

Article

Energy Potential of Selected Sedges (*Carex* spp.) as a Renewable Biomass Feedstock

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Abstract

The increasing demand for energy, the finite nature of fossil fuel resources, and the necessity to reduce greenhouse gas emissions have intensified research on renewable energy sources of plant origin. Among potential energy feedstocks, herbaceous biomass has attracted growing interest due to its high productivity, rapid growth, and widespread occurrence. The aim of this study was to evaluate the energy potential of select sedge species (*Carex* spp.) commonly occurring in Poland as an alternative to fossil fuels. Aboveground biomass of eight sedge species was collected from natural habitats located in the Warta River valley. Cellulose, lignin, holocellulose, hemicellulose, and ash content in the biomass was determined. In addition, key energy parameters, namely net calorific value and gross calorific value, were analyzed. Differences among species were assessed using one-way analysis of variance, while similarities were explored using hierarchical clustering methods. The results revealed significant interspecific variation in both chemical composition and energy properties. Most analyzed sedge species had favorable lignocellulosic composition and energy parameters comparable to those of woody biomass, particularly willow and poplar. In contrast, *Carex riparia* was distinguished by a high ash content and lower calorific values, limiting its suitability for energy applications. Overall, the findings indicate that select *Carex* species may represent a valuable renewable feedstock for energy production, especially in the context of local and decentralized biomass-based energy systems.



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1. Introduction

The development of modern societies and economies is inherently dependent on access to energy [1], which remains the fundamental driver of industrial growth and social progress. Despite dynamic advancements in renewable energy technologies, fossil fuels—particularly coal—continue to play a dominant role in global energy production. Hard coal

and lignite are still widely used for electricity and heat generation, both in Poland and worldwide [2].

In 2023, global hard coal production reached 9.1 billion tonnes, representing a 3.1% increase compared with 2022. This growth was primarily driven by increased extraction in Asian countries, notably China, India, and Indonesia [3]. While coal consumption declined in Europe by approximately 7%, production surpluses persisted in Asia, reflecting regional disparities in energy demand. Despite the rapid expansion of solar and wind power capacity in 2024, fossil fuels still accounted for approximately 85% of global primary energy consumption, with coal alone contributing more than 27% [4].

The extensive use of fossil fuels for electricity generation continues to result in high carbon dioxide emissions, particularly in the context of increasing energy demand from developing economies. Consequently, coal-fired power plants remain a cornerstone of energy systems in many countries [5]. At the same time, the adoption and gradual implementation of the Paris Agreement [6] and related international climate frameworks have intensified global efforts to reduce greenhouse gas emissions and accelerate the transition toward low-carbon energy systems.

According to data from Statistics Poland [7,8], the primary energy consumption structure in Poland in 2024 was dominated by hard coal, crude oil, and natural gas. Despite a downward trend, these energy carriers accounted for a total of 4039.3 PJ, whereas renewable energy sources contributed 618.8 PJ. The Directive 2009/28/EC of the European Parliament and of the Council [9] established a national target of 15% of gross national energy consumption to be from renewable energy sources by 2020 in Poland. This target was exceeded, reaching (16.1%).

The updated Directive (EU) 2023/2413 [10] introduced more ambitious targets for Member States by 2030. In 2024, the share of renewable energy in Poland's gross final energy consumption reached 17.7%, with a declared target of 21% by 2030 [8,11,12]. In 2023, solid biofuels dominated renewable primary energy production in Poland, accounting for 60.1% (EU average: 37%), whereas liquid biofuels and biogas contributed only 7.7% and 2.7%, respectively [7,8].

Analyses of inland renewable energy consumption by energy carriers reveal the continued dominance of solid biofuels (55.6%). However, household energy consumption per capita in 2023 indicates that hard coal remains a significant energy source in Poland, exceeding 20% of total consumption, compared with an EU average of only 2.2% [7,8]. These figures highlight the persistent dependence on coal and underscore the need for alternative, sustainable biomass resources.

Ongoing economic growth, increasing environmental degradation, and the gradual depletion of fossil fuel reserves have stimulated research into alternative energy carriers capable of supporting the energy sector [13]. Expanding the share of renewable energy sources has become a key component of energy transition strategies worldwide and is widely recognized as a necessary pathway toward sustainable development [5].

Under Polish legislation, solid fuels include not only coal but also biomass derived from trees, shrubs, and agricultural plant materials [14]. Within this category, biomass originating from semi-natural grasslands represents a largely underexplored resource. Among such biomass types, sedges (*Carex* spp.) constitute a particularly promising group.

Sedges are perennial herbaceous plants belonging to the family *Cyperaceae* and are widely distributed across diverse climatic zones and habitat types. The *Cyperaceae* family plays an important ecological and economic role, especially in wetland and marsh ecosystems [15,16]. Species of the genus *Carex* display two primary growth forms—tussock-forming and rhizomatous—both of which are associated with high biomass productivity and rapid vegetative expansion.

Although sedges are capable of sexual reproduction through seed formation, vegetative propagation is often the dominant mode of expansion. Seed germination is frequently limited by morphological constraints, such as the presence of a persistent perigynium, which may delay or inhibit emergence [17]. Consequently, many *Carex* species exhibit substantial annual biomass accumulation through clonal growth. Large rhizomatous species, such as *Carex riparia*, can form extensive monospecific stands characterized by high biomass yields within a single growing season [18–21].

The area of wetland resources in Poland in 2024 was estimated at approximately 4.4 million hectares, which corresponds to 14.2% of the total area of the country [22]. The area occupied by tall sedge communities accounts for less than 3% of the land [23] and is mainly concentrated in river valleys, with most of these areas being used for agricultural purposes. Due to the low forage value of the hay, it is primarily harvested for use as bedding for livestock.

The high productivity and widespread occurrence of this annual species make it a reasonable renewable energy feedstock. Despite their abundance in natural and semi-natural ecosystems, sedges remain underrepresented in studies addressing biomass-based energy production. Although interest in herbaceous biomass for bioenergy applications is increasing, information on the energy-related properties of *Carex* species remains limited. Previous studies have focused on their biomass productivity potential and ecological significance, while their energy-related properties are not fully understood. The present study addresses this gap by providing a comprehensive evaluation of the energy properties of select sedge species, including analysis of the structural composition of biomass and basic fuel parameters, which allows for a more objective assessment of their suitability as feedstock for energy production.

The aim of this study was to evaluate the energy potential of select *Carex* species based on their chemical composition and fuel parameters. The aim of this study was to evaluate and identify *Carex* species suitable as renewable lignocellulosic energy feedstock.

2. Materials and Methods

2.1. Material Collection

Field studies and the collection of plant material in the form of aboveground biomass of select sedge species were conducted during the 2014 growing season. In the same year, chemical composition analyses of the collected material were also performed.

Eight *Carex* species commonly occurring in Poland and frequently found in plant communities associated with river valleys were selected for the study. The investigated species included *Carex praecox* Schreb., *C. riparia* Curt., *C. spicata* Huds., *C. pilulifera* L., *C. diandra* Schrank, *C. vulpina* L., *C. brizoides* L., and *C. leporina* L. were selected for the study. Plant material was collected exclusively from natural stands.

Species were selected to represent a broad range of morphological growth forms and ecological strategies, which directly influence energy value. To facilitate the interpretation of interspecific differences, a brief characterization of the individual species is presented in Table 1.

The study area encompassed the Warta River valley and included five sampling locations: Olchowo (52°10'52" N, 17°56'56" E)—*C. diandra*; Radojewo (52°29'52" N, 16°58'02" E)—*C. praecox* and *C. riparia*; Słonawy (52°39'57" N, 16°47'13" E)—*C. vulpina* and *C. brizoides*; Obrzycko (52°42'03" N, 16°35'42" E)—*C. spicata*; and Sieraków (52°38'15" N, 16°03'49" E)—*C. leporina* and *C. pilulifera*. The sites are located within or adjacent to protected areas belonging to the Natura 2000 network, including Ostoja Nadwarciańska (PLH300009), Biedrusko (PLH300001), Puszcza Notecka (PLB300015), Dąbrowy Obrzyckie (PLH300003), and Ostoja Międzychodzko–Sierakowska (PLH300032).

Table 1. Characteristics of selected sedge species.

Species	Morphology	Habitat	Association
<i>C. praecox</i>	low-growing plant (10–40 cm) forming thin, elongated rhizomes, often producing spatially separated shoots that may intergrow with neighboring individuals and form extensive patches	plant communities associated with dry habitats	frequently as a pioneer species in open habitats
<i>C. riparia</i>	large plant (80–200 cm), rhizomatous and stoloniferous with thick culms and wide leaves, forming dense and often monospecific patches with high biomass production	wet to moist, frequently recorded in stagnant waters or low peat bogs	characteristic of the <i>Caricetum ripariae</i>
<i>C. spicata</i>	medium height plant (20–60 cm) (morphological variability of tussock size often depends on the type of the plant community) forms dense, well-foliated tussocks with numerous flowering culms	it exhibits a broad ecological amplitude, but most commonly occurs in moderately moist, slightly shaded habitats such as grasslands, pastures, lawns, and forest edges	most often in <i>Epilobietea angustifolii</i> ; can also be found in <i>Trifolio-Geranietea sanguinei</i> and <i>Rhamno-Prunetea</i>
<i>C. pilulifera</i>	forms small to moderately dense tussocks with leaves distinctly shorter than the culms	it typically grows on nutrient-poor soils, often in forests or at forest margins, and shows high tolerance to water deficit	characteristic of the <i>Hieracio (vulgati)-Nardetum</i> , <i>Nardo-Callunetea</i> and <i>Quercetea robori-petraeae</i>
<i>C. diandra</i>	produces loose, large tussocks with long, slender culms and numerous delicate leaves	wet to moist and periodically flooded habitats, particularly transitional and low peatlands or their margins	characteristic of the <i>Caricetum diandrae</i>
<i>C. vulpina</i>	rhizomatous species forming fewer compact swords or occurring as scattered individuals. It is characterized by relatively robust culms and sparse foliage, with leaves produced at distinct intervals along the culm	wet and moist meadows, pastures, ditches, and the margins of both stagnant and flowing waters	characteristic of the <i>Caricetum vulpinae</i>
<i>C. brizoides</i>	develop long rhizomes and flexible, often reclining culms. It is distinguished by narrow, elongated leaves that frequently exceed the culm length. When growing in dense stands, it forms characteristic patches with high biomass production	occurs mainly in moist habitats, particularly deciduous forests, forest clearings, and semi-shaded sites	most often in <i>Quercio-Fagetea</i>
<i>C. leporina</i>	forms relatively dense tussocks with stiff culms and leaves distinctly shorter than the culms, typically confined to the basal part	low habitat requirements and is commonly found in moist meadows and pastures, as well as grasslands and forest margins	most often in <i>Molinio-Arrhenatheretea</i> , <i>Nardetalia</i> and <i>Caricetalia fuscae</i>

The Wielkopolska region is characterized by a lowland landscape and seasonal variation in isotherm orientation, with zonal patterns prevailing in summer and meridional patterns in winter. The mean annual air temperature is approximately 8.5 °C, with a spatial gradient of up to 0.9 °C between the northern and south-western parts of the region. Annual precipitation totals range from 500 to 550 mm, although lower values—by up to 100 mm—are occasionally recorded in the Gniezno Lakeland region [24].

Given that all sampling sites are located within the Warta River valley, meteorological data from the Poznań–Ławica station were used as representatives of the study area. Long-term climate data for the period 1991–2020 indicate a mean annual temperature of 9.4 °C and average annual precipitation of 538.9 mm. July is characterized by the highest mean temperature (19.5 °C) and precipitation (84.4 mm), whereas January records the lowest mean temperature (−0.4 °C). The lowest monthly precipitation totals occur in April (28.6 mm) and February (30.7 mm) [25].

Biomass samples (in three replications) were collected from plant communities in which the target species exhibited the highest constancy and abundance. These communities occurred mainly on medium-quality grasslands (2z) as well as poor and very poor grasslands (3z), developed on alluvial soils, silty peat soils, and organic–mineral and muck soils. Soil texture types included light loamy sands, weakly loamy sands, loose sands, and light loams [26].

2.2. Chemical Composition

The determination of the basic chemical components of the biomass was performed using standard analytical methods commonly applied to plant-derived raw materials, following the procedures described in previous studies [27,28]. The following parameters were determined:

- Cellulose content using the acetylacetone and dioxane method according to Seifert [29].
- Lignin content using 72% nitric acid [30].
- Holocellulose content using the sodium chlorite method [31].

All results are expressed as a percentage of dry matter. The theoretical hemicellulose content was calculated as the arithmetic difference between holocellulose and cellulose contents. Ash content was determined in accordance with the DIN 51731 standard [32]. Gross calorific value (GCV), also referred to as higher heating value (HHV), represents the total amount of heat released during the complete combustion of fuel when the water produced during combustion is fully condensed. Net calorific value (NCV), also known as lower heating value (LHV), represents the useful heat obtained from combustion after subtracting the latent heat of vaporization of water formed during the combustion process. In this study, GCV was determined experimentally using a bomb calorimeter according to PN-81/G-04513 [33], whereas NCV was calculated from the obtained GCV values.

2.3. Statistical Analysis

To access differences among the studied sedge species, a permutational multivariate analysis of variance (PERMANOVA) was performed. This method was selected due to its suitability for multivariate datasets and its robustness to deviations from normality.

Moreover, differences among mean values of chemical composition parameters, including cellulose, lignin, holocellulose, and hemicellulose contents, as well as ash content, gross calorific value (GCV), and net calorific value (NCV), were evaluated using one-way analysis of variance (ANOVA). This approach was chosen as an appropriate method for comparing means across multiple independent groups.

Post hoc comparisons between individual *Carex* species were performed using Tukey's honest significant difference (HSD) test at a significance level of $p < 0.05$. Additionally, the coefficient of variation was calculated for all parameters of chemical composition as well as for the NCV and GCV.

Differences and similarities among the analyzed *Carex* species were further explored using hierarchical cluster analysis. Clustering was performed using the unweighted pair-group method with arithmetic mean (UPGMA) and the Bray–Curtis similarity index. These methods were selected due to their widespread application in ecological and environmental studies and their suitability for quantitative compositional data. The dendrograms presented in this study were created separately for each analyzed parameter.

The Bray–Curtis similarity measure allows for the assessment of differences based on both the presence and relative proportions of variables, making it particularly useful for ecological datasets. The combination of Bray–Curtis similarity and UPGMA clustering enables the visualization of similarity patterns and the identification of the groups based on multivariate relationships.

Additionally, to illustrate the structural composition of sedge biomass, a scatter plot was prepared showing the proportions of cellulose, hemicellulose, and lignin. Pearson's correlation analysis was also performed to evaluate relationships between chemical composition and energy parameters.

All statistical analyses were conducted using R software version 4.4.0 [34], with the *agricolae* [35], *dplyr* [36], and *vegan* [37] packages. Dendrograms, Pearson correlation result, and scatter plot of biomass structural composition were visualized using PAST 4.16c software [38,39] while principal component analysis (PCA) was performed using R [34].

3. Results and Discussion

The chemical composition of plant biomass is influenced by multiple factors, including species, growth conditions, habitat type, and the part of the plant. Even within a single species, substantial variation in the proportion of individual components may occur [40–42].

Multivariate analysis revealed statistically significant differences in chemical composition, ash content, NCV, and GCV among the analyzed sedge species ($F = 25.12$; $p = 0.001$). Species as a factor explained 91.7% of the total variance in the dataset ($R^2 = 0.917$), indicating a very strong separation among the analyzed groups. Additionally, the analyzed parameters exhibited high discriminatory power, enabling effective differentiation of individual sedge species.

Furthermore, the univariate analyses confirmed statistically significant differences in all major chemical composition components among the investigated *Carex* species (Table 2).

Statistically significant differences were observed among the analyzed *Carex* species for all major chemical components. In the case of cellulose and lignin contents, four homogeneous groups ("a–d") and one subgroup ("bc") were distinguished. Holocellulose content formed three homogeneous groups ("a", "b", "d") and two subgroups ("bc", "cd"), whereas hemicellulose content was characterized by five homogeneous groups ("a–e") and one subgroup ("bc").

The coefficients of variation (CV) calculated for all analyzed components across the investigated *Carex* species were low, generally not exceeding 2%. This low variability indicates high repeatability of the measurements and confirms the representativeness and stability of the analyzed samples. Additionally, a scatter plot illustrating the structural composition of the biomass is presented in Figure 1.

Table 2. Main components of selected grass species with statistically significant differences (Tukey’s test) and coefficient of variation (CV). Mean values with standard deviation for each species are presented (statistically significant at $p < 0.05$).

Species	Lignin [%]	CV	Cellulose	CV	Hemicellulose	CV	Holocellulose	CV
<i>C. praecox</i>	13.0 ^d ± 0.26	2.04	29.9 ^d ± 0.70	2.34	20.2 ^b ± 0.46	2.27	50.1 ^d ± 1.15	2.30
<i>C. riparia</i>	25.3 ^a ± 0.59	2.31	42.8 ^a ± 0.91	2.12	12.2 ^e ± 0.36	2.96	55.0 ^{bc} ± 1.27	2.30
<i>C. spicata</i>	13.1 ^d ± 0.26	2.02	30.1 ^d ± 0.70	2.33	22.9 ^a ± 0.53	2.31	53.0 ^{cd} ± 1.23	2.32
<i>C. pilulifera</i>	19.0 ^{bc} ± 0.44	2.29	37.8 ^b ± 0.89	2.35	19.0 ^{bc} ± 0.44	2.29	56.8 ^b ± 1.32	2.33
<i>C. diandra</i>	19.9 ^b ± 0.44	2.19	37.7 ^b ± 0.89	2.36	22.6 ^a ± 0.49	2.18	60.3 ^a ± 1.38	2.29
<i>C. vulpine</i>	19.1 ^{bc} ± 0.44	2.28	34.9 ^c ± 0.79	2.27	14.9 ^d ± 0.36	2.42	49.8 ^d ± 1.15	2.32
<i>C. brizoides</i>	18.3 ^c ± 0.44	2.38	37.8 ^b ± 0.89	2.35	16.1 ^d ± 0.35	2.15	53.9 ^{bc} ± 1.23	2.28
<i>C. leporine</i>	18.7 ^c ± 0.44	2.33	35.9 ^{bc} ± 0.79	2.21	18.9 ^c ± 0.44	2.31	54.8 ^{bc} ± 1.23	2.24
Mean	18.3 ± 3.78	20.66	35.9 ± 4.15	11.57	18.4 ± 3.59	19.51	54.2 ± 3.45	6.36

^{a, b, c, d, e}—homogeneous groups.

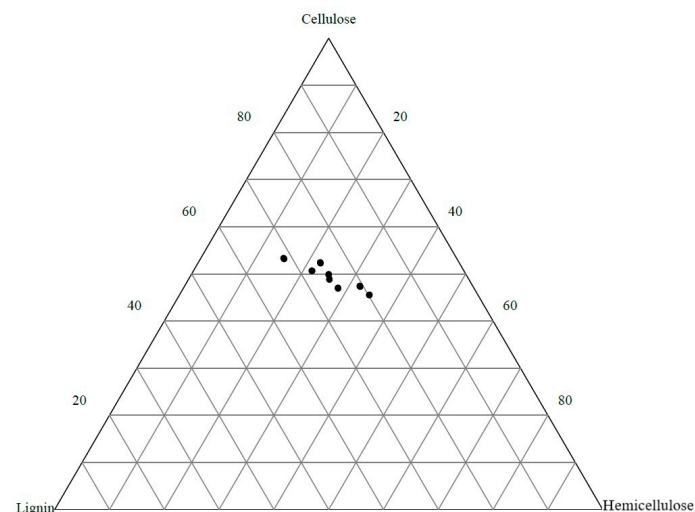


Figure 1. Scatter plot of structural composition of sedges biomass.

The lowest lignin contents (Table 2) were recorded in *C. praecox* (13.0%) and *C. spicata* (13.1%), whereas the highest lignin content, similar to cellulose, was observed in *C. riparia* (25.3%). The remaining sedge species exhibit lignin content ranging from 18.3% to 19.9%. The mean lignin across all analyzed species was 18.3%, with a coefficient of variation (CV) of 20.66%. Comparable lignin contents (16.8–19.2%) for other sedge species were reported by Grzelak et al. [43], while Czubaszek et al. [44] reported values of 16.0% and 20.8%. Considerable variation in lignin content has also been observed among grasses and other monocotyledonous plants, even when originating from similar habitats [42,44]. Bamboo represents an extreme example, with lignin contents reported in the range of 21.9–29.7% [45] and even as high as 39–46% [46].

The mean cellulose content in the analyzed *Carex* species ranged from 29.9% in *C. praecox* to 42.8% in *C. riparia*. Cellulose content in *C. spicata* was 30.1% while the remaining species exhibited comparable cellulose levels, ranging from 34.9% to 37.8%. The mean cellulose content across all analyzed species was 35.9%, with a coefficient of variation (CV) of 11.57%.

Comparable cellulose contents have been reported in the literature for other sedge species. Grzelak et al. [43] reported values ranging from 31.5% to 40.61% for *C. vesicaria*, *C. rostrata*, *C. panicea*, *C. lasiocarpa*, and *C. elata*. Lower cellulose contents were reported by Czubaszek et al. [44] for *C. elata* (26.8%) and for a mixture of *C. acutiformis* and *C. elata* (29.4%). Similar cellulose levels (35.1–38.7%) to those observed in the present study have also been reported for various grass species from Polish meadows [42]. In contrast, significantly higher cellulose contents have been documented for bamboo species, ranging from 40% to 75% [45], and even from 61% to 78% for *Bambusa vulgaris* [46]. These differences in cellulose content may be associated with species-specific anatomical structure and habitat conditions.

The total carbohydrate content, expressed as holocellulose, ranged from 49.8% to 60.3% in the analyzed sedge species, with a mean value of 54.2% and the lowest coefficient of variation among all components (CV = 6.36%). The highest holocellulose content was observed in *C. diandra*, whereas the lowest was recorded in *C. vulpina*. A relatively low holocellulose content (50.1%) was also found in *C. praecox*. In the remaining species, holocellulose content ranged from 53.0% to 56.8%. Similar values (48.98–57.15%) for sedge species were reported by Grzelak et al. [43]. In contrast, higher holocellulose contents, approximately 70%, have been reported for other monocotyledonous [42].

Hemicelluloses, representing low-polymerized structural carbohydrates, typically occur in plant biomass at levels of approximately 20–25%. In the present study, relatively low hemicellulose contents were observed in *C. riparia* (12.2%) and *C. vulpina* (14.9%), while slightly higher values were recorded for *C. brizoides* (16.1%). The highest hemicellulose contents were found in *C. spicata* (22.9%) and *C. diandra* (22.6%), although these values remain lower than those typically reported for grasses [41]. The mean hemicellulose content across all analyzed species was 18.4%, with a coefficient of variation (CV) of 19.51%. Considerably higher hemicellulose contents in monocotyledonous plants were reported by Czubaszek et al. [44].

Analysis of the similarity dendrogram (Figure 2) indicates that no clear relationships among the analyzed *Carex* species can be identified based on taxonomic affiliation, habitat preferences, or morphological traits.

In terms of cellulose content (Figure 2a), a distinct cluster is formed by *C. spicata* and *C. praecox*, with a similarity level slightly above 88%. *C. praecox* typically prefers sandy substrates, dry grasslands, and roadside habitats, whereas *C. spicata* exhibits a broader ecological amplitude that also includes habitats characteristic of *C. praecox*, such as well-insulated and relatively dry sites. Additionally, *C. spicata* is known to exhibit considerable morphological variability of its vegetative organs [47].

A species clearly separated from the remaining taxa is *C. riparia*, which diverges at the first similarity level (approximately 93%). This species is unique among the analyzed taxa in occupying permanently waterlogged habitats and sites with stagnant water throughout the growing season. It is highly probable that these specific habitat conditions contributed to the distinctiveness of *C. riparia* relative to the other species, including *C. praecox* and *C. spicata*, which originate from comparatively dry habitats.

The third cluster, formed at the second similarity level (approximately 97%), includes the remaining taxa and can be further divided into two closely related subgroups. The first subgroup, comprising *C. leporina* and *C. vulpina*, exhibits certain morphological similarities, primarily related to reduced leaf abundance in the second half of the growing season during the stage of full perigynium maturity. These species also share partially overlapping habitat requirements and may occur in similar ecological conditions, although they are not closely related taxonomically.

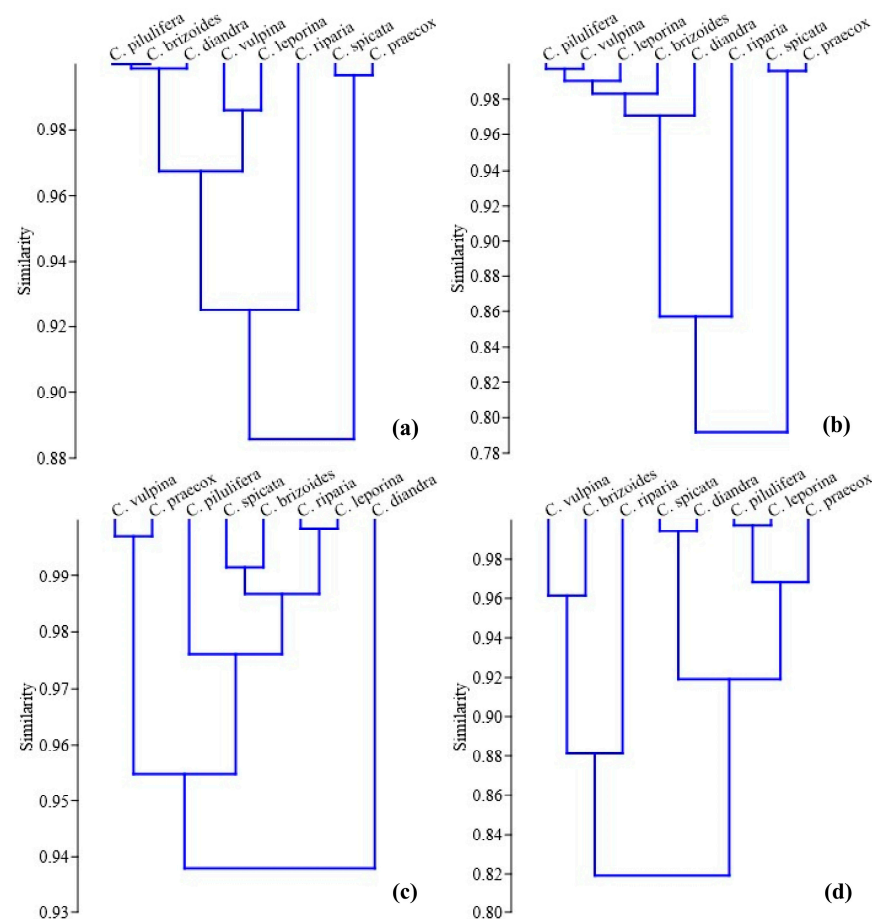


Figure 2. UPGMA-based classification dendrograms of cellulose “(a)”, lignin “(b)”, holocellulose “(c)”, and hemicellulose “(d)” contents in the biomass of the analyzed *Carex* species, constructed using the Bray–Curtis similarity index.

The second subgroup, consisting of *C. pilulifera*, *C. diandra*, and *C. brizoides*, does not show any clear associations in terms of the analyzed morphological or ecological traits.

For lignin content (Figure 2b), clustering patterns were similar to those observed for cellulose. A distinct group consisting of *C. spicata* and *C. praecox* was again identified, along with a separate position of *C. riparia*. The remaining five taxa formed a single cluster, which appears to reflect a gradient of habitat moisture preferences, with similarity reaching approximately 97%. This gradient ranges from the wettest habitats preferred by *C. diandra* to the relatively dry conditions characteristic of *C. pilulifera*.

In contrast, dendrograms based on holocellulose and hemicellulose contents (Figure 2c,d) did not reveal any clear relationships or grouping patterns among the analyzed *Carex* species.

The ash content of wood, which represents the most commonly used solid biomass fuel, is typically below 1% [40,48,49]. In contrast, annual and perennial herbaceous plants, such as sedges, grasses, and cereals, are characterized by substantially higher ash contents than woody biomass, with reported values reaching several tens of percent in extreme cases [50,51].

The analyzed *Carex* species exhibited considerable variation in ash content, which resulted in their classification into three homogeneous groups (“a”, “b”, “d”) and two subgroups (“bc” and “cd”) (Table 3). The mean ash content across all investigated sedge species was 6.4%, with a coefficient of variation (CV) of 20.47%, indicating substantial interspecific variability in mineral matter accumulation.

Table 3. Ash content, NCV, and GCV with statistically significant differences (Tukey’s test) and coefficient of variation (CV). Mean values with standard deviation for each sedge species are presented (statistically significant for $p < 0.05$).

Species	Ash	CV	NCV	CV	GCV	CV
	[%]		[MJ·kg ^{−1}]	[%]	[MJ·kg ^{−1}]	[%]
<i>C. praecox</i>	6.9 ^b ± 0.20	2.90	17.8 ^a ± 0.14	0.78	19.8 ^a ± 0.23	1.18
<i>C. riparia</i>	9.2 ^a ± 0.50	5.43	16.6 ^b ± 0.48	2.90	17.7 ^c ± 0.39	2.20
<i>C. spicata</i>	6.6 ^b ± 0.31	4.65	18.0 ^a ± 0.13	0.70	19.5 ^{ab} ± 0.15	0.77
<i>C. pilulifera</i>	6.7 ^b ± 0.40	6.06	17.2 ^{ab} ± 0.13	0.75	18.8 ^b ± 0.21	1.13
<i>C. diandra</i>	5.4 ^{cd} ± 0.31	5.69	17.5 ^a ± 0.06	0.34	19.2 ^{ab} ± 0.26	1.34
<i>C. vulpina</i>	5.0 ^d ± 0.36	7.21	17.8 ^a ± 0.40	2.25	19.3 ^{ab} ± 0.46	2.40
<i>C. brizoides</i>	5.3 ^{cd} ± 0.20	3.77	17.8 ^a ± 0.41	2.30	19.5 ^{ab} ± 0.30	1.54
<i>C. leporina</i>	6.2 ^{bc} ± 0.42	6.68	18.0 ^a ± 0.18	1.01	19.2 ^{ab} ± 0.61	3.17
Mean	6.4 ± 1.31	20.47	17.6 ± 0.52	2.96	19.1 ± 0.68	3.55

^{a, b, c, d}—homogeneous groups.

The highest ash content (9.2%) was recorded for *C. riparia*, whereas the lowest value (5.0%) was observed in *C. vulpina*. The coefficient of variation calculated for individual species ranged from 2.90% to 7.21%. Four of the analyzed sedge species contained mineral matter in the range of 6.2–6.9%, while *C. brizoides* and *C. diandra* exhibited lower ash contents of 5.3% and 5.4%, respectively.

In studies conducted by Grzelak et al. [52], ash contents of 8.1% and 8.6% were reported for *C. praecox* and *C. riparia*, respectively, whereas values for other sedge species ranged from 6.8% to 8.2%. Similarly, Grzelak et al. [43] reported higher ash contents in sedges, ranging from 6.9% to 7.8%. Lower ash contents were reported by Zajac et al. [51] for miscanthus and common reed biomass (2.36–3.63%). For comparison, Liang et al. [45] reported ash contents in bamboo ranging from 1.17% to 3.77%, while Pochwatka et al. [53] reported an ash content of 7.3% for tobacco biomass, representing dicotyledonous plants.

Ash content is a critical parameter for biomass intended for combustion, as its physical properties may adversely affect combustion processes and necessitate the use of specialized boilers to prevent operational issues such as grate clogging or slag formation [54].

Analysis of the NCV of the investigated sedge species (Table 2) revealed that the highest values, reaching 18.0 MJ·kg^{−1} (mean: 17.6 MJ·kg^{−1}), were recorded for *C. spicata* and *C. leporina*. In contrast, the lowest NCV (16.6 MJ·kg^{−1}) was observed for *C. riparia*, which was the only species assigned to homogeneous group “b” and exhibited the highest coefficient of variation (CV = 2.90%). This result confirms the comparatively unfavorable energetic properties of *C. riparia*.

The remaining *Carex* species displayed more favorable characteristics, with NCV values ranging from 17.2 to 18.0 MJ·kg^{−1}. These values indicate that most of the analyzed sedge species can be classified as energetically valuable lignocellulosic biomass resources. Lower NCV values for sedges were reported by Grzelak et al. [43,52], ranging from 15.8 to 16.9 MJ·kg^{−1} and from 16.0 to 18.7 MJ·kg^{−1}, respectively. In particular, *C. riparia* and *C. praecox* analyzed by Grzelak et al. [52] exhibited lower energy values than those reported in the present study. Lower NCV values were also reported for various grass species (excluding *Calamagrostis epigejos*) by Waliszewska et al. [42], as well as for tobacco biomass by Pochwatka et al. [53].

The GCV values of the analyzed *Carex* species were relatively high and, for most taxa, ranged from 19.2 to 19.8 MJ·kg^{−1} (homogeneous group “a” and subgroup “ab”), with an overall mean of 19.1 MJ·kg^{−1} (Table 3). Only *C. riparia* exhibited a distinctly lower GCV (17.7 MJ·kg^{−1}), comparable to values reported by Grzelak et al. [52]. The mean coefficient of variation for all species was 3.55%, exceeding the CV values calculated for individual taxa (0.77–3.17%).

The relatively high GCV of sedge biomass are comparable to those reported for various willow clones, ranging from 18.3 to 18.7 MJ·kg^{−1} (dry matter) [55]. Similarly, Krzyżaniak et al. [41] reported GCV values of 19.36–19.58 MJ·kg^{−1} for seven willow clones, while Stolarski et al. [56] reported an average GCV of approximately 20 MJ·kg^{−1} for poplar wood. The comparable GCV of sedge biomass relative to willow and poplar wood indicates that *Carex* species are a valuable plant-based biomass suitable for energy production. Additionally, it is worth noting the energetic potential of bamboo biomass, which—despite its absence in Poland—exhibits GCV ranging from 18 to 21 MJ·kg^{−1} [45].

The results of the Pearson correlation analysis are presented in Figure 3. Cellulose content showed a positive correlation with lignin and ash content, whereas negative correlations were observed with hemicellulose content and NCV, amounting to −0.61 and −0.68, respectively. The negative correlation between cellulose and hemicellulose is contrary to the results reported by Park et al. [57]. This discrepancy may be because the cited authors investigated dicotyledonous species and wood, which are characterized by relatively high cellulose content, whereas the present study focused on monocotyledonous sedge species. A moderate negative correlation was also observed between lignin content and NCV (−0.69). In contrast, hemicellulose was the only structural component positively correlated with NCV (0.46), which may appear unusual, as this relationship has been reported as negative for wood and dicotyledonous plants [57]. Additionally, a negative correlation was observed between ash content and NCV (−0.60), which is consistent with previous studies indicating that higher mineral content generally reduces the fuel quality of biomass. In general, lignin is considered the biomass component most strongly associated with higher calorific value due to its higher aromaticity and carbon content compared with cellulose and hemicellulose. However, the correlations obtained in the present study suggest that, within the analyzed sedge biomass, hemicellulose content showed the strongest positive association with NCV.

This pattern may reflect species-specific structural characteristics of sedge biomass as well as the relatively narrow range of variation observed for lignin and cellulose contents among the analyzed species. Nevertheless, due to the limited number of analyzed species, these relationships should be interpreted with caution. And require further verification in broader studies, including a larger number of taxa and environmental conditions.

To determine the range and the direction of variability of the analyzed chemical composition parameters, a principal component analysis (PCA) was performed (Table 4, Figure 4). The eigenvalues of the first two principal components (2.72 and 0.80) explained 87.9% of the total variability of the dataset (PC1—68%, PC2—19.9%), indicating that the ordination adequately represents the relationships among the analyzed species.

The relationships between the PCA axes and the analyzed parameters indicate a strong positive association between lignin (1.478) and cellulose (1.433). The taxa are arranged along PC1 according to increasing contents of plant cell wall components, indicating their dominance relative to hemicellulose.

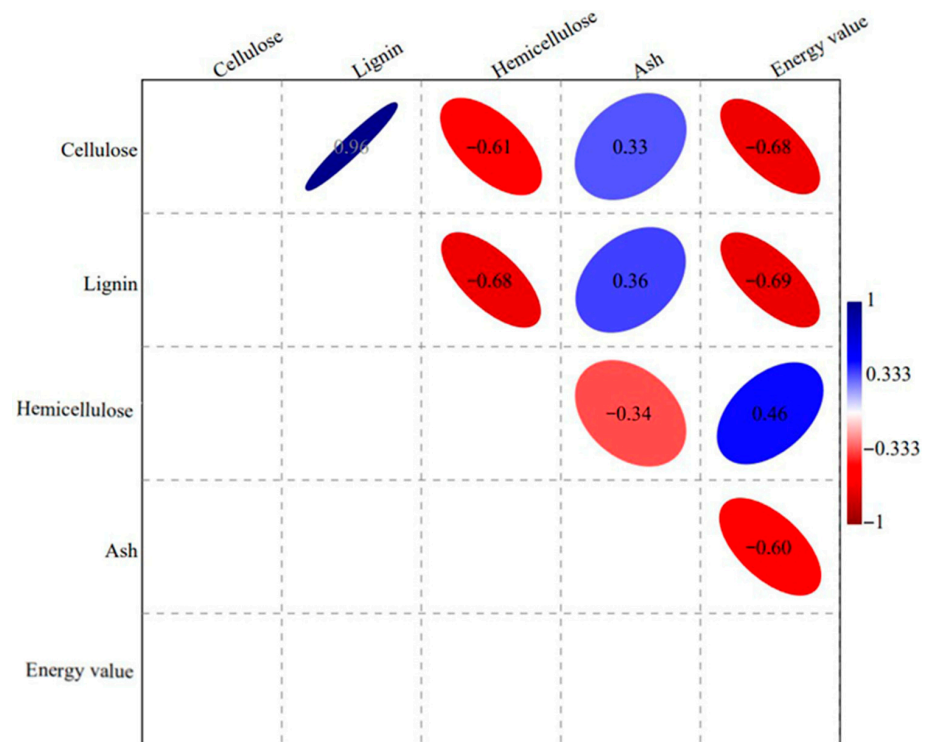


Figure 3. Result of Pearson correlation coefficient.

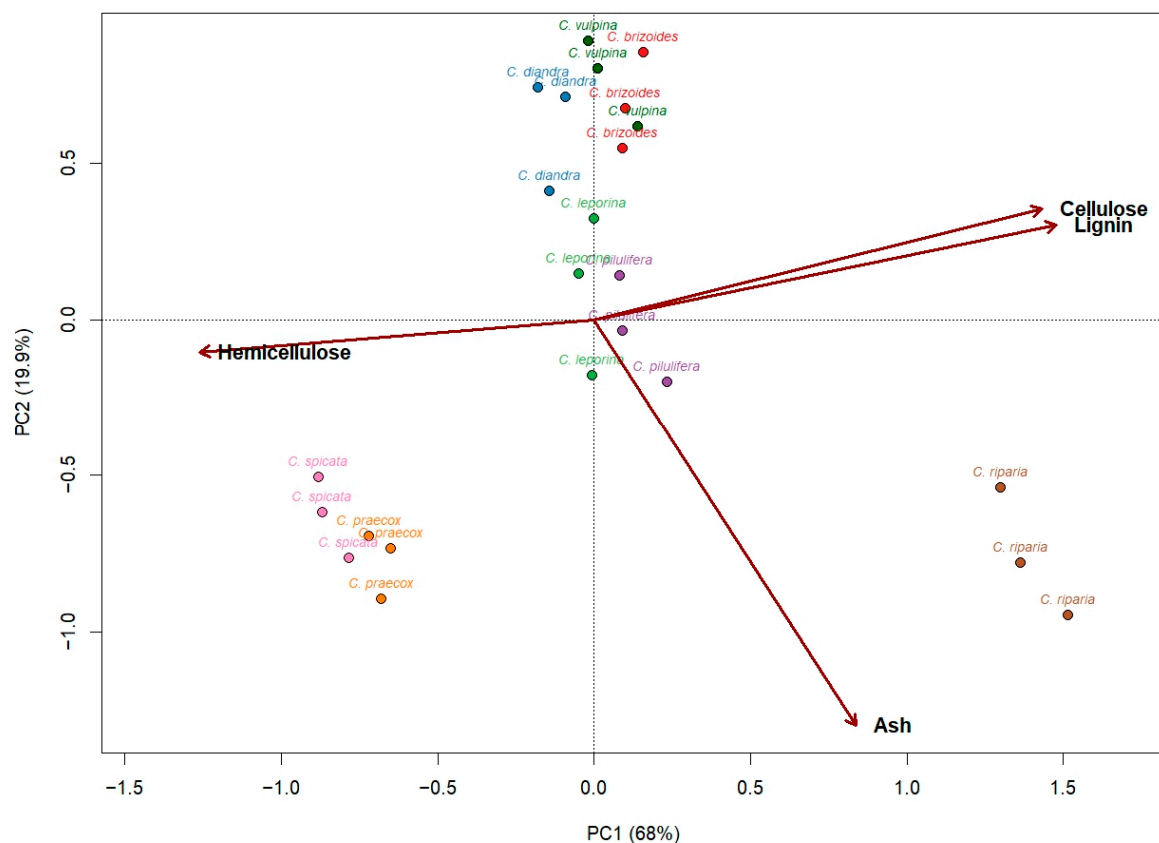


Figure 4. PCA analysis of selected chemical composition factors (lignin, cellulose, hemicellulose, ash) along the first two coordinate axes. The species are color-coded: pink—*C. spicata*, orange—*C. praecox*, purple—*C. pilulifera*, brown—*C. riparia*, blue—*C. diandra*, dark green—*C. vulpina*, green—*C. leporina*, red—*C. brizoides*.

Table 4. Correlation coefficients between the PCA axes and lignin, cellulose, hemicellulose, and ash.

Axis	1	2	3	4
Eigenvalue	2.72	0.80	0.45	0.03
Variance [%]	68.0	19.9	11.2	0.8
Lignin	1.478	0.303	−0.282	−0.208
Cellulose	1.433	0.354	−0.430	0.189
Hemicellulose	−1.261	−0.104	−0.893	−0.026
Ash	0.837	−1.298	−0.111	0.005

The results also show a negative relationship between PC2 and ash content, allowing a clear separation of species characterized by a higher capacity for mineral accumulation from those with lower ash contents. The distribution of species in the ordination space suggests that the analyzed sedges form distinct functional groups in terms of both structural traits and chemical composition.

To further emphasize the relationships between chemical composition and energy-related parameters, an additional PCA analysis was performed, including lignin, hemicellulose, ash content, and NCV (Table 5, Figure 5). The first two principal components explained 84.3% of the total variability of the dataset (PC1—64.8%, PC2—19.95%).

Table 5. Correlation coefficients between the PCA axes and lignin, hemicellulose, ash, and NCV.

Axis	1	2	3	4
Eigenvalue	2.59	0.78	0.44	0.19
Variance [%]	64.8	19.5	10.9	4.8
Lignin	1.346	−0.498	0.360	0.457
Hemicellulose	−1.200	0.715	0.623	0.240
Ash	1.076	0.996	−0.461	0.193
NCV	−1.343	−0.341	−0.565	0.398

The ordination results indicate a strong negative relationship between NCV and both lignin and ash content along the first principal component (NCV −1.343; lignin 1.346; ash 1.076). The analyzed taxa are arranged along a gradient from species characterized by lower ash and lignin contents to those with higher proportions of these components.

Hemicellulose was negatively associated with lignin but was positioned on the same side of the ordination space as NCV, suggesting that species with higher calorific values tend to have lower ash content, even when the hemicellulose proportion is relatively high. These results indicate that ash content may play a more important role in determining NCV than the proportion of high-energy lignin alone.

The second principal component analysis showed a positive relationship between ash content (0.996) and hemicellulose (0.715). The distribution of species along this axis suggests differentiation between taxa characterized by higher hemicellulose and ash contents (positive PC2 values) and those dominated by lignin in their structural composition.

These results indicate that the energetic quality of the analyzed sedge biomass is determined not only by the proportion of structural components such as lignin and hemicellulose but also strongly influenced by ash content, which may significantly affect the practical suitability of individual *Carex* species as solid biofuel feedstocks.

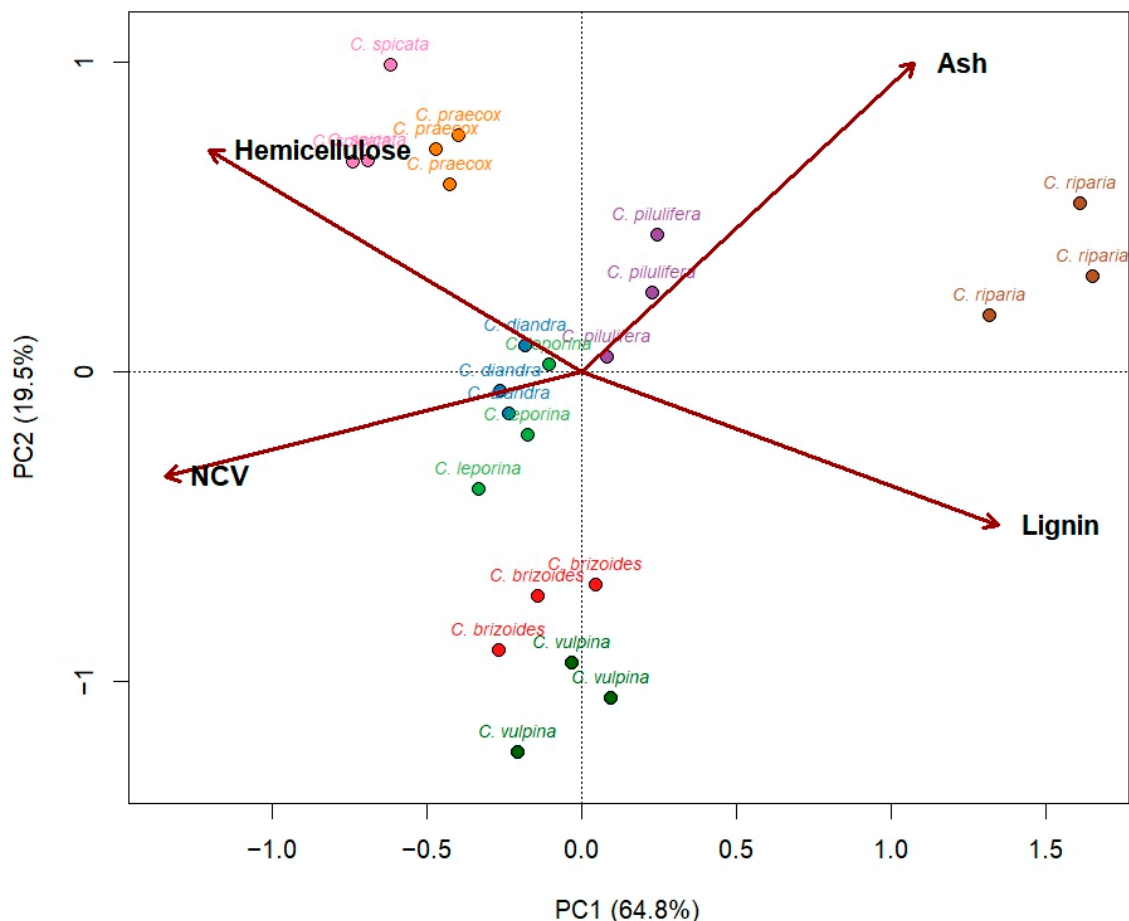


Figure 5. PCA analysis of selected chemical composition components (lignin, hemicellulose, ash) and NCV along the first two coordinate axes. The species are color-coded: pink—*C. spicata*, orange—*C. praecox*, purple—*C. pilulifera*, brown—*C. riparia*, blue—*C. diandra*, dark green—*C. vulpina*, green—*C. leporina*, red—*C. brizoides*.

The dendrogram illustrating ash content in the analyzed samples (Figure 6a) clearly indicates a pronounced separation of *C. riparia*. As noted previously, this species is unique among the analyzed taxa in occupying specific habitats characterized by frequent and prolonged water stagnation. Moreover, in contrast to the remaining species, *C. riparia* develops robust, thick culms and exhibits a high biomass accumulation within a single growing season.

The two remaining clusters suggest a division primarily driven by habitat moisture conditions. *C. spicata*, *C. pilulifera*, *C. leporina*, and *C. praecox* typically occur under comparatively drier soil conditions, whereas *C. brizoides*, *C. vulpina*, and *C. diandra* are associated with more humid habitats.

For NCV (Figure 6b), *C. riparia* again forms a distinct cluster, which may be attributed to its specific morphological and ecological characteristics. Within the group formed by the remaining species, two subgroups can be distinguished at the first similarity level (exceeding 98%). However, no clear or meaningful taxonomic, morphological, or habitat-related relationships can be identified within these subgroups. A similar pattern is observed for GCV (Figure 6c), where *C. riparia* is clearly separated from the other species. This distinctiveness is most likely related to its unique morphology, including large size, structural rigidity, specific habitat preferences, and rapid biomass accumulation rate. The remaining seven *Carex* taxa do not exhibit any clear mutual relationships in the dendrogram.

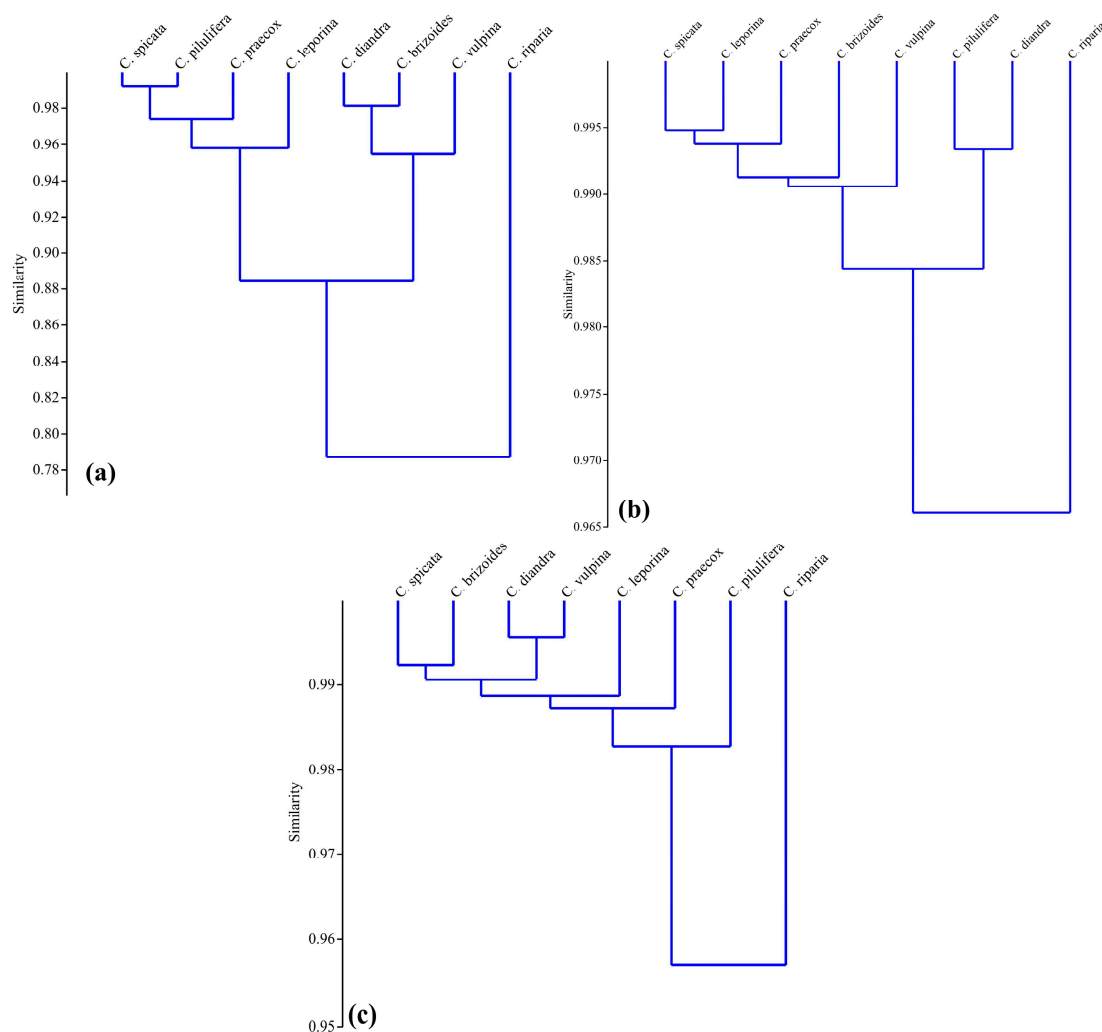


Figure 6. UPGMA-based classification dendrograms of ash content “(a)”, NCV “(b)”, and GCV “(c)” in the biomass of the analyzed *Carex* species, constructed using the Bray–Curtis similarity index.

A key factor determining the energy properties of fuels is their chemical composition, which affects both the calorific value and the course of thermochemical conversion processes [58–62]. In the case of fossil fuels, the high content of carbon and hydrogen is one of the main factors responsible for their high calorific value [63,64]. In contrast, the energy properties of plant biomass are largely related to the structural composition of the cell wall, primarily including lignin, cellulose, and hemicellulose, as well as ash content. These components influence both the calorific value of biomass and the course of combustion and other thermochemical conversion processes; therefore, their analysis is essential for assessing the suitability of biomass as a renewable energy source. Although this aspect was not directly addressed in the present study, it has been discussed in earlier publications by Janyszek et al. [65,66]. In contrast to liquid crude oil and gaseous natural gas, solid fossil fuels such as hard coal and lignite are characterized by the presence of inherent moisture, hygroscopic behavior, and measurable ash content [64,67]. Nevertheless, the high concentrations of carbon and hydrogen remain the principal factors determining the calorific value of fossil fuels.

The calorific value of lignocellulosic biomass is generally lower than that of fossil fuels, but it is comparable to many other types of biomass currently used for energy production (Figure 7).

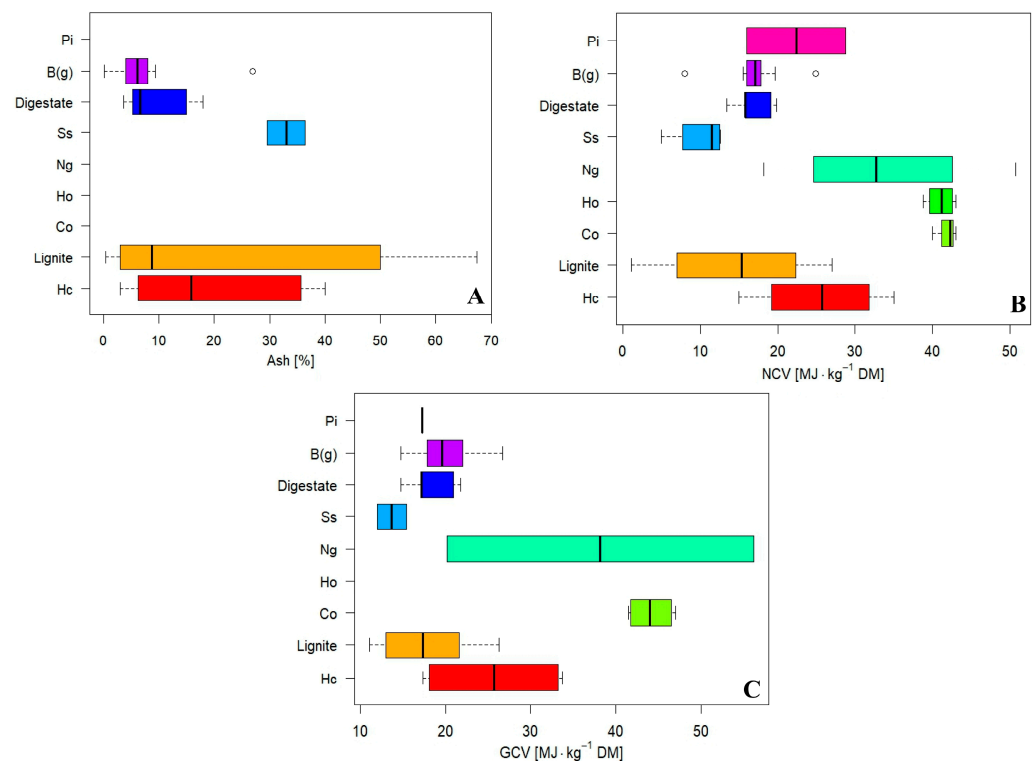


Figure 7. Ash content (A), NCV (B), and GCV (C) of selected solid and liquid conventional fuels and alternative energy sources, based on selected literature sources. Hc—hard coal [59,60,64,68–71], lignite [13,59,61,67–73], Co—crude oil [3,74], Ho—heating oil [70,75,76], Ng—natural gas [59,70,76], Ss—sewage sludge [68,77,78], Digestate [13,54,79], B(g)—biomass (general) [51,59,68,69,71,80] and Pi—pulp industry [77].

The calorific values obtained in the present study indicate that sedge biomass may represent a promising alternative to traditional solid fuels. For example, the calorific value of hard coal typically ranges from approximately 24 to 30 MJ · kg⁻¹, while lignite usually ranges from 8 to 15 MJ · kg⁻¹. In the case of woody biomass, calorific values commonly range between 18 and 20 MJ · kg⁻¹, whereas cereal straw typically exhibits values of approximately 16–18 MJ · kg⁻¹. The values obtained in this study for sedge biomass fall within the range typical for lignocellulosic biomass, indicating its potential suitability as a renewable fuel source. However, it should be emphasized that, in addition to calorific value, other fuel-related parameters, such as ash content and structural biomass composition, are also important. The variation observed among the analyzed sedge species suggests that suitability as an energy feedstock may differ among species. In the context of the increasing importance of renewable energy sources and the need to utilize biomass from wetland and marginal habitats, sedges may represent an attractive bioenergy resource, particularly within local biomass utilization systems.

Fossil fuels constitute a valuable source of energy; however, their resources are finite. In contrast, the availability and energetic properties of alternative energy sources are determined by different factors. In the case of wood and wood-derived fuels, the amount of energy obtained depends primarily on species composition, chemical structure, and moisture content, while the time required for feedstock acquisition is relatively long due to tree growth cycles.

In contrast, sewage sludge, digestate, and agricultural biomass are characterized by continuous availability. For sewage sludge and digestate, calorific value is strongly influenced by chemical composition, particle fraction, and source of origin. Agricultural biomass, dominated by monocotyledonous plants such as cereals (straw), grasses, and

sedges, exhibits high potential for resource acquisition. In the case of grasses and sedges, up to three harvests per growing season are possible, allowing for the production of substantial amounts of feedstock with favorable chemical composition and good calorific value.

The results obtained in this study indicate that the biomass of the analyzed sedge species may represent a potential source of bioenergy feedstock, particularly in the context of utilizing biomass derived from wetland and marginal habitats. In many regions of Europe, biomass originating from such ecosystems remains underutilized, despite the fact that its periodic removal is often required for habitat conservation and maintenance of ecological balance. In this context, the use of sedge biomass as a renewable fuel feedstock may represent an element of sustainable biomass management, combining both environmental and energy-related objectives. The results of this study suggest that differences in the structural composition of biomass among sedge species may play an important role in evaluating their energy suitability as energy feedstock.

3.1. Why Is the Energy Potential of *C. riparia* Biomass Lower than That of Other Species?

Among the analyzed species, *C. riparia* showed the least favorable energy-related parameters, including the highest ash content and the lowest calorific value. The elevated ash content indicates a greater accumulation of mineral components in plant tissues, which may reduce the calorific value of biomass and increase the risk of slagging during combustion processes. Therefore, the obtained results suggest that *C. riparia* biomass may be less suitable for solid biofuel production compared with the other analyzed sedge species.

3.2. Limitations of the Study

The presented results should be interpreted with consideration of several methodological and environmental limitations. The analysis was based on biomass samples collected during a single growing season, which may not fully reflect the variability in the chemical and energy-related properties of the analyzed species. An additional factor that could have influenced the obtained results is the variability of environmental conditions among the sampling sites, including differences in soil moisture, soil nutrient availability, and other uncontrolled habitat factors. It should also be emphasized that part of the research was conducted in areas protected under the Natura 2000 network, which may have limited the extent of environmental intervention and the possibility of conducting more intensive field studies. Therefore, further research covering a greater number of growing seasons and study sites would allow for a more comprehensive assessment of the energy potential of the analyzed species.

3.3. Direction for Future Research

The obtained results indicate a differentiated energy potential of the analyzed sedge species; however, a comprehensive assessment of their suitability as solid fuel requires further research. Combustion tests, including an assessment of pollutant emissions, should be conducted. Likewise, the suitability of the biomass for densification processes, such as pellet or briquette production, should also be investigated. An important direction for future research includes multi-season and multi-site experiments, which would allow the stability of biomass productivity and energy parameters to be evaluated. Furthermore, it would be beneficial to determine energy productivity per unit area and to compare the studied species with other herbaceous plants currently used in bioenergy production. Based on literature data, the annual dry matter production of sedge communities may reach levels that justify considering their use for bioenergy purposes. However, biomass yield is strongly dependent on species, habitat conditions (moisture regime and trophic status), management practices, and fertilization [81–88]. Average yields, depending on

the species, may range from 2.8 to 7.8 Mg·ha^{−1} [81,83]. Among the species analyzed in this study, the highest biomass yield was recorded for *C. riparia*, as reported by Grzelak et al. [81,82]. Similar or even higher yields are achieved by other species, such as in *C. gracilis* and *C. acutiformis*, which occur in habitats similar to those of *C. riparia* [81–83]. It is also worth noting plant communities with a diverse species composition, in which the proportion of sedges ranges from 17.8 to 51.8%, while the average yield varies from 3.7 to 4.85 Mg·ha^{−1} DM [85,86].

4. Conclusions

The ash content in sedge biomass was higher than that in woody biomass; however, it was comparable to that of other herbaceous feedstocks, such as grasses or straw. At the same time, most of the analyzed species exhibited ash contents within ranges acceptable for biomass combustion processes. The NCV and GCV of the biomass of most *Carex* species were comparable to the energy parameters of woody biomass, particularly willow and poplar, allowing these species to be classified as valuable lignocellulosic feedstocks for energy purposes. Among the analyzed species, *C. riparia* had unfavorable energy-related parameters, including the highest ash content and the lowest NCV and GCV, which limit its potential application in energy production compared with the other species. The widespread occurrence of sedges, their relatively high biomass productivity, and the possibility of multiple harvests per growing season indicate that selected *Carex* species may represent a valuable supplementary biomass resource in renewable energy systems. The obtained results also reveal a significant positive correlation between hemicellulose content and the energy value of the biomass, whereas ash content showed a negative correlation with the energy-related parameters. However, it should be emphasized that the available literature data mainly concern the biomass of dicotyledonous plants and wood; therefore, the results obtained in this study indicate that the importance of hemicellulose in monocotyledonous plants requires further investigation, including a larger number of species.

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