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Assessment of Common Reed (*Phragmites australis* (Cav.) Trin. ex Steud.) Biomass Suitability for Solid Biofuels Production

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Abstract: From the uncontrolled proliferation of invasive plants, several challenges for the environment arise. Invasive wetland grasses biomass can be collected for biofuel production, thus offering a sustainable solution for invasive plants' management and contributing to the renewable energy sector. The straw-like shoot biomass of common reed (*Phragmites australis*), widespread across temperate and tropical zones, has been examined to assess its potential use for energy purposes. We seek to determine the fuel-energy characteristics of common reed biomass, which are necessary for converting it into energy through combustion. A comprehensive analysis was conducted to determine the physical and chemical properties of biomass according to the ISO standards for solid biofuels. These properties included calorific values, moisture, ash and volatile matter contents, and contents of C, H, N, and major and minor elements, as well as ash melting behaviour. The measured values were also compared to standard limits for different classes of densified biofuels. Based on the results, the net calorific value (15.33 MJ/kg ar) and other parameters met the requirements for the class A quality of non-woody briquettes and pellets. The only parameters which exceeded the class A limits were ash content (7.1% d.b.) and Cl content (0.16% d.b.). The findings of this study are important for the potential utilisation of common reed biomass for bioenergy as a step towards contribution to the Sustainable Development Goals.

Keywords: biomass to energy; calorific value; fuel-energy properties; *Phragmites australis*; renewable energy; solid biofuels; thermal power

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1. Introduction

The biomass of plants is an essential alternative feedstock for fuel. Biofuels from biomass are carbon neutral, and their utilisation can contribute to the mitigation of greenhouse gas effects on the environment. The best-suited biomass for this purpose is from non-food (feed) crops, such as agricultural residues and dedicated energy crops [1]. Currently, woody materials are the most used renewable source for the generation of thermal energy. Herbaceous plants have emerged as a promising feedstock for bioenergy production, which plays an important role in sustainable development. Incorporating solid biofuel made of grasses into bioenergy production systems aligns with Sustainable Development Goals. This approach promotes the use of widely available, renewable, and affordable feedstock. It can contribute to energy security by diversifying the energy mix.

Due to renewable energy targets in different countries, there is a rising interest in finding novel approaches to obtain large amounts of valuable biomass while minimising reliance on chemical fertilisers and pesticides, decreasing nitrate leaching, and fostering greater agricultural biodiversity. Thanks to the wide distribution of some invasive plants, their biomass can be locally prolific and abundantly available in many regions. However, the impacts of invasive plant species in ecosystems are broadly reported. There is a need for proactive measures to address and mitigate these ecological challenges. A growing concern for the effective eradication of invasive plant species has emphasised the possibilities of utilising the biomass offered by them [2].

Common reed (botanical Latin name *Phragmites australis*) is a perennial plant with evidenced extensive distribution on the global scale. This plant is considered invasive, and the original native distribution of common reed is uncertain and might be extremely wide. It can be found on every continent (except Antarctica) in temperate, tropical, and even arid regions between 70° N and 43° S. Dense and monodominant stands of rhizomatous plants with branchless stems of up to 4 m are often formed on the banks of lakes, rivers, and ditches, in peatlands, and in freshwater to brackish swamps [3]. The growth rate of *P. australis* was reported to reach up to 4 cm per day, with dense stands comprising approximately 200 shoots per 1 m^2 [4]. The quantity of biomass is determined by several factors, such as the total area of a country, the area of wetlands, the area of specially protected natural territories, and requirements for the management of water bodies. Available biomass and its quality could differ within the water body due to various factors [5].

The present research and other current studies are focused on exploring the potential of invasive weed biomass, like *P. australis*, as a renewable bioresource. According to Burry et al. [6], this approach not only addresses the disposal issues and reduces reliance on chemical pesticides but also opens up opportunities for bioenergy production.

Harvesting biomass from areas unsuitable for thatching (e.g., areas with aged or heterogeneous vegetation stands) but abundant in *P. australis* could be a viable option for combustion-based bioenergy production [7]. Highlighting that territories with *P. australis* beds are not typically competing for land suitable for food production underscores the potential for utilising such areas without impacting food security. This diminishes environmental concerns and contributes to sustainable energy production and land management. The negative impacts of invasive plants often outweigh the positive, making their monitoring and management crucial. The tall and dense stands of common reed, when having dry shoots, pose a fire risk. Monospecific stands displace native vegetation, reduce animal diversity, and change environmental conditions [8]. According to Fogli et al. [9], mowing of common reed is recommended in August and later to avoid nesting birds. Meyer et al. [10] indicated that common reed offers suitable habitats for various landbirds in summer and autumn but provides a limited habitat for many marsh-nesting birds. Consequently, restoring meadow marsh habitats by reducing common reed is recommended to support the breeding of marsh-nesting birds. Managers should also consider reducing the size of non-native common reed stands to enhance edge effects and bird usage, potentially benefiting wetland birds. Human preferences in landscape management can be as crucial as environmental factors for the future of *P. australis*-dominated wetlands. In internationally significant constructed wetlands, *P. australis* plays a key role as a habitat former. Using *P. australis* as a raw material and alternative energy source can benefit biotope care [11].

According to Kuhlman et al. [12], direct combustion of *P. australis,* either for district heating or electricity generation, appears to be the most promising, at least with the present state of technology. Wichmann [7] mentioned that common reed could be prepared for combustion in the form of bales as a typical straw-like feedstock. Based on the commercial viability study focusing on harvesting [13], it was found that winter mowing of *P. australis* for direct combustion can be more cost efficient than biogas production through anaerobic digestion. Also, Demko et al. [14] published that the combustion of *P. australis* biomass is more profitable than anaerobic digestion. Moreover, there are studies and promising findings from the testing of various advanced technologies for *P. australis* biomass processing for energy purposes such as pyrolysis [15] and biochar production [16].

The study by Lin et al. [17] demonstrated that common reed biomass has a conversion rate to bioethanol comparable to corn stover, considered one of the most promising feedstocks for bioethanol production. The life cycle assessment of common reed bioethanol was studied by Shuai et al. [18]. Gao et al. [19] investigated *P. australis* as a feedstock for lignocellulosic butanol.

Assessments and projects are underway regarding the utilisation of *P. australis* biomass. Four different scenarios were examined for the potential of multifunctional reed cultivation in the Netherlands [12]. Financial assessments were also conducted in the energy-deficient region in Serbia [4] and in China (Inner Mongolia) [20]. Effective strategies could be adopted for invasions elsewhere.

Previous studies have reported measurements of certain fuel-energy parameters of *P. australis* biomass (e.g., [21–25]), indicating its wide-ranging distribution. However, the biomass was not evaluated taking into account every quality parameter with the standard requirements. The assessments of biomass quality lacked comprehensiveness for comparative analysis to meet the standards for solid biofuels.

This work aimed to determine the fuel-energy parameters of *P. australis* biomass to assess its suitability for solid biofuel production while ensuring compliance with ISO standards. These standards align with the Sustainable Development Goals 7, 9, 11, 12, and 13.

2. Materials and Methods

2.1. Origin of Material and Preparation of Analytical Sample

Specifying the origin and source of raw material is mandatory for all solid biofuels. The aerial biomass of common reed is classified as originating from Aquaculture. Aerial above-ground biomass (i.e., stems, leaves, and panicles) of common reed (*Phragmites australis* (Cav.) Trin. ex Steud) (Figure 1) was manually harvested in late November 2022 from a plant natural stand in the Republic of Kazakhstan (Akmola region, coordinates of the field/collection site: 51°8′41.021″ N 71°19′0.343″ E). Biomass was collected from ten randomly selected field plots of 1 m^2 area/each. Harvested biomass was tied into bunch bundles (Figure 2), transported, and stored at room temperature. Afterwards, the biomass was chopped, and a stockpile for the sub-sample collection was formed. In order to obtain a representative sample, sub-samples were first taken from the collecting points of the stockpile as shown in the sampling methodology of the BS EN 14778 [26] standard. Then, the small representative portion was prepared from sub-samples by coning and quartering as required by BS EN 14780 [27].

Figure 1. Common reed stand at the collection site.

To obtain a homogeneous analytical sample with a particle size below 1 mm (Figure 2) for the following laboratory testing, about 200 g of the representative biomass sample was ground using a knife mill Grindomix GM 200 (Retsch GmbH, Haan, Germany; without sieve) and then strained through the sieve with the opening size of 1 mm.

Figure 2. Material collected from the site (**left**) and analytical sample (**right**).

2.2. Determination of the Principal Fuel Parameters—Proximate Analysis and Calorimetry

In the laboratory analysis of biomaterials intended for solid biofuel production, the proximate analysis includes the determination of moisture content (MC), ash content (AC), and volatile matter (VM). The thermogravimetric analyser with multi-sample capacity TGA-701 (LECO Corporation, St. Joseph, MI, USA) was employed for the instrumental measurements in compliance with ISO methodology.

The MC was determined following the ISO 18134-3 [28], which involves drying the analytical sample at 105 °C until it is a constant weight (for about 3 h).

The AC was determined according to the standard ISO 18122 [29], where around 1 g of analytical sample, which had been previously dried at 105 °C, was heated from an ambient temperature to 250 °C over 30 min then held at this temperature for a further 60 min. Subsequently, the temperature was gradually increased to 550 °C over 30 min and maintained at this level for 120 min.

The content of VM was determined based on ISO 18123 [30] by heating the analytical sample in a crucible with a lid at 900 °C for 7 min.

According to the methodology of ISO 18125 [31], the gross calorific value (GCV, dry basis and as received) was determined by calorimetry using an automatic isoperibol bomb calorimeter 6400 (Parr Instrument Company, Moline, IL, USA), and the net calorific value (NCV, dry basis and as received) was calculated from the gross.

The measurement result for each parameter was calculated as a mean of replicates and within the repeatability precision prescribed for the parameter.

2.3. Ultimate Analysis and Determination of Major Elements in Ash

The Carbon (C), Hydrogen (H), and Nitrogen (N) contents (in weight percent) were automatically measured with the elemental analyser TruSpec macro sample CHN (LECO, St. Joseph, MI, USA) following the ISO 16948 [32]. Sulphur (S) and Chlorine (Cl) contents were measured by ion chromatograph 883 Basic (IC Plus, Methrom, Zofingen, Switzerland) after the combustion of the sample in the bomb calorimeter and the ulterior recovery of sulphate and chloride in an aqueous solution, following ISO 16994 [33]. Sulphate determination was carried out by CHN628/628 S (LECO, MI, USA) in line with the provisions of ISO 16948 [32].

The percentage (weight percent) of Aluminium (Al), Barium (Ba), Calcium (Ca), Iron (Fe), Potassium (K), Magnesium (Mg), Manganese (Mn), Sodium (Na), Phosphorus (P), Silicon (Si), Strontium (Sr), and Titanium (Ti) was determined according to ISO 16967 [34] using microwave digestion (Ethos Pro, Milestone, Sorisole, BG, Italy) and inductively coupled plasma optical emission spectrometer (ICP-OES) model IRIS AP (Jarrell ash, Thermo Scientific, Waltham, MA, USA) as follows: biomass ash obtained at 550 °C was acid-digested in a microwave furnace using HNO_3, H_2O_2, and HF as a first step and H_3BO_3 as a second step before being further analysed by ICP-OES.

2.4. Determination of Minor Elements in Ash

Due to environmental concerns, the presence of the main trace elements concentrated in biomass and biofuels should be detected. The ISO 16968 [35] standard describing wet chemical methods for concentration determination of Arsenic (As), Cadmium (Cd), Chromium (Cr), Copper (Cu), Mercury (Hg), Nickel (Ni), Lead (Pb), and Zinc (Zn) was applied for the analysis. Heavy metal concentrations were determined after aqua regia digestion using HotBlock Digestion System (Environmental Express, Charleston, SC, USA). Measurements were subsequently performed using different technologies as follows: Electrothermal Atomisation Atomic Absorption Spectroscopy (ETA-AAS) was used to determine the As and Cd content, Flame Atomic Absorption Spectrometry (FAAS) was used for Cr, Cu, Ni, Pb, and Zn detection, and the mercury analyser AMA 254 (Altec, CR, Birmingham, UK) was used for Hg content determination.

2.5. Ash Melting Behaviour Analysis

The automated analyser optical heating microscope HT15 (Hesse instruments, Osterode am Harz, Germany) (see Figure 3) was used for the thermo-optical analysis of the ash melting behaviour (fusibility method) following the standard ISO 18122 [36] for solid biofuels.

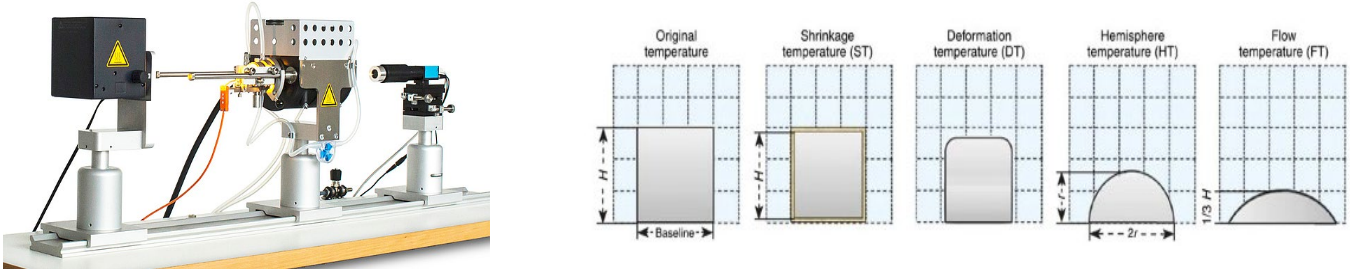

Figure 3. Optical heating microscope (**left**) and standard temperatures of ash melting behaviour (**right**).

This laboratory method is based on observing changes in the shape of a cylindrical pellet (3 mm diameter and 3 mm height) prepared from the biomass ash. The detection of changes was carried out during the process of heating from the room temperature (in an air atmosphere) to 1450 °C—the maximum operational temperature of the device. Characteristic temperatures of ash melting include the following (see Figure 3):

1. Shrinkage starting temperature (the area of the test piece falls below 95% of the original test piece area at 550 °C due to the shrinking of the pellet);
2. Deformation temperature (the first signs of melting occur);
3. Hemisphere temperature (the test pellet forms approximately a hemisphere, i.e., when the height is half of the base diameter);
4. Fluid temperature (the ash is spread out over the supporting tile in a layer, the height of which is half the height of the test piece at the hemisphere temperature).

3. Results and Discussion

Common reed biomass must meet several requirements regarding its physical and chemical properties to be considered a high-quality non-woody solid biofuel according to ISO standards. Based on this, in the following chapters, the results of the obtained measurements are summarised and compared with the prescribed limit values. The assessment also includes a comparative analysis of key properties with other biomass materials used for solid biofuels.

3.1. Analysis of Principal Fuel Characteristics and Ultimate Analysis

The evaluation of the overall fuel quality of *P. australis* biomass was performed through the detailed analysis of the solid biofuels' parameters.

A primary determinant of energy conversion efficiency was analysed, and the calorimetry of the sample resulted in 17.85 MJ/kg GCV on a dry basis and 16.67 MJ/kg GCV as received (MC = 6.6% wet basis). Based on the GCV, the NCV was found to be 16.58 MJ/kg on a dry basis and 15.33 MJ/kg as received. The net calorific value of *P. australis* presented in the literature varied, with measurements of 12.62 MJ/kg [25], 15.30 MJ/kg [23], 17.7 MJ/kg [21], and 17.9 MJ/kg [37]. For comparison with other commonly used solid fuels, the GCVs on a dry basis, indicated by Reichel et al. [38], are as follows: brown coal (Central Germany) 24.29 MJ/kg, spruce wood chips including bark 20.15 MJ/kg, and wheat straw 17.94 MJ/kg. Chaloupková et al. [39] reported a GCV of 16.40 MJ/kg for rice straw.

The volatile matter content of tested reed biomass resulted in a relatively high value of 75.7% (dry basis). According to Ivanova et al. [40], the highest volatile matter content in biomass in general is approximately 80%, and the higher the volatile matter content, the more heat is produced. Also, a high value of this parameter indicates that it is easier to ignite and burn biomass-derived solid biofuel. However, the combustion is expected to be rapid and difficult to control [41]. In contrast, lower-volatility matter causes more smoke and releases toxic gases [42]. Other studies on *P. australis* [21,22,24] published some lower VC values: 66.8%, 69.99%, and 70.01%, respectively.

Regarding the main elemental composition, *P. australis* biomass contained 0.38% (dry basis) Nitrogen, which is low. This finding is desirable since N contributes to the formation of harmful nitrogen oxides (NO_x) during combustion [40]. Other authors found N content as follows: 0.3% [21], 0.57% [23], and 1.31% [22]. Guo et al. [24] published a higher value of 1.68%, which exceeds the N limits for the class A quality non-woody biofuels.

Carbon in *P. australis*, comprising a significant portion of biomass, accounted for 45.9% (dry basis). The present result is in the range of other studies, which measured 42.00% [23], 42.78% [22], 44.50% [24], 46.5% [21], and 49.6% [25].

It was found that the biomass of *P. australis* contained 5.8% (dry basis) Hydrogen. The value also aligns with the findings reported earlier: 5.9% [21], 5.10% [23], 5.17% [22], and 5.73% [24]. However, Kulikova et al. [25] published a higher value of 7.1%.

Based on the ultimate analysis, O content in *P. australis* was 40.60% (dry basis), S content was low and equal to 0.06% (dry basis), and Cl content was 0.16% (dry basis). Generally, higher S content in fuels is undesirable as it tends to generate corrosion and deterioration of combustion equipment [43].

The presence of inorganic matter in biomass was also detected. According to Vespere and Popluga [5], reeds typically contain a significant amount of ash; thus, using straw-burning furnaces becomes essential to ensure complete combustion and optimise biomass utilisation. The measured value of ash content in the tested biomass of *P. australis* was 7.1% (dry basis). Similar results were found by Kostin et al. [23] and Kulikova et al. [25]: 6.6–7.6% and 6.14%, respectively. Other studies detected higher values: 8.8% [21], 11.89% [24], and 12.32% [22]. Demko et al. [14] measured AC in different parts of the common reed shoot: 5.77% (AC of panicle), 7.17% (stalk), and 8.81% (leaves). For comparison, the AC values (dry basis) of other frequently used solid fuels are as follows: brown coal (Central Germany) 17.67%, spruce wood chips including bark 1.45%, wheat straw 8.16% [38], rice straw 16.11% [39].

3.2. Assessment of Ash Melting Behaviour and Major Elements

Per the ISO standard for the classification of solid biofuels, ash melting behaviour is an informative parameter, lacking specified limits as outlined in the standard. It should be expressly mentioned concerning a specific material.

The results obtained from the laboratory apparatus are summarised in Table 1 and compared to the other studies and other materials.

Table 1. Ash melting behaviour of *P. australis* biomass—characteristic temperatures.

Material	Shrinkage Temperature (°C)	Deformation Temperature (°C)	Hemisphere Temperature (°C)	Flow Temperature (°C)	Reference
P. australis	>1450	>1450	>1450	>1450	Present study
P. australis	1139	1349	1444	1458	[37]
Poplar wood	>1400	>1400	>1400	>1400	[44]
Wheat straw	850	1040	1120	1320	[44]
Rice straw	750	1063	1225	>1341	[39]

Table 1 shows that, for each phase of the measurement process, characteristic temperatures of common reed were higher than 1450 °C. The results are similar, but actually better than, the values reported by Jasinskas et al. [37]. This outcome is promising, demonstrating that the ash melting behaviour of reed biomass is comparable to that of wood and outperforms typical herbaceous/agricultural waste biomasses. According to Fernández and Carrasco [44], biomass flow temperature is usually much higher than the shrinkage temperature, and frequently higher than the operational limit temperature of the optical heating microscope utilised. These authors also stated that a shrinkage temperature well above 1100 °C indicates a low tendency of biomass to sinter at lower temperatures. Based on the above and considering the measured results, it is apparent that there is a low risk of slagging, fouling, and hard spot formation (on the walls of a combustion chamber and in tubes) during the combustion of *P. australis* biomass.

Moreover, it is important to mention that the study of Fernández and Carrasco [44] compared five laboratory methods for predicting ash sintering (particle softening and surface flow) occurring during biomass combustion, and the results from combustion tests in a combustion plant confirmed that the fusibility method is adequate and reliable in predicting biomass ash sintering using its shrinkage temperature. Nevertheless, minimal sintering may sometimes occur at temperatures below shrinkage. According to Li et al. [45], ash melting behaviour temperatures are usually used to provide references for a reactor design and the selection of operation parameters. However, reproducibility of the resulting temperatures may be challenging.

Overall, the elemental composition of plant biomass affects its combustibility and suitability for combustion techniques. Understanding the chemical composition of biomass and biomass ash (major and minor elements) provides insights for optimising combustion processes considering the specific attributes of each element and its influence on combustion and residue formation (or formation of combustion products). The detailed compositions of major elements and their oxides in the aerial biomass of *P. australis* are presented in Table 2.

Table 2. Composition of major elements in the *P. australis* ash.

Parameter	Units	Value	Parameter	Unit	Value
Aluminium, Al	% d.b.	0.17	Aluminium oxide, Al_2O_3	% d.b.	0.33
Barium, Ba	% d.b.	0.020	Barium oxide, BaO	% d.b.	0.022
Calcium, Ca	% d.b.	1.2	Calcium oxide, CaO	% d.b.	1.7
Iron, Fe	% d.b.	0.20	Iron(III) oxide, Fe_2O_3	% d.b.	0.28
Potassium, K	% d.b.	2.6	Potassium oxide, K_2O	% d.b.	3.1
Magnesium, Mg	% d.b.	0.54	Magnesium oxide, MgO	% d.b.	0.90
Manganese, Mn	% d.b.	0.11	Manganese(III) oxide, Mn_2O_3	% d.b.	0.17
Sodium, Na	% d.b.	1.2	Sodium oxide, Na_2O	% d.b.	1.6
Phosphorus, P	% d.b.	0.33	Phosphorus pentoxide, P_2O_5	% d.b.	0.76
Silicon, Si	% d.b.	42	Silicon dioxide, SiO_2	% d.b.	89
Strontium, Sr	% d.b.	0.052	Strontium oxide, SrO	% d.b.	0.062
Titanium, Ti	% d.b.	0.013	Titanium dioxide, TiO_2	% d.b.	0.022

%—weight percent, d.b.—dry basis.

Based on Table 2, the result of the ash analysis is summarised in decreasing order of elements/oxides content: Si > K > Ca $\geq$ Na > Mg > P > Fe > Al > Mn > Sr > Ba > Ti/SiO_2 > K_2O > CaO > Na_2O > MgO > P_2O_5 > Al_2O_3 > Fe_2O_3 > Mn_2O_3 > SrO > BaO $\geq$ TiO_2.

According to Ovčačíková et al. [46], oxides in biomass ash can be divided into acidic (SiO_2, Al_2O_3, TiO_2, etc.) and basic (K_2O, CaO, MgO, Na_2O, Fe_2O_3, P_2O_5, etc.). Acidic oxides increase the melting point of ash, i.e., the higher the content of acidic oxides, the higher the melting point. On the other hand, basic oxides lower the melting point of the ash. In contrast, Wang et al. [47] published that Ca and Mg concentrations increase the ash melting point. Li et al. [45] stated that the ash sintering characteristics are closely related to alkali metals content (especially Na). According to Kask et al. [48], the amounts of alkali metals (mainly K and Na) that negatively affect ash fusibility, formation of ash deposits, and boiler corrosion differ during the year, showing higher values in summer-harvested reed. Thus, reed biomass harvested in winter is a better fuel (from the point of view of ash composition), which is supported by the present study.

Generally, the formation of slag and corrosive alkalis results in higher maintenance expenses, shorter lifespan of combustion equipment, and decreased economic viability of converting biomass feedstocks into fuel [49]. Biomass is a very complex type of fuel. Its combustion leads to the formation of alkaline ash and gases with a corrosive effect on refractory linings. However, corrosion is very complex, and it has not been completely described yet [46]. From Table 2, it is visible that Silicon is the main component of the reed ash. The study of Kostin et al. [23] also determined its SiO_2 content and found a similar value of 90.83%. Si is usually plentiful in biomass sources resembling grass. According to Monti et al. [50], Si in the fuel itself would not be a problem, thanks to its high melting point, but, in the presence of K or Ca, Si readily reacts with them, forming alkali silicates with much lower melting points. P can increase the slagging potential of deposits too. Wang et al. [47] also added that, at low combustion temperatures (about 700 °C), Si can react with elements such as Al and Cl, yielding slag deposits and corrosive compounds and ultimately diminishing the efficiency of thermochemical conversion processes. Overall, Monti et al. [50] and Wang et al. [47] agreed that, due to the influence on slagging, the K–Ca–Si ratio should be considered in biofuel quality evaluation, and biofuels containing high Si and Ca, along with a low K, should be better suited to energy end use. A recommended ratio/problematic values were still not found in the literature.

3.3. Evaluating Common Reed Biomass in Compliance with Standard Limit Values

Production of densified solid biofuels from the bulky biomass of common reed can be beneficial due to the reduced transportation and storage costs. In order to evaluate the above-ground common reed biomass applicability for the production of biofuels for combustion, it is crucial to verify the compliance of obtained results with the limit in solid biofuels standards. The selection of appropriate standards ensures that the evaluation aligns with regulatory requirements and industry benchmarks. ISO standards provide specific values for allowable fuel-energy properties, guiding the assessment process. Limit values of standards ISO 17225-6 [51] and ISO 17225-7 [52] are presented in Table 3 for a comparative analysis of the obtained results.

Table 3 illustrates the expected quality of solid biofuels produced from the common reed biomass, which is relatively high. Higher ash and Cl contents are the only two properties that do not meet class A limits. Nevertheless, as indicated by Silva et al. [53], it has been experimentally demonstrated and widely recognised that biomass ash has a good potential for soil amelioration and nutrient recycling. Considering the resulting concentrations of trace elements, it can be stated that the ash of *P. australis* can be safely used for these purposes.

Table 3. Comparison of *P. australis* properties with the standard limit values for non-woody pellets and briquettes.

Parameter	**Unit**	**Non-Woody Pellets**		**Non-Woody Briquettes**			***P. australis***
		A	**B**	**A1**	**A2**	**B**	
Moisture, MC	% ar	≤12	≤15	≤12	≤12	≤15	6.6
Ash, AC	% d.b.	≤6	≤10	≤3	≤6	≤10	7.1
Net calorific value, NCV	MJ/kg ar	≥14.5	≥14.5	≥14.5	≥14.5	≥14.5	15.33
Nitrogen, N	% d.b.	≤1.5	≤2	≤1.5	≤1.5	≤2	0.38
Sulphur, S	% d.b.	≤0.20	≤0.30	≤0.20	≤0.20	≤0.30	0.06
Chlorine, Cl	% d.b.	≤0.10	≤0.40	≤0.10	≤0.20	≤0.30	0.16
Arsenic, As	mg/kg d.b.	≤1	≤1.5	≤1	≤1	≤1.5	<0.50
Cadmium, Cd	mg/kg d.b.	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	<0.10
Chromium, Cr	mg/kg d.b.	≤50	≤50	≤50	≤50	≤50	7.68
Copper, Cu	mg/kg d.b.	≤20	≤20	≤20	≤20	≤20	<2.50
Lead, Pb	mg/kg d.b.	≤10	≤10	≤10	≤10	≤10	<2.50
Mercury, Hg	mg/kg d.b.	≤0.1	≤0.1	≤0.1	≤0.1	≤0.1	<0.009
Nickel, Ni	mg/kg d.b.	≤10	≤10	≤10	≤10	≤10	<2.50
Zinc, Zn	mg/kg d.b.	≤100	≤100	≤100	≤100	≤100	10.6

%—weight percent, ar—as received, d.b.—dry basis; A (A1) is the higher-quality class.

Chlorine in the biomass occurs mainly in a form of various compounds of mineral salts [54]. Cl content should be taken into account as it may react with K during combustion and form primary fouling compounds. Cl plays a role in transporting alkali to surfaces, thus contributing to the corrosion of tubes of power plants and heat exchangers [50]. Based on Szydełko et al. [54], one way to prevent this issue is by using mineral additives during the combustion (e.g., Calcium compounds from dolomite and limestone or aluminosilicates from kaolins and halloysite), which bind with the Cl and reduce the amount of chlorides emitted.

Future research should focus on producing and testing densified solid biofuels (e.g., briquettes) from the common reed biomass. Specifically, evaluating their mechanical durability, combustion performance, and emissions from combustion furnaces is essential. Optimisation of the main fuel-energy properties of this promising biomass via torrefaction/the pyrolysis process and thermogravimetric analysis will be another focus of the future research.

4. Conclusions

P. australis is an invasive alien plant generating large quantities of widely available biomass. The management of invasions in affected regions can benefit sustainable development, if the biomass is processed properly as a feedstock for valuable products, where one of the solutions is solid biofuel production.

The present study investigated the fuel-energy parameters of *P. australis* biomass, revealing its highly promising energy utilisation potential. Compared to the standard requirements, the derived solid biofuel is expected to have a calorific value typical for non-woody feedstock and low heavy metal concentrations. Based on the findings, most *P. australis* biomass characteristics fully correspond to the limits of class A1 quality of graded non-woody briquettes and class A of non-woody pellets. Favourable combustion processes and suitability for energy utilisation could also be supported by the high ash melting temperatures, desirable ash composition, and low contents of the emissions-releasing compounds. Only the ash and Chlorine contents of the studied biomass showed slightly higher values than class A limits; however, they easily fulfilled class B requirements.

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