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The Energy Potential of White Mulberry Waste Biomass

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Abstract

White mulberry (*Morus alba* L.) is a tree growing up to 15 m in height. It is a plant whose cultivation is historically associated with silk production. Mulberry leaves are the only food source of the mulberry silkworm caterpillars (*Bombyx mori* L.). The cultivation of this tree has recently gained renewed importance. Due to the content of numerous bioactive substances, mulberry is a valuable raw material for the food, pharmaceutical and herbal industries. This article presents the results of tests on pellets from 1-, 3- and 5-year-old branches, which are waste biomass remaining after pruning mulberry shrubs cultivated to obtain leaves to feed silkworms. Additionally, analyses of pellets from mulberry leaves were also carried out. For the specified mulberry biomass yield, analyses of chemical composition of mulberry biomass (branches and leaves) were carried out, and energy properties (heat of combustion and calorific value) and energy potential were calculated. The heat of combustion of pellet from mulberry branches was, on average, 19,266 MJ·Mg^{-1}, and the calorific value was 17,726 MJ·Mg^{-1}. The energy potential, on the other hand, was, on average, 159 GJ·ha^{-1} and 44 MWh·ha^{-1}. The obtained results indicate the possibility of the effective use of mulberry branches after the annual pruning of bushes in plantations for energy purposes.

Keywords: solid biofuels; pellet; waste management; bioenergy production; biomass yield

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1. Introduction

The global demand for energy is constantly growing, and the use of fossil fuels is becoming not only an ecological problem but also a geopolitical and socio-economic one [1]. The seriousness of the problem was noticed by the European Union and the United Nations, and is reflected in their legislation. Currently, the subject of renewable energy sources is discussed, among others, in The European Green Deal [2], The Sustainable Development Goals [3], and The Net-zero Industry Act [4]. Through its policy, the European Union aims to phase out the use of fossil fuels in favor of renewable, sustainable energy sources and reduce carbon dioxide emissions. The EU Directive defines energy from renewable sources as: "energy from renewable non-fossil sources, namely wind, solar (solar thermal and so-lar photovoltaic) and geothermal energy, ambient energy, tide, wave and other ocean energy, hydropower, biomass, landfill gas, sewage treatment plant gas, and biogas" [5].

Biomass for biofuel production can come from various sources. There are crops intended for energy purposes—for this purpose, *Salix viminalis* (L.) [6], *Miscanthus* × *giganteus* [7,8], *Brassica napus* (L.) var. *napus* [9,10] and *Sida hermaphrodita* ((L.) Rusby) [11,12] are grown. However, they compete with agricultural crops, occupying arable land. It is therefore advisable to search for and use plant biomass for energy purposes, which is a by-product or waste, which will ensure the full use of resources and will be in line with the principles of a circular economy [13].

Waste plant biomass can be used to produce solid, liquid and gaseous biofuels [14,15]. Pelletization is one of the simplest methods of processing plant biomass [16]. Pellet production does not require the use of many expensive devices or the carrying out of specialist chemical or biochemical processes. This method of biomass processing is therefore possible to carry out even on small farms independently by farmers or farm workers [17]. Moreover, the pellet itself is suitable for use as heating fuel on the same farms without the need to invest in special installations. Pellet production from waste plant biomass, directly at the place of its acquisition, is, therefore, a way to use waste or by-products in a sustainable way and can provide additional income for farms [18].

White mulberry (*Morus alba* L.) is a plant that has been known and used for thousands of years. It is a perennial shrub or tree that can grow up to 15 m in height. The species is characterized by heterophily and the presence of milky sap in its shoots [19,20]. Its leaves, fruits and seeds are rich sources of nutrients, vitamins and micro- and macroelements [21–23]. Additionally, white mulberry leaves are notable for their high content of proteins, fibers and polyphenols, including quercetin and rutin. The seeds are a valuable source of unsaturated fatty acids, while the fruits are abundant in micro- and macroelements such as nitrogen, potassium, magnesium, iron, zinc and manganese. Due to the presence of numerous bioactive compounds, mulberry serves as a valuable raw material for the food, pharmaceutical and herbal industries [24,25]. The bark extracted from mulberry can also be used as a natural dye plant owing to its tannin content in the woody biomass [25]. Due to its fast growth—annual shoot increments range from 2 to 2.5 m, and breast height reaches 60–80 cm in the first 40–50 years [26,27]—mulberry can also be successfully used as an energy crop for the production of pellets and briquettes [28].

The interest in white mulberry has been increasing recently, with an emphasis the growth of its cultivation acreage. In order to increase plantations' productivity, it is necessary to prune the shoots frequently and remove sick or fallen leaves to protect plants from pathogens. The review of the literature and an analysis of other available scientific sources conducted by the authors show that there is little information on the energy properties of white mulberry, especially in the form of pellets. One of the few comprehensive studies of white mulberry pellets was conducted from domestic waste biomass originating from the subtropical Mediterranean environment [29]. Therefore, the aim of this work was to analyze the yield and chemical and elemental compositions of mulberry biomass, which is a waste in the sericulture industry, from a plantation located in Central Europe in a temperate climate. A statistical analysis of the chemical components of the obtained results was also conducted. Moreover, the energy properties of mulberry pellets and the energy potential per 1 Mg of waste biomass were investigated.

2. Materials and Methods

2.1. Mulberry Biomass

The feedstock for the research was the mulberry biomass of the *Żółwińska wielkolistna* cultivar. To reduce variability, all samples were collected from the same season and site–

Pętkowo Experimental Farm (52°12′39″ N 17°15′20″ E), which belongs to the Institute of Natural Fibers and Medicinal Plants—National Research Institute (Poland). The branches and leaves were harvested in 2021 before and during the vegetation period, respectively. The size of the mulberry plantation is approx. 5000 m^2. A reference amount of biomass from the whole area (5 kg) was collected in 6 samples and mixed for pellet production and chemical analysis.

2.2. Solid Biofuel Production from Mulberry Biomass

The mulberry branches were cut using secateurs and afterward subjected to preliminary crushing to particles of a size of 20–40 mm and dried at 50–55 °C for 24 h. Next, the feedstock was disintegrated on a knife mill with sieves of a mesh size of 2 mm (Retsch SM-200, Haan, Germany).

The Pellet-Presse PP120B (qteck GmbH, Bergen, Germany) was used for pellet production. A pinch of potato starch was used if necessary to bind the biomass together better. For each biomass sample, 4 kg of pellet was produced.

2.3. Analytical Methods

The chemical composition of the mulberry biomass was analyzed at the Faculty of Wood Technology, Poznan University of Life Sciences (PULS), according to the PN-92/P-50092 standard for plant material. The following parameters were determined:

- Moisture content using the oven-dry (gravimetric) method;
- Cellulose using a mixture of acetylacetone and dioxane, according to Seifert;
- Holocellulose using sodium chlorite;
- Lignin using concentrated sulfuric acid, according to Tappi;
- Pentosanes using the trihydroxybenzene method;
- Mineral substances according to the DIN 51731 standard [30].

Experimental samples were ground in a Pulverisette 15 laboratory mill, with the analytical fraction of 0.4–0.1 mm being separated on sieves [31].

The elemental composition measurements in the dry mulberry biomass were also performed at PULS, according to the PN-EN 15104:2011 [32] and PN-EN 15289:2011 [33] standards.

2.4. Calculations

The heat of combustion of the analyzed samples was carried out at PULS on a KL-12Mn calorimeter under a 3-bar oxygen atmosphere according to PN-81/G-04513 [34], which is designed to measure the gross calorific value of solid fuels. The experiments consisted of determining the increase in water temperature in a calorimetric vessel, the heat capacity of which was 13,122 J/g. Including the value of heat of combustion of the wire (6699 $J \cdot g^{-1}$), the substrate heat of combustion (Q_s) ($J \cdot g^{-1}$) was calculated according to the following formula:

$$Q_s = \frac{C\,(D_t - k) - c}{m} \tag{1}$$

where:

C—the heat capacity of the calorimeter ($J \cdot K^{-1}$);
D_t—the general increase in the main period temperature (K);
K—a correction for the calorimeter's heat exchange with its surroundings (K);
C—the heat correction emitted during wire burning (J);
M—the mass of the solid fuel sample (g) [35].

For each substrate, five repetitions were made, and the arithmetic mean was calculated.

A net calorific value was determined to complete the characterization of the analyzed raw material. It is the gross calorific value decreased by the heat of vaporization of water separated from the fuel during combustion. Considering the moisture of the samples and the hydrogen content of the straw, the substrate calorific value (Q_w) ($J \cdot g^{-1}$) was calculated from the following formula:

$$Q_w = Q_S - 24.42\ (W_a + 8.94\ H_a) \quad (2)$$

where:

Q_s—the heat of combustion of the test sample fuel in the analytical state ($J \cdot g^{-1}$);
W_a—the moisture content in the test sample (%);
H_a—the hydrogen content of the test sample (%) [27].

The amount of energy produced by burning mulberry pellets ($GJ \cdot ha^{-1}$) was calculated according to the obtained results about the biomass yield and heat of combustion, and by using the following formula:

$$E_J = \frac{m\ Q_w}{S} \quad (3)$$

where:

m—harvested amount of mulberry biomass (Mg);
Q_s—calorific value of the test sample fuel in the analytical state ($J \cdot g^{-1}$);
S—unit of area (1 ha = 10,000 m^2).

To express the produced energy amount also in $MWh \cdot ha^{-1}$, the results were converted as follows:

$$E_E = \frac{E_J}{3.6} \quad (4)$$

where:

E_J—produced energy amount ($GJ \cdot ha^{-1}$);
1 MWh = 3.6 GJ [36].

2.5. Statistical Analysis

In order to compare the chemical composition of mulberry obtained in different rotation periods of harvest, an analysis of variance (ANOVA) was performed for the experiment performed in a completely random design with 6 replications for each treatment.

The normality of the residuals in the model was checked with the Shapiro–Wilk W-test, while the homogeneity of variance was tested using the Fligner–Killeen test. The post hoc Tukey's test (alpha = 0.05) was used to explore significant differences between means for rotation periods.

3. Results and Discussion

3.1. Mulberry Biomass Yield

The results of the fresh and dry matter yield of mulberry leaves and branches as well as the biomass humidity showed significant differences between the analyzed feedstocks (Figure 1).

Generally, the mulberry biomass yield increased with the duration of the plant rotation. The lowest yield on average was found for annual branches at 28 $Mg \cdot ha^{-1}$ for fresh mass and 9 $Mg \cdot ha^{-1}$ for dry mass, and the highest for five-year-old biomass (136 and 61, respectively).

Most of the mulberry yield research has been carried out for sericulture or the herbal industry [37–39]. Nevertheless, the obtained results relate to waste biomass. In this case, old leaves showing traces of pathogen occurrence, which are not useful for mulberry silkworms or herb production, were the raw material for energy production. Therefore, the obtained yield was mostly lower compared with the mulberry industrial plantation. However, such a use of waste biomass better refers to the circular economy principles [40–42].

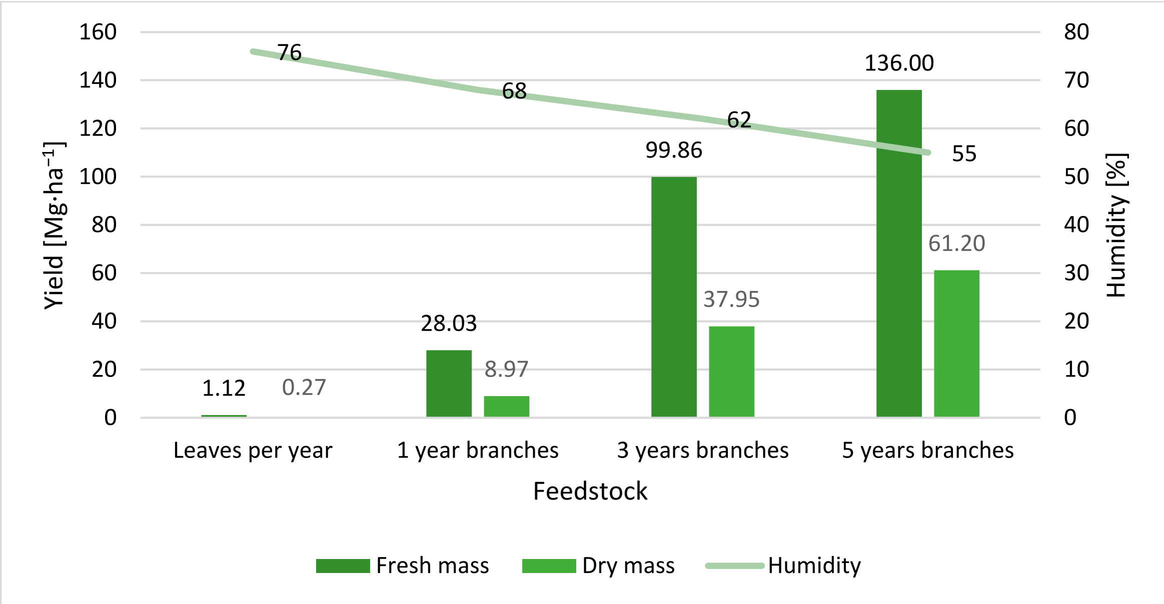

Figure 1. Average mulberry biomass yield [Mg·ha^{-1}] and biomass humidity [%].

3.2. Chemical Composition of Mulberry Biomass

Subsequently, the determination of the chemical composition (extractive substances, cellulose, lignin, holocellulose, pentosans, substances soluble in cold water, substances soluble in hot water, substances soluble in 1% sodium hydroxide and mineral substances) of mulberry waste biomass was also investigated (Table 1, Figure 2).

Table 1. Chemical composition of mulberry biomass—leaves [%].

Substance	Average Content [%]
Extractive substances	20.26
Cellulose	18.69
Lignin	10.07
Holocellulose	55.97
Pentosans	12.46
Substances soluble in cold H_2O	15.09
Substances soluble in hot H_2O	16.69
Substances soluble in 1% NaOH	80.99
Mineral substances	16.62

Significant differences in the content were found for the tested samples of mulberry biomass. From each experimental plot, the chemical composition of leaves was completely different compared to branches. Nevertheless, the chemical composition of mulberry waste biomass is comparable to other research described in the literature. The content of mineral substances in leaves (16.5–16.7%) was five to eight times higher, according to results obtained from branches harvested in a five-year-old rotation period. On the other hand, leaves contained less lignin, cellulose, and holocellulose than the woody parts of plants [43–45].

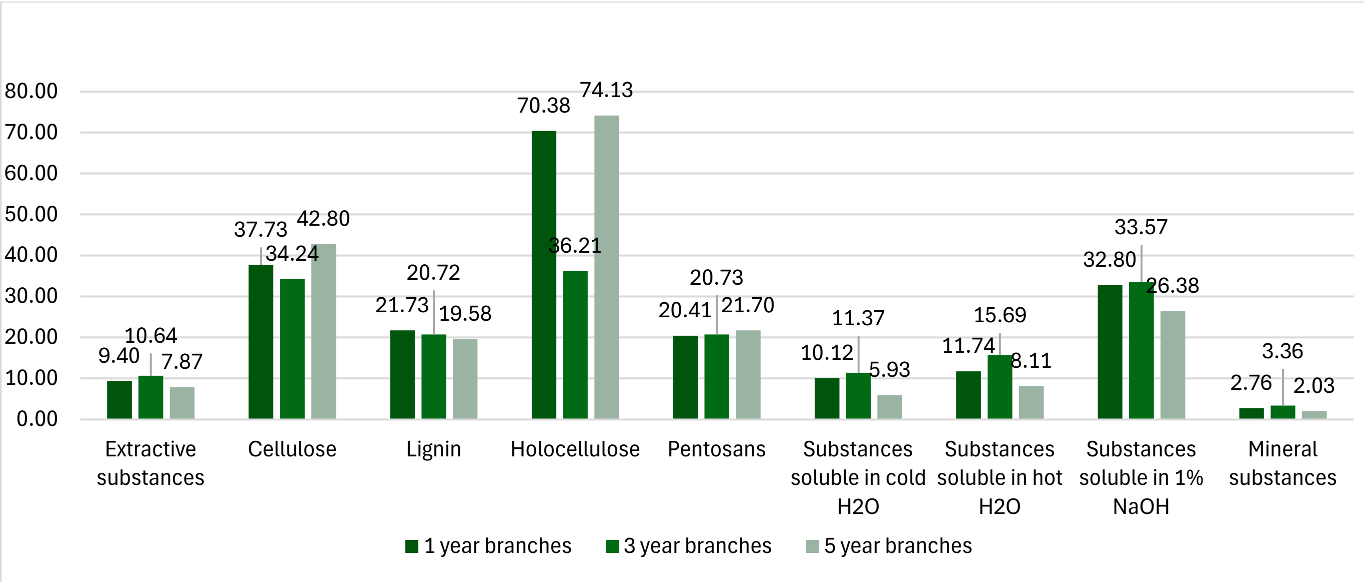

Figure 2. Chemical composition of mulberry biomass—branches [%].

The content of chemical substances in mulberry branches varied as plants aged. The average cellulose content was higher for five-year-old branches (42.8%), as well as the holocellulose content (74.1%) and pentosans content (21.7%). In turn, the lowest levels of other substances were recorded in the five-year-old branches. Interestingly, in the case of cellulose and holocellulose, a decrease in the content of these substances was noted in three-year-old branches compared to one- and five-year old branches. However, the authors believe that this phenomenon requires confirmation in further research. The results of the statistical analysis of chemical components of mulberry biomass are shown in Table 2.

Table 2. Statistical analysis of chemical components in white mulberry biomass from different harvest ages (mean ± SD; ANOVA and Tukey's test).

	Cellulose		**Lignin**		**Holocellulose**		**Mineral Substances**	
General Analysis—Results								
Type of Analysis	ANOVA		ANOVA		ANOVA		ANOVA	
df	3; 20		3; 20		3; 20		3; 20	
F	199,504		153,915		938,484,00		162,071	
p-value	$<2 \times 10^{-16}$ ***		$<2 \times 10^{-16}$ ***		$<2 \times 10^{-16}$ ***		$<2 \times 10^{-16}$ ***	
Mean Values for Treatments/Results of Post Hoc Tests α = 0.05								
General mean	33.37		18.02		59.17		6.19	
1 year old branches	37.73 (±0.04)	b	21.73 (±0.03)	a	70.38 (±0.06)	b	2.76 (±0.04)	c
3 year old branches	34.24 (±0.02)	c	20.72 (±0.04)	b	36.21 (±0.04)	d	3.36 (±0.04)	b
5 year old branches	42.8 (±0.06)	a	19.58 (±0.04)	c	74.13 (±0.03)	a	2.03 (±0.04)	d
Leaves per year	18.69 (±0.09)	d	10.065 (±0.02)	d	55.97 (±0.03)	c	16.62 (±0.05)	a

*** indicates statistically significant differences at $p < 0.001$ (ANOVA). Means followed by a common letter are not significantly different as per the Tukey post-hoc test at the 5% level of significance.

The statistical analysis showed significant differences between the mean percentages of the examined chemical components in the material from the different rotation periods of harvest for all analyzed compounds (Table 2). The highest cellulose content (42.8%) was found for five-year-old rhizomes, and it was significantly higher than the average for the remaining treatments. For leaves, the content of this component was more than half than for one- and five-year-old rhizomes and amounted to 18.7%.

Five-year-old rhizomes were also characterized by the highest content of holocellulose (74.1%), which is 3.8% more than for one-year-old rhizomes; statistically significant differences between means for mentioned treatments were found. The lowest average value of holocellulose was found for three-year-old rhizomes (36.2%). The content of lignin decreased with the age of rhizomes and differed significantly for all rotation periods. The analysis of the content of mineral substances showed the opposite tendency than in the case of the content of cellulose for the treatments. Their highest average content was found for leaves, and it was significantly higher than the average content of minerals in rhizomes, of which the three-year-old rhizomes turned out to be the richest in this substrate (3.4%).

Furthermore, the elemental composition of pellets produced from analyzed substrates was investigated (Table 3).

Table 3. Elemental composition of analyzed substrates [%].

Sample of Pellet	[%]	N	C	H	Cl	S
1: Leaves	Content	3.75	43.37	5.77	0.22	0.21
	SD	0.26	0.79	0.07	0.02	0.02
2: 1-year old branches	Content	0.43	47.59	6.33	0.02	0.07
	SD	0.03	0.87	0.05	-	0.01
3: 3-year old branches	Content	0.47	47.62	6.33	0.01	0.06
	SD	0.03	1.10	0.03	-	0.01
4: 5-year old branches	Content	0.48	48.04	6.28	0.01	0.04
	SD	0.03	0.89	0.04	-	0.01

The pellets from waste mulberry biomass were created including four samples: 1—from mulberry leaves; 2—one-year-old mulberry branches; 3—three-year-old mulberry branches; and 4—five-year-old mulberry branches. The highest percentage of nitrogen, chlorine and sulfur was recorded in pellet samples from mulberry leaf biomass. It was 7.8–8.7 times higher for nitrogen, 11.0–22.0 times higher for chlorine and 3.0–5.3 times higher for sulfur than in the branches. For carbon and hydrogen, no such significant differences were noted.

Wood pellets from mulberry pruning were also studied by Christoforou's team [29]. In addition to mulberry, they also analyzed pellets from walnut shells, three-phase olive pomace and exhausted olive husk. For mulberry, in the case of carbon and hydrogen, results were obtained that were comparable to the studies presented in this article. The content of the elements mentioned was 49.5% and 5.9%, respectively. The nitrogen content was, however, almost twice as high (0.9%). The mulberry pellets, in comparison to others from the cited study, differ significantly only in the nitrogen content. For example, for a sample consisting of 100% chemically untreated wood shaving, the nitrogen content was 0.4%, and for exhausted olive husk, it was 2.2%. When comparing the composition of pellets from other tree species (debarked or un-debarked wood of *Robinia pseudoacacia*, *Populus*, *Quercus* and *Pinus pinea*) [17] with mulberry pellets, differences in nitrogen content can be observed, with the lowest nitrogen content recorded in the case of the only coniferous tree species tested—0.1%. A comparison of the elemental composition of pellets from leaves and branches of different ages is illustrated in Figure 3. The radar chart highlights significant differences in nitrogen, chlorine and sulfur contents between leaf biomass and woody parts, with the axes scaled independently based on the range of each element.

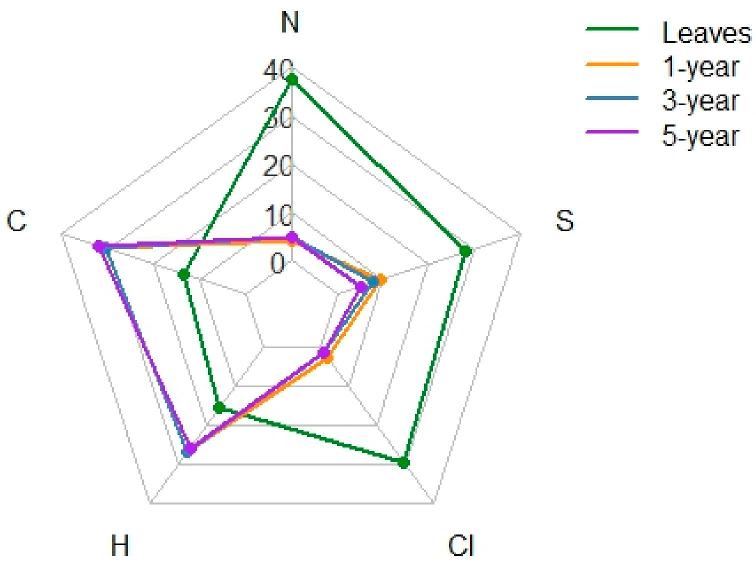

Figure 3. Elemental composition of mulberry pellets—radar chart. The radar chart presents the percentage content of selected elements (N, C, H, Cl, S) in mulberry pellets made from leaves and 1-, 3-, and 5-year-old wood. The axis scales are variable and based on the individual minimum and maximum values for each element, allowing the comparison of elemental composition profiles despite differences in absolute value ranges.

To further explore the variation in chemical and elemental parameters across the different mulberry biomass types, a standardized heatmap was generated (Figure 4). This visualization clearly highlights the distinct chemical profiles of leaves versus woody biomass, particularly the elevated nitrogen and mineral content in leaves, and the increasing cellulose and holocellulose levels with biomass age.

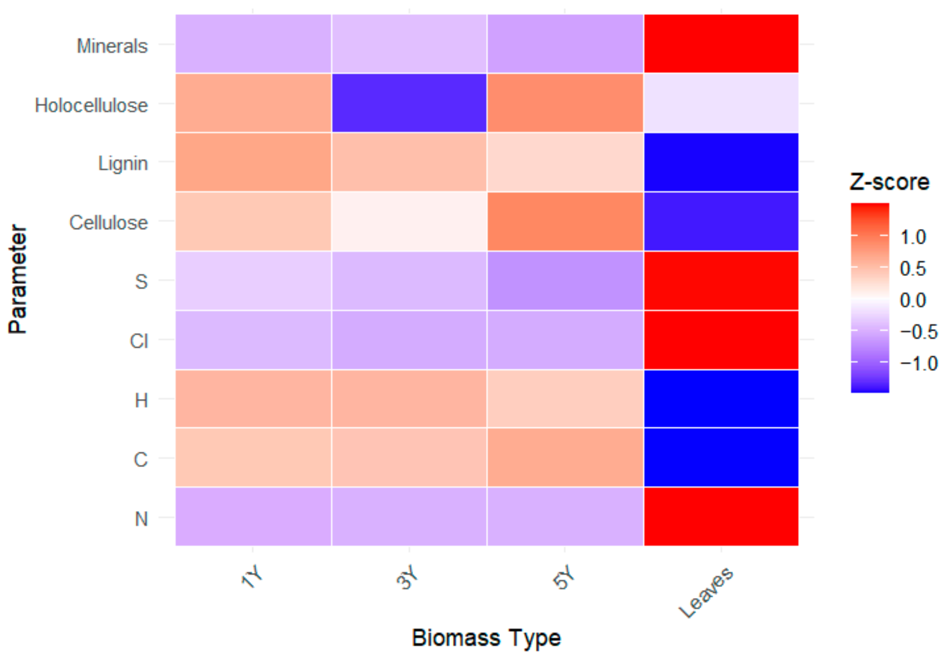

Figure 4. Standardized heatmap of the chemical and elemental composition of mulberry biomass. The heatmap visualizes standardized values (Z-scores) for selected chemical and elemental parameters across different mulberry biomass types: leaves and 1-, 3-, and 5-year-old branches. The scaling highlights relative differences between samples by normalizing all parameters to a common scale. Red shades indicate higher-than-average values, while blue indicates lower-than-average levels for each parameter.

3.3. Energy Properties and Potential of Mulberry Pellets

The energy properties and humidity of mulberry pellets are shown in Figure 5.

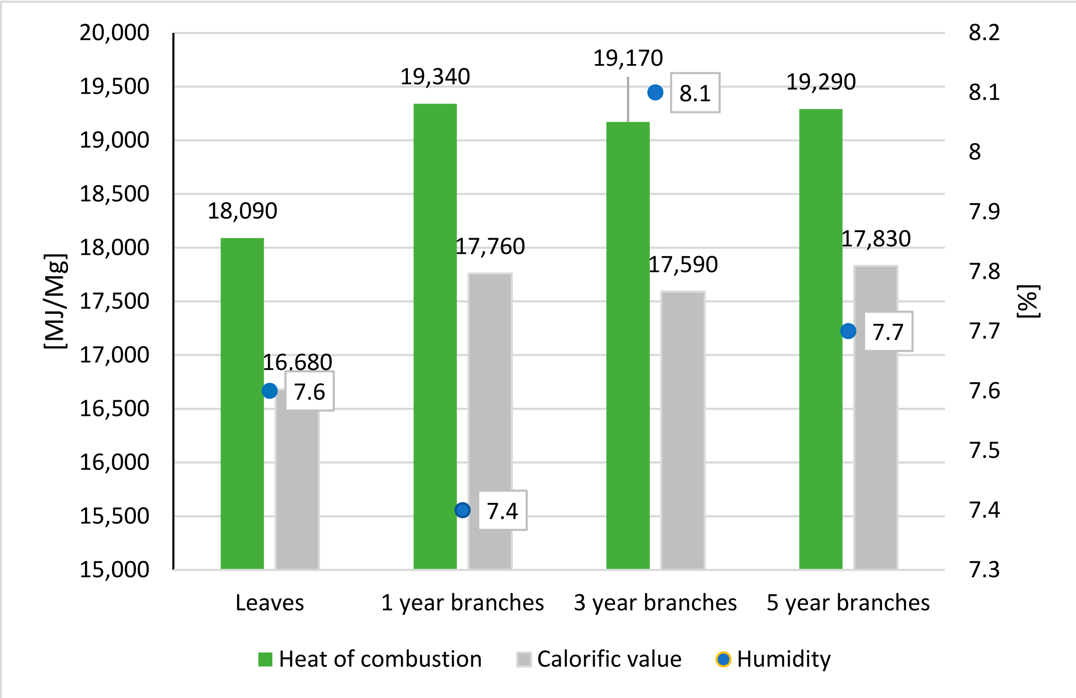

Figure 5. Energy properties [MJ·Mg^{-1}] and humidity [%] of mulberry pellets.

For the branches, values ranged from 19,170 MJ·Mg^{-1} to 19,340 MJ·Mg^{-1} for the heat of combustion and from 17,590 MJ·Mg^{-1} to 17,830 MJ·Mg^{-1} for the calorific value, with the highest heat of combustion recorded for one-year-old branches and the highest calorific value for five-year-old branches. In the pellet studies cited above [29], the energy properties were also examined. For the mulberry pellet, a similar calorific value was obtained as in this study—17,730 MJ·Mg^{-1}; however, it was the lowest value among all the tested samples. The highest was achieved by the pellet from 100 vol% three-phase olive pomace —19,240 MJ·Mg^{-1}. For comparison, in other studies, the calorific value of one-year-old mulberry branches from 2- to over 20-year-old shrubs growing in different conditions was examined. The average value given by the authors was 17,053 MJ·Mg^{-1} and was also lower than the calorific value of branches of other studied tree species, such as *Quercus*, *Pinus* or *Coriaria*, but higher than the branches of *Eucalyptus* and *Leucaena* and also *Oryza*, *Triticum aestivum* subsp. *aestivum* and *Zea mays* (L.) straw, as well as *Saccharum officinarum* (L.), but lower than *Eupatorium*, which is a perennial plant [46]. In turn, when comparing the research results with the results obtained for energetic woody plants such as *Salix* sp. or *Populus* sp., it is worth paying attention to the work of Stolarski's team [47]. In the research conducted on the thermophysical properties of pellets from growing in short rotation coppice plantations, the higher heating value of *Salix* sp. pellets was 19.61 GJ·Mg^{-1} and *Populus* sp. 19.71 GJ·Mg^{-1}. Grasses are also very popular energy plants. Research conducted by Jasinskas et al. indicates high suitability of this raw material: the calorific value of *Phragmites* sp. was 17.86 MJ·kg^{-1} and that of *Phalaris arundinacea* (L.) was 17.38 MJ·kg^{-1} [48].

The lowest heat of combustion and calorific value, which were 18,090 MJ·Mg^{-1} and 16,680 MJ·Mg^{-1}, respectively, were characteristic of pellets made from mulberry leaf biomass, which does not indicate suitability of using this type of plant biomass for energy purposes. The energy potential of mulberry waste biomass per 1 ton of dry mass is presented in Table 4.

Table 4. Energy potential per 1 Mg of mulberry dry mass.

Sample of Pellet	Produced Energy Amount [GJ·ha^{-1}]	Produced Energy Amount [MWh·ha^{-1}]
1: Leaves	4.50	1.25
2: 1-year old branches	159.30	44.25
3: 3-year old branches	157.80	43.83
4: 5-year old branches	159.90	44.42

Finally, the energy potential was calculated. For the analyzed samples of mulberry branches' dry mass, the average value was 159 GJ·ha^{-1} and 44 MWh·ha^{-1}. Leaf dry mass has a very low energy potential of 4.5 GJ·ha^{-1} and 1.25 MWh·ha^{-1}. In order to optimally utilize this co-product, another use must be found. The literature sources indicate the high value of mulberry leaves as, for example, a herbal raw material [49] or the possibility of using them in medicine and pharmacy [50,51], or animal nutrition [52,53].

4. Conclusions

Alternative energy sources are gaining importance and should be sought and used not only in industrial conditions but also to increase the energy self-sufficiency of smaller enterprises and farms. A perfect example of this is the processing of white mulberry branches, which are waste from shrub cultivation, e.g., for silk or herbal purposes, into pellets.

The heat of combustion value of pellet from mulberry branches averaged 19,266 MJ·Mg^{-1} with a calorific value of 17,726 MJ·Mg^{-1}. The energy potential averaged values were 159.00 GJ·ha^{-1} and 44.17 MWh·ha^{-1}. These are not the highest values among raw materials from trees such as *Quercus* or *Pinus*, but considering that they are created as a by-product, their use is most appropriate. It is also an excellent practice within the circular economy.

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