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Sida hermaphrodita Cultivation on Light Soil—A Closer Look at Fertilization and Sowing Density

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Abstract: *Sida hermaphrodita* (L.) Rusby is a promising perennial biomass crop to provide sustainable bioenergy via combustion. This study investigated cultivation practices for *Sida hermaphrodita* (L.) Rusby on light soils in temperate climates. Therefore, two cultivation factors were varied over 8 years in a field trial: (i) fertilization with compost from urban green spaces (0, 10 and 20 t ha^{-1}), and (ii) seeding amount (1, 2 and 3 kg ha^{-1}). Compost fertilization and high seeding amount contributed to an increase in the number and height of *Sida* shoots while their thickness decreased. The applied compost fertilization increased the dry matter yield (DMY) of the plants by 24.9% and 50.7%, respectively, in all experimental years compared to the control. Compared to the lowest seeding rate, increasing the seeding rate to 2 and 3 kg ha^{-1} increased the DMY by 35.0% and 71.6%, respectively. Thus, the highest energy value of DMY of *Sida hermaphrodita* plants per unit area was also obtained for combining the highest organic compost fertilization and seeding strength. From this, it can be deduced that on light soils, it does not seem reasonable to choose a compost fertilizer rate below 20 kg ha^{-1} and a seeding amount below 3 kg ha^{-1}.

Keywords: bioenergy; biomass yield; low-input cultivation; perennial crop; sustainable agricultural intensification

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1. Introduction

The growing demand for energy and the need to protect the environment and the independence of man from the effects of limited resources of fossil fuels means that in the energy development strategies of many countries, especially the European Union, despite numerous discussions on economic profitability, more and more emphasis is placed on obtaining energy from renewable sources [1–3]. Obtaining energy in this way, according to many authors [4–9], results in increasing the energy security of a region (especially areas with underdeveloped energy infrastructure), the reduction of greenhouse gas emissions, gradual replacement of conventional fuels with renewable energy sources, revitalisation of the rural economy and economic recovery by creating new jobs and new technologies.

In Poland, due to the favourable climate and good geographical location and habitat conditions, biomass is considered as one of the essential components of future supplies for the bioeconomy [9–11]. In Poland, biomass for energy originates mainly from forest residues and the wood industry [12]. The continuous increases in energy demand and the implementation of EU commitments necessitate obtaining it from specially cultivated plants [12,13].

So far, the most popular among growers are perennial plants such as willow (*Salix viminalis*), poplar (*Populus* L.), sugar miscanthus (*Miscanthus sacchariflorus*) and giant miscanthus (*Miscanthus* × *giganteus*), as well as species containing sufficient amounts of oil and carbohydrates necessary to obtain energy carriers [14,15]. Little attention is paid to the cultivation of Virginia fanpetals (hereafter referred to as *Sida*) which can be established by sowing (most species introduced into Poland must be planted from prepared cuttings) and the use of compost from a waste of green areas for cultivating them as fertilizer. Currently, *Sida* is grown in Central Europe, mainly in experiments in research centres and universities, and small areas for production purpose are found in Austria, Romania, Lithuania, and Hungary, as well as in Poland (approximately 300 ha) and Germany—approximately 100–150 ha [14,16].

Sida develops an extensive root system allowing access to water and nutrients and grows well on light soils (marginal lands) [8,10,17,18]. *Sida*'s biomass dry matter yields (DMYs) vary between 9 t ha^{-1} on light soils and 25 t ha^{-1} on rich soils [16,17]. Energy crops should be located on poor-quality soils to avoid competition with food production. In such conditions, biomass DMYs range from 10 t ha^{-1} to 12 t ha^{-1} [16,19–21] after the first two years of growth in various mineral fertilization variants. Generally, plants respond well to nitrogen fertilization, which significantly increases biomass yield, while phosphorus fertilization promotes better stem formation and yield, especially in poor soils [22,23]. Biomass dry matter production of *Sida* depends on several factors: soil quality, climatic conditions, cultivation, fertilization, plant density and establishment method (seeds, seedlings, root cuttings) [16,22]. Sowing seeds is the most cost-efficient method for growing *Sida* but the germination rate can be very low (even 5–15%) and slow. This unpredictable germination rate can cause weed growth and low biomass yield [16,21,22]. A useful number of seeds for *Sida* plantation establishment is considered to be approximately 200,000–300,000 seeds per hectare or 1 kg ha^{-1} [21,22]. As Cumplido-Marin [22] indicated on the basis of her research review, the number of seeds used ranged from 1.5 to even 9 kg ha^{-1}, and usually, a higher seedling amount results in higher yields. Seed preparation methods such as extension of the storage period, scarification of seeds, or pretreatment in hot water is used to increase the germination rate up to 90% [16,21,22]. In the case of energy crops grown in marginal soils (light soils), fertilization can substantially increase biomass DMY [19]. Research indicates that *Sida is* efficiently applicable using the nutrients from alternative sources such as sewage sludge [24], sludge compost [25], and digestates from anaerobic digestion [17,23,26,27]. Research conducted in Germany by Veste et al. [28] and in Poland by Ociepa-Kubicka and Pachura [29] on the influence of differentiated fertilization on the DMY of *Sida* indicates the possibility of using a combination of different doses of compost and mineral fertilization, which significantly influences the increase in DMY. However, few studies report a period longer than four years of cultivation of *Sida*, which is vital for plants with the highest DMY after the second year of use and alternative sources of nutrients in the fertilization of poor-quality soils intended for energy crops.

The work aimed to determine the effect of organic fertilization with urban green compost and mineral NPK fertilization on the DMY of *Sida* cultivated under varying sowing densities for energy purposes in light soil conditions. The underlying research question was whether the establishment via sowing is suitable for cultivating *Sida* on light soils.

2. Materials and Methods

2.1. Study Site and Experimental Design

A *Sida* field trial was established in the West Pomeranian region of Poland, in Lipnik, near Stargard (N 53°20′35.8″, E 14°98′10.8″), in 2009, using the random sub-block (split-plot) method in triplicate with a single plot area of 12 m^2. *Sida* was sown on 5 May 2009 with a row seeder with an inter-row spacing of 0.5 m in the amount assumed in the second study factor. The seeds came from another plantation of energy crops in Poland (West Pomeranian voivodeship), and the seed germination capacity before sowing was 49%.

The soil in the experiment was made of loamy sand, and, according to the WRB, represented Haplic Luvisols (Humic) [30].The content of total macroelement forms in the soil before the experiment was as follows: C—8.10 g kg^{-1} DM, N—0.92 g kg^{-1} DM, S—0.02 g kg^{-1} DM, P—0.45 g kg^{-1} DM, K—0.66 g kg^{-1} DM, Mg—0.91 g kg^{-1} DM. The soil reaction was acid (pH$_{KCl}$—5.2). The observation period ranged from years 2009 to 2016. The experiment was established in a post after oats were harvested for seeds. Before planting, the following agrotechnical operations were carried out: post-harvest tillage and medium ploughing. In the spring, before sowing, compost fertilization mixed with the soil was applied in the amount assumed in the first factor of the study. The compost was made from waste from the care of urban greenery in Szczecin, which included: a green mass of cut plants, leaves (of trees and shrubs), cones and other plant waste. Immediately before sowing the plants in the first year of the experiment, mineral fertilization with phosphorus and potassium in 80 kg ha^{-1} and 100 kg ha^{-1} was applied to all the study objects, and in the full years of cultivation, fertilization with phosphorus and potassium was applied before starting the plant vegetation Phosphorus was used as 19% superphosphate (phosphorus in the form of P_2O_5) and potassium as 60% potassium salt (potassium in the form of K_2O). Nitrogen fertilization in the form of ammonium nitrate was used in the amount of 100 kg ha^{-1} (every year of cultivation) in the year of establishment in two equal doses (the first month after sowing the plants, while the second one was used six weeks later), and in the years of full use, once in spring, before starting the plant vegetation. The tested factors included: factor I—compost doses: 0, 10 and 20 t ha^{-1} of dry matter and factor II—seeding amount: 1, 2 and 3 kg ha^{-1}.

2.2. Physicochemical Properties of the Compost

Basic physicochemical parameters were determined in the compost. The compost reaction (pH in 1M KCl and in H_2O) was determined potentiometrically, and the specific electrical conductivity was performed conductometrically in a water suspension. Total carbon, nitrogen and sulphur content were determined by means of elementary analyser COSTECH ECS 4010. The content of macroelements (P, K, Mg, Na) and microelements (Fe, Mn, Cr, Zn, Cd), soluble in the mixture of concentrated acids HNO_3 + $HClO_4$, was determined by compost mineralisation in this mixture, using atomic absorption spectrophotometer Unicam Solaar 929. Phosphorus was obtained colorimetrically. From the analysis of the chemical composition of the compost, it should be stated that the compost reaction was neutral, the total carbon, total nitrogen and magnesium content was low, and phosphorus, potassium, sulphur, calcium, and sodium were high (Table 1). The contents of trace elements in the compost (Cu, Fe, Mn, Cr, and Zn) did not exceed their permissible amounts adopted in the industry standard (BN–89/9103–09).

Table 1. Physicochemical properties of the compost used in this study and total doses of minerals brought in with compost fertilization.

Parameter	pH in 1M KCl	pH in H_2O	EC [1]	Ctot [2]	Ntot [3]	C/N [4]	Total Content of Elements											
							P	K	Ca	Mg	Na	S	Cu	Fe	Mn	Cr	Zn	Cd
			µS cm^{-1}	g kg^{-1}			g kg^{-1}						mg kg^{-1}					
Value	6.78	7.08	624.10	142.01	9.52	14.93	1.95	3.54	34.973	2.91	0.34	0.74	26.39	8698.30	312.18	12.13	172.50	1.26
Total doses of minerals brought in with the compost in kg ha^{-1}																		
						N	P	K	Ca	Mg	Na	S	Cu	Fe	Mn	Cr	Zn	Cd
Compost doses 10 t ha^{-1}						95.2	19.5	35.4	349.73	29.1	3.4	7.4	0.26	86.98	3.12	0.12	1.73	0.01
Compost doses 20 t ha^{-1}						190.4	39	70.8	699.46	58.2	6.8	14.8	0.53	173.97	6.24	0.24	3.45	0.03

[1] electrical conductivity, [2] total carbon, [3] total nitrogen, [4] total carbon and total nitrogen ratio.

2.3. Observations of Plant Development and Plant Harvests

During the study period, observations of plant development and growth were carried out (Figure 1), and biometric measurements were made on 25 plants or shoots, which included: length (cm) and thickness of shoots (mm), number of shoots on one plant (pcs) and harvested biomass DMY (t ha^{-1}). The length, thickness of shoots and number of shoots per plant were carried out at the time of harvesting the plants for biomass. The yield of green and dry matter (t ha^{-1}) was determined on all plots. Plants for biomass were harvested after the end of vegetation in the March of the following year of the study (i.e., on 24 March 2010, 1 March 2011, 8 March 2012, 6 March 2013, 11 March 2014, 5 March 2016, 9 March 2016, and 8 March 2017).

Figure 1. *Sida* in various stages of development.

The energy value of dry plant matter was determined in the laboratory of the Department of Environmental Management, West Pomeranian University of Technology in Szczecin, using the KL-10 calorimeter manufactured by the Cooperative PRECYZJA from Bydgoszcz following PN-81/G-04513 as well as the technical and operational documentation of the KL-10 automatic calorimeter.

2.4. Statistical Analysis

The obtained study results were statistically processed by applying classic analysis of variance using the ANAWAR 5.3 software (developed by Professor Franciszek Rudnicki) and correlation analysis. Software ANAWAR 5.3 is used to analyse variance with the regression of source data from agricultural experiments. It contains computational programs for orthogonal data from single and multiple single-, double- and three-factor experiments. It considers the experimental systems most often used in experimental agricultural research. The significance of result diversity was determined by the Tukey test at the level of $p = 0.05$. Using Software Statistica 12.5, multivariate analysis was performed using principal component analysis (PCA).

2.5. Characteristics of Climatic Conditions during the Study

According to research [11,20–22], the amount of precipitation and temperature distribution is one of the most critical factors modifying the development of plants and, thus, their DMY. Meteorological data were obtained from the Agricultural Experimental Station in Lipnik for the years 2009–2016 and 1980–2008 (Table 2), and they indicate differences in air temperatures and the amount of precipitation during the study.

The average air temperature and the amount of atmospheric precipitation throughout the growing season during the study years were higher than in the corresponding period over the years (Table 2).

Within the study years, the warmest years were 2009, 2014, 2013 and 2016, in which the average air temperature during plant growth was 14.7, 16.7, 16.4 and 15.5 °C, which exceeded the average value over many years. The warmest months in 2009 were July and August, in which the average temperature was 19.4 and 19.6 °C; in 2014, they were July, August and September; in 2013, they were June and July; and in 2016, they were May–September, in which the average temperatures were higher than the average for the same period over many years.

In the years of the study, atmospheric precipitation was characterised by significant differentiated distribution in individual months and years. The most considerable precipitation was observed in 2010—755.1 mm; the lowest was in 2016—473.7 mm. In 2010, the highest rainfall was recorded during the growing season (IV–X), which was 481.1 mm; 20.0 mm less rainfall during plant vegetation was recorded in 2014, 122.1 and 109.6 mm higher than the multiannual average for this period, respectively. The lowest rainfall during the growing season was recorded in 2015—300.2 mm (Table 2), while the month with the lowest rainfall was November in 2011—1.0 mm, and the highest was August in

2010—184.4 mm. In 2015, 2016 and 2013, the sums of rainfall during the growing season were 283.6, 304.7 and 343.8 mm, respectively, and they were significantly lower than in 2010 and lower by 75.4, 54.3, 19.7 and 15.2 mm than in the same period of many years.

Table 2. Average monthly air temperature and monthly total rainfall in the years 2009–2016.

Year	Month													
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Total for the Year	IV–X
Temperature [°C]														
Multi-year Average	−1.1	−0.3	2.8	7.4	12.7	16.0	17.6	17.2	13.3	8.8	3.8	0.4	9.6	15.0
2009	−3.1	1.5	−3.9	12.3	13.4	15.4	19.4	19.6	14.7	7.8	6.7	−0.2	12.1	14.7
2010	−5.5	−0.6	3.8	8.7	11.1	17.0	22.2	18.5	13.2	7.5	4.7	−4.7	8.0	14.0
2011	0.7	−0.9	3.9	11.9	14.3	18.2	17.7	18.3	14.9	9.5	4.1	3.9	9.7	15.0
2012	1.5	−2.3	6.3	8.8	15.5	16.2	18.6	18.1	14.5	8.7	5.1	−0.7	9.2	14.3
2013	−3.5	4.0	3.5	11.4	17.5	20.3	21.2	18.5	14.8	11.1	5.2	3.0	10.6	16.4
2014	−0.5	1.7	6.4	11.1	14.0	16.9	21.8	21.5	20.2	11.1	6.2	2.0	11.0	16.7
2015	1.1	0.0	3.9	9.7	11.9	14.5	17.6	20.1	13.0	7.3	5.6	5.3	9.2	13.4
2016	−1.2	3.2	4.2	8.9	16.9	19.2	19.4	18.2	17.1	8.8	3.9	2.7	10.1	15.5
Precipitation [mm]														
Multi-year Average	54.6	31.6	25.5	20.8	88.1	112.5	50.4	35.9	43.9	45.8	37.8	37.7	584.6	397.4
2009	19.4	49.4	53.4	16.6	70.3	60.7	61.9	58.0	45.4	82.7	46.9	32.7	597.4	395.6
2010	36.1	21.2	43.8	16.8	91.6	10.6	86.7	184.4	56.3	34.7	100.3	72.6	755.1	481.1
2011	31.0	33.4	23.9	12.5	27.9	44.8	148.5	57.7	52.2	37.9	1.0	70.8	541.6	381.5
2012	64.7	41.1	18.0	32.4	21.1	45.8	103.4	90.2	25.1	53.5	40.5	39.1	574.9	371.5
2013	54.6	31.6	25.5	20.8	88.1	112.5	50.4	35.9	43.9	45.8	37.8	37.7	584.6	397.4
2014	39.6	14.6	25.3	39.1	94.0	45.0	100.6	88.1	59.3	35.0	7.7	74.0	622.3	461.1
2015	71.0	4.9	39.3	18.3	42.6	51.3	68.0	17.8	66.1	35.8	53.2	35.3	503.9	300.2
2016	32.6	34.5	25.7	25.7	43.7	70.6	68.7	41.2	9.7	45.1	50.5	25.7	473.7	304.7

3. Results and Discussion

3.1. Plant Density

The analysis of results of plant density on the surface in full performance years was relatively stable and was at the level obtained in the sowing year; hence, the paper presents only their average density from the years of study (Table 3).

Table 3. Effects of seeding amount and fertilization with compost on the *Sida* plant density during the years of full use (2010–2016).

Seeding Amount (kg ha^{-1})	Compost Fertilization (t ha^{-1})			Average Plant Density (Plants m^{-2})
	0	10	20	
	Plant Density (Plants m^{-2})			
1	6.8	12.0	13.1	10.6
2	10.3	12.7	13.7	12.2
3	11.1	14.7	16.7	14.2
Average	9.4	13.1	14.5	12.4
$LSD_{0.05}$ for:	2009–2016			
Compost fertilization—I	1.46			
Seeding amount—II	0.63			

It should be noted that emergence uniformity on the surface occurred at their seeding in the amount of 3 kg of seeds per hectare, and the lowest density and the least uniformity occurred at the objects where 1 kg of seeds was sown. This density status continued until the last year of the study. On average, from the years of the study, the density at seeding 2 kg of seeds was higher by 15.1%, and at seeding 3 kg of seeds it was higher by 39.9% compared to the density at objects where 1 kg of seeds was sown. The obtained plant density was similar to that recommended by Borkowska and Styk [31]. Often, the reason for the low plant density when establishing plantations by sowing, according to Tworkowski et al. [32], Kurucz et al. [33] and Packa et al. [34], is the low germination capacity of seeds in the sowing year, which results, among others, from the occurrence of "hard seeds" in the seeding material, characterised by the presence of an impermeable seed coat for water and gases. The density of plants planted directly into the ground was stable in the first and subsequent years of the study. Bury et al. [11] and Tworkowski et al. [32] found results of falling out in a significant number of plants sown into the ground in comparison planted ones (germination capacity, preparation of seeds, rainfall in the period of emergence and early development). The plant population of *Sida* should be 20–60 thousand plants per 1 ha when grown for biomass on good soils [11,31], thus showing that higher seeding of *Sida* seeds allows for higher DMY and better quality [8].

In the case of poor soils, the fertilization of the *Sida* crop positively affects the density of the sown plant. Molas et al. [35] indicated that fertilization in the amount of 20 N, 20 P and 40 K in kg ha^{-1} increased the plant density by more than 5 plants per 1 m^2 compared to the combination without fertilization. Therefore, the use of alternative nutrient sources such as compost or sewage sludge can also have beneficial effects, which was confirmed by the obtained results. The assessment of the impact of applied pre-sowing doses of compost (0, 10 and 20 t ha^{-1}) on plant density showed that the use of compost contributed to an increase in the density of *Sida* plants by 39.4% and 54.3%, respectively, in relation to the number of plants not fertilized with compost.

3.2. Plant Development and Morphology

Depending on the applied fertilization level and seeding amount in the first year of the study (year of plant establishment), plants produced from 1.1 to 2.2 shoots. In the years of full use of the plants (2010–2016), the number of shoots produced by plants was many times higher (Table 4), which is typical of this species [11,20]. In the case of the research of Tworkowski et al. in 2014 [32], plants sown from seeds in the first year of cultivation with mineral fertilization had only one shoot. In the following year, the number of shoots increased to 7, while in the case of seedlings, the number of shoots even reached 15 [36]. Research shows that in the case of plants from seedlings, more significant amounts of plant shoots are recorded, especially in the first and second years of cultivation [11,32]. A significant increase in the number of shoots per plant under the influence of compost fertilization was found in the subsequent years of use. On objects fertilized with compost at 10 and 20 t ha^{-1}, the number of shoots per plant was 14.6% and 23.6% higher, respectively, compared to the object not fertilized with the compost. Similar effects were also obtained in the case of mineral fertilization [31].

Applied standards for *Sida* seeding 1, 2 and 3 kg ha^{-1} in the years of full use contributed to a significant increase in the number of shoots on one plant. Plants produced more shoots on objects where a higher seeding standard was used by 13.5% and 23.7%, respectively, compared to the number of shoots produced by plants on the object with the lowest seeding standard. The results are consistent with those obtained by Tworkowski et al. [32], in which the number of stems on the plant grown from root cuttings and seedlings was more remarkable than those from seed seeding.

Table 4. Effects of seeding amount and fertilization with compost on the number of *Sida* shoots during the years of full use (2010–2016).

Seeding Amount (kg ha^{-1})	Compost Fertilization (t ha^{-1})			Average
	0	10	20	
	Number of Shoots			
1	7.9	9.0	9.9	8.9
2	8.9	10.4	11.1	10.1
3	9.8	11.3	12.1	11.1
Average	8.9	10.2	11.0	10.0
$LSD_{0.05}$ for:	2009–2016			
Compost fertilization—I	1.46			
Seeding amount—II	0.63			

The productivity of *Sida* crops and the quality of the biomass obtained for combustion were tested by Chołuj et al. [37], Szyszlak-Bargłowicz et al. [38], Borkowska et al. [39] Bilandžija et al. [40], and Możdżer et al. [41], who claim that the productivity and quality depend on many factors. One of them is the morphological structure (e.g., height and diameter of shoots) of the plant affecting the productivity of the biomass obtained. PCA analysis (Figure 2) showed the relationship between *Sida* morphological parameters: plant height, number of shoots and thickness, which modify the energy yield.

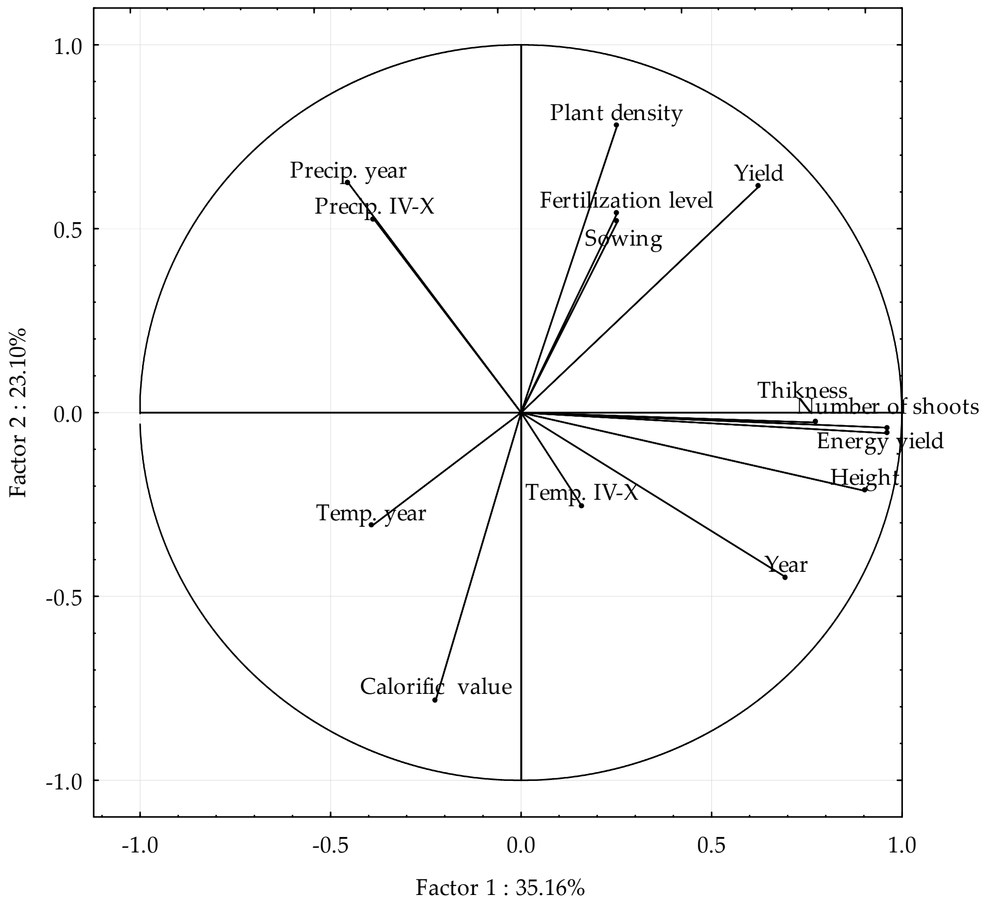

Figure 2. The principal component analysis (PCA) for *Sida* DMY, biometric parameters, energetic parameters and climatic conditions.

On objects not fertilized with compost, the average height of shoots was 249.3 cm, while the height of *Sida* plants on objects fertilized with compost in the amount of 10 and 20 t ha^{-1} (Table 5) was not significantly differentiated: only the trend of increasing the height of shoots was noted—by 1.5% and 2.8%. Similarly to the level of compost fertilization, the impact of the seed sowing amount on the height of *Sida* shoots was shaped, the differences between the objects were not statistically significant, and only a slight lengthening occurred with the increase in the seeding amount. Similarly, no significant effect of fertilization and seeding amount on the average thickness of shoots was found (Table 6). Veste et al. [28], in the studies on the effect of fertilization with compost, indicated an increase in the height of fertilized plants compared to the control, while in the first year of the experiments, the plants reached the height of 120 cm, and strong effects were also obtained in the fertilization with digestate [17]. The obtained average plant height results were similar to the results of Borkowska et al. [19] in the case of plants fertilized with nitrogen in a dose of 100 and 200 kg ha^{-1} and phosphorus in a dose of 39.28 and 52.38 kg ha^{-1} and the same level of K fertilization on light sandy loam. With similar fertilization but on better soil (composed of dust and clay), Borkowska et al. [17] obtained a higher average plant height, more than 290 cm in the fourth year of production, while the plants fertilized with sewage sludge in Croatia reached an average height of 310 cm [42], although weather conditions could also have a significant impact.

Table 5. Effects of seeding amount and fertilization with compost on the average height of the *Sida* shoots (cm) during the years of full use (2010–2016).

Seeding Amount (kg ha^{-1})	Compost Fertilization (t ha^{-1})			Average Height of Shoots (cm)
	0	10	20	
	Height of Shoots (cm)			
1	249.3	254.0	258.0	253.8
2	255.7	259.1	263.2	259.3
3	258.9	262.2	264.1	261.7
Average	254.6	258.4	261.7	258.3
$LSD_{0.05}$ for:	2009–2016			
Compost fertilization—I	i. d. *			
Seeding amount—II	i. d. *			

* insignificant difference.

Table 6. Effects of seeding amount and fertilization with compost on the average thickness of the *Sida* shoots (mm) during the years of full use (2010–2016).

Seeding Amount (kg ha^{-1})	Compost Fertilization (t ha^{-1})			Average Thickness of Shoots (mm)
	0	10	20	
	Thickness of Shoots (mm)			
1	16.2	16.2	16.0	16.1
2	16.0	15.9	15.9	16.0
3	15.9	16.0	15.8	15.9
Average	16.1	16.0	15.9	16.0
$LSD_{0.05}$ for:	2009–2016			
Compost fertilization—I	i. d. *			
Seeding amount—II	i. d. *			

* insignificant difference.

The assessment of the *Sida* shoots' thickness indicates that they were not significantly dependent on the factors studied (Table 6). Organic compost fertilizers applied to the ground (10 and 20 t ha^{-1}) and seeding amount influence a slight decrease in the thickness of produced shoots of the plant; on average, from the years of the research, the thickness of the shoots decreased by 0.2 and 0.3 mm, i.e., by 1%, 2% and 1.8% relating to the thickness of shoots produced on the object not fertilized with compost and with the lowest seeding amount. The number of shoots and their length and thickness influence the overall DMY [16,36].

3.3. Dry Matter Yield

The applied research factors (organic compost fertilization and seeding amount) affected the amount of DMY of *Sida* plants (Table 7). The applied levels of compost fertilization (10 and 20 t ha^{-1}) positively affected the obtained DMY. In all the years of the study, the increase in DMY was significant, and compared to the DMY from an object not fertilized with compost, it was was 24.9% and 50.7%, respectively, on average during all the years of observation (2009–2016).

Table 7. Effects of seeding amount and fertilization with compost on the DMY (t ha^{-1}) of *Sida* during the years of observation.

Year	Compost Fertilization (t ha^{-1})	Seeding Amount (kg ha^{-1})			Average Dry Matter Yield (t ha^{-1})	$LSD_{0.05}$
		1	2	3		
		Dry Matter Yield (t ha^{-1})				
2009	0	0.50	0.94	1.64	1.03	I—i.d. *
	10	1.05	1.38	1.91	1.45	II—0.34
	20	1.24	1.69	2.01	1.65	
	Average	0.93	1.34	1.85	1.37	
2010	0	5.88	8.63	12.69	9.07	I—0.89
	10	8.00	11.63	16.38	12.00	II—0.96
	20	13.38	13.94	22.69	16.67	
	Average	9.09	11.40	17.25	12.58	
2011	0	5.63	8.75	10.31	8.23	I—1.53
	10	7.81	12.19	13.44	11.15	II—1.86
	20	9.06	13.75	16.25	13.02	
	Average	7.50	11.56	13.33	10.80	
2012	0	3.75	5.00	6.25	5.00	I—1.79
	10	6.25	8.00	10.00	8.08	II—0.50
	20	9.62	11.94	15.00	12.19	
	Average	6.54	8.31	10.42	8.42	
2013	0	4.21	5.26	6.46	5.31	I—0.14
	10	5.23	7.46	8.26	6.98	II—0.18
	20	5.68	8.24	9.24	7.72	
	Average	5.04	6.99	7.99	6.67	
2014	0	6.12	8.46	10.28	8.29	I—0.18
	10	7.21	9.24	11.28	9.24	II—0.16
	20	7.86	10.43	11.68	9.99	
	Average	7.06	9.38	11.08	9.17	
2015	0	5.86	8.28	11.24	8.46	I—0.16
	10	6.48	8.42	11.84	8.91	II—0.15
	20	7.26	9.36	12.24	9.62	
	Average	6.53	8.69	11.77	9.00	
2016	0	5.26	7.68	9.23	7.39	I—0.16
	10	6.12	8.24	10.41	8.26	II—0.14
	20	6.74	8.67	10.89	8.77	
	Average	6.04	8.20	10.18	8.14	

Table 7. *Cont.*

Year	Compost Fertilization (t ha^{-1})	Seeding Amount (kg ha^{-1}) 1	2	3	Average Dry Matter Yield (t ha^{-1})	$LSD_{0.05}$
		Dry Matter Yield (t ha^{-1})				
Average (2010–2016)	0	5.24	7.44	9.49	7.39	I—0.95 II—0.33
	10	6.73	9.31	11.66	9.23	
	20	8.51	10.90	14.00	11.14	
	Average	6.83	9.22	11.72	9.25	

* insignificant difference.

When assessing the impact of seeding amount on the DMY, it should be stated that increasing the seeding amount significantly increased the DMY by 35.0% on average at the 2 kg ha^{-1} and 71.6% when seeding 3 kg ha^{-1} compared to the lowest seeding rate (Table 7). PCA analysis (Figure 2) showed that *Sida*'s DMY depends on the seeding amount and the subsequent plant density and fertilization. The influence of the amount of precipitation in individual years and growing seasons was also noticeable.

Analysis of the DMY of *Sida* plants in years of use shows that the lowest DMY was produced by plants in the sowing year (2009), which ranged from 0.5 to 2.0 t ha^{-1}. In the years of full use, the DMY was many times higher and ranged from 3.75 to 22.69 t ha^{-1}, depending on the factors studied and the year of the experiment. The highest DMY in the tested conditions was obtained in the first year of full use (2010), which on average for the examined factors was 12.58 t ha^{-1}, which was higher by 14.1% in the second, 33.1% in the third, 47.0% in the fourth, 27.1% in the fifth, 28.5% in the sixth and 35.3% in the seventh year of the full use.

The DMY of crops grown for energy purposes is influenced not only by agrotechnical factors (e.g., fertilization, soil tillage, cultivation) but also by weather in the subsequent years of plantation use [7,40–45]. The course of meteorological conditions affects the condition of plants; they can determine their performance and the quality of harvested DMY in subsequent years. The results of previous studies confirmed low DMYs in the first year and much higher DMYs in the second and subsequent years of use. Perennial species usually reach their full DMY in the third–fourth year after sowing or planting [40,41]. The annual DMY of *Sida* plant biomass ranges from 8.7 to 20.3 t ha^{-1} DM. In most studies, the annual capacity of *Sida* exceeded 10 t ha^{-1} after the first two years of growth, harvested from October [45] until February [32]. The diversity of cultivation technologies and variability of habitat conditions cause significant differences in the DMY of energy crops, including *Sida* [6,45–48]. Average crop DMYs under real EU production conditions are 10–12 t ha^{-1}, with fluctuations 6–15 t ha^{-1} [8,20,34,45,49–53]. In our research, the highest DMY of *Sida* was obtained in the second year after sowing, but in subsequent years, the obtained DMY coincided with those obtained by other authors [7,16,20,32,39]. Borkowska et al. [20] report that in the second year, under favourable habitat conditions, a significant DMY of *Sida* can be harvested, and in subsequent years, the DMYs reach maximum values, and the average DMYs from eight years of cultivation exceeded 11 t ha^{-1} DM. During the eight years of research—from the second to the ninth year of cultivation—the highest DMYs were obtained significantly in the eighth (2010), fifth (2006) and sixth (2007) years of use [20]. Results of the personal research in time-space were slightly different, but their DMY was comparable. The research confirms that compost from municipal waste with additional NPK fertilization can be successfully used to cultivate energy crops on poor and marginal soils. The increase in DMYs after the use of substitutes for mineral fertilization was also confirmed in other studies, although the effects were varied [17,23,27–29,41]. Veste et al. [28], in the combination of compost fertilization (which constitutes 20% of the substrate) and nitrogen fertilization (100 kg ha^{-1}), obtained an almost eight-fold increase in the DMY of *Sida* in the first year of cultivation, while in the case of using only compost (which constitutes 50% of the substrate), the increase in the DMY compared to control was almost two-fold. Interesting results were obtained by Barbosa et al. [27] and Nabel et al. [17], and Nabel et al. [18], who showed that fertilization with the digestate brings better results on poor soils (marginal) compared to the use of NPK fertilization with fertilizer doses of 160 kg N ha^{-1}. Similar relationships were also shown by earlier pot tests on light soils, where sewage sludge in the highest doses of 40 and 60 t ha^{-1} had the greatest positive effect on the mallow DMYs compared to mineral fertilization and compost from various sources [29]. Šurić et al. [42] also noted the positive effect of fertilization with sewage sludge and noted that these effects were significant when using sufficiently high doses of sludge (more than 10 t ha^{-1}).

3.4. Energy Yield and Calorific Value

The energy yield of *Sida* plants in light soil conditions was modified by the examined factors and years of research, but its height was closely correlated with the impact of the studied factors on the DMYs of plants (Table 7, Figure 2).

The applied compost fertilization increased the energy yield of the obtained biomass of *Sida* plants in all the years of the research. The average energy yield of plants fertilized with compost in the amount of 10 and 20 t·ha^{-1} was higher by 12.1% and 21.0% than the energy yield of plants not fertilized with compost (Table 8). The obtained energy yield results for plants under the influence of the applied seeding amount (1, 2 and 3 kg ha^{-1}) prove that it was significantly higher for plants from objects with higher seeding amount than for plants from objects with the lowest seeding amount. On average, from the research years, the increase in energy yield at objects with higher seeding amount increased by 14.9% and 22.6%, respectively. The cultivation and seeding amount method influences the energy yield and is directly related to the DMY [33]. According to Šiaudinis et al. [51] and Jankowski et al. [52], the energy yield of *Sida* plants is favourable for combustion compared to the biomass of other herbaceous plants, and according to Jablonowski et al. [8], its combustion properties are similar to those of wood biomass, while their values range from 105 to 236 GJ ha^{-1} [20,39,54–56]. The energy yield of *Sida* in our research was consistent with the results mentioned above which were obtained under conditions of different fertilization levels of plants with compost and different norms of *Sida* seeding. Energy yields determined for *Sida* by Šiaudinis et al. [51] and Jankowski et al. [52] are much lower than those reported by Jablonowski et al. [8]. The difference in energy yield that the authors reported was due to the amount of DMY obtained rather than its energy value. The most significant interest in *Sida* lies in its potential as a renewable energy source.

Table 8. Effects of seeding amount and fertilization with compost on the average energy yield (GJ ha^{-1}) of *Sida* during the years of full use (2010–2016).

Seeding Amount (kg ha^{-1})	Compost Fertilization (kg ha^{-1})			Average Energy Yield (GJ ha^{-1})
	0	10	20	
	Energy Yield (GJ ha^{-1})			
1	136.94	153.08	165.38	151.80
2	155.60	177.35	190.08	174.34
3	168.79	186.87	202.56	186.07
Average	153.78	172.43	186.01	170.74
$LSD_{0.05}$ for:	2009–2016			
Compost fertilization—I	6.03			
Seeding amount—II	11.30			

Therefore, research on this species was focused on its thermophysical and biochemical properties in the context of direct combustion and biogas production. The parameters determining its energy usefulness are higher heat values (HHVs) and lower heat values (LHVs).

In the literature, the HHVs for *Sida* were between 16.5 and 19.5 MJ kg^{-1} DM (average 18.4 MJ kg^{-1} DM), while the LHVs were between 14.0 and 17.2 MJ kg^{-1} (average 16.1 MJ kg^{-1} DM) [7,8,21,26,40,43].

The calorific value of the harvested biomass in the years of the study ranged from 16.8 to 17.4 MJ kg^{-1} DM, and no significant influence of the examined factors on its concentration in plants was found (Table 9). The obtained values of the calorific value of *Sida* were similar to the results indicated in the literature [8,39,40,43]. It is worth noting that the quality of the biomass improves when the harvest date is delayed, which affects the composition of the main elements (C, H, N, O, S), lignocellulose and moisture in plants [8,27,33] which determines the energy value, however, no significant impact of the method of establishing the cultivation and sowing density on the quality of the biomass was confirmed [32,33].

Table 9. Effects of seeding amount and fertilization with compost on the average calorific value (MJ kg^{-1} DM) of *Sida* during the years of full use (2010–2016).

Seeding Amount (kg ha^{-1})	Compost Fertilization (kg ha^{-1})			Average Calorific Value (MJ kg^{-1} DM)
	0	10	20	
	Calorific Value (MJ kg^{-1} DM)			
1	17.4	17.2	16.9	17.2
2	17.3	17.1	16.8	17.1
3	17.1	16.9	16.8	16.9
Average	17.3	17.1	16.8	17.1
$LSD_{0.05}$ for:	2009–2016			
Compost fertilization—I	i. d. *			
Seeding amount—II	i. d. *			

* insignificant difference.

4. Conclusions

The applied levels of compost fertilization (10 and 20 t ha^{-1}) increased the plant DMY in all the years of the research compared to plants not fertilized with compost, and their DMY was 24.9% and 50.7% higher, respectively, on average from the years of the study. Analysing the impact of the applied seeding amount (1, 2 and 3 kg ha^{-1}) on the DMY of *Sida* in light soil conditions, it should be stated that this factor significantly increased the crop DMY in all the years of the research and on average, it increased by 35.0% and 71.6% compared to the lowest seeding rate. Analysis of the DMY of *Sida* in the years of use shows that the lowest DMY was obtained by plants in the sowing year (2009), which is typical for *Sida*. In the years of full use, the DMY was many times higher and ranged from 3.75 to 22.69 t ha^{-1}, depending on the factors studied and the year of the research. The highest energy value of *Sida* was observed under the highest organic compost fertilization and highest seeding amount. It can therefore be concluded that this study confirms the suitability of establishment via sowing for cultivating *Sida* on light soils. Furthermore, the use of organic fertilization with urban green compost and nitrogen allows for a biomass yield at a level similar to mineral fertilization described in other studies [16,19,32,57].

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