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The Quality of Virginia Fanpetals Biomass as an Energy Source, Depending on the Type of Propagating Material and Plantation Age

Jacek Kwiatkowski [1,]*, Łukasz Graban [1] and Mariusz Jerzy Stolarski [1,2,]*

[1] Department of Genetics, Plant Breeding and Bioresource Engineering, Faculty of Agriculture and Forestry, University of Warmia and Mazury in Olsztyn, Plac Łódzki 3, 10-724 Olsztyn, Poland; lukasz.graban@uwm.edu.pl

[2] Centre for Bioeconomy and Renewable Energies, University of Warmia and Mazury in Olsztyn, Plac Łódzki 3, 10-724 Olsztyn, Poland

* Correspondence: jacek.kwiatkowski@uwm.edu.pl (J.K.); mariusz.stolarski@uwm.edu.pl (M.J.S.); Tel.: +48-89-5245326 (J.K.); +48-89-5234838 (M.J.S.)

Abstract: Plant biomass is still the main raw material in the production of energy from renewable sources. Virginia fanpetals may be an alternative and complementary source of solid biomass to that obtained from forests and the wood industry. In this respect, it is important to assess the variability of the qualitative characteristics of Sida biomass as a solid biofuel over a long period of use of a plantation of this species. Three types of propagating material were used to establish the plantation: seeds, root cuttings (rhizomes), and seedlings, at two sowing/planting densities. The quality of the biomass, obtained during 14 consecutive years of harvest, was tested, including the moisture content, ash content, higher heating value (HHV), lower heating value (LHV), and the carbon, hydrogen, sulfur, and nitrogen content. It was found that both thermophysical properties and elemental composition were mostly determined by the years of vegetation. An important role in this respect was played by the juvenile period of the plants' development. The biomass obtained after 1 year of vegetation contained a larger concentration of ash, nitrogen, and sulfur and less carbon and hydrogen, which reduced its energy value. The results confirm the possibility of obtaining biomass with low moisture, which favorably places it from an energy point of view.

Keywords: Virginia fanpetals; *Sida hermaphrodita*; herbaceous crops; lignocellulosic biomass; ash content; sulfur content; nitrogen content

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1. Introduction

Virginia fanpetals (*Sida hermaphrodita* (L.) Rusby) is a rapidly growing perennial plant that produces large quantities of green (fresh) or dry biomass each year [1,2]. This species was initially recognized as a new source of fiber and, later, feed, whereas in the 1980s, it attracted considerable attention as an energy source [3,4]. Sida has a high energy value and high yield potential [5]. The fact that Virginia fanpetals plants can regrow multiple times after cutting is an additional advantage. The species can be grown on low-quality soils that are unsuitable for food production, and due to its distinctiveness (at the genus and species level), it contributes to biodiversity in agricultural production [6,7]. Virginia fanpetals is also a valuable source of nectar for entomofauna because it flowers abundantly and has a long blooming period [8]. Sida green biomass can be processed by anaerobic digestion, and it is a valuable co-substrate for agricultural biogas plants [1,9,10]. Green biomass can also be used in the production of hydrogen-rich gas [11]. According to Borkowska and Styk [12], Sida can be harvested up to three times per year. The biomass yield of Virginia fanpetals ranges from 8–14 Mg ha^{-1} DM, when plants are harvested once a year, to 15–20 Mg ha^{-1}, when plants are harvested twice a year. In a study by Žavoronkova [13], Sida biomass yield ranged from more than 10 Mg ha^{-1} DM, when harvested in the bud development stage, to nearly 30 Mg ha^{-1} DM, when harvested in the fruit development stage. Frequent and intensive cutting decreases productivity in the following years of growth and shortens the productive lifespan of Virginia fanpetals plantations to 4–5 years [12].

In our previous study, the average Sida biomass yield over 13 consecutive years was 6.99 Mg ha^{-1} DM; it increased until harvest seasons 4–5 (13.63 Mg ha^{-1} DM on average in 2012) and then decreased rapidly [14].

When Virginia fanpetals is produced as an energy crop, dry stems are harvested in winter, shredded, and directly burned or processed into pellets and briquettes [15–17]. The dry matter yield of Sida shoots is determined by environmental conditions, plant age, and harvest date, and it ranges from several to more than 20 Mg ha^{-1} DM [9,18–23]. The productive lifespan of plantations where dry stems are harvested in winter is estimated at 20–25 years [16,24]. When Sida biomass is used as a source of energy, the most important practical consideration for potential producers would be the economic efficiency of its production, resulting from biomass yields and value as well as the incurred costs and inputs [25].

There is a general scarcity of research on the quality of Sida biomass harvested from long-term plantations as a source of solid biofuel. Most published studies describe the results of 2- to 3-year experiments, usually with data obtained in the first productive years (years 2–5). Therefore, the aim of this study was to evaluate the thermophysical properties and the elemental composition of Sida biomass harvested in winter over 14 consecutive years.

2. Materials and Methods

2.1. Field Experiment

This study analyzes the results of a 14-year field experiment (2009–2022) during which Virginia fanpetals (*Sida hermaphrodita* Rusby L.) was cultivated for the production of solid biofuel [14]. The experiment was conducted at the Agricultural Experiment Station in Bałdy (53°35′48.1″ N 20°36′12.4″ E), which is the property of the University of Warmia and Mazury in Olsztyn. Virginia fanpetals was grown on soil developed from heavy loamy sand underlain by silty clay. The average content of organic matter in the surface layer was 11%. Soil pH was determined at 7.2. The experimental factors were three types of propagating material—seeds, root cuttings: rhizomes, and seedlings—which were sown/planted at two densities. Seeds were sown at a density of 1.5 or 4.5 kg ha^{-1}, whereas rhizomes and seedlings were planted at a density of 20,000 or 60,000 plants ha^{-1}. The experiment was established on 48 plots, where six combinations of the experimental factors (three types of propagating material × two sowing/planting densities) were analyzed in 8 replications. Propagating materials were produced by the Department of Genetics, Plant Breeding and Bioresource Engineering of the University of Warmia and Mazury in Olsztyn. Before the experiment, seeds for sowing and seedling production had been scarified with concentrated sulfuric acid [26]. Root cuttings (rhizomes with an estimated length of 10 cm) had been prepared directly before planting. The experiment was established on plots with an area of 15 m^2 (3 × 5 m) each, and it had a randomized block design with 8 replications [14].

Sida biomass was harvested 14 times, in late January of the calendar year following the growing season. The first harvest took place after the growing season of 2009; the second harvest took place after the growing season of 2010; the third harvest took place after the growing season of 2011, etc. Dry stems were harvested in winter. The stems were leafless, with very few inflorescences (Figure 1). During each harvest, representative samples of around 1 kg each were collected from each plot for laboratory analyses. All analyses were conducted at the Energy Crop Laboratory of the Department of Genetics, Plant Breeding and Bioresource Engineering.

Figure 1. Virginia fanpetals: (**A**) plants at harvest and (**B**) biomass samples prepared for laboratory analyses.

2.2. Laboratory Analyses

In the laboratory, the moisture content of the biomass (%) was determined by the gravimetric method (PN-EN ISO 18134-1:2015-11 [27]) at a temperature of 105 °C with the use of a BINDER FD 53 drying oven (Tuttlingen, Germany) and a RADWAG WBT 2000 analytical balance (Radom, Poland) with an accuracy of 0.01 g. The samples were shredded and ground in a Retsch SM 200 cutting mill (Haan, Germany) with the use of a bottom sieve with a 1.0 mm aperture size. The mass of each ground sample was reduced to around 50 g according to Standard PN-EN ISO 14780:2017-07 [28]. The samples were stored in closed laboratory containers until further analysis.

The total content of carbon (C), hydrogen (H), and sulfur (S) in Sida biomass was determined with the ELTRA CHS-500 analyzer (Neuss, Germany) based on Standards PN-EN ISO 16948:2015-07 [29] and PN-EN ISO 16994:2016-10 [30]. Nitrogen (N) content was determined by the Kjeldahl method with the use of a BUCHI K-435 digestion unit and a BUCHI B-324 distillation unit (Flawil, Switzerland). The ash content of the biomass was determined in the ELTRA TGA-THERMOSTEP thermogravimetric analyzer (Neuss, Germany) according to Standard PN-EN ISO 18122:2016-01 [31].

The lower heating value (LHV) was calculated based on the higher heating value (HHV) of Sida biomass, which was determined in the IKA C2000 combustion calorimeter (Taufen, Germany) with the use of the dynamic method based on measurements of hydrogen and moisture content (PN-EN ISO 18125:2017-07 [32]).

2.3. Statistical Analysis

The moisture content, ash content, carbon content, hydrogen content, sulfur content, nitrogen content, LHV, and HHV of Sida biomass were processed statistically by repeated measures ANOVA. This resulted from the fact that the experiment was conducted over a long period of time, with Virginia fanpetals plants regrowing from the same rootstocks at the same location. Therefore, biomass was also harvested from the same location in consecutive harvest seasons. The type of propagating material and initial plant density were the fixed grouping factors, whereas 14 years of Virginia fanpetals cultivation (2009–2022) were the repeated measurement factor.

Arithmetic means and standard deviation were calculated for all analyzed parameters. Homogeneous groups were identified by Tukey's honest significant difference (HSD) test at a significance level of $p < 0.05$. Descriptive statistics, including mean, median, minimum and maximum values, upper and lower quartile, standard deviation, and the coefficient of variation, were also determined. All analyses were performed with the Statistica 13.3 program (TIBCO Software Inc., Palo Alto, CA, USA).

3. Weather Conditions during the Harvest of Virginia Fanpetals Biomass (January)

During the 14-year experiment, the average temperature in January ranged from −8.9 °C (2010) to 2.6 °C (2020) (Table 1).

Table 1. Weather conditions during the harvest of Virginia fanpetals biomass (January) in each year of the experiment [1].

Year	Range of Maximum Daily Temperature (°C)		Range of Minimum Daily Temperature (°C)		Average Daily Temperature (°C)	Total Daily Rainfall (mm)	Average Daily Relative Humidity (%)
2010	0.0	−13.8	−4.5	−25.3	−8.9	29.1	85.3
2011	6.3	−6.1	4	−11.8	−1.4	36.8	93.4
2012	8.0	−9.2	3.8	−16.3	−1.7	66.0	91.5
2013	6.9	−11.8	3.9	−18.0	−4.7	44.3	90.3
2014	8.0	−12.5	4.1	−19.5	−3.9	64.3	86.4
2015	9.2	−5.3	4.4	−12.3	0.4	47.9	85.1
2016	7.8	−11.3	3.6	−16.9	−3.9	21.1	86.8
2017	2.8	−10.7	0.3	−20.7	−3.3	19.0	84.8
2018	9.5	−6.4	4.3	−8.9	−0.3	40.6	87.2
2019	6.1	−5.6	2.4	−11.7	−2.4	52.7	86.1
2020	9.2	0.9	6.1	−3.6	2.6	44.9	88.1
2021	7.2	−11.8	2.8	−21.8	−2.1	41.4	89.3
2022	10.2	−1.7	6.4	−8.3	0.8	64.2	90.6
2023	15.7	−2.0	12.1	−4.7	2.2	45.8	88.1

[1] Source: Institute of Meteorology and Water Management—National Research Institute.

Weather conditions during seven harvest seasons (2011–2012, 2014, 2016–2017, 2019, and 2021) did not differ significantly from the long-term average and were considered normal (Table 2). In two harvest seasons, daily mean temperature was below the long-term average, including in 2010, which was a very cool year. In the remaining five harvest seasons, daily mean temperature exceeded the long-term average, and these years were described as moderately warm (2015 and 2018), warm (2020 and 2023), and very warm (2022).

Table 2. Classification of thermal conditions and precipitation levels during the harvest of Virginia fanpetals biomass [1].

Year	Thermal Conditions in January	Precipitation Levels in January
2010	very cool	dry
2011	normal	normal
2012	normal	extremely humid
2013	moderately cool	humid
2014	normal	extremely humid
2015	moderately warm	very humid
2016	normal	very dry
2017	normal	very dry
2018	moderately warm	normal
2019	normal	very humid
2020	warm	normal
2021	normal	normal
2022	very warm	extremely humid
2023	warm	normal

[1] Source: own elaboration based on [33].

Total precipitation levels did not differ significantly from the long-term average in five harvest seasons (2011, 2018, 2020, 2021, and 2023). In six harvest seasons, precipitation exceeded the long-term average, and January was an extremely wet month in 2012, 2014, and 2022. Total precipitation was below the long-term average in three harvest seasons (2010, 2016, 2017), and January was a very dry month in 2016 and 2017.

In the analyzed harvest seasons, mean daily relative humidity ranged from 84.8% (2017) to 93.4% (2011). During the entire 14-year experiment (2009–2023), temperature and relative humidity approximated the long-term average in only two harvest seasons (January of 2011 and 2021)

4. Results and Discussion

4.1. Evaluation of the Thermophysical Properties of Virginia Fanpetals Biomass

The average moisture content of Sida biomass during the 14-year experiment was 25.25% (Figure 2A). This parameter differed significantly across years, ranging from 21.10% (harvest in January 2013) to 31.95% (harvest in January 2019). The type of propagating material and plant density had no significant effect on the moisture content of the biomass. In most cases, the moisture content of the biomass derived from the analyzed types of propagating material did not differ by more than one percentage point (pp), and the difference in moisture content reached 1.30–1.41 pp in three harvest seasons (2010, 2013, 2020). Only in 2019 was the moisture content of the biomass produced from rhizomes 3.77 pp higher than the moisture content of the biomass derived from seeds and 2.58 pp higher than the moisture content of the biomass produced from seedlings.

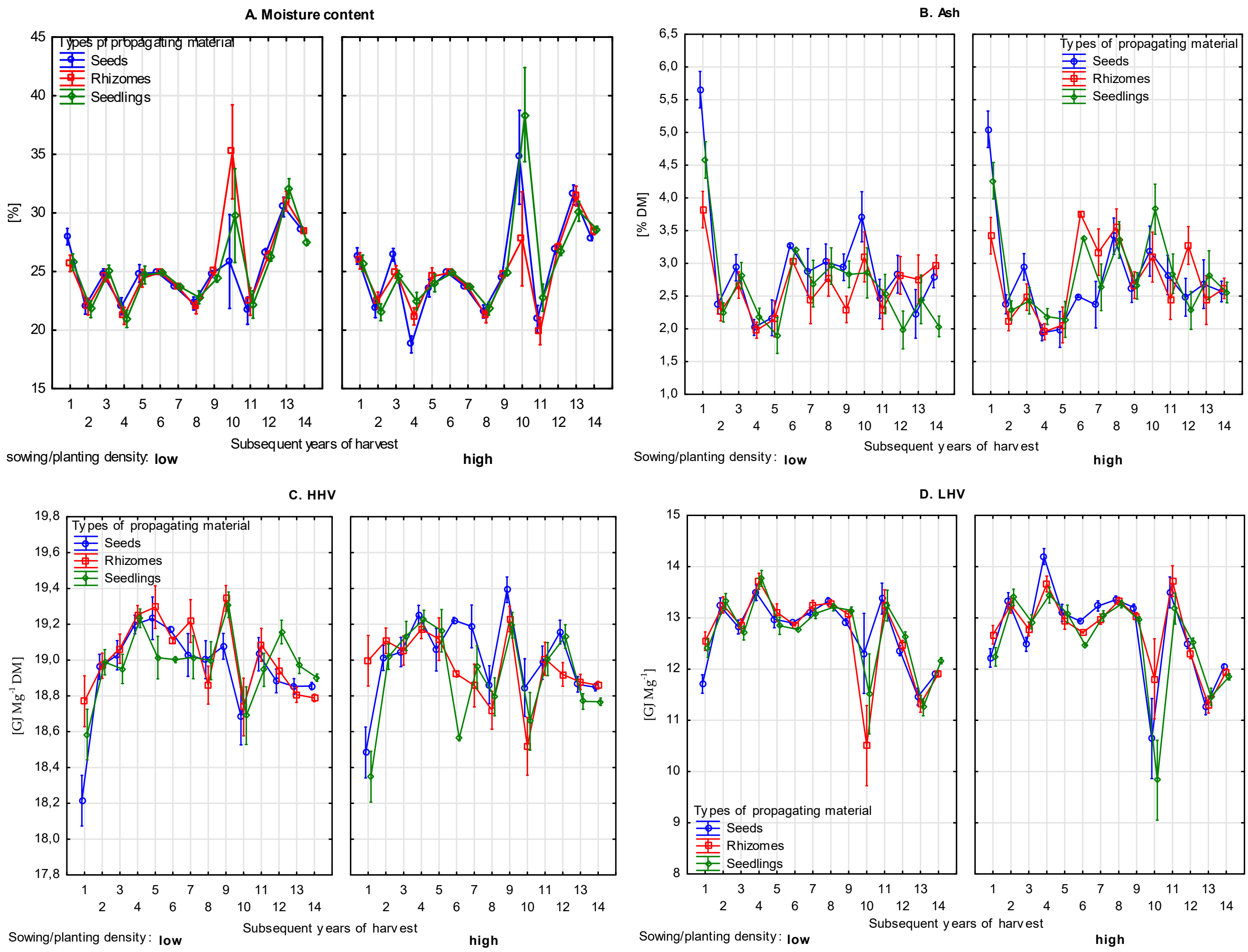

Figure 2. Thermophysical properties of Virginia fanpetals biomass harvested in winter over 14 consecutive years: (**A**) moisture content (%), (**B**) ash content (% DM), (**C**) higher heating value (GJ Mg^{-1} DM), and (**D**) lower heating value (GJ Mg^{-1}). Note: ',' on Y axis means decimal point.

The results of the statistical analysis for 14 harvest seasons, three types of propagating material, two sowing/planting densities, and three replications (Table 3) indicate that the moisture content of Sida biomass was generally low at harvest and that this parameter was characterized by low variation.

Table 3. Selected statistical analysis indicators for the parameters of Virginia fanpetals biomass from 14 years of harvest (N valid = 672).

Parameter	Mean	Median	Minimum Value	Maximum Value	Lower Quartile	Upper Quartile	Standard Deviation	Coefficient of Variation (%)
Moisture content (%)	25.25	24.83	17.02	46.17	22.88	26.67	3.85	15.27
Ash content (% DM)	2.78	2.65	1.41	6.14	2.23	3.19	0.76	27.17
Higher heating value (GJ Mg^{-1} DM)	18.97	19.00	17.83	19.60	18.85	19.16	0.25	1.33
Lower heating value (GJ Mg^{-1})	12.69	12.87	8.21	14.60	12.31	13.21	0.85	6.68
Carbon content (% DM)	49.20	49.64	43.27	53.09	47.51	50.77	2.05	4.17
Hydrogen content (% DM)	5.98	5.97	5.04	6.80	5.84	6.24	0.36	6.05
Sulfur content (% DM)	0.05	0.04	0.02	0.12	0.04	0.06	0.01	28.01
Nitrogen content (% DM)	0.41	0.38	0.16	1.34	0.31	0.47	0.16	39.09

Biomass for the production of solid biofuels should have low moisture content at harvest. The moisture content of Virginia fanpetals biomass is lower than that of lignified biomass [34]. Numerous studies have shown that delayed harvest decreases the moisture content of Virginia fanpetals shoots from more than 40% in the fall to around 20–25% in the winter [35–38]. According to Jablonowski et al. [9], the moisture content of Sida biomass decreased to around 10% when dry shoots were left in the field until March (data not published). Weather conditions directly before harvest, in particular, relative humidity, significantly influence the moisture content of the biomass [34].

The average ash content of Sida biomass was 2.78% DM, and It differed considerably across years (Figure 2B). Ash content was significantly highest (4.47% DM) after the first growing season (2010) (Figure 2B). The lowest ash contents were noted in 2013 (2.05% DM), 2014 (2.07% DM), and 2011 (2.28% DM). In the remaining harvest seasons, the values of this parameter formed two homogeneous groups in the range of 2.56–2.71% DM and 3.18–3.30% DM.

The ash content of Sida biomass produced from seeds was only somewhat higher than the ash content of the biomass obtained from rhizomes and seedlings, but the difference was statistically significant. No significant differences were noted between the ash content of the biomass derived from rhizomes and seedlings (Figure 2B). These results could be attributed to the high ash content of one-year-old shoots propagated from seeds.

Ash content was significantly higher in biomass from young, one-year-old shoots, in particular, in plants grown from seeds and rhizomes, which contributed to variation in this parameter during the experiment. The ash content of the biomass derived from older plants was characterized by low variation (Table 3). The ash content of Virginia fanpetals biomass was similar in other studies [9,24,39,40]. Dry Sida biomass contains more ash than wood biomass derived from willows and oaks [39]. However, Sida biomass is less abundant in ash than other species of perennial herbaceous crops [20,41] and other sources of agricultural biomass, such as rapeseed straw [42]. According to Stolarski et al. [43,44], ash content was lower in biomass derived from two-year-old and older plants than from one-year-old plants. The cited authors also noted that ash concentration in the biomass decreased when harvest was delayed [34,37].

In all harvest seasons, the HHV of Sida biomass was determined at 18.97 GJ Mg^{-1} DM on average, and all experimental factors induced minor but statistically significant differences in this parameter (Figure 2C). The HHV of the biomass was significantly highest in the ninth growing season (2018) (19.26 GJ Mg^{-1} DM) and lowest in the first growing season (2010) (18.57 GJ Mg^{-1} DM). Much smaller, but significant, differences in this parameter were observed between biomass samples derived from various propagating materials. The values of HHV were significantly higher in treatments where Virginia fanpetals was grown from seedlings (18.99 GJ Mg^{-1} DM) and seeds (18.98 GJ Mg^{-1} DM), compared to rhizomes (18.95 GJ Mg^{-1} DM).

The HHV of the biomass was significantly higher in treatments with lower plant density than in those with higher plant density, although the difference was minimal at only 0.02 GJ Mg^{-1} DM. The HHV was the least varied trait in the group of the analyzed parameters (Table 3). The HHV was bound by a relatively strong negative correlation with ash content, a moderately strong negative correlation with nitrogen content, and weak, but significant, negative correlations with the moisture content and sulfur content of the biomass (Table 4). A weak positive correlation was also noted between the HHV and the carbon content of the biomass.

Table 4. Pearson's correlation coefficient matrix for the studied parameters.

Item	MC	Ash	HHV	LHV	C	H	S	N
MC	1.00							
Ash	0.27 *	1.00						
HHV	−0.34 *	−0.62 *	1.00					
LHV	−0.98 *	−0.35 *	0.52 *	1.00				
Carbon	0.06	−0.30 *	0.27 *	−0.02	1.00			
Hydrogen	0.16 *	−0.39 *	0.07	−0.19 *	0.42 *	1.00		
Sulfur	0.02	0.46 *	−0.19 *	−0.05	−0.01	−0.21 *	1.00	
Nitrogen	0.23 *	0.76 *	−0.52 *	−0.30 *	−0.21 *	−0.34 *	0.62 *	1.00

* Significant values ($p < 0.05$).

The LHV of the biomass was significantly correlated with the year of harvest and the interactions between the year and the remaining experimental factors. The LHV was most significantly differentiated by year (75.3%) (Table 5); it was highest after the fourth growing season (2013) and lowest after the tenth growing season (2019) (Figure 2D). This parameter was not differentiated by the type of propagating material or plant density.

Table 5. The percentage of the effects in the overall variance for the characteristics of Virginia fanpetals biomass.

Source of Variation	df	MC	Ash	HHV	LHV	C	H	S	N
Types of propagating material (A)	2	0.1	0.6	0.5	0.2	0.0	0.1	7.1	2.3
Initial plant density (B)	1	0.0	0.1	0.2	0.0	0.0	0.0	0.4	0.2
A × B	2	0.4	1.0	1.7	0.4	0.5	0.0	0.4	0.3
Error 1	42	1.7	2.4	1.5	1.4	0.6	0.7	2.5	0.7
Years (Y)	13	70.8	61.6	54.1	75.3	82.4	86.6	30.7	58.0
Y × A	26	1.8	10.0	11.1	2.1	2.1	1.4	14.0	16.6
Y × B	13	1.7	2.0	2.7	1.4	0.6	0.4	6.0	2.3
Y × A × B	26	7.8	4.1	6.3	5.5	2.6	1.2	9.2	5.7
Error 2	546	15.7	18.2	21.9	13.5	11.1	9.5	29.7	13.9
Total		100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0

The LHV was strongly negatively correlated with the moisture content of the biomass (Table 4). The LHV was also bound by a weak, but significant, negative correlation with the concentrations of ash, nitrogen, and hydrogen in Sida biomass. The LHV was characterized by very low variation during the entire 14-year experiment (Table 3).

Sida biomass is characterized by a high energy value compared to other types of agricultural biomass. In the present study, the energy value of Virginia fanpetals biomass approximated the higher range of HHV values and the lower range of LHV values reported by other authors [24,34,35,37]. These parameters were similar to the values noted in wood biomass [34,39]. In other studies, the HHV and LHV of Virginia fanpetals biomass varied across years, and minor differences resulting from the harvest date (fall, winter, early spring) were noted [9,34,35,37,43,44]. The HHV and LHV of the biomass were generally higher when Virginia fanpetals was harvested in the spring rather than in the fall [38], but these trends varied [34,37]. Szyszlak et al. [45] observed that the HHV was affected by the thickness of Virginia fanpetals shoots and suggested that the value of this parameter could be influenced by plant density.

4.2. Evaluation of the Elemental Composition of Virginia Fanpetals Biomass

The elemental composition of Virginia fanpetals biomass (concentrations of carbon, hydrogen, sulfur, and nitrogen) differed significantly across years (harvest seasons) (Table 6). Carbon, sulfur, and nitrogen contents were also significantly influenced by the interactions between the year and the main experimental factors. Hydrogen, sulfur, and nitrogen contents were significantly differentiated by the type of propagating material, whereas plant density significantly affected the sulfur and nitrogen contents of the biomass (Table 6).

Table 6. Statistics of *p* values from the repeated measures analysis of variance for the elemental composition of Virginia fanpetals biomass.

Source of Variation	df	MC	Ash	HHV	LHV	C	H	S	N
Types of propagating material (A)	2	0.261	<0.001 *	0.003 *	0.082	0.539	0.021 *	<0.001 *	<0.001 *
Initial plant density (B)	1	0.666	0.259	0.028 *	0.366	0.419	0.716	0.011 *	<0.001 *
A × B	2	<0.001 *	<0.001 *	<0.001 *	0.006 *	0.001 *	0.411	0.048 *	0.002 *
Years (Y)	13	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *
Y × A	26	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *
Y × B	13	<0.001 *	<0.001 *	<0.001 *	<0.001 *	0.004 *	0.058	<0.001 *	<0.001 *
Y × A × B	26	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *	<0.001 *

* Significant values ($p < 0.05$).

The average carbon content of Sida biomass was 49.20% DM. Carbon concentration was highest in the biomass harvested in the tenth growing season (2019) and lowest in the biomass harvested in the first growing season (Figure 3A). In these years, carbon concentration was significantly differentiated by the type of propagating material and plant density. Carbon content was the least varied trait in the elemental analysis (Table 3).

Carbon is the main component of solid fuels, and its concentration increases the HHV of fuel [37]. In the present study, the carbon content of Sida biomass was bound by a weak, but significant, correlation with the HHV. Carbon concentration was similar to that noted by Stolarski et al. [42] and Šurić et al. [38], and it was higher than that reported by Šiaudinis et al. [43]. In the work of Bilandžija et al. [37], carbon concentration was much lower when Sida biomass was harvested in January (32.22% DM) than in November and March (46.79% and 50.08% DM, respectively). In other studies, carbon concentration was higher when the biomass was harvested in early spring (March) than in the fall (November) [35,38]. Sida biomass is less abundant in carbon than woody plants. In the group of herbaceous plants, the carbon content of Virginia fanpetals biomass is similar to that noted in *H. salicifolius*, *H. tuberosus*, and *S. pectinata* and higher than that reported in *M. sinensis*, *A. donax*, and *S perfoliatum* [35]. Ţîţei [20] demonstrated that Sida biomass was more abundant in carbon than eight other perennial energy crops.

The average hydrogen concentration in Sida biomass was 5.98% DM. Hydrogen content was highest in the biomass harvested in the 13th growing season (2022) and, similar to carbon content, lowest in the biomass harvested in the first growing season (2010) (Figure 3B). In these years, hydrogen content was also differentiated by the type of propagating material and plant density. Hydrogen concentration in the biomass was minimally higher in plants propagated from seeds than from seedlings. This difference reached only 0.03 pp, but it was statistically significant.

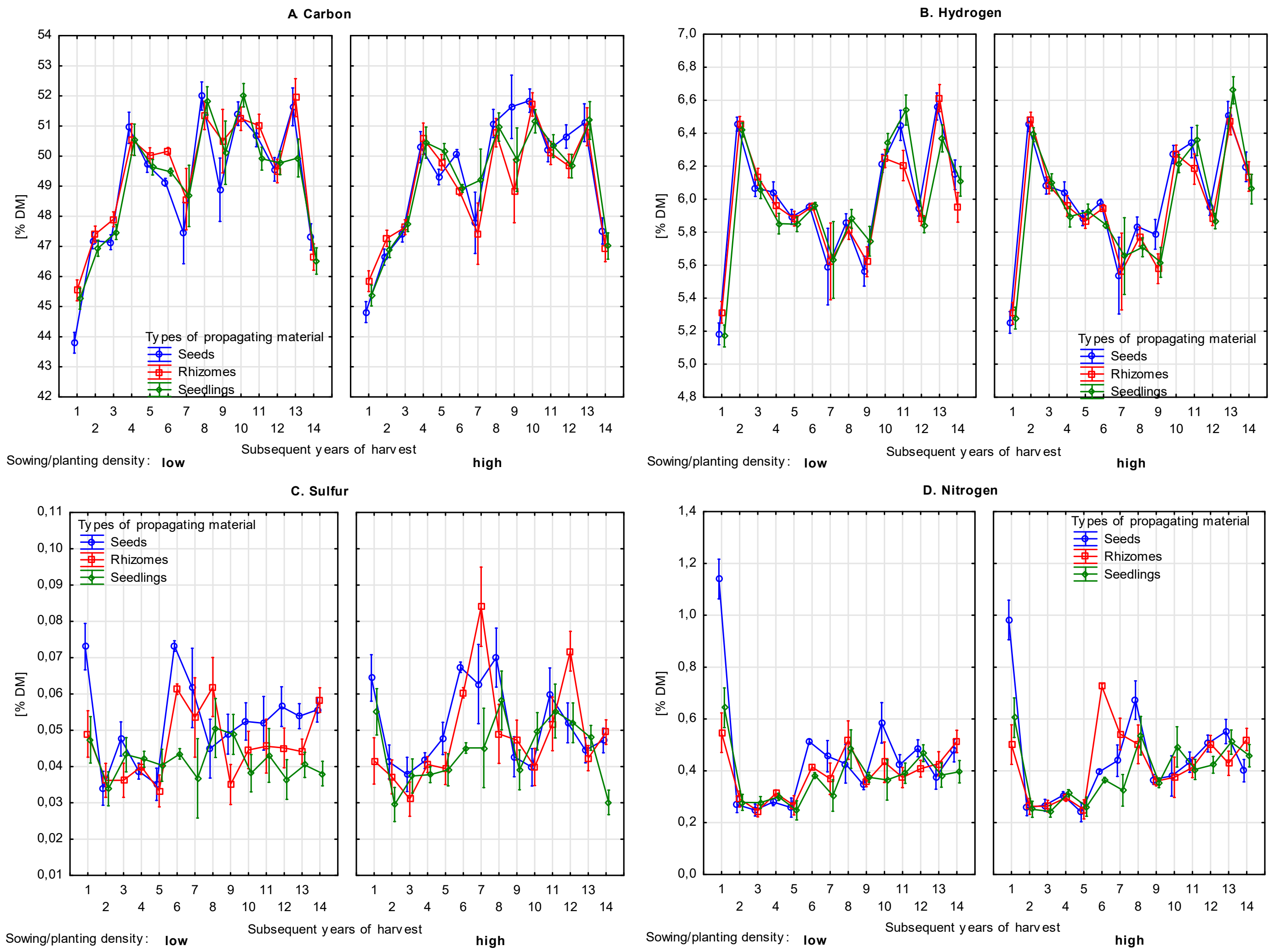

Figure 3. The elemental composition of Virginia fanpetals biomass harvested in winter over 14 consecutive years: (**A**) carbon content (% DM), (**B**) hydrogen content (% DM), (**C**) sulfur content (% DM), and (**D**) nitrogen content (% DM). Note: ',' on Y axis means decimal point.

Similar to carbon, hydrogen is also one of the most important components of solid fuels. The hydrogen content of Sida biomass approximates 6% [37,41,43]. Virginia fanpetals biomass is more abundant in hydrogen than other herbaceous plants, and its hydrogen content is only somewhat lower than that noted in many species of woody plants [20,35]. In a study by Stolarski et al. [35], hydrogen concentration in the biomass was much higher when Virginia fanpetals was harvested in March than in November or January. Other authors did not report such clear differences in the hydrogen content of the biomass across harvest seasons [37,38].

All experimental factors and their interactions induced small, but significant, differences in the sulfur content of Sida biomass. Sulfur concentration was most significantly differentiated by year. During the 14-year experiment, the sulfur content of the biomass ranged from 0.035% DM in the second growing season to 0.058% DM in the sixth growing season. Sulfur concentration in the biomass harvested in treatments where Virginia fanpetals was grown from seeds was 0.004 pp higher in comparison to treatments where plants were grown from seedlings and 0.09 pp higher in comparison to treatments where plants were grown from rhizomes. Sulfur concentration was highest in the seventh harvest season in treatments where seedlings were planted at a density of 60,000 seedlings ha^{-1} (0.084% DM) and lowest in the second growing season in treatments where rhizomes were planted at a density of 60,000 rhizomes ha^{-1} (0.029% DM) (Figure 3C). Similar observations were made by other researchers [20,41,46]. Significantly higher sulfur concentration in Sida biomass was reported only by Bilandžija et al. [37]. In other studies, the biomass of *S. hemaphrodita* was characterized by the significantly lowest sulfur content (0.031% DM on average) in the analyzed group of 26 genotypes of perennial energy crops, including woody and perennial plant species [35,47]. Stolarski et al. [35] and Bilandžija et al. [37] found that sulfur content decreased when harvest was delayed from fall to early spring.

The average nitrogen content of Sida biomass was 0.41% DM, and similar to sulfur content, it was differentiated by all examined factors and their interactions, in particular, the year, which contributed most to the observed variation. Nitrogen concentration was highest in the biomass harvested after the first growing season (0.736% DM) and lowest in the biomass harvested after the fifth (0.254% DM), third (0.258% DM), and second (0.269% DM) growing season, and the values noted in the fifth, third, and second harvest season formed a homogeneous group. Nitrogen concentration was highest in the biomass harvested from treatments where Virginia fanpetals was grown from seeds, and it was 0.038 pp higher in comparison to treatments where plants were propagated from seedlings and 0.059 pp higher in comparison to treatments where plants were grown from rhizomes. An analysis of the interactions between all experimental factors and years revealed that the nitrogen content was highest in the biomass harvested after the first growing season from treatments where plants were grown from seeds sown at 1.5 kg ha^{-1} (1.140% DM) and lowest in the biomass harvested after the fifth growing season (2013) from treatments where plants were grown from seeds sown at 4.5 kg ha^{-1} (0.240% DM) (Figure 3D). The lowest nitrogen values belonged to a homogeneous group of values (0.240–0.380% DM) that were noted across years in 39 treatments with different types of propagating material and plant densities. Nitrogen concentration was bound by a strong positive correlation with ash content and a moderate positive correlation with sulfur concentration. Weak, but significant, negative correlations were found between nitrogen concentration and the carbon and hydrogen content of Sida biomass.

The nitrogen content of Sida biomass noted in this study approximated the values reported by other authors [20,37,38,42,48]. Studies examining other species of perennial energy crops revealed that Virginia fanpetals biomass was characterized by the lowest nitrogen concentration [20,35,48]. In this respect, Sida biomass meets the solid biofuel requirements stipulated in Standard DIN EN ISO 17225-7:2014-09 [9]. Stolarski et al. [35] and Šurić et al. [38] found that Virginia fanpetals biomass was less abundant in nitrogen when harvested in early spring (March) than in late fall (November).

The elemental composition of Sida biomass is determined by various factors, including environmental conditions, fertilization, plantation age, plant growth stage, and others. When Virginia fanpetals is grown for solid biofuel, its biomass consists mostly of dry stems. The quality of such raw material remains relatively stable. According to Siaudinis [43], the crude fiber content (strongly correlated with the HHV) is lower when Virginia fanpetals plants still have leaves and flowers. The content of cellulose and lignin in stems stabilizes already during flowering and remains relatively unchanged until the end of December, whereas it increases in leaves over the same period [9]. Therefore, the proportion of plant parts other than stems (leaves, seeds) in the biomass harvested at the end of the growing season may also contribute to variability in its elemental composition. Sida biomass harvested in winter is characterized by lower concentrations of nitrogen and sulfur, higher carbon content, and higher LHV than in Sida biomass harvested at the end of the growing season.

5. Conclusions

The quality of Virginia fanpetals biomass harvested during a 14-year experiment was analyzed in this study. In the literature, the quality of Virginia fanpetals biomass was usually investigated during short, 2- to 3-year experiments. This study presents the results of a long-term experiment, where Virginia fanpetals was produced from three types of propagating material at two sowing/planting densities. The thermophysical properties and the elemental composition of the biomass were influenced mainly by year. Despite the fact that weather conditions at harvest differed across years, Sida biomass was generally characterized by low moisture content (average 25.25%), which suggests that it is well suited for energy generation, compared to other biomass types. The examined biomass parameters differed across years, which could be attributed to the specific life cycle of the analyzed species. In the first growing season, Virginia fanpetals plants grew at a slow rate; shoots were not lignified; and biomass yields were low. As a result, the harvested biomass was more abundant in ash, nitrogen, and sulfur and less abundant in carbon and hydrogen, which decreased its energy value. The quality of Virginia fanpetals biomass was stabilized at a similar level in successive years of growth. The average values of the analyzed parameters were as follows: HHV (18.97 GJ Mg^{-1} DM), LHV (12.69 GJ Mg^{-1}), ash (2.78% DM), carbon (49.20% DM), hydrogen (5.98% DM), nitrogen (0.41% DM), and sulfur (0.05% DM). It should be stressed that Sida biomass used as a source of solid biofuel should be harvested in winter or early spring, after longer frost spells. Delayed harvest contributes to improving the thermophysical properties and the elemental composition of the biomass for energy generation.

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