences) was harvested in the Noteć Leniwa and Noteć Bystra valley (Wielkopolskie province, Białośliwie and Trzcianka communes) and in Rakowo (Lubuskie province, Skwierzyna commune). They are semi-natural grassland ecosystems, and farmers, when realizing the Environmental Management Scheme, run their farms in an environmentally friendly manner. The harvested biomass exhibits an average fodder value, but it is a valuable raw material for the production of pellet and briquettes used for energy generation. The share of certain dominant species in the plant community reaches up to 80% or even 100%, e.g., in the case of reeds or canary grass. The study area covered 148 ha.

The communities from which the research material was collected are semi-natural grassy ecosystems subject to extensive use. The grasses were harvested in the initial stage of heading, from the end of May to mid-August (2020), depending on the phase of growth and development of a given species. About 1 kg of material was collected from a homogeneous 10 × 10 m surface area. The harvested material was processed in an air-conditioned facility until constant moisture content was attained. Next, it was cut manually and ground in an SM 200 laboratory mill (Retsch). For chemical analyses, the 0.1–0.4 mm analytical fraction was isolated, and for heat of combustion, the <0.1 mm fraction was used in the analyses.

The chemical composition of the investigated grasses was assayed using standard methods applied in analyses of plant biomass:

- Extractive contents were determined using 96% ethanol according to Soxhlet (TAPPI-T 204 cm-07) [24];
- Cellulose content was determined by the Seifert method with a mixture of acetylacetone and dioxane at an acid pH [25];
- Lignin content was determined by the Tappi method using 72% sulfuric acid (TAPPI-T 222 om-06) [26];
- Holocellulose content was assayed using sodium chlorite (TAPPI-T 9 wd-75) [27];
- The theoretical content of hemicellulose was calculated mathematically as a difference between holocellulose and cellulose contents;
- Contents of ash were determined according to the DIN 51731 standards [28].

All results were calculated in relation to the raw material's dry mass and given as a mean from three measurements. Moisture content was determined using the oven-dry method. This consists in weighing approx. 2 g of the sample and drying in a dryer at a temperature of  $103 \pm 2$  °C until constant mass. The difference between weighed values did not exceed 0.01%.

The heat of combustion was determined according to the PN-81/G-04513 standard in a ZKL-4 calorimeter, designed for determination of the heat of combustion ( $Q_s^a$ ) of solid fuels. A 1 g analytical sample of raw material was completely combusted under oxygen atmosphere and 3 MPa pressure.

The values were calculated according to the formula:

$$Q_s^a = \frac{C(D_t - k) - c}{m} \quad (\text{kJ/kg}) \quad (1)$$

where

C is the heat capacity of the calorimeter, 12,783.69 (J/°C);

$D_t$  is the temperature rise in the main period (°C);

k is a correction for heat exchange with the surroundings (°C);

c is the sum of corrections for additional thermal effects (J);

m is the mass of the fuel sample (g).

To provide a more comprehensive characterization of the analyzed raw material, the heating value of the investigated grasses was also calculated, as the heat of combustion reduced by the heat of vaporization of water released during combustion.

The values were calculated according to the following formula:

$$Q_i^a = Q_s^a - 24.42(W^a - 8.94H^a) \quad (\text{kJ/kg}) \quad (2)$$

where

$Q_s^a$  is the average gross calorific value of solid fuel in the analytical state (J/g);

The heat of vaporization of water at 25 °C is 24.42, corresponding to 1% of water in the fuel (J/g);

$W^a$  is the moisture content in the analytical sample of fuel (%);

The analytical factor for the conversion of hydrogen content to water content is 8.94;

$H^a$  is the hydrogen content in the analytical sample of fuel, according to the PN-EN ISO 16948: 2015-07 [29].

#### Statistical Analysis

The statistical analysis of the chemical composition of the grasses was performed using STATISTICA 10 (StatSoft LTD, Cracow, Poland), including analysis of variance (ANOVA) followed by a post hoc Tukey's honestly significant difference (HSD) test. Identical letters in columns represent no differences at a significance level of  $p = 0.05$ .

### 3. Results

Analysis of the data given in Table 1 indicates the differences in the amounts of structural components in the investigated grass species. The content of the basic component, cellulose, ranged from 33.38% in the case of *Agropyron repens* to 38.68% in *Phalaris arundinacea*. Five of the studied species had very similar levels of cellulose, within the range 35.05–35.60%. These were *Calamagrostis epigejos*, *Phragmites australis*, *Bromus inermis*, *Arrhenatherum elatius* and *Anthoxanthum odoratum*. A high cellulose content of over 38% was recorded in *Agrostis capillaris*, and a slightly lower level (37.71%) in *Dacylis glomerata*. In *Holcus lanatus*, 36.43% cellulose was recorded.

The variation in lignin content in the investigated grass species was over 6.5%, which was greater than in the case of cellulose. The highest level of lignin, 21.99%, was found in *Phragmites australis*, and the lowest, 15.42%, in *Phalaris arundinacea*, in which the greatest cellulose content was recorded (Table 1). Over 20% lignin was also found in two other species, *Calamagrostis epigejos* and *Agrostis capillaris*. Similar lignin contents were observed in *Arrhenatherum elatius*, *Anthoxanthum odoratum* and *Holcus lanatus* (17.54%, 17.68% and 17.18%, respectively). Statistical analysis confirms these similarities.

**Table 1.** The chemical composition of investigated grass species.

Grass Species	Contents [%] DM				
	Extractives	Cellulose	Lignin	Holocellulose	Hemicellulose
<i>Phalaris arundinacea</i> L.	12.77 ± 0.22 <sup>c</sup>	38.68 ± 0.01 <sup>d</sup>	15.42 ± 0.01 <sup>a</sup>	70.39 ± 0.89 <sup>b</sup>	31.71 ± 1.46 <sup>abcd</sup>
<i>Phragmites australis</i> (Cav.) Trin. ex Steud	14.46 ± 0.06 <sup>d</sup>	35.05 ± 0.14 <sup>b</sup>	21.99 ± 0.15 <sup>f</sup>	65.32 ± 0.23 <sup>a</sup>	30.27 ± 0.15 <sup>a</sup>
<i>Dactylis glomerata</i> L.	10.59 ± 0.15 <sup>ab</sup>	37.71 ± 0.41 <sup>cd</sup>	19.33 ± 0.05 <sup>d</sup>	69.19 ± 1.29 <sup>b</sup>	31.48 ± 1.13 <sup>abc</sup>
<i>Arrhenatherum elatius</i>	15.00 ± 0.17 <sup>d</sup>	35.46 ± 0.20 <sup>b</sup>	17.54 ± 0.15 <sup>c</sup>	68.63 ± 0.09 <sup>b</sup>	33.17 ± 0.25 <sup>cde</sup>
<i>Bromus inermis</i> Leyss.	18.26 ± 0.05 <sup>e</sup>	35.6 ± 0.51 <sup>b</sup>	16.5 ± 0.60 <sup>b</sup>	69.31 ± 0.95 <sup>b</sup>	33.71 ± 1.15 <sup>e</sup>
<i>Agrostis capillaris</i> L.	11.29 ± 0.44 <sup>b</sup>	38.29 ± 0.18 <sup>d</sup>	20.48 ± 0.14 <sup>e</sup>	69.37 ± 0.39 <sup>b</sup>	31.08 ± 0.39 <sup>ab</sup>
<i>Calamagrostis epigejos</i> L. (Roth)	9.42 ± 0.01 <sup>a</sup>	35.35 ± 0.19 <sup>b</sup>	20.96 ± 0.09 <sup>e</sup>	69.01 ± 0.43 <sup>b</sup>	33.66 ± 0.9 <sup>de</sup>
<i>Agropyron repens</i> L.	15.52 ± 1.07 <sup>d</sup>	33.38 ± 1.35 <sup>a</sup>	18.76 ± 0.19 <sup>d</sup>	64.22 ± 0.52 <sup>a</sup>	30.84 ± 0.84 <sup>ab</sup>
<i>Anthoxanthum odoratum</i> L.	9.72 ± 0.28 <sup>a</sup>	35.18 ± 0.28 <sup>b</sup>	17.68 ± 0.04 <sup>c</sup>	69.49 ± 0.48 <sup>b</sup>	34.31 ± 0.20 <sup>e</sup>
<i>Holcus lanatus</i> L.	13.07 ± 0.17 <sup>c</sup>	36.43 ± 0.40 <sup>c</sup>	17.18 ± 0.16 <sup>c</sup>	69.00 ± 0.55 <sup>b</sup>	32.57 ± 0.32 <sup>bcde</sup>

Mean values (n = 3) ± standard deviations; identical superscripts (a–e) in a column denote no significant difference ( $p < 0.05$ ) between mean values according to Tukey's HSD test (ANOVA).

A low content of this component (16.50%) was recorded in *Bromus inermis*. *Agropyron repens* contained 18.76% lignin, and *Dactylis glomerata* 19.34%.

Holocellulose content in the studied grass species was in the range 69.00–69.49% (Table 1) for the species *Holcus lanatus*, *Calamagrostis epigejos*, *Dactylis glomerata*, *Bromus inermis*, *Agrostis capillaris* and *Holcus lanatus*. Only *Phalaris arundinacea* contained over 70% holocellulose, while *Agropyron repens* had 64.22%, and *Phragmites australis* 65.32%.

The calculated contents of hemicellulose exhibited a slight variation. They ranged from 30.27% in common reed to 34.31% in *Holcus lanatus* (Table 1). Slightly over 33% hemicellulose was found in *Arrhenatherum elatius*, *Calamagrostis epigejos* and *Bromus inermis*. Low contents were recorded in *Agropyron repens* (30.84%), *Agrostis capillaris* (31.08%), *Dactylis glomerata* (31.48%) and *Phalaris arundinacea* (31.71%). *Holcus lanatus* contained 32.57% carbohydrates with a low degree of polymerization.

Among the assayed compounds, the greatest variation between grass species was observed in the contents of substances extracted with ethanol. The differences were almost as high as 100% (Table 1). The highest level of these compounds (18.26%) was recorded in *Bromus inermis*, and the lowest in wood small-reed (9.42%) and *Anthoxanthum odoratum* (9.72%). Slightly higher contents of extractives were recorded in cock's foot (10.59%) and common bent (11.29%). *Agropyron repens* and *Arrhenatherum elatius* contained large amounts of extractives (15.52% and 15.00%, respectively). A slightly lower level of these substances, 14.46%, was found in *Phragmites australis*. In *Anthoxanthum odoratum* and *Phalaris arundinacea*, comparable amounts of extractives were recorded (13.07% and 12.77%, respectively).

The plant material for analyses was stored (for about two weeks) in an air-conditioned facility, which resulted in very similar moisture contents for all samples, within a narrow range from 6.2% to 6.7% (Table 2). (In practice, the grasses are dried in the meadow and reach a humidity of about 15%.) This was a low moisture content, which had no marked effect on the variation in heat of combustion. The hydrogen content in the tested grass samples is presented in Table 3.

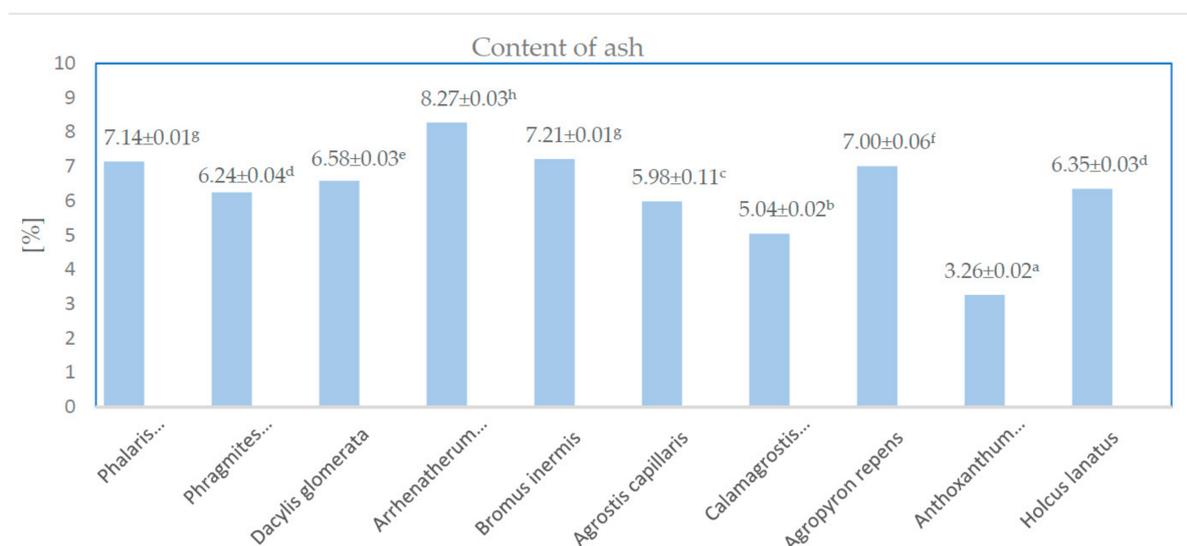
**Table 2.** Moisture content, heat of combustion and heating value of investigated grass species.

Grass Species	Moisture Content (%)	Heat of Combustion (MJ/kg)	Heating Value (MJ/kg)
<i>Phalaris arundinacea</i> L.	6.4 ± 0.02	18.757 ± 0.031	17.293 ± 0.030
<i>Phragmites australis</i> (Cav.) Trin. ex Steud	6.7 ± 0.09	18.842 ± 0.032	17.386 ± 0.031
<i>Dactylis glomerata</i> L.	6.2 ± 0.05	17.598 ± 0.019	16.129 ± 0.019
<i>Arrhenatherum elatius</i>	6.7 ± 0.05	18.455 ± 0.037	16.989 ± 0.036
<i>Bromus inermis</i> Leyss.	6.2 ± 0.03	18.707 ± 0.010	17.231 ± 0.010
<i>Agrostis capillaris</i> L.	6.4 ± 0.01	17.527 ± 0.001	16.066 ± 0.002
<i>Calamagrostis epigejos</i> L. (Roth)	6.4 ± 0.01	19.496 ± 0.032	18.037 ± 0.032
<i>Agropyron repens</i> L.	6.6 ± 0.05	19.252 ± 0.037	17.793 ± 0.036
<i>Anthoxanthum odoratum</i> L.	6.3 ± 0.06	17.912 ± 0.038	16.436 ± 0.036
<i>Holcus lanatus</i> L.	6.7 ± 0.05	17.502 ± 0.039	16.029 ± 0.038

**Table 3.** Hydrogen content in analytical samples.

Grass Species	H (%) DM	Grass Species	H [%] DM
<i>Phalaris arundinacea</i> L.	6.17 ± 0.04	<i>Agrostis capillaris</i> L.	6.04 ± 0.04
<i>Phragmites australis</i> (Cav.) Trin. ex Steud	5.83 ± 0.08	<i>Calamagrostis epigejos</i> L. (Roth)	6.08 ± 0.09
<i>Dactylis glomerata</i> L.	5.90 ± 0.08	<i>Agropyron repens</i> L.	6.07 ± 0.03
<i>Arrhenatherum elatius</i>	6.02 ± 0.06	<i>Anthoxanthum odoratum</i> L.	6.04 ± 0.06
<i>Bromus inermis</i> Leyss.	6.03 ± 0.02	<i>Holcus lanatus</i> L.	5.99 ± 0.04

The contents of ash in the studied grass species are given in Figure 1. The levels of these compounds were relatively varied, ranging from 3.26% in the case of sweet vernal grass to 8.27% in false oat-grass. Large amounts of ash (7.00–7.21%) were recorded in three more species: *Agropyron repens*, *Phalaris arundinacea* and *Bromus inermis*. *Calamagrostis epigejos* had a 5.04% ash content. The ash contents in *Phragmites australis*, *Holcus lanatus*, *Dactylis glomerata* and *Agrostis capillaris* were comparable, in the range 5.98–6.58%.



**Figure 1.** Content of ash. Mean values (n = 3) ± standard deviations; identical superscripts (a, b, c . . . ) denote no significant difference ( $p < 0.05$ ) between mean values according to Tukey's HSD test (ANOVA).

Based on the heat of combustion, the studied grass species could be divided into three groups. The first group, with the highest values (over 19.000 MJ/kg), consisted of *Calamagrostis epigejos* (19.496 MJ/kg) and *Agropyron repens* (19.252 MJ/kg) (Table 2). For the second

group of grasses, the heat of combustion was in the range 18.455–18.842 MJ/kg, while the third group had the lowest values, from 17.500 to slightly over 17.900 MJ/kg. Low heats of combustion were recorded for *Agrostis capillaris*, *Dactylis glomerata* and *Holcus lanatus*.

The heating value of the investigated grass species, i.e., their heat of combustion reduced by the heat of water vaporization, followed a similar pattern (Table 2). Only *Calamagrostis epigejos* had a heating value over 18.000 MJ/kg. Five species had heating values in the range 16.029–16.989 MJ/kg. For the other species, slightly higher heating values were recorded, from 17.231 to 17.793 MJ/kg.

#### 4. Discussion

In Poland, the production of fodders using organic cultivation methods in the Natura 2000 area covers a rich mosaic of habitats associated with high levels of groundwaters. This has contributed to the maintenance of the highly natural character of habitats, and the plant communities developed under these conditions exhibit considerable potential for the production of biomass at a simultaneously high nature value. In the case of extensively managed areas, an excess of produced fodder is a valuable substrate for the production of fuel.

For the appropriate and optimal utilization of biomass, it is crucial to know the contents of its individual components [30]. Plant biomass used for energy generation purposes needs to meet specific requirements [31]. Its value is typically assessed based on the heat of combustion and heating value. However, information on the contents of its chemical components may also be a valuable indicator for the optimal utilization of this raw material.

The primary component of lignocellulose materials is cellulose, which due to its fibrous structure provides cells with mechanical strength. The amount of cellulose in plants varies greatly and depends on many factors, such as species, plant age and growth conditions, as well as the part of the plant [32–35]. Plant biomass of annual species contains approximately 20–40% cellulose. The highest level of pure cellulose is found in cotton, in which it may be as high as 98%, while ramie has a level of approx. 76%, flax approx. 71% and straw approx. 40% [32]. *Miscanthus* is gaining in popularity as an energy crop providing high yields of biomass. Some varieties are cultivated even under difficult growth conditions (such as those in Siberia), giving satisfactory biomass yields [23]. In that study, cellulose contents in five *Miscanthus* plants aged from 1 to 5 years, determined by the Kürschner method, were reported to range from 42% to 54%. This is a relatively high amount of cellulose in grasses harvested in a 1-year cycle. Doczekalska et al. [36], in a study on the chemical composition of three *Miscanthus* species (*M. giganteus*, *M. sacchariflorus* and *M. sinensis*) to be used for biochar, reported the content of cellulose to range from 44.12% to 45.12%, while in switchgrass (*Panicum virgatum*), it was 40.30%. This is approximately 10% higher than the cellulose content of the grass species investigated in this study. In turn, in grasses from the genus *Carex*, very similar contents of the main biomass component were reported in most cases, from 35% to 40% [37]. Only *Carex praecox* was found to have a low level of cellulose (30.1%), while in *Carex riparia*, it was as high as 46.2%. The cellulose content of *C. riparia* was comparable to that of *Miscanthus* species, and almost 8% higher than that of reed canary grass, which contained 38.68% of these compounds. A low content of cellulose of approximately 31% in different grass species (*Lolium perenne*, *Dactylis glomerata*, *Poa pratensis* and *Festuca pratensis*) was reported by Dandikas et al. [22], who investigated the relationship between the chemical composition of plants and the yield of biogas. A similar amount of cellulose, ranging from 36% to 42%, in Napier grass (*Pennisetum purpureum*) was recorded by Ansah et al. [38]. Among the fast-growing plants used for energy generation purposes, an important example is *Salix viminalis*, a species with a number of varieties and clones. The amount of cellulose in the wood of different clones (Corda, Tur, Turbo, Duotur, UWM 046) harvested in a 1-year cycle was 39–41%, comparable to the contents of cellulose in reed canary grass (38.68%) and common bent (38.29%).

Lignin is the second most abundant component of plant biomass. Its content in lignocellulose raw materials amounts to 16–32%. It is a natural bonding component enhancing the stability of biomass, while its chemical structure gives it a high heating value. Among the investigated grasses, the greatest amount of lignin, almost 22%, was recorded in common reed, which is comparable to the value for *Miscanthus giganteus* reported by Doczekalska et al. [36]. Those authors reported approx. 20% lignin in *Miscanthus sacchariflorus*, *M. sinensis* and *P. virgatum* (switchgrass), comparable to the values for several grass species investigated in this study (wood small-reed, common bent and cock's foot). Similar lignin contents were found in grasses from the genus *Carex*—*C. acutiformis* (20.3%) and *C. paniculata* (20.8%) [37]. Many grasses, however, have lower lignin contents (approx. 15–17%); in this study, these were reed canary grass, downy brome, false oat-grass, sweet vernal grass and velvet grass. Similar amounts of lignin were also recorded in *C. flava* and *C. brizoides* [37]. A considerable variation in lignin contents (from 15.7% to 28.1%) in grasses from extensively managed meadows in the Wielkopolska region was reported by Murawski et al. [39]. Strongly lignified stems of energy crops, such as *Salix viminalis* or clones from the genus *Salix* (UWM 006 and UWM 043), showed slightly higher levels of lignin, close to 25% [40], while values reported for the clones Turbo and Duotur were 25.27% and 24.71%, respectively [41]. (In Poland, *Salix viminalis* is a commonly cultivated species, and it is generally called energy crop willow. It is a fast-growing species, providing high yields within a short cycle and characterized by a high heating value.) A high lignin content, 24.8%, in bamboo wood was recorded by Chen et al. [42]. A very low amount of lignin, from 8.9% to 13.8%, in Napier grass was reported by Ansah et al. [38]. According to the literature data, woody plant parts contain slightly more lignin than grasses harvested in a 1-year cycle. However, differences in the contents of this component are not large, and their amounts are sometimes comparable. The amount of lignin in the investigated grasses in this study was characteristic for this type of plants harvested in a 1-year cycle. The low lignin content in *Phalaris arundinacea* did not reduce the heat of combustion of that grass species.

The total content of polysaccharide substances (holocellulose) in the studied grasses (64.22–70.39%) was slightly lower than that of hardwood (70–78%) [32]. This is connected with the relatively high level of extractives in grasses (9–18%). However, it did not result in a considerable reduction in the heat of combustion in the investigated grasses. A low content of holocellulose, amounting to 52.4–68.1%, in grasses from extensively managed meadows was reported by Murawski et al. [39]. Compared to the wood of an energy crop in the genus *Salix* (clones UWM 006 and UWM 043), this is a much lower level of holocellulose, since as stated by Krzyżaniak et al. [40], these clones contained approx. 75% polysaccharides. In turn, Stolarski et al. [41] determined the content of polysaccharide substances in the wood of 2- and 3-year *Salix* clones (Corda, Tur, Turbo, Duotur) at 67–70%. Woody bamboo stems were found to contain approx. 71% holocellulose [42]. The above analysis shows that plant biomass harvested over a short cycle exhibits similar polysaccharide contents, which may affect the heat of combustion. However, confirmation of this assumption will require additional research.

Hemicelluloses, i.e., carbohydrates with a low degree of polymerization, in plants play the role of the skeleton substance (pentosans) and nutrients (hexosans). They amount to approx. 20–30% in the xylem [32]. Similar levels of hemicellulose were reported by Stolarski et al. [41] in the wood of *Salix* clones harvested in a 1-year cycle (they found from 26.56% to 31.89% of these substances). In turn, Gismatulina and Budaeva [23] recorded from 20.0% to 25.3% pentosans alone in biomass from *Miscanthus*, whereas Doczekalska et al. [36] showed the hemicellulose content of various *Miscanthus* species to be approx. 29%, and that of switchgrass to be 30.5%. These values are comparable to those obtained in this study. In the investigated grass species, the hemicellulose content ranged from 30.27% to 34.31% (in sweet vernal grass). Slightly lower contents of hemicellulose were reported by Ansah et al. [38] in Napier grass varieties, which contained from 19.55% to 25.23% carbohydrates with a low degree of polymerization. When investigating several grass species to be used

in the production of biogas, Dandikas et al. [22] found approx. 27% hemicellulose. The level of hemicellulose in those grasses was more than twice as high as in bamboo wood, where it is as low as 14% [42]. The investigated grass species contained large amounts of hemicellulose compared with various other sources of plant biomass, which may encourage the utilization of these grass species in the production of biogas [43,44].

Extractives in wood account for a very low percentage of dry matter, as little as 2–6%, and their level depends on the species, the part of the plant and the extraction mixture [32]. Grasses contain much greater amounts of these compounds. In this study, the level of substances soluble in ethanol ranged from 9.72% to 18.26%. These amounts showed the greatest variability among the chemical components of biomass. Murawski et al. [39] reported similar contents of extractives in sedge grasses, from 9.7% to 17.7%. Waliszewska et al. [37] found 8.1–8.3% extractives in *Carex riparia* and *C. paniculata*, and 13.6% to 23.1% in seven other *Carex* species. A mixture of ethanol and benzene is a very good solvent of waxes, fats, resins and tannins, among others. Chen et al. [42], when using this solvent in the analysis of bamboo wood, recorded the content of these substances at approximately 9.5%. According to Doczekalska et al. [36], grasses from the genus *Miscanthus* contained from 2.54% to 2.97% extractives depending on the species, while in switchgrass, the content was 3.14%. In *Miscanthus*, slightly higher amounts (2.8–5.7%) of these compounds, depending on the age of the plants, were reported by Gismatulina and Budaeva [23]. The analysis of literature data shows that grasses are characterized by relatively high amounts of compounds soluble in organic solvents, and their levels fall within a wide range of values. Grasses may be a source of many valuable active substances. Gismatulina and Budaeva identified as many as 24 fatty acids in extracts from *Miscanthus*.

It is essential to know the ash contents of fuels used for energy generation purposes. The mean ash content in non-woody solid fuels ranges from 4% to 7%. The investigated grass species contained from 5.04% to 8.27% mineral compounds, except for sweet vernal grass, which contained 3.26% ash. Generally, grasses and cereal straw contain greater amounts of mineral substances than wood, which, depending on the species, plant part and felling date, contains from 0.2% to 1.0% of these compounds [32]. However, this may not be necessarily a disadvantage of plant biomass, since ash—due to its contents of micro- and macroelements—may be used as a fertilizer [45]. Kalembasa [46] recorded the content of macronutrients at 91.9% in ash from *Miscanthus*, including calcium at 38.6% and potassium at 33.0%, while the content of microelements was 4.87%, thus showing the potential for soil enrichment using this ash. Maiden silvergrass (*Miscanthus sinensis*) contained 5.25% ash, Virginia fanpetals (*Sida hermaphrodita*) 5.95% and osier (*Salix* sp.) 3.15% [46]. The contents of minerals in plants are also affected by growth conditions. Gismatulina and Budaeva [23] recorded relatively high amounts of minerals in the *Miscanthus* var. *Soranovskii* genotype growing in the severe continental climate of Siberia, ranging from 3.57% to 6.30%. Similar levels of ash in *Miscanthus sinensis* (5.25%) and *Sida hermaphrodita* (5.95%) were reported by Kalembasa [46]. These levels were comparable to the ash contents in the grasses investigated in this study. Doczekalska et al. [36] recorded much lower amounts of mineral compounds in *Miscanthus giganteus*, *M. sacchariflorus* and *M. sinensis* coming from experimental plantations in Poznań, amounting to 2.63%, 2.16% and 2.54%, respectively, while the content in switchgrass was 2.20%. Aboveground parts of grasses from the genus *Carex* harvested in a 1-year cycle contained from 4.2% to 7.3% minerals, except for *C. riparia*, which had as much as 12.3% ash [37]. Murawski et al. [39] recorded 6.5–7.1% mineral substances in grasses harvested from extensively managed meadows. These amounts of ash were comparable to those found in this study in annual grasses. A slightly higher than average ash content (8.1%) in the *Carex praecox* community was also reported by Grzelak et al. [47]. Various genotypes of Napier grass contained from 6.0% to 6.9% ash [38]. Kowalczyk-Juśko [48], when investigating the contents of mineral substances and their composition in *Miscanthus sacchariflorus*, *Spartina pectinata*, *Sida hermaphrodita*, *Helianthus tuberosus* and *Rosa multiflora*, recorded 3.70%, 4.10%, 2.80%, 5.60% and 3.10% contents of these compounds, respectively. Among other crops grown for energy generation

purposes and harvested in a 1-year cycle, *Silphium perfoliatum* contains approx. 3.4% ash [49], while in *Helianthus tuberosus*, ash contents range from 2.52% [50] to 5.60% [51], *Spartina pectinata* L. contains 4.9–5.4% ash [52] and *Agropyron elongatum* Host. has 3.2% ash [53]. The levels of ash in these plants are comparable to or slightly lower than those in the grasses investigated in this study. The presented literature data indicate that the amount of ash in grasses does not differ from that in annual plants grown and used for energy generation purposes, while slightly higher contents of ash may even be advantageous in view of the potential for use in soil fertilization. Studied grasses come from extensively managed meadows, and they are not polluted areas, but semi-natural grassy communities. However, to ensure low contents of hazardous elements, their contents will be determined in ash.

The determined heat of combustion for the grasses fell within a range of 17.500–18.800 MJ/kg. Only wood small-reed and common couch had values exceeding 19.000 MJ/kg. Compared with the heat of combustion of wood from willow species grown for energy generation purposes, amounting to approx. 19.350 [54] and 19.500 MJ/kg [40], these values were slightly lower, while in the case of wood small-reed and common couch, they were comparable. The fact that the ash contents of grasses exceed that of willow wood does not cause a significant reduction in the heat of combustion in the studied grasses. Slightly higher values of the heat of combustion than those found in this study were reported for *Carex* grasses by Waliszewska et al. [37]. For most of these grasses, the heat of combustion ranged from 19.000 to 19.750 MJ/kg; only *Carex riparia*, which has a high ash content (12.3%), had a lower heat of combustion (17.790 MJ/kg). Additionally, Murawski et al. [39] gave almost identical values of the heat of combustion, from 17.1 to 19.4 MJ/kg, for grasses from extensively managed meadows. High values of the heat of combustion (from 19.000 to 19.450 MJ/kg) for grasses from meadows in the Noteć valley were reported by Grzelak et al. [47], with only *Caricetum ripariae* producing a lower value (17.790 MJ/kg). The values of the heat of combustion obtained for grasses in this study are sufficiently high for them to be considered as sources of biomass for combustion for energy generation purposes.

The heating value is the amount of heat obtained at complete combustion of a unit of fuel at a constant volume. This is lower than the heat of combustion by the heat of condensation of the water vapor contained in the combustion gases. For the investigated grass species, this value ranged from 16.029 to 17.793 MJ/kg, except in the case of wood small-reed, where it exceeded 18.000 MJ/kg. Grasses from the Noteć valley were found to have similar heating values, ranging from 16.040 to 17.930 MJ/kg dry matter [47]. It should be noted that for laboratory tests, the grasses were dried in a climatic room, and their humidity was low. Grass naturally dried in a meadow may have higher humidity. Consequently, the calorific value may be lower. According to Murawski et al. [39], heating values for grasses from extensively managed meadows range from 16.1 to 18.1 MJ/kg d.m., while for sedges, they range from 16.0 to 18.7 MJ/kg. Almost identical heating values for sedges, from 16.040 to 18.010 MJ/kg, were given by Waliszewska et al. [37]. These are very similar to the values obtained in this study. Plants grown for energy generation purposes and harvested in a 1-year cycle include, for instance, Virginia fanpetal and various *Miscanthus* varieties. Mirowski et al. [55] reported the heating value for Virginia fanpetal at 14.5–16.1 MJ/kg, and that for *Miscanthus* at 11.1–16.1 MJ/kg. According to Kołodziej and Matyka [56], the heating value of Virginia fanpetal biomass is 17.3 MJ/kg, while for *Miscanthus*, it is 17.4 MJ/kg. Heating values of various types of cereal straw (rye, wheat, triticale, barley, maize, rape and flax) are reported at 17.1–17.8 MJ/kg [55]; the same study determined the heating value of meadow grass at 16.5 MJ/kg and that of reed at 16.4 MJ/kg. According to Kowalczyk-Juśko [57], the heating value of dry matter biomass in prairie cordgrass was 17.24–17.84 MJ/kg depending on the vegetation year. The results of Mirowski et al. [55], Kowalczyk-Juśko [57], Waliszewska et al. [37] and the above-mentioned authors are all very similar to those obtained for the grasses investigated in this study. The mean heating value of dry ash-free matter for monocotyledonous plants (grasses,

cereal straw and reeds) according to the Technical Specifications (CEN/TS 14961:2007) is 18.4–18.5 MJ/kg. Based on this information, it may be stated that the results obtained in this study show the investigated grass species to have slightly lower than average heating values for plant biomass. In turn, biomass derived from the aboveground parts of the studied grass species may be a good renewable raw material for energy generation.

## 5. Conclusions

1. According to the hypothesis, Polish grasses from ecological sites are suitable for bioenergy conversion.
2. The contents of cellulose, lignin and holocellulose do not differ from those in other annual plants. High contents of cellulose in reed canary grass and common bent indicate the potential for conversion of these species to produce cellulose as a valuable raw material.
3. The above-average content of polysaccharides with a low degree of polymerization indicates the potential use of such plant biomass in biogas production. In this respect, three species seem to be of particular interest: *Bromus inermis*, *Calamagrostis epigejos* and *Anthoxanthum odoratum*.
4. The studied grass species had high contents of extractives, which suggests that they may be sources of valuable active substances for use as dietary supplements or in cosmetics. The analyses show that the best species in this respect would be *Agropyron repens*, *Bromus inermis* and *Arrhenatherum elatius*.
5. No correlation was found between contents of individual chemical components and the heat of combustion of the investigated grasses (data not shown). Neither the content of cellulose, nor that of lignin showed a definite effect on the heating value or heat of combustion. The best suited for use in energy generation are the species whose heating value exceeded 17.000 MJ/kg. These were *Phalaris arundinacea*, *Calamagrostis epigejos*, *Phragmites australis*, *Agropyron repens* and *Bromus inermis*.
6. The higher contents of ash characteristics for grasses do not reduce the energy properties of these plants, while ash may additionally be used in soil fertilization. Among the investigated grass species, the most favorable in this respect were *Agropyron repens*, *Bromus inermis* and *Arrhenatherum elatius*.

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