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Effects of plantation establishment on yields and morphological traits of *Sida hermaphrodita* and *Silphium perfoliatum* for sustainable biomass production †

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Abstract: The morphological features and biomass yield of the two perennial energy plants *Sida hermaphrodita* and *Silphium perfoliatum* as a feedstock for biogas were evaluated throughout four growing periods (2016-2019) in an open field experiment. The aim of the paper was to assess the effect of plantation establishing methods and various harvest dates on biomass production of these perennial crops, grown on marginal soil in north-western Poland. The collected fresh matter yield (FMY) of Sida and Silphium significantly differed between the years and methods of establishing the plantation. The lowest yield was obtained in the establishing year (2016) - about 4.3-6.5 Mg·ha^{1}. Up the second year produced the plants big above ground biomass. The higher FMY was obtained by growing Silphium in comparison to Sida. The establishing of plantation by sowing seeds resulted in higher biomass yield compared to the planting method, due to the higher plant density. The strategy of single harvest (one cut term) resulted in higher FMY compared to the double harvest (two cuts). Sida1 (a phenotype from southern Germany) produced a higher FMY compared to Sida2 (a phenotype from northern Germany) regardless of the harvesting strategy (single or double cut).

Keywords: Virginia mallow (*Sida hermaphrodita* L. Rusby); cup plant (*Silphium perfoliatum* L.); morphological traits; biomass yields for biogas; methods of establishing plantation; harvest strategy

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1. Introduction

The biomass production for the replacement of fossil fuels is one of the pillars of the EU strategy for renewable energy sources. The biomass production should not compete with crop production traditionally used for food and feed and should be restricted to land that is unsuitable for food production and the controversy food versus fuel on highly valuable arable land should be avoided [1]. In addition, the plant species characterized by high yield potential and low nutrients requirements should be used.

The cultivation of perennial plants and perennial grasses could be a good alternative for sustainable farming and for the replacement of annual plants, e.g. maize, in crop rotation. The perennial plants may even exhibit additional benefits for environment, especially for soil protection and pollinators. Many perennial energy crops, except to the ability of large biomass production, have possibility to grow on low quality soils and under poor climatic conditions, i.e. water scarcity and high temperatures [2–10]. *Miscanthus* species, *Silphium* species, *Sida hermaphrodita* L. Rusby are some of the representatives of energy crops reported to be suitable for cultivation on marginal soils [3,11–18]. Biomass of above mentioned species has usability in different conversion paths [7,19–25]. In the recent years, Sida and Silphium, both North American species, attracted more attention as promising plants for bioenergy production in Europe due their high-yield biomass, good adaptation to climatic and soil condition and benefit to ecosystem [5,7,19,21–23].

We investigated the perennial plants Virginia mallow or Virginia fanpetals *Sida hermaphrodita* (L.) Rusby (hereafter referred to as Sida) and cup plant *Silphium perfoliatum* L. (hereafter referred to as Silphium) to tackle relevant aspects of biomass production for energy purposes.

The aim of the paper was to assess the effect of plantation establishing methods and various harvest strategies (single cut and double cut strategy during the vegetation season) on morphological features and biomass production of two above-mentioned crops, grown on marginal soil in north-western Poland.

2. Materials and Methods

The field experiment with Sida and Silphium was carried out during four vegetative seasons 2016–2019 at the Agricultural Experimental Station (AES) Lipnik near Stargard (53°20′35.8" N, 14°58′10.8" E, 21 m above sea level), which belongs to the West Pomeranian University of Technology Szczecin (Poland).

The experiment was two-factorial: factor A—two phenotypes of Sida (Sida1 and Sida2) and one phenotype of Silphium; and factor B—a method of plantation establishing: by seeds sown directly to the soil (seed), and vegetative by transplanting seedlings at the stage of 3–4 leaves (planting) to the experimental plots. Moreover, the additional factor of the number of harvests in a season was introduced: single harvest (at the beginning/ mid-October, BBCH 79-81 or double harvest (the first date: at middle of June, BBCH 55-59 and the second date: after regrowth in early/ mid-October, BBCH 69-71). The experiment was set-up in a randomized block design in four replications.

Both Sida phenotypes were obtained from Germany and were selected from the two most remote habitats (southern and northern Germany) and different original climatic conditions. Seedlings and seeds of Sida1 were obtained from Baden-Württemberg (MK Jungpflanzen GmbH, Biberach District) and of Sida2 from Lower Saxony (farm enterprise of Dirk Helling-Junghans in the vicinity of Osnabrück). Seedlings and seeds of Silphium were obtained also from Germany (N.L. Chrestensen Erfurter Samen und Pflanzenzucht GmbH (Thüringen)). During the experiment, there were no clear differences in the morphological features of both phenotypes of Sida, particularly in reference to the shape and size of leaves, color, and shape of stalks, and the structure and color of flowers.

The seeds were homogeneous in size and of high quality with a germination rate of ca. 70% by Sida and 84% by Silphium. Seeds were sown on 20 May 2016 with a Øyjord type precision seed drill in an amount of 3.0 kg per unit area (by seed weight), in row spacing of 0.45 m to a depth of 2–3 cm and covered by the furrow closers in the form of a bent flat steel plate finished with so called dovetail. The seedlings were transplanted on 20 June 2016 by hand in a plant distance of 0.50 m and a row distance of 0.45 m to a depth of ca. 10 cm (the distance between the rows was the same like by seeds), which equaling a planting capacity of 44,000·ha^{-1}. Crops were not rainfed. The harvested area inside one plot was 12.6 m^2 (total one plot area was 16 m^2). The side rows and one meter at all row ends were discarded to avoid border effects.

Spring barley harvested for grain was the fore crop for test plants. After harvesting the fore crop, a traditional method of tillage was used (stubble cultivation and pre-winter plowing). In spring 2016, before sowing and planting, identical mineral fertilization was applied in the amount of 100 kg·ha^{-1} N (Ammonium nitrate, Anwil S.A., Poland), 35 kg·ha^{-1} P (Triple Superphosphate, Fosfory Sp. z o.o., Poland) and 110 kg·ha^{-1} K (Potassium salt, Fosfory Sp. z o.o., Poland), which were mixed with the rototiller used to soil preparation. In subsequent years (in 2017, 2018 and 2019), after the start of vegetation, before re-growth of the plants, the same mineral fertilization (100 kg·ha^{-1} N, 35 kg·ha^{-1} P, 110 kg·ha^{-1} K) was applied.

After the emergence of plants in 2016, weeds were controlled manually per hand with hoes. The mechanical weed control was conducted only in the first year of the research. In the remaining years, the weed infestation was negligible. There was also no need to use pesticides since no relevant pests or diseases have been recorded for Sida or cup plant.

2.1. Data collection

We counted the number of plants per area unit after emergence and in the next years at the beginning of vegetation.

In the first year of vegetation (2016), sampling and harvesting were carried out on 17 October, when the Sida plants had reached the beginning of the flowering stage (BBCH 55-59) and in that time Silphium plants built only a big rosette of leaves. We measured the height of plants by calculating the mean of all shoots from ten Sida plants and all leaves with petioles from ten Silphium plants.

In the second, third and fourth year, sampling and harvesting were carried out once or twice in mid of June and October, depends on harvest strategy.

2.2. Harvest Management

The harvest during the vegetation season was done once (one harvest strategy): at the beginning/ mid-October, BBCH 79-81 and twice (two harvest strategy): the first term was at the middle of June, BBCH 55-59 and the second term was after regrowth in early/ mid-October, BBCH 69-71. Plants were harvested from each plot separately by hand using a petrol brush cutter. Before harvesting, the height of plants stem (referred to as a stalk or shoot), and diameter of the shoot at the height of mowing (a cutting height of about 10 cm above ground) were determined using an electronic caliper (140 mm ± 0.01 mm; Limit Co.), as well as the number of shoots per plant. Plants after harvest were ground in a laboratory chopper. The yields of fresh mass from each plot were weighed and the content of dry mass was determined by drying the biomass (1 kg) at 105 °C for 48 h until obtaining a constant weight (PN 8/G–04511). After that, the DMY was calculated (Mg·ha^{-1}).

2.3. Soil Characteristics and Weather Conditions

The experimental field is characterized by rusty, incomplete soils, made of sand and light silty loamy sand. Rusty soils are sandy soils typical of post-glacial areas of the temperate climate zone. In international classifications these soils are treated as a Cambisols or in the classification of WRB, they are most often classified as Arenosols (Dystric Brunic Arenosols).

The soil was moderately acidic (pH KCL 5.90), the content of organic matter in the 0–30 cm layer was 1.36%, and the content of macro elements was: N-0.92, P-0.45, K-0.62, Ca-0.78, Mg-0.90 and S-0.15 g·kg^{-1} D.M. The content of available forms of phosphorus, potassium and magnesium in soil was medium.

The area of AES Lipnik has a transitional climate (variable) oceanic-continental humid and temperate cold climate (according to Köppen–Geiger climate classification: Dfb climate). The average annual temperature is 8.2 °C and annual precipitation is 536 mm. The study years 2016–2019 were very specific about the weather conditions compared to the average of the multi-year 1981–2010. The most rainfall during the growing season (IV–X) was recorded in 2017 (614.6 mm), and the least in 2018 (253.4 mm).

2.4. Statistical Analysis

The test result was statistically processed by the ANOVA multi-way procedure using the statistical program Statistica 10.1 software (Dell Technologies, Round Rock, TX, USA). Differences (Honest significant difference) between the means were assessed using the Tukey's test at a significance level of $p \leq 0.05$.

3. Results and Discussion

3.1. Plant Density

The plant density of Sida and Silphium depended on the method of establishing plantation. The number of plants on plots established with the planting method was approximately stable and slightly decreased from 44000 per 1 ha during the years of vegetation by only 5-10%, regardless of the harvest method (Table 1,2). In contrast, the plant density on plots established with the sowing method after emergence in the first year was high (about 120,000·ha^{-1}). Then the number of plants sharply decreased over the years to around 85,000 plants per 1 ha (Table 1,2).

Table 1. The number of plants of Sida and Silphium [1000·ha^{-1}] on plots harvested twice a year

Crop / Establishing method	Year				Mean
	2016[1]	2017	2018	2019	
Sida1 seed	114000	86000	74000	52000	81500
Sida1 planting	44000	44000	42000	40000	42500
Sida2 seed	108000	82000	70000	50000	77500
Sida2 planting	44000	44000	42000	42000	43000
Silphium seed	144000	104000	76000	64000	97000
Silphium planting	44000	44000	42000	42000	43000
Mean values[2]					
Sida1	79000^{A}	65000^{A}	58000^{A}	46000^{A}	62000^{A}
Sida2	76000^{A}	63000^{A}	56000^{A}	46000^{A}	60250^{A}
Silphium	94000^{B}	74000^{B}	59000^{A}	53000^{B}	70000^{A}
Establishing meth. seed	122000^{b}	90700^{b}	73300^{b}	55300^{b}	85300^{b}
Establishing meth. planting	44000^{a}	44000^{a}	42000^{a}	41300^{a}	42800^{a}
HSD (AxB)	10130	5973	n.s.	5936	n.s.

[1] Establishing year. [2] Data marked with the same letters do not differ statistically according to Tukey test at $p \leq 0.05$. Uppercase letters indicate the differences between species (A), lowercase letters indicate the effect of the method of plantation establishing (B). HSD Honest significant difference, n.s. - not significant.

Table 2. The number of plants of Sida and Silphium [1000·ha^{-1}] on plots harvested once a year

Crop / Establishing method	Year				Mean
	2016[1]	2017	2018	2019	
Sida1 seed	112000	84000	68000	50000	78500
Sida1 planting	44000	44000	42000	42000	43000
Sida2 seed	108000	80000	64000	49000	75250
Sida2 planting	44000	44000	42800	42000	43200
Silphium seed	140000	110000	72000	62000	96000
Silphium planting	44000	44000	42000	42000	43000
Mean values[2]					
Sida1	78000^{A}	64000^{A}	55000^{A}	46000^{A}	60750^{A}
Sida2	76000^{A}	62000^{A}	53400^{A}	45500^{A}	59230^{A}
Silphium	92000^{B}	77000^{B}	57000^{A}	52000^{B}	69500^{A}
Establishing meth. seed	120000^{b}	91300^{b}	68000^{b}	53700^{b}	83250^{b}
Establishing meth. planting	44000^{a}	44000^{a}	42300^{a}	42000^{a}	43100^{a}
HSD (AxB)	7562	5347	n.s.	4966	n.s.

[1] Establishing year, [2] as in table 1.

Many authors obtained similar results. [4,7,22] have considered 250,000 plants per 1 ha to be the optimal density by establishing of plantation by seeds. [31] reported similar results by Silphium. [21] received the highest yields of Sida biomass with a plant population of 40,000 plants per 1 ha, established by the planting of seedlings.

3.2. The height of plants

The height of the plants depended on the method of establishing the plantation and harvest strategy. There were no significant differences between the height of Sida and Silphium plants. The higher plants were observed on the plots established by the sowing method (seed) compared to the plants in the plots established by the planting method (Table 3,4). Plants harvested twice during the vegetation period were smaller than plants harvested once a year (October). Also, the date of harvest influenced plant height. Plants cut in June (BBCH 55-59) were higher than plants harvested after regrowth in October - BBCH 69-71 (Table 3).

Table 3. The height [cm] of plants of Sida and Silphium harvested twice.

Year	**2016**[1]	**2017**		**2018**		**2019**		**2017-019**		
Crop /Establishing meth.	**Harvest month**									
	(X)	**(VI)**	**(X)**	**(VI)**	**(X)**	**(VI)**	**(X)**	**(VI)**	**(X)**	**mean**
Sida1 seed	124	150	129	150	120	168	137	156.0	128.7	142.3
Sida1 planting	98	133	117	134	109	153	120	140.0	115.3	127.7
Sida2 seed	92	154	139	168	123	146	143	156.0	135.0	145.5
Sida2 planting	71	141	115	134	107	138	134	137.7	118.7	128.2
Silphium seed	48[2]	140	125	126	108	132	128	132.7	120.3	126.5
Silphium planting	40[2]	138	116	113	89	129	125	126.7	110.0	118.3
Mean values[3]										
Sida1	111.0^{C}	141.5^{A}	123.0^{AB}	142.0^{B}	114.5^{A}	160.5^{C}	128.5^{AB}	148.0^{A}	122.0^{A}	135.0^{B}
Sida2	81.5^{B}	147.5^{B}	127.0^{B}	151.0^{B}	115.0^{A}	142.0^{B}	138.5^{B}	146.8^{A}	126.8^{A}	136.8^{B}
Silphium	44.0^{A}	139.0^{A}	120.5^{A}	$119.^{5A}$	98.5^{A}	130.5^{A}	126.5^{A}	129.7^{A}	115.2^{A}	122.4^{A}
Establishing meth. seed	88.0^{b}	148.0^{b}	131.0^{b}	148.0_{b}	117.0^{b}	148.7^{b}	136.0^{b}	148.2^{a}	128.0^{b}	138.1^{b}
Establishing meth. planting	69.7^{a}	137.3^{a}	116.0^{a}	127.0^{a}	101.7^{a}	140.0^{a}	126.3^{a}	134.8^{a}	114.7^{b}	124.7^{a}
Date of harvest (VI)	-	142.7*		137.5*		144.3*		141.5*		141.5*
Date of harvest (X)	-	123.5		109.3		131.2		121.3		121.3
HSD (AxB)	7.42	4.21		n.s.		n.s.		n.s.		n.s.
HSD (AxC)	-	n.s.		7.07		7.93		n.s.		n.s.
HSD (BxC)	-	n.s.		n.s.		n.s.		n.s.		n.s.
AxBxC	-	n.s.		n.s.		n.s.		n.s.		n.s.

[1] Establishing year; [2] height of rosette. [3] Data marked with the same letters do not differ statistically according to Tukey test at $p \leq 0.05$. Uppercase letters indicate the differences between **species** (**A**), lowercase letters indicate the effect of the **method of plantation establishing** (**B**). Symbol * indicate the **date of harvest** (**C**). HSD Honest significant difference, n.s. - not significant.

Table 4. The height [cm] of plants of Sida and Silphium harvested once

Year	**2016**[1]	**2017**	**2018**	**2019**	**2017-2019**
Crop /Establishing method	**(X)**	**(X)**	**(X)**	**(X)**	**Mean**
Sida1 seed	120	229	222	216	222.3
Sida1 planting	102	216	204	197	205.7
Sida2 seed	98	226	238	208	224.0
Sida2 planting	85	207	216	203	208.7
Silphium seed	46[2]	221	175	215	203.7
Silphium planting	42[2]	208	164	184	185.3
Mean values[3]					
Sida1	111.0^{C}	222.5^{A}	213.0^{B}	206.5^{A}	214.0^{A}
Sida2	91.5^{B}	216.5^{A}	227.0^{C}	205.5^{A}	216.3^{A}
Silphium	44.0^{A}	214.5^{A}	169.5^{A}	199.5^{A}	194.5^{A}
Establishing meth. seed	88.0^{b}	225.3^{b}	211.7^{b}	213.0^{b}	216.7^{a}
Establishing meth. planting	76.3^{a}	210.3^{a}	194.7^{a}	194.7a	199.9^{a}
HSD (AxB)	n.s.	n.s.	n.s.	11.42	n.s.

[1] Establishing year, [2,3] as in table 1.

[18,22] reported a similar plant height of Sida in Germany and in Poland [4]. The height of the Silphium plants at many sites in northern and eastern Germany ranged from 2.20 to 3.00 m, dependent on weather conditions and soil quality [18], but individual plants can reach a height of up to 3 m [16].

3.3. The total above-ground fresh biomass yield

The Silphium plant developed in the first year only rosette of leaves without shoots, which is connected to specific growth of this species and in the agricultural practice Silphium is not harvested (the leaves of Silphium disappear during the winter). Contrary, Sida built the one or rare two shoots in the first year and Sida plants are harvested in the establishing year. The FMY of both crops in the establishing year was very small - about 4.3-6.5 $Mg \cdot ha^{1} \cdot yr^{1}$ (Table 5,6).

Up the second year, the FMY was bigger regardless of the experimental factors.

Sida produced significantly less biomass than Silphium. In the case of the two-cut strategy, the FMY of Silphium was almost three times higher than that of the Sida (Table 5), and in the case of single harvesting - more than twice as high (Table 6).

Sida 1 (a phenotype from southern Germany) produced a greater average total biomass yield than Sida2 (a phenotype from northern Germany) by about 15.6% for the double harvest strategy (Table 5) and by about 7.0% for the single harvest strategy (Table 6).

Establishing of plantation by sowing resulted in a higher biomass yield compared to establishing a plantation by planting. In the case of the double-harvest strategy (Table 5) the FMY was 17% higher compared to the planting method, and by the single-harvest strategy - the difference was 12.5% (Table 6).

The FMY by the double harvest strategy was almost three times higher when the biomass was harvested in June (the first cut at BBCH 55-59 stage) compared to the biomass harvested in the second term (the second at BBCH 69-71 stage) - in October (Table 5).

The mean total biomass yield (2017-2019 average) for the double harvest strategy was definitely lower than the FMY of biomass harvested once a season (Table 5,6).

Table 5. The fresh mass yield [$Mg \cdot ha^{-1}$] of plants of Sida and Silphium, harvested twice.

Year	**2016**[1]	**2017**		**2018**		**2019**		**2017-019**		
Crop /Establishing meth.	**Harvest month**									
	(X)	**(VI)**	**(X)**	**(VI)**	**(X)**	**(VI)**	**(X)**	**(VI)**	**(X)**	**Mean**
Sida1 seed	5.58	35.98	6.02	15.86	7.76	27.11	11.77	26.32	8.52	17.42
Sida1 planting	5.17	30.76	7.09	15.79	7.03	19.97	8.51	22.17	7.54	14.86
Sida2 seed	5.15	32.19	6.87	17.94	8.56	21.38	14.57	23.84	10.00	16.92
Sida2 planting	3.37	20.05	4.37	10.87	5.75	13.59	11.42	14.84	7.18	11.01
Silphium seed	6.77[2]	72.54	28.76	48.38	22.65	95.49	21.40	72.22	24.27	48.25
Silphium planting	6.18[2]	67.22	31.05	50.11	14.81	79.59	24.89	65.64	23.58	44.61
Mean values[3]										
Sida1	5.38^{B}	33.37^{B}	6.55^{A}	15.83^{A}	7.40^{A}	23.54^{A}	10.14^{A}	24.25^{A}	8.03^{A}	16.14^{A}
Sida2	4.26^{A}	26.12^{A}	5.62^{A}	14.41^{A}	7.16^{A}	17.49^{A}	13.00^{A}	19.34^{A}	8.59^{A}	13.96^{A}
Silphium	6.48^{C}	69.88^{D}	29.91^{E}	49.25^{F}	18.73^{D}	87.67^{D}	23.15^{D}	68.93^{B}	23.93^{B}	46.43^{B}
Establishing meth. seed	5.83^{b}	46.90^{b}	13.88^{a}	27.39^{a}	12.99^{b}	47.99^{b}	15.91^{a}	40.79^{a}	14.28^{a}	27.53^{b}
Establishing meth. planting	4.91^{a}	39.34^{a}	14.17^{a}	25.59^{a}	9.20^{a}	37.71^{a}	14.94^{a}	34.22^{a}	12.77^{a}	23.49^{a}
Date of harvest (VI)	-	43.12*		26.49*		42.90*		37.50*		37.50*
Date of harvest (X)	-	14.03		11.09		15.43		13.52		13.52
HSD (AxB)	n.s.	1.11		n.s.		n.s.		n.s.		n.s.
HSD (AxC)	-	1.28		3.12		3.76		7.41		7.41
HSD (BxC)	-	1.05		n.s.		3.07		n.s.		n.s.
AxBxC	-	n.s.		n.s.		n.s.		n.s.		n.s.

[1,2,3] as in table 3.

Table 6. The fresh mass yield [$Mg \cdot ha^{-1}$] of plants of Sida and Silphium, harvested once

Year	**2016**[1]	**2017**	**2018**	**2019**	**2017-2019**
Establishing method	**(X)**	**(X)**	**(X)**	**(X)**	**Mean**
Sida1 seed	6.29	25.89	28.92	49.74	34.85
Sida1 planting	5.63	25.50	26.56	45.07	32.38
Sida2 seed	4.83	32.02	28.33	44.56	34.97
Sida2 planting	3.81	20.15	23.34	40.51	28.00
Silphium seed	6.71	68.68	66.42	92.72	75.94
Silphium planting	6.39	70.90	57.79	78.81	69.17

Mean values[2]					
Sida1	5.96[B]	25.70[A]	27.74[A]	47.41[A]	33.61[A]
Sida2	4.32[A]	26.09[A]	25.84[A]	42.54[A]	31.49[A]
Silphium	6.55[C]	69.79[E]	62.11[E]	85.77[D]	72.55[E]
Establishing meth. seed	5.95[b]	42.20[b]	41.22[b]	62.34[b]	48.59[b]
Establishing meth. planting	5.28[a]	38.85[a]	35.90[a]	54.80[a]	43.18[a]
HSD (AxB)	0.32	2.72	3.27	5.61	n.s.

[1] Establishing year, [2] as in table 1.

4. Conclusions

The conducted study showed that Virginia mallow (*Sida hermaphrodita* L. Rusby) and cup plant (*Silphium perfoliatum* L.) can be considered as a source of biomass used for biogas production. The higher FMY was obtained by growing Silphium in comparison to Sida. The method of plantation establishment, by sowing seeds (seed) and vegetative by transplanting seedlings (planting), clearly influenced the obtained results. The FMY of plants established with the sowing method was higher than the FMY of plants established with the planting method due to the higher number of shoots per unit area. By two harvest strategy, the total biomass yield (two cuts in June - BBCH 55-59 and October - BBCH 69-71) was smaller, in contrast, to one harvest strategy (harvest only in October - BBCH 79-81). Both crops could provide a large amount of biomass and be an alternative to growing maize.

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