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Assessment of Different Doses of Sewage Sludge Application on Virginia Fanpetals Biomass Feedstock Production

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1. Introduction

Poland is a country where two-thirds of energy comes from coal mining, and the other energy sources are a.a. hydroelectric and wind plants and lately – solid biomass, liquid biofuels and biogas (Igliński et al. 2011). Biomass incineration or co-incineration makes above 80% of renewable energy. Technical potential of biomass in Poland is estimated at approximately 900 PJ year^{-1}, being the highest in the case of forest and agriculture origin biomass. Straw, cereal, rapeseed, wastes from agro-food and wood industries as well as dedicated energy plantations give the greatest potential for energy production. Agricultural and natural-environmental determinants permit energy crops cultivation at the area estimated from 1.6 to 2.0 million ha, which by 2020 could increase to approximately 2.9 million ha (Bartoszewicz-Burczy 2012). Thus, there is a need to enlargement the surface area by introducing the cultivation of new crops such as Virginia fanpetals (Slepetys et al. 2012, Matyka 2013, Szyszlak-Bargłowicz 2014, Nahm & Mohrat 2018, von Gehrena et al. 2019). However, it is worth mentioning that energy crops even though do not compete directly with food crops, use the same land resources, sometimes of high ecological value.

Virginia fanpetals (*Sida hermaphrodita* Rusby) is a perennial energy plant from Malvaceae family, originated from the southern states of the USA and occurring in the natural state in the North and South America, Africa and Asia (Borkowska 1991, Borkowska & Styk 2006, Borkowska & Molas 2012, Nahm & Mohrat 2018). It is classified as a highly endangered species in its original habitat (Spooner et al. 1985). *S. hermaphrodita* is a species with wide possibilities of use, however almost unknown outside of Europe (Borkowska & Molas 2013, Matyka & Kuś 2018, Nahm & Mohrat 2018). Due to the considerable fiber content in the stems, originally it was used by Indians as a fiber plant, however, fiber is of poor quality (Spooner et al. 1985). It belongs to melliferous plants that is also suitable for covering slopes, soils exposed to erosion. Due to good performance and quality bleached cellulose can be used in the pulp and paper industry. Seeking is also as a raw material for the pharmaceutical industry and feed for animals (Borkowska 1991, Borkowska & Styk 2006, Matyka & Kuś 2018). Its stalks can be subjected also to direct combustion (the biomass can be granulated easily during pellets and briquettes production), conversion to bioethanol or as a substrate for biogas production (Borkowska & Molas 2013; Jasinskas et al. 2014, Szempliński et al. 2014, Šiaudinis et al. 2015). That species was introduced from the USA (via USSR) to Poland in the 1950s and now is cultivated at the area of about 300 hectares (Borkowska & Styk 2006, Borkowska & Molas 2012, Nahm & Mohrat 2018, von Gehrena et al. 2019), however potential area designated for cultivation of Virginia fanpetals for energy purposes is estimated at above 2.4 million ha (Jadczyszyn et al. 2008). Recently new plantations of this species arose in Germany, Romania and Lithuania (Jasinskas et al. 2014, Kurucz et al. 2014, Barbosa et al. 2014, Franzaring et al. 2014, Nahm & Mohrat 2018).

Virginia fanpetals is a plant having relatively low input requirements, great potential for C mitigation, drought tolerance and ability to maintain high yields under a wide range of environmental conditions. This species has low requirements for soil fertility and efficiently use water. It is a plant capable of generative (direct seeds sowing or by seedlings) and vegetative reproduction (through root sections, parts of the bush or rooted herbaceous stems), however so far there is no practical experience using *in vitro* biotechnology method (Borkowska & Styk, 2006, Borkowska & Molas 2012, Kurucz et al. 2014, Augustynowicz et al. 2008, Matyka & Kuś 2018, Nahm & Mohrat 2018).

Annual yields of *S. hermaphrodita* range from 10 to above 20 Mg ha^{-1} DM and over 220-400 GJ ha^{-1} a^{-1} and the similar yields of cellulose-ethanol per hectare as switchgrass (Borkowska & Molas 2012, 2013). The full establishment of *S. hermaphrodita* stand takes from 2 to 3 years, depending on the climatic conditions, but productive life span its estimated between 15 and 20 years (Borkowska & Styk 2006, Borkowska et al. 2009, Borkowska & Molas 2012, Nahm & Mohrat 2018).

Although Virginia fanpetals has many traits that make it ideal for biofuel production, environmental and management conditions can affect its productivity (Matyka 2013, Borkowska 1991, Borkowska & Molas 2012, Kalembasa & Wiśniewska 2006, Kuś & Matyka 2009, Strzelczyk 2013, Matyka & Kuś 2018, Nahm & Mohrat 2018). Virginia fanpetals can produce much higher biomass yield after applying fertilizer, e.g. municipal sewage sludge, which is the source of many valuable nutrients and has a value close to the manure, however contains a number of potentially harmful constituents such as heavy metals (Borkowska & Wardzinska 2003, Singh & Agrawal 2008, Seleiman et al. 2013, Gondek et al. 2014). The use of sewage sludge could not only increase yields but also positively affects biological and physico-chemical properties of the soil profile (Singh & Agrawal 2008, Seleiman et al. 2013, Casado-Vela et al. 2006, Usman et al. 2012). Hence the interest in the use of sewage sludge in the cultivation of energy crops such as Virginia fanpetals has been studied by many authors (Augustynowicz et al. 2008, Strzelczyk 2013, Borkowska & Wardzińska 2003).

Thus, the main limiting factors in widespread production of this species are: low germination capacity, lack of plantlets or root cuttings mechanical system or large-scale technology, lack of chemical weed control or pests management and inadequate information about fertilization and ecological requirements (Kurucz et al. 2014). In order to expand and complete the missing information about *S. hermaphrodita* culture a six-year field experiment was established, aiming to determine the effect of increasing municipal sewage sludge doses on Virginia fanpetals yielding and biomass quality as well as indicate an optimal dose to minimize an environmental impact but guaranty sufficient yield. We assumed that due to the fact that this species is not used for food production, municipal sewage sludge could be used for its fertilization as a valuable source of minerals, preferably affecting plant growth and development. Additionally, efforts were made to assess sewage sludge impact on chemical composition and structure of the experimental plant yield and selected physico-chemical properties of the soil. The study also attempted to determine the best method of Virginia fanpetals plantation establishment (by roots sections or plantlets) in the conditions of south-eastern Poland and indicate the optimum harvest date of its biomass (autumn, winter and spring).

2. Materials and methods

This experiment is a part of long-term research on sewage sludge application in ten, different species of energy plants cultivation, aiming at finding the most suitable one for phytoremediation and at the same time characterizing by favorable energy parameters.

2.1. Experimental site and design

A six year (2008-2013) field studies were established at the landfill belonging to the Janów Lubelski Department of Public Utilities in south-eastern Poland (50°43'17.7"N 22°22'08.0"E). The soil was a clay loam belonging to Cambisols, which was characterized by slightly acidic pH (6.29), average humus content (1.45%), low phosphorus (30.09 $mg \cdot kg^{-1}$ DM), potassium (91.3 $mg \cdot kg^{-1}$ DM) and magnesium (27.6 $mg \cdot kg^{-1}$ DM) content and the heavy metal content remained at the natural level (Kabata-Pendias 2011). The average air temperature recorded in sorghum vegetation period in 2008-2013 was higher than the average of long-term period by 1°C, while the total precipitation exceeded the average by 334 mm. However, each of the years of the experiment were characterized by considerable variability. The lowest rainfall and air temperature was marked by the first year of the experiment, while the best conditions for the growth and development of sorghum was recorded in 2010. The complete characteristic of soil and meteorological conditions were described in our previous papers (Kołodziej et al. 2015, 2016).

The experiment design was a split-split-plot based on randomized complete block design with three replications. Main plots were five doses of sewage sludge, two methods of plantation establishment were sub plots, while three harvest dates were arranged in sub-sub plots. Rows were 0.75 cm apart and each split-split plot was 4.8 m long for a harvest area of 14.4 m^2. Prior to the study the field was fallow, without conventional disk tillage. In September 2007 municipal sewage sludge was applied in doses according to experiment design and mixed with a topsoil. In spring 2008, several weeks before planting, the seedbed was prepared by tilling with a moldboard plow and disk harrow. The experiment was established as follows: 24 April 2008 by planting roots sections (vegetatively) and 15 May 2008 by planting the seedlings of Virginia fanpetals (generatively) at spacing of 0.75×0.4 m (33 325 units ha^{-1}). Seedlings of Virginia fanpetals were produced in multi-cell trays located in an unheated greenhouse from early April to mid-May and were transplanted to the field after the spring frost. The experiment comprised five levels of municipal sewage sludge (main plots), three dates of biomass harvesting (split-split plots) and two methods of plantation establishment – split plots – (from seeding of root stock (parts of roots) and the nurse-in-tray plantlets production). Roots used as a rootstock for vegetative propagation were 8-12 cm long with several buds, while in the case of generative propagation, seeds were sown in the multi-cell trays in the first decade of April (2-3 seeds per cell) and kept in an unheated greenhouse. After emergence, one plant per cell was left for further growth. Peat moss was the substrate for seedlings produced in multi-cell trays (cell dimension 4×4×6 cm). At the phase of 3-4 leaves (mid-May), they were transplanted into the field along with substrate clods. Single split-split plot (3.0×4.8 m) comprised 4 rows (interrows of 0.75 m) with 12 plants per row (0.4 m between plants in row).

Sewage sludge were applied only once, before experiment establishment at four rates: I – 60 Mg ha^{-1} DM; II – 40 Mg ha^{-1} DM; III – 20 Mg ha^{-1} DM; IV – 10 Mg ha^{-1} DM; control objects were not fertilized with sewage sludge: V – 0 Mg ha^{-1} DM. In the experiment, compressed and stored for 1 year in a lagoon municipal sewage sludge was used. Municipal sewage sludge characteristic: pH_{KCl} – 6.04; dry matter – 13.3%; organic matter – 59.4% DM; total N content – 7.45%; N ammonium content – 2.35%; available forms of: P –

2.25mg·kg^{-1} DM; Mg – 0.28 mg·kg^{-1} DM; Ca content – 0.29 mg·kg^{-1} DM; general forms of: Cd – 2.35 mg·kg^{-1} DM, Pb – 42.9 mg·kg^{-1} DM, Ni – 14.8 mg·kg^{-1} DM, Cr – 25.4 mg·kg^{-1} DM, Hg – 1.12 mg·kg^{-1} DM, Zn – 1005 mg·kg^{-1} DM, Cu – 111 mg·kg^{-1} DM. The sewage sludge was characterized by relatively low content of heavy metals compared to that found in the literature (Singh, Agrawal, 2008; Usman et al., 2012). Due to the high water content, it had been mixed with topsoil in the autumn of 2007. In addition, due to the low levels of potassium in the soil and in the sludge a supplemental fertilization with 100 kg K ha^{-1} was applied to all plots. A twice mechanical weeding were applied during the first growing season, while in the subsequent years plants covered the inter-rows and weeds were removed incidentally.

2.2 Sampling and analytical methods employed

In order to check the dynamics of dry matter content in the biomass and indicate the best date of biomass harvesting in terms of energy use (for combustion) there were used three harvest dates: autumn (beginning in November, after the first frost), winter (mid-January) and spring one (end of March following the growing season). Plants were harvested using hand implements at a stubble height of ca. 10 cm and stems were counted in the plots. During autumn biomass harvesting, two weeks before plants cutting, a biometric measurements were performed (height and diameter at the base of 10 stems per plant as well as weight of stems and leaves per single plant of five randomly selected plants in each plot). After that, dry biomass yield was determined and all aerial biomass from plot was chopped in a commercial chipper shredder Bear Cat 70080 s-8HP (Colorado, USA) and three subsamples (600 g, 1000 g and 2000 g) were taken. 600 g subsamples were collected in a paper bag and dried in an air force oven at 70°C for 48 h in order to adjust fresh mass to a dry matter basis, 2000 g subsamples of Virginia fanpetals feedstock obtained vegetatively (by roots sections) collected in autumn were used for its energy characteristics (placed in aplastic bags), whereas three 1000 g subsamples from each plot were taken for chemical analysis and dried at 70°C for 48 h in a paper bag. That subsamples was ground in a laboratory mill to pass a 1.0 mm (20 mesh) screen and analyzed for macronutrients by ICP-AES and total nitrogen content – by Kjeldahl method and phosphorus by spectrophotometer (Ostrowska et al. 1991, Nelson & Somers 1975, Jones & Case 1991). In order to assess the suitability of the test plants for disposal of sewage sludge an index of bioaccumulation (IBA) as a ratio of element concentration in Virginia fanpetals plants to element concentration in soil was calculated. For evaluation a four-scale bioaccumulation rate were adopted, where 0.001-0.01 was the lack of bioaccumulation, the bioaccumulation index 0.01-0.10 – a slight degree of bioaccumulation, 0.1-1.0 – a medium degree of bioaccumulation, the rate of 1.0-10.0 – an intensive degree of bioaccumulation (Kabata-Pendias 2011). In the collected just after the autumn harvest and placed in a plastic bags 2000 g sample of raw material the moisture content (EN-14774-1), ash content (EN 14775), sulfur content (EN 15289) as well net calorific value (in a calorimetric bomb LECO AC 500) in accordance with the requirements of EN 14918 were also determined. Additionally, the primary energy yield was calculated as a product from the dry biomass yield and net calorific value.

Furthermore, soil samples were collected each autumn (acc. to ISO 10381-5:2005) from the layer of 0-20 cm, separately for each plot, dried and sieved (2 mm) for analytical purposes. In the soil were determined: pH by potentiometry, hydrolytic acidity by Kappen method, organic carbon by Tiurin method, total nitrogen by the Kjeldahl method, available phosphorus and potassium using the Egner-Riehm method, and magnesium absorbed by Schachtschabel method (Ostrowska et al. 1991, Jones & Case 1991).

2.3. Statistical analysis

Plant characteristics, macronutrient content, and yield changes due to the sludge dose, method of plantation establishment, harvesting date and their interactions over the course of the experiment were analyses were carried out using the Statistica 6.0 software programme. For soil characteristics and bioaccumulation index differences between means of treatments were compared by Tukey's test. Prior to the analysis, all data were tested for normality with the Shapiro-Wilk test. Homogeneity of variance was checked using Levene′s test. Statistical analysis (ANOVA at the 0.05 confidence limit followed by a Tukey post hoc test) were conducted with sewage sludge dose (as a whole plot effect), plantation establishment method (split effect) and harvest date (split-split effects).

3. Results and discussion

3.1. Virginia fanpetals yield and characteristic

Across the 6-year period, we observed a tendency of increasing plant size and weight in successive years of cultivation (Table 1). The average final height of Virginia fanpetals reached 2.8-3.0 m, which was in accordance with Borkowska et al. (2009), Kuś & Matyka (2009), Slepetys et al. (2012), Matyka (2013), Matyka & Kuś (2018) as well as Franzaring et al. (2014) indications. There was noted a clear trend to increase Virginia fanpetals height along with increasing sewage sludge dose (up to 288 cm across the 6-year period – Table 1). Plants reached maximum height in the fourth year, whereas the lowest ones were recorded in the first year of the experiment. In the fifth year of vegetation, plants created a big number of shorter and thinner stems than in the previous and next year, probably due to unfavorable weather conditions (water shortage in the soil, as a result of 39% lower rainfall during July and August). It is consistent with

Borkowska & Molas (2012) as well as Kuś & Matyka (2009) indications, who showed that Virginia fanpetals productivity significantly depended on the precipitation.

Average height of plants grown on plots where vegetative propagation (roots) were used for plantation establishment was significantly higher than those with generative propagation method (plantlets), likewise in Borkowska and Wardzińska (2003) research. Stem number per plant reached 11-17 units plant^{-1}, while basal stem diameter changed from 23 mm in the first year to 13-16 mm in subsequent years, and was larger than in Borkowska (1991) study with a frequent cutting as a fodder, but comparable to Matyka (2013) as well as Kuś & Matyka (2009) and Matyka & Kuś (2018) findings. Across the 6-year period, the average number of stems increased significantly, from approximately 3 stalks per plant in the first year, to about 14-17 stems per plant in the last two years of vegetation, which was in accordance with Borkowska & Wardzińska (2003), Borkowska et al. (2009) and Borkowska & Molas (2012) findings, but those latter authors noted a significantly higher number of stems per plant in the fifth and sixth years of vegetation. We observed a significantly higher number of stems in the case of plants grown on plots with root cuttings planting, which were better developed (higher, thicker and heavier) than on plots with seedlings planting and a tendency to increase stems number per plant along with increasing sewage sludge dose.

The average dry weight of aboveground parts of plant from a single plant comprised within the range of 176 in the first year of vegetation to 639 g plant^{-1} in the sixth year of culture, which was consistent with the results of Barbosa et al. (2014) studies. Total dry weight of single Virginia fanpetals plant increased significantly along with increasing sludge doses applied, being however significantly higher in objects with root cuttings used for Virginia fanpetals plantation establishment. Similar relationship of yields increasing along with increasing digestate doses observed also Nabel et al. (2014), however higher doses of digestate did not result in significantly higher biomass yields, but increased the risk of harmful effects with delayed plant development or even caused the loss of plants. It is worth to underline, that an increase in dry weight of single plant was a consequence of its stems weight increment (leaves share reached from 4 to 7%) (Table 1), which was in accordance with Franzaring et al. (2014) as well as Kalembasa & Wiśniewska (2006) findings. Moreover, higher sewage sludge doses promoted shoot development, like in Nabel et al. (2014) investigations with biogas-digestate.

Table 1. Characteristics of single Virginia fanpetals plant depending on the applied experimental factors

Treatment		Average height (cm)	Stem diameter (mm)	Stem number per plant	Leaves dry weight (g plant^{-1})	Stem dry weight (g plant^{-1})	Single plant dry weight (g plant^{-1})
Sewage sludge DM dose†	0 Mg ha^{-1}	234.0^{a}	12.97^{a}	10.0^{a}	12.2^{a}	251.5^{a}	263.7^{a}
	10 Mg ha^{-1}	260.0^{b}	15.70^{b}	11.2^{b}	19.0^{b}	404.3^{b}	423.3^{b}
	20 Mg ha^{-1}	275.3^{cd}	16.74^{c}	11.9^{b}	35.4^{c}	464.9^{c}	500.3^{c}
	40 Mg ha^{-1}	288.0^{c}	17.79^{d}	12.3^{c}	40.4^{d}	521.4^{c}	548.5^{c}
	60 Mg ha^{-1}	288.7^{c}	18.23^{d}	13.5^{d}	35.5^{c}	562.1^{d}	597.6^{cd}
	P	***	***	***	***	***	***
Plantation establishment method†	root cuttings	278.6^{b}	16.66^{b}	12.4^{b}	30.0^{b}	479.0^{a}	509.2^{b}
	plantlets	269.8^{a}	15.89^{a}	12.0^{a}	26.9^{a}	451.9^{b}	484.2^{a}
	P	***	***	***	*	***	***
Year	1st year	173.3^{a}	23.69^{c}	3.2^{a}	47.4^{f}	142.6^{a}	176.0^{a}
	2nd year	273.9^{b}	16.37^{b}	9.8^{b}	20.8^{c}	392.6^{b}	411.0^{b}
	3rd year	287.4^{c}	14.73^{a}	11.4^{c}	32.3^{d}	522.4^{d}	554.7^{e}
	4th year	300.7^{cd}	15.22^{a}	15.2^{d}	35.8^{e}	494.9^{b}	530.6^{d}
	5th year	292.8^{c}	13.90^{a}	17.0^{e}	19.9^{b}	468.7^{bc}	488.5^{c}
	6th year	296.2^{c}	13.75^{ad}	14.0^{c}	17.3^{a}	621.9^{e}	639.1^{e}
	P	***	***	***	***	***	***
sludge dose × establish. method		n.s.	**	*	n.s.	n.s.	n.s.
sludge dose × year		***	***	***	***	***	***
establishment method × year		***	n.s.	n.s.	***	***	***
sludge dose × establish. method × year		*	***	***	n.s.	n.s.	n.s.

The level of significance are indicated by an asterisk (*0.01< $P \leq$ 0.05; **0.001< $P \leq$ 0.01; *** $P \leq$ 0.001; n.s. - not significant) – results of multivariate Anova; the values designated by different lower case letters are significantly different (results of Tukey test); †Values presented for sewage sludge DM dose and plantation establishment method are the means across 6 years and other treatments

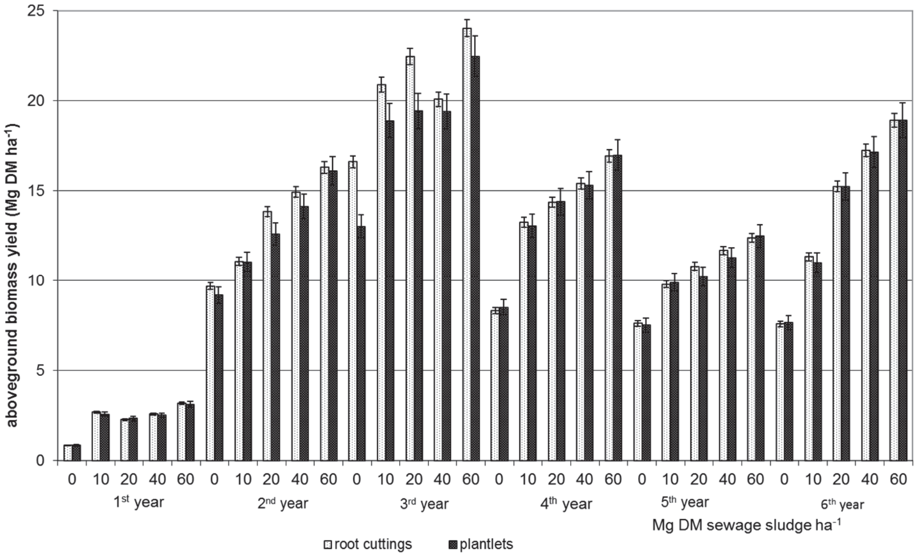

Fig. 1. Yields of dry weight of Virginia fanpetals biomass harvested in the autumn depending on the applied experimental factors (average from six following years of its vegetation). The vertical bars indicate the standard error of the mean values (n = 3)

Dry biomass yields of Virginia fanpetals over the following six years of cultivation are shown in Table 2, 3 as well as at Figure 1 (derived from the autumn harvesting only). In the first year of the field vegetation Virginia fanpetals productivity was negligible (Figure 1), similarly as in Borkowska & Wardzińska (2003), Borkowska (2005), Borkowska et al. (2009), Borkowska & Molas (2012, 2013) as well as von Gehrena et al. (2019) experiments. Hence, it should be taken into account that the yield from the first year caused a significant decrease in the 6-year average values – Table 2. Mean productivity of Virginia fanpetals harvested in autumn observed in this study (Figure 1) was close to the one reported by other researchers, who worked in the same area (Table 4). However, in Borkowska & Molas (2012, 2013) experiments, Virginia fanpetals yields reached about 20 Mg ha^{-1} DM in the fourth year of plant vegetation, whereas in our study similar 'ceiling' biomass yields were obtained already in the second year of plant vegetation. In the following year we observed an increases in Virginia fanpetals yielding (probably as a result of favorable weather conditions) but after that, the average dry biomass yields significantly decreased, remaining almost at the second year yield level (Figure 1, Table 2, 3). In Kuś & Matyka (2009) experiment however Virginia fanpetals yields increased progressively along with following years of the experiment. That phenomenon could be explained by different soil type and fertilization in our and Kuś & Matyka (2009) as well as Matyka & Kuś (2018) experiments (in our study soil were enriched in sewage sludge only once, before plantation establishment), the exhaustion of crops after record-breaking yields in the previous year and the poor weather conditions. The confirmation of that explanation was the changes of autumn yielding on the object control (without fertilization) – Figure 1, where there was no such high reductions in yielding of plant as on the objects with sewage sludge application. Similar level of Virginia fanpetals yields noted also Slepetys et al. (2012) and Šiaudinis et al. (2015) in Lithuania. Dry biomass yield was significantly affected by the method of plantation establishment, sludge dose, year, harvest date and all their interactions (Table 2, 3). The plants propagated as seedlings produced 8% lower dry biomass yields over the six years of cultivation than those propagated through root cuttings ($P < 0.0001$). Research on Virginia fanpetals' cultivation under Central-East European growth and climate conditions has indicated the possibility of harvesting 9-17 Mg ha^{-1} DW yearly, from plantation established by seeds (Borkowska & Wardzińska 2003), and 20 Mg ha^{-1} DM oven dry, planted by root cuttings (Borkowska & Styk 2006). Differences in dry biomass yield due to method of plantation establishment of Virginia fanpetals have also been reported by other researchers (Borkowska & Wardzińska 2003). However, in our experiment such evident differences were obtained in the first three years of vegetation, probably due to the better growth of vegetatively propagated plants and the weather conditions (lower precipitation in June and July during seedlings establishing at the field, while plants from root cuttings benefited more from the stocks of water stored in the soil before planting). What is more, in the first year of vegetation plants from nurse-in-tray plantlets production stayed in the field shorter than plants propagated by roots. In the consecutive years of plant vegetation differences in Virginia fanpetals yielding caused by two compared methods of plantation establishment almost disappeared (Figure 1 – autumn harvesting), which was consistent with Borkowska & Styk (2006) as well Nahm & Mohrat (2018) results.

It was confirmed also by biometric measurements indicated significant differences between plants from the two compared methods of plantation establishment over the six year period (Table 1).

Table 2. Yields of dry weight (Mg ha^{-1}) of biomass as well as primary energy yields (MJ·Mg^{-1}·a^{-1}) of Virginia fanpetals depending on the applied experimental factors

Treatment		Yield of air dry weight of biomass (Mg ha^{-1})	Primary energy yields (MJ·Mg^{-1}·a^{-1})
Sewage sludge DM dose	0 Mg ha^{-1}	6.44^{a}	107.6^{a}
	10 Mg ha^{-1}	8.45^{b}	140.3^{b}
	20 Mg ha^{-1}	10.53^{c}	159.7^{c}
	40 Mg ha^{-1}	11.40^{d}	186.4^{d}
	60 Mg ha^{-1}	11.38^{d}	184.5^{d}
	P	***	***
Plantation esta-blishment	root cuttings	9.99^{b}	161.2^{b}
	plantlets	9.18^{a}	148.3^{a}
	P	***	***
Harvest date	autumn	12.13^{c}	196.0^{c}
	winter	9.19^{b}	148.4^{b}
	spring	7.42^{a}	119.7^{a}
	P	***	***
Year	1st year	1.83^{a}	29.7^{a}
	2nd year	11.06^{d}	178.8^{b}
	3rd year	14.53^{e}	235.0^{d}
	4th year	11.02^{d}	177.9^{c}
	5th year	8.39^{b}	135.5^{e}
	6th year	10.64^{c}	171.3^{f}
	P	***	***

*** significant at the 0.001 probability level; n.s. – not significant – results of multivariate Anova; the values designated by different lower case letters are significantly different (results of Tukey test)

Sewage sludge application significantly affected dry biomass yield across the methods of plantation establishment and the dates of harvesting. The highest average dry yields of biomass were collected from plots fertilized with the highest municipal sewage sludge doses, while lower sewage sludge doses (10 and 20 Mg ha^{-1} DM) introduced into the soil before the experiment establishment caused on average 31 and 63% yield increment compared to the control object, respectively. This could be due to the nutrients present in sewage sludge which might have enhanced plant growth even without the application of inorganic fertilizer as a source of plant nutrition (Singh & Agrawal 2008, Seleiman et al. 2013, Usman et al. 2012). It is worth to underline that higher sewage sludge application was connected with almost equal *S. hermaphrodita* yielding, without any significant differences (Table 2). Thus, an inversion point of the relationship between the sewage sludge application and yield increases indicated that sludge supply beyond 40 Mg ha^{-1} DM is not reasonable.

Table 3. Analysis of variance of Virginia fanpetals dry weight yield and primary energy yields based on measurements from six following years of its vegetation

Effect	*DF*	Yield of air dry weight of biomass		Primary energy yields	
		F value	*P* value	*F* value	*P* value
Sludge dose	4	454.95	0.0001	454.95	0.0001
Establishment method	1	200.19	0.0001	200.19	0.0001
Harvest date	2	953.18	0.0001	953.18	0.0001
`Year	5	1493.88	0.0001	1493.88	0.0001
Sludge dose × establishment method	4	4.61	0.012	4.61	0.012
Sludge dose × harvest date	8	22.24	0.0001	22.24	0.0001
Establishment method × harvest date	2	8.93	0.002	8.93	0.002
Sludge dose × year	20	25.47	0.0001	25.47	0.0001
Establishment method × year	5	30.06	0.0001	30.06	0.0001
Harvest date × year	10	85.59	0.0001	85.59	0.0001
Sludge dose × establishment method × year	20	3.71	0.001	3.71	0.001
Sludge dose × harvest date × year	40	2.18	0.8889	2.18	0.8889
Establishment method × harvest date × year	10	4.30	0.0001	4.30	0.0001
Sludge dose × establishment method × harvest date	8	3.26	0.0013	3.26	0.0013

Similar relationship of yields increasing along with increasing sewage sludge dose observed also Nabel et al. (2014) after digestate application as well as Seleiman et al. (2013) – in other energy plants. Measurements of single Virginia fanpetals plant (Table 1) indicate that they perfectly use fertilization potential of sludge. Positive reaction of *S. hermaphrodita* plant for sludge application noted also Borkowska et al. (2001), Augustynowicz et al. (2008) and Strzelczyk (2013).

We also observed a significant effect ($P < 0.0001$) of year (age of plant and climatic conditions) on Virginia fanpetals productivity. We recorded a significant increase in yield up to the third year of vegetation, when the major minerals resources brought into the soil along with increasing doses of sludge applied were available for plants, and then a significant reduction of biomass yields. This confirms earlier observations of Szempliński et al. (2014), who reported yield increase during first three years of *S. hermaphrodita* vegetation and after that yields naturally decreasing.

Table 4. Sample dry yields of Virginia fanpetals' biomass in the studies conducted in Poland

No. year after establishment	Borkowska and Wardzińska (2003)	Borkowska et al. (2009)	Borkowska and Molas (2013)	Szempliński et al. (2014)	Kuś and Matyka (2009)	Borkowska et al. (2001)
1	3.71	2.61	2.51	n.d.	n.d.	4.85
2	10.2	8.12	14.47	10.3	n.d.	3.93
3	7.99	11.98	15.52	11.6	9.0	9.28
4	n.d.	11.00	19.6	7.8	11.4	9.35
5	n.d.	n.d.	n.d.	n.d.	9.6	n.d.
6	n.d.	n.d.	n.d.	n.d.	6.9	n.d.

n.d. – no data

Delaying of biomass harvesting causes usually a reduction in energy crop yields and at the same time an increase of cellulose content in the dry matter and a water reduction (Lewandowski & Heinz, 2003). In the current study three dates of biomass harvesting (performed in late autumn, in winter and in the spring) were compared. An autumn harvesting¸ carried out immediately at the end of growing season, proved to be the most favorable. Virginia fanpetals plants harvested at that time produced significantly ($P < 0.0001$) the highest yield of dry biomass (Table 2, 3). During the winter average dry biomass yields were significantly lower (by 24.2%) compared to those obtained in the autumn. The lowest biomass yields were obtained at early spring – the reduction reached almost 38.8% compared to the autumn harvest. The mean daily loss observed in a current study was 0.25% day^{-1}. Thus, autumn harvest offers better yields than late harvesting, mainly due to a loss of harvestable biomass during winter, but on the other side, in the spring a significant reduction of water and improvement of combustion quality was observed by Borkowska (2005) and was described by Nahm & Mohrat (2018). Similar relationship in experiments with delayed miscanthus harvesting observed Lewandowski & Heinz (2003). We also observed a significant interactions of sludge dose, year, and the harvest date in Virginia fanpetals biomass yields within 6-year study (Table 3).

3.2. Biomass characteristic

Moisture content in Virginia fanpetals biomass harvested in autumn reached up to 30% (Table 5) and was comparable to Borkowska (2005), Kuś & Matyka (2009), Szyszlak-Bargłowicz & Piekarski (2009) as well as Borkowska & Molas (2013) findings, but lower than that obtained in Slepetys et al. (2012) experiments. Borkowska (2005) as well as Borkowska & Molas (2013) studies indicated, that there is an advantage to the late harvest as it reduces the amount of drying that is required to obtain low moisture content. Lower moisture content in *S. hermaphrodita* biomass was achieved in objects with the lowest doses of sewage sludge, probably associated with smaller stems which tend to dry faster.

A very important indicator of biomass quality is also ash and sulphur content. Biomass ash has a relatively low melting point, which can lead to slagging and fouling the combustion chamber or boiler, while high sulfur content can pose corrosion problems (Obernberger et al. 1997). A positive feature of Virginia fanpetals biomass were significantly low ash (from 3.5 to 5.7%) and sulfur content (from 0.03 to 0.09%), which was comparable with Kalembasa & Wiśniewska (2008) as well as Slepetys et al. (2012) and von Gehrena et al. (2019) findings.

Table 5. The fuel characteristics of Virginia fanpetals biomass depending on the sewage sludge dose

Treatment		Moisture content (%)	Ash content (%)	Sulfur content (%)	Net calorific value (MJ·kg^{-1})
Sewage sludge DM dose	0 Mg ha^{-1}	24.6^{b}	3.5^{a}	0.03^{a}	16.61^{c}
	10 Mg ha^{-1}	25.6^{c}	4.7^{b}	0.09^{c}	16.59^{c}
	20 Mg ha^{-1}	23.1^{a}	3.9^{a}	0.03^{a}	16.71^{d}
	40 Mg ha^{-1}	25.1^{c}	5.1^{c}	0.05^{b}	16.35^{b}
	60 Mg ha^{-1}	30^{d}	5.7^{c}	0.06^{b}	16.22^{a}
	P	***	***	***	***

*** significant at the 0.001 probability level – results of one-way Anova; the values designated by different lower case letters are significantly different (results of Tukey test)

The thermal energy was assessed also on the basis of the net calorific values (lower heating values). The highest values of the net calorific value as well as the lowest ash and sulfur content were obtained on the control objects and after application lower doses of sludge. Similarly, in the case of other energy crops, there was noted an increase of lower heating value after sewage sludge was applied (Seleiman et al. 2013). The net calorific value was shaped by percentage of moisture content in the biomass. Obtained in the current study LHV levels were in accordance with Szyszlak-Bargłowicz & Piekarski (2009), whereas Jasinskas et al. (2014), Szempliński et al. (2014) and von Gehrena et al. (2019) stated slightly higher gross calorific value of *Sida*, but confirmed the differences between calorific values of biomass collected in the winter and spring.

In the case of energy crops a very important indicator of its quality is the energy value of yield (Table 2, 3). Significantly ($P < 0.001$) the highest value of the parameter was obtained for plantation established by roots (161.2 MJ Mg^{-1} a^{-1}). On average, about 8% less energy value was found in plants grown on plots with plantlets planting. However, regardless of the plantation establishment method and the harvest date, the highest average Virginia fanpetals biomass energy value was calculated for the objects fertilized with 40 and 60 Mg ha^{-1} sewage sludge (Table 2). Alike in the case of other energy crops, increasing gross energy yields were produced following sewage sludge application (Seleiman et al. 2013). Similar level of energy efficiency reported Szempliński et al. (2014) and Matyka (2013), while higher energy production from 1 ha of land by *S. hermaphrodita* noted Borkowska & Molas (2012), but those authors adopted for calculations the one, high value of the higher heat value of 18.74 MJ kg^{-1} of dry biomass, while comparable energy yields were obtained by Borkowska et al. (2009) in the experiment with different mineral fertilization doses. When it comes to identify the optimum date for biomass harvesting, an autumn date proved to be the most favorable, as the plants produced the highest yields of aboveground parts with a relatively high calorific value. Slightly less favorable seems to be a winter harvesting, when we recorded an average energy value yield lower by 24.3% compared to that obtained in the autumn. The lowest energy value of biomass (mainly due to significantly lower biomass yields) was obtained in the case of harvesting conducted in the early spring – on average by 38.9% lower in relation to the autumn one – Table 2. Observed trend of decreasing of total thermal energy potentially produced by combustion of Virginia fanpetals biomass during later harvesting was in accordance with Lewandowski & Heinz (2003) findings on miscanthus. The effect of date of harvesting interacted with sludge application ($P < 0.0001$) and plantation establishment method in primary energy yields within the study.

3.3. Plant nutrient concentration and accumulation

For biofuel purposes, high cellulose content and low lignin content, minimum moisture, ash and other mineral elements (N, P, K, S and to a lesser degree Ca, Mg) are desired biomass chemical characteristics to improve conversion efficiency (Obernberger et al. 1997). Excessive mineral nutrients levels within the harvested material can cause corrosion, slagging, fouling and environmentally harmful emissions (Szyszlak-Bargłowicz 2014).

In the current study, sewage sludge dose and morphological part of plant significantly affected macronutrients content by Virginia fanpetals plants (Table 6). Generally, *S. hermaphrodita* stalks contained significantly higher amounts of nitrogen, phosphorus, potassium, and magnesium, while its leaves accumulated more sodium and calcium (Table 7). An opposite tendency was obtained by Kalembasa & Wiśniewska (2006, 2008) and Szyszlak-Bargłowicz (2014), who noted higher content of all analyzed macroelements in *Sida* leaves, but their examination was performed in full plants vegetation phase, while our results were collected just before leaves dropping and plants harvesting in late autumn. What is more, content of all studied elements in *S. hermaphrodita* plants strictly depended on the dose of sewage sludge introduced before the establishment of the experiment (increasing the dose caused an increase in the content of elements studied in the aerial parts of plants). A similar tendency was observed in Strzelczyk (2013) studies, while the opposite trend was stated in the case of other energy plants by Seleiman et al. (2013). Wherein the content was not strictly proportional, because 6-fold increase in sludge dose caused a relatively small increase in the content of macronutrients in plant tissues. Independently of the plantation establishment method, significantly greater macronutrients concentrations were noted in *S. hermaphrodita* biomass obtained from plots fertilized with the maximum dose of sewage sludge, suggesting its important fertilizer role.

On the other side, the lowest macronutrients content was stated in the control object, which was characterized only by natural content of biogenic elements in the soil. The same tendency were reported in Strzelczyk (2013) experiments with Virginia fanpetals grown in soil irrigated with municipal wastewater, Barbosa et al. (2014) experiments with digestate fertilization, Kalembasa & Wiśniewska (2006) with increasing mineral fertilization level, while Kalembasa & Wiśniewska (2008), Szyszlak-Bargłowicz (2014) as well as Slepetys et al. (2012) did not observed significant changes in elements analyzed content on plots with increasing mineral fertilization. The effect of the sewage sludge dose interacted with morphological part of plant ($P < 0.001$) in macronutrients under study within six following years of *Sida* vegetation. However, despite slightly lower amount of N, P and K in generatively propagated tissues, we did not recorded a significant effect of the method of plantation establishment of *S. hermaphrodita* on the content of N, Ca and Mg in plant biomass (Table 6). Minerals concentration in Virginia fanpetals tissues was comparable to Borkowska (1991), Krzywy-Gawrońska (2012), Barbosa et al. (2014) experiments, while the concentration of macronutrients occurring in the samples in this trail was higher than in Matyka (2013) study. The effect of the method of plantation establishment interacted with dose of sludge ($P < 0.001$) and morphological part in macronutrients under study within six following years of *Sida* vegetation.

Table 6. Macronutrients content (in g DM kg^{-1}) in aboveground parts of Virginia fanpetals plants depending on the applied experimental factors

Treatment		N	P	K	Na	Ca	Mg
Sewage sludge DM dose	0 Mg ha^{-1}	1.03^{a}	0.66^{a}	3.62^{a}	0.36^{a}	9.34^{a}	0.87^{a}
	10 Mg ha^{-1}	1.27^{b}	0.77^{b}	3.94^{b}	0.38^{b}	10.32^{b}	0.94^{b}
	20 Mg ha^{-1}	1.80^{c}	0.85^{c}	4.50^{bc}	0.41^{c}	11.03^{c}	1.01^{b}
	40 Mg ha^{-1}	1.91^{c}	0.90^{c}	4.78^{c}	0.43^{d}	11.88^{a}	1.19^{c}
	60 Mg ha^{-1}	2.02^{d}	1.54^{d}	5.94^{d}	0.48^{e}	12.10^{e}	1.33^{d}
	P	***	***	***	***	***	***
Morphological part of plant	leaves	2.77^{b}	1.58^{b}	6.63^{b}	0.29^{a}	10.33^{a}	1.74^{b}
	stems	0.45^{a}	0.30^{a}	2.48^{a}	0.55^{b}	14.97^{b}	0.39^{a}
	P	***	***	***	***	***	***
Plantation establishment method	root cuttings	1.66	0.98^{b}	4.94^{b}	0.29^{a}	10.33	1.06
	plantlets	1.55	0.91^{a}	4.17^{a}	0.54^{b}	11.54	1.08
	P	n.s.	**	**	***	n.s.	n.s.
sludge dose × morphological part		***	***	***	***	***	***
sludge dose × establishment method		***	***	***	***	***	***
establishment method × morph. part		n.s.	**	**	***	*	n.s.
sludge dose × establ. meth. × morph. part		***	***	***	***	n.s.	*

The level of significance are indicated by an asterisk (*$0.01 < P \leq 0.05$; **$0.001 < P \leq 0.01$; *** $P \leq 0.001$; n.s. - not significant) – results of multivariate Anova; the values designated by different lower case letters are significantly different (results of Tukey test)

Table 7. Macronutrients uptake (in kg ha^{-1}) depending on the applied experimental factors

Treatment		N	P	K	Na	Ca	Mg
Sewage sludge DM dose	0 Mg ha^{-1}	24.61^{a}	18.97^{a}	183.15^{a}	22.24	288.04	28.20
	10 Mg ha^{-1}	30.03^{b}	24.65^{b}	219.95^{b}	24.02	349.30	33.91
	20 Mg ha^{-1}	52.50^{c}	34.62^{c}	285.94^{b}	30.29	420.47	43.49
	40 Mg ha^{-1}	71.73^{d}	39.55^{c}	342.84^{b}	34.15	474.14	52.61
	60 Mg ha^{-1}	90.02^{e}	59.24^{d}	399.31^{c}	42.27	544.45	67.36
	P	***	*	*	n.s.	n.s.	n.s.
Plantation esta-blishment method	root cuttings	46.00	33.64	251.54	27.61	369.43	42.99
	plantlets	61.56	37.17	320.93	33.58	461.12	47.24
	P	n.s.	n.s.	n.s.	n.s.	n.s.	n.s.
sludge dose × establish-ment method *P*		**	***	*	*	n.s.	**

The level of significance are indicated by an asterisk (*0.01< $P \le 0.05$; **0.001< $P \le 0.01$; *** $P \le 0.001$; n.s. - not significant) – results of two-way Anova; the values designated by different lower case letters are significantly different (results of Tukey test)

When energy crops are cultivated on the soil where sewage sludge is used, it is crucial to determine the uptake of individual minerals. Despite the significant effect of sewage sludge dose on macronutrients content in Virginia fanpetals tissues we did not observed the same relation in the case of macronutients uptake. Sludge dose significantly affected the uptake of N, P and K as in Kalembasa & Wiśniewska (2008) experiments, while despite a slightly higher macro-elements uptake by plants grown from plantlets, statistical analyses did not confirmed significance of such differences (Table 7). Like in the nutrients content, the smallest uptake of macro-elements were noted in the control objects, whereas all the doses of sewage sludge caused a significant increase in macronutrients uptake (the highest being after 60 Mg sewage sludge ha^{-1} application). Similar level of analyzed macronutrients uptake observed Kalembasa & Wiśniewska (2008), while Krzywy-Gawrońska (2012) noted higher N uptake increasing along with increasing fertilization. The reverse trend in N uptake, but similar in P uptake after sludge application in maize, hemp and oilseed rape was observed by Seleiman et al. (2013). Uptake of all studied elements by *S. hermaphrodita* tissues delivered from plants grown on plots with plantlets produced in multi-cell trays used for plantation establishment method were similar as that one from plots with roots cuttings planting (Table 7).

3.4. Soil characteristic

Soil pH and hydrolytic acidity was clearly modified by the use of experimental factors under study (Table 8). The highest pH_{KCl} was recorded on control plots, while increasing doses of sludge resulted in gradual decrease in soil pH. Similar observations have made also Casado-Vela et al. (2006). However, Singh and Agrawal (2008) pointed out that the use of biosolids may also result in increasing the acidity of the soil and changes in heavy metals binding. On the other side, the lowest hydrolytic acidity was recorded in control objects, and increasing doses of sewage sludge applied to the soil resulted in its significant increase.

We also observed a clear linear relationship between sludge dose and accumulation of C_{org} in the soil (Table 8), similarly as in Nabel et al. (2014) as well as Casado-Vela *et al.*, (2006) experiments. The use of increasing doses of sludge resulted in a systematic increase in the content of organic carbon in the soil. A similar relationship was also observed in the total nitrogen content. Thus there was a build-up of a soil nitrogen and organic matter pool providing a longer lasting N reservoir for the plants. Similarly, the content of phosphorus, potassium and magnesium was positively correlated with increasing dose of sewage sludge and their content in the soil profile, which was consistent with the results of Casado-Vela et al. (2006), Singh & Agrawal (2008) and Usman *et al.*, (2012). C_{org} and N_t in the soil was consistent with Nabel et al. (2014) results, while macronutrients contents were higher, probably as a result of their higher amounts applied to the soil with the municipal sewage sludge.

3.5. Index of bioaccumulation

Bioaccumulation index (IBA) is calculated as the quotient of the contents of the element in the plant to its content in the soil. This is a parameter that indicates the size and speed of movement of the elements contained in the soil profile to the interior of plant cells. It has been recognized that a high biomass and a high bioaccumulation factor are two key factors for successful phytoextraction (Zhao et al. 2003). Nitrogen was subjected to intensive bioaccumulation in the tissues of Virginia fanpetals (Table 9).

Table 8. Chosen physical and chemical parameters of soil under Virginia fanpetals culture depending on the sewage sludge dose

Sewage sludge DM dose	pH_{KCL}	Hydrolytic acidity (mmol(+) kg^{-1})	C_{org}	N_t	P	K	Mg
			(g kg^{-1} DM of soil)			(mg kg^{-1} DM of soil)	
0 Mg ha^{-1}	6.46^a	10.77^a	12.46^a	1.38^a	27.57^a	88.03^a	46.51^a
10 Mg ha^{-1}	5.56^b	13.46^b	12.89^a	1.42^b	29.36^b	98.15^b	50.42^b
20 Mg ha^{-1}	5.38^c	19.75^c	15.16^b	1.53^b	31.42^c	102.72^c	51.29^b
40 Mg ha^{-1}	5.35^c	24.88^d	17.62^c	1.67^c	42.73^d	126.83^d	51.52^b
60 Mg ha^{-1}	5.85^d	35.66^e	20.14^d	1.89^d	49.93^e	132.37^e	54.22^c
P	***	***	***	*	***	***	***

The level of significance are indicated by an asterisk (*$0.01 < P \leq 0.05$; *** $P \leq 0.001$) – results of one-way Anova; the values designated by different lower case letters are significantly different (results of Tukey test)

Table 9. Index of bioaccumulation (IBA) of chosen macronutrients in Virginia fanpetals plant depending on the sewage sludge dose

Treatment		N	P	K	Mg
Sewage sludge DM dose	0 Mg ha^{-1}	0.167^a	0.007	0.021	0.006^a
	10 Mg ha^{-1}	0.204^b	0.009	0.022	0.007^b
	20 Mg ha^{-1}	0.278^c	0.009	0.024	0.007^b
	40 Mg ha^{-1}	0.318^d	0.008	0.022	0.009^c
	60 Mg ha^{-1}	0.336^e	0.009	0.023	0.010^d
	P	***	n.s.	n.s.	***

*** significant at the 0.001 probability level; n.s. – not significant – results of one-way Anova; the values designated by different lower case letters are significantly different (results of Tukey test)

We observed that the highest ratio of the content of the element in the plant in relation to its amount in the soil was found in objects with the highest dose of sewage sludge application. IBA of phosphorus ranged from 0.007 to 0.009 – Table 9, which, according to Kabata-Pendias (2011) indicates lack of bioaccumulation. In the case of potassium bioconcentration factor was known to be a weak, reaching the highest value after lower doses of municipal sewage sludge application. The bioconcentration factor of Mg was also weak and ranged from 0.006 to 0.01. The highest values was recorded after the higher doses of sewage sludge application (Table 9).

4. Conclusions

Sida hermaphrodita (L.) Rusby is an energy plant achieving stable, 'ceiling' biomass yield in the second year after planting, exceeded 20 Mg ha^{-1} a^{1} in an optimized system within this study. Virginia fanpetals seems to be a species effectively using fertilization potential of sewage sludge. Increasing doses of municipal sewage sludge stimulated production of significantly more thicker, higher and heavier stems per plant and as a result dry yields biomass from the unit area. 40 Mg ha^{-1} DM municipal sewage sludge could be recommended in cultivation of Virginia fanpetals for energy purpose.

Under the influence of increasing doses of sewage sludge macronutrients content and uptake increased steadily, taking the highest value after its maximum dose application. Virginia fanpetals intensively bioaccumulated nitrogen, while potassium and magnesium bioaccumulation factors were weak. Sludge cause changes in the physico-chemical properties of the soil (ie. reducing of the pH value while increasing hydrolytic acidity, total nitrogen content as well as the content of available phosphorus, potassium and magnesium). Applied sewage sludge also contributed to increase the organic carbon content, which varied primarily due to different its doses.

Significantly higher dry biomass yield (especially in the first three years of plants vegetation) was obtained using root cuttings for plantation establishment in comparison to the nurse-in-tray plantlets.

During autumn harvesting *S. hermaphrodita* biomass intended for combustion was characterized by a relatively low moisture content (23-30%), high net calorific value (16.2-16.7 MJ kg^{-1}) as well as low ash and sulfur concentrations. The harvest window of Virginia fanpetals is between October and March. Delaying harvesting date, however, was connected with significant loss of biomass yield relative to the peak yield noted in the autumn.

Thus, Virginia fanpetals an important energy plant in Poland has a potential for the use of municipal sewage sludge, but the short-term advantage of sludge applying as a fertilizer requires continuous monitoring.

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Abstract

The objective of this study was to determine the effect of increasing municipal sewage sludge doses on *Sida hermaphrodita* Rusby (Virginia fanpetals) yielding and bioenergy feedstock characteristics. In a six-year-lasting field experiment two methods of plantation establishment (by roots cuttings and nurse-in-tray plantlets) and three dates of biomass harvesting (autumn, winter and spring one) were additionally tested in climatic conditions of south-eastern Poland.

Virginia fanpetals dry yields increased each year and exceeded 20 Mg ha^{-1} in the second year of culture. Application of 40 Mg ha^{-1} sludge DM resulted in obtaining the highest yield. Similarly the content, uptake and index of bioaccumulation of macronutrients contained in the sludge increased along with increasing its dose. Biomass was characterized by a favorable parameters: net calorific values were in the range of 16.2-16.7 MJ kg^{-1}. The highest energy value of biomass yield was obtained with root cuttings use for plantation establishment, especially in objects with high dose of sludge during autumn harvest. Both, winter and spring harvesting significantly reduced yields, while using root cuttings for plantation establishment gave better yields only during the first three years of plant vegetation, than biomass yields equalized with the ones obtained by plantlets planting.

Keywords:
biomass yield, harvest date, municipal sewage sludge, propagation,
Sida hermaphrodita Rusby

Ocena efektów stosowania różnych dawek osadów ściekowych w produkcji biomasy ślazowca pensylwańskiego

Streszczenie

Celem badań było określenie wpływu zwiększających się dawek komunalnych osadów ściekowych na plonowanie i cechy jakościowe surowca energetycznego sidy-ślazowca pensylwańskiego (*Sida hermaphrodita* Rusby). W sześcioletnim doświadczeniu polowym przetestowano dodatkowo dwie metody zakładania plantacji (z sadzonek korzeniowych i rozsady wyprodukowanej w paletach wielokomórkowych) oraz trzy terminy zbioru biomasy (jesienny, zimowy i wiosenny) w warunkach klimatycznych południowo-wschodniej Polski.

Plony suchej masy ślazowca pensylwańskiego zwiększały się w kolejnych latach badań przekraczając 20 Mg ha^{-1} w drugim roku uprawy. Zastosowanie 40 Mg sm osadu ha^{-1} spowodowało uzyskanie najwyższych plonów biomasy. Notowano również zwiększenie zawartości, pobrania i wartości indeksu bioakumulacji makroelementów zawartych w osadach wraz ze zwiększaniem ich dawki. Biomasa ślazowca charakteryzowała się korzystnymi cechami: jej wartość opałowa mieściła się w przedziale 16,2-16,7 MJ kg^{-1}. Największą wartość energetyczną plonu biomasy uzyskano przy zastosowaniu sadzonek korzeniowych do zakładania plantacji, zwłaszcza na obiektach z aplikacją wysokich dawek osadu i podczas jesiennych zbiorów biomasy. Zarówno podczas zbioru zimowego, jak i wiosennego notowano istotne zmniejszenie plonów biomasy sidy, a wykorzystanie sadzonek korzeniowych do założenia plantacji wiązało się z lepszym plonowaniem tylko w pierwszych trzech latach wegetacji roślin, w okresie późniejszym plonowanie roślin było podobne jak na obiektach z wysadzaniem rozsady.

Słowa kluczowe:
plony biomasy, termin zbioru, komunalne osady ściekowe, rozmnażanie, *Sida hermaphrodita* Rusby