Archives of Environmental Protection
Vol. 44 no. 3 pp. 42–50

PL ISSN 2083-4772
DOI 10.24425/122285

Effect of sewage sludge on the yield and energy value of the aboveground biomass of Jerusalem artichoke (*Helianthus tuberosus* L.)

Małgorzata Szostek[1]*, Janina Kaniuczak[1], Edmund Hajduk[1], Jadwiga Stanek-Tarkowska[1], Tadeusz Jasiński[2], Witold Niemiec[2], Robert Smusz[2]

[1]University of Rzeszow, Poland
Department of Soil Science, Environmental Chemistry and Hydrology
[2]Rzeszow University of Technology, Poland
Department of Physics and Medical Engineering

*Corresponding author's e-mail: mszostek@ur.edu.pl

Keywords: sewage sludge, biomass, energy value, Jerusalem artichoke.

Abstract: The sewage treatment process is inherently associated with formation of sewage sludge, which has to be managed properly due to its properties. The paper presents a possibility of application of sewage sludge in the cultivation of Jerusalem artichoke as an energy crop. The experiment consisted in single application of sewage sludge pads with varied thickness under the sod-humic horizon of silty fallow soil. Physicochemical and chemical analyses of the sewage sludge and soil treated with the pads were carried out in accordance with legal guidelines. The results of the experiment were compared with the control, i.e. an object without the application of the sewage sludge pad. The paper presents the effect of the addition of sewage sludge on the yield and energy parameters (moisture and ash content, HHV, LHV) in the aboveground biomass of Jerusalem artichoke. The content of moisture and ash as well as HHV and LHV, i.e. biofuel parameters, were determined in accordance with Polish Standards. It was found that the yield of aboveground biomass of Jerusalem artichoke increased with the thickness of the sewage sludge pads and the yield potential of this plant increased with years. Additionally, the aboveground Jerusalem artichoke biomass was characterized by generally favorable energy parameters of biofuels, e.g. low moisture or ash content. The investigations have demonstrated that the application of sewage sludge can be a good alternative to mineral fertilization of energy crops.

Introduction

Socio-economic development of countries is associated with production of increasing amounts of wastes, which have to be treated in accordance with the environmental protection requirements. The wastewater treatment process is inevitably associated with production of sewage sludge, which is a high--nuisance waste in the natural environment due to its numerous chemical and biological contaminants. Large volumes of sludge need to be disposed of or treated in some manner (Wang et al. 2008).

Sewage sludge is the subject of European Parliament and Council Directive on waste, that regulates recycling of wastes, including sewage sludge. One of the key objectives of the above- mentioned Directive, is to maximize the utilisation of biogenic substances contained in sewage sludge in accordance with all sanitary, chemical, and environmental safety provisions (Directive 2008).

About 40% of the total sludge produced in the EU is used for agriculture purposes (Kacprzak et al. 2017). The application of sewage sludge on agricultural soils has been widespread in many countries around the world and this has been shown to improve soil properties and increase plant productivity (Wang et al. 2008). Also in Poland, intensive research has been conducted for many years on the methods for natural sewage sludge management, which could be employed due to their low cost and high efficiency (Kaniuczak et al. 2005 a, b, Krzywy et al. 2011, Kacprzak et al. 2017). Municipal sewage sludge from biological waste treatment plants is particularly suitable for natural application, e.g. for fertilization or reclamation, as it contains all components indispensable for proper functioning of plants, often in optimum quantities and proportions for fertilization purposes (Kaniuczak et al. 2005 a, b, Niemiec et al 2007).

Energy crops intended for biomass production are wild growing or cultivated plants characterized by production of large amounts of energy in a low-cost production process (Chołuj et al. 2008). In turn, Tworkowski (2012) defined energy crops as plants cultivated in arable lands and processed into biofuels, biocomponents, and heat or electrical energy.

Energy crops should be characterized by long-term growth and development, a high proportion of stems in the aboveground parts, generative reproduction, high annual growth, high calorific value, and high disease- and pest-resistance (Chołuj et al. 2008, Czeczko 2011). Additionally, such plants should have relatively low soil requirements, as energy crop plantations should mainly be established on poorer fallowed or idle soils and in uncultivated croplands (Kaniuczak et al. 2005 b, Faber et al. 2007, Piskier 2009, Decer et al. 2012). In terms of cultivation, the Jerusalem artichoke meets all the requirements for energy crops and its high yield potential, low plantation costs, high adaptability to soil conditions, and wide application support the popularization of this species in Poland (Czeczko 2011, Kowalczyk-Juśko et al. 2012).

The Jerusalem artichoke exhibits a high capacity of solar energy binding and biomass production (Kowalczyk-Juśko et al. 2012). Besides maize, beetroot, and some grass species, it represents plants with the highest potential for organic matter formation in our climatic zone (Prośba-Białczyk 2007). Jerusalem artichoke biomass can be used for energy purposes in direct combustion or co-incineration with coal. Given the high content of carbohydrates, Jerusalem artichoke tubers can be used in food, pharmaceutical, chemical, and energy industries for production of ethanol and biogas, while stems can be used for production of paper and firewood (Prośba--Białczyk 2007, Rodrigues et al. 2007, Sawicka and Kalembasa 2008, Kowalczyk-Juśko et al. 2012). Dry aboveground parts of the Jerusalem artichoke can be burnt or used for manufacturing briquettes and pellets, while fresh biomass collected even several times during the growing season can be utilized in biogas production (Kołodziej et al. 2010, Kowalczyk-Juśko et al. 2017). Bioethanol is widely produced from the Jerusalem artichoke in Spain, China, Korea, and Canada (Chen et al. 2011). A special application of this species is its use in ground--vegetable wastewater treatment plants and in revitalization of contaminated areas, open-cast mine landfills, or sewage sludge (Kołodziej et al. 2010, Gizińska-Górna et al. 2016, Gizińska--Górna et al. 2017).

The aim of the study was to assess the effect of a single application of sewage sludge pads with varied thickness on the yield and energy value of the aboveground biomass of Jerusalem artichoke plants cultivated during a 6-year period.

Materials and methods

The field experiment was set up in autumn 2005 on a long-term fallow soil in Nowa Wieś, Trzebownisko Commune, situated in the central part of Podkarpackie Province (50°05›54.8»N 22°03›37.5»E). The Jerusalem artichoke cultivation experiment was conducted from 2006 to 2011. The long-term fallow soil was classified as *Haplic Gleysol*. Before the experiment, the silty fallow soil in the sod-humic horizon (0–25 cm) was characterized by slightly acidic reaction, high organic matter content (2.84%), very low available forms of phosphorus content – 9.11 mg·kg^{-1} P, low available forms of potassium content – 91.47 mg·kg^{-1} K, and very high available forms of magnesium content – 207 mg·kg^{-1} Mg.

The long-term fallow soil was agromeliorated with sewage sludge in autumn 2005 by a single application of pads with varied thickness (0, 10, 20, and 30 cm) placed under the sod-humic horizon of silty fallow soil (at a depth below 25 cm) to restore its production value (revitalization). The thickness of the sewage sludge pads corresponded to the doses of 125, 250, and 375 Mg·ha^{-1} dry weight of sludge, which was equal to 0.5, 1, and 1.5 of the maximum dose of dry sludge used at a single application per 3 years, as specified by the binding legislation (Law Gazette 2002). These amounts of sewage sludge introduced 56, 113, and 169 Mg·ha^{-1} of organic matter, respectively, into the soil. No additional mineral NPK fertilization was used in the experiment.

The experimental plots set up in this way were left until the following year to achieve stabilization of the conditions. The experiment was established in a randomized block design with 4 replications. The different values of the thickness of the sewage sludge pads and their impact on the yield and energy value of the Jerusalem artichoke aboveground biomass were the analyzed variables. The sewage sludge was obtained from a "LEMNA" type biological sewage treatment plant located in Nowa Wieś village, Trzebownisko Commune. The characteristics of the sewage sludge used in the experiment and specified in previous investigations are presented in Table 1 (Kaniuczak et al. 2009). Due to the presence of pathogenic organisms, the sewage sludge used in the experiment was accepted to be used only for non-agricultural purposes, in accordance with the legislation binding at that time (Law Gazette 2002). In accordance with this Regulation, the soil (layer 0–25 cm) treated with the sewage sludge was characterized by natural content of heavy metals and met the requirements for sewage sludge management for agricultural purposes, including food and feed plant production.

In spring 2006, the soil profiles in the plots treated with the sewage sludge pads were exposed in order to determine their current thickness. The thickness of the applied pads was found to be 6, 9, and 17 cm, which was by ca. 45% lower than the original value. In March 2006, Jerusalem artichoke var. *Albik* tubers were planted in the experimental plots at a depth of 10 cm and 65 × 35 cm spacing. The Jerusalem artichoke biomass was harvested twice in each experimental year, i.e. in mid-July and late October. The surface area of one plot was 16 m^2. The paper presents the total yield of fresh biomass obtained in harvest I and II in the individual study years. The Jerusalem artichoke tubers were left in the soil each year to restore the plantation in subsequent years.

Hydrothermal data described by the Sielianinov coefficient (k) are presented in Table 2. Coefficient k was calculated using the formula $k = 0.1P/\Sigma t$, where P is the monthly precipitation in mm and Σt is the sum of temperatures < 0°C in the individual months (Skowera and Puła 2004). The data used for calculation of coefficient k were provided by the Rzeszów-Jasionka Meteorological Station. The values of coefficient k allowed for the identification of 10 classes of hydrothermal conditions, including extremely dry and extremely wet conditions (Skowera and Puła 2004).

The analytical moisture content (W^a) and ash content (A^a) were determined in the samples of the aboveground Jerusalem artichoke biomass in accordance with Polish standards (1980, 2002 a). The higher heating value (HHV) was measured using Polish standards (2002 b). As specified by these standards, the higher heat value (HHV) of a solid fuel is the amount of heat emitted at complete combustion of the fuel in a bomb

Table 1. Parameters of the sewage sludge used in the experiment (Source: Kaniuczak et al. 2009)

Parameter	Mean	Range min-max	V (%)
pH $_{H2O}$	–	6.10–6.95	–
		(g·kg^{-1})	
Dry matter	126	100–134	13.5
Organic matter	460	211–608	32.4
N	30.2	8.3–46.1	45.2
P	18.8	5.0–29.6	46.2
K	3.7	2.0–6.0	45.54
Ca	31.6	21.4–40.2	17.35
Mg	15.7	12.9–18.5	11.5
		(mg·kg^{-1})	
Fe	7323	5412–9245	15.76
Mn	212	180–320	28.6
Zn	2230	30.5–4200	96.4
Cu	291	104–356	40.2
Ni	30.1	8.9–50.4	78.5
Co	0.91	0.5–1.89	72.3
Cr	31	6.9–78.0	64.5
Cd	2.08	0.005–5.48	99.6
Pb	10.49	5.43–13.21	54.8
Hg	0.62	0.21–0.84	38.6

calorimeter at an oxygen atmosphere and a temperature of 25°C per fuel mass unit. The end products of the combustion are gases, e.g. oxygen, nitrogen, carbon dioxide, and sulphur dioxide, cooled to ambient temperature.

The lower heating value (LHV) was calculated based on the recommendations specified in Polish standards (2002 b). The LHV of a solid fuel is the HHV minus the heat of evaporation of water released during fuel combustion and formed from the hydrogen contained in the fuel.

Mean values of the yield and energy parameters of the aboveground Jerusalem artichoke biomass as well as standard deviations (SD) and variation coefficients (V) were calculated. The significance of the differences between the values of the analyzed properties in relation to the sewage sludge pad was determined. The level of statistical significance was adopted at $\alpha = 0.05$. If the assumptions of variance were fulfilled (normal distribution, homogeneity of variance), the significance of the differences was tested using *post hoc* Tukey's test. If at least one of the assumptions was not met, the significance of the differences was analyzed with the non-parametric Kruskal-Wallis test. Normality of the distribution was determined with the Shapiro-Wilk test and the variance homogeneity was analyzed using Levene's test. The significance of the differences in the investigated properties between the experimental objects was tested at the significance level with one-way analysis of variance ANOVA.

The statistical analysis was carried out in STATISTICA 10 program (StatSoft 2011).

Results and discussion

The Jerusalem artichoke is characterized by high yield potential, which is largely dependent on the soil culture and fertility as well as agricultural practices (Czeczko 2011). Some research reports demonstrate that the Jerusalem artichoke is tolerant in terms of soil requirements, it can be cultivated on various agronomic category soils and high yields of the plant can be achieved on very acidic soil as well (Prośba-Białczyk 2007). Among the many direct determinants, weather conditions play a fundamental role in plant yielding. Plant growth and development are largely dependent on the distribution of precipitation and thermal conditions prevailing during the vegetation season. As reported by Kowalczyk-Juśko (2003), the Jerusalem artichoke has low climatic requirements, therefore, it tolerates variable meteorological conditions and low temperatures. Tuber formation is more efficient during a warm and sunny growing season, whereas production of green biomass dominates during cooler periods.

Sielianinov coefficients (k) calculated based on the meteorological data from each study year allowed for detailed analyses of the hydrothermal conditions. They showed variable weather conditions prevailing during the individual study months (Table 2).

In the first half of the growing season in 2006, optimal to very wet conditions prevailed, which was also found for August. The other months of this vegetation season were dry and extremely dry. In 2007, the conditions from April to

May were characterized by precipitation deficiency, while optimal to extremely wet conditions prevailed from August to October. A major part of the vegetation season in 2008 was assessed as relatively wet with August as the dry month. In turn, April in the growing season 2009 was an extremely dry month and August and September were dry and very dry, respectively. The hydrothermal conditions in the other months of this period ranged between optimal and extremely wet. In 2010, the conditions during the greatest part of the growing season ranged from wet to extremely wet. October was the only relatively dry month. In turn, relatively dry and very dry conditions dominated in 2011 (V, VIII, IX, X), and the other months were characterized by relatively wet and extremely wet conditions. This analysis revealed that months with wet to extremely wet hydrothermal conditions were predominant during the 6-year study period. Only three months of this period were characterized by optimal conditions, while relatively dry to extremely dry conditions prevailed in the other months. The hydrothermal conditions noted during the study did not allow to achieve the full Jerusalem artichoke biomass potential.

The total yield of fresh aboveground biomass of the Jerusalem artichoke (harvest I+II) obtained during the 6-year study period ranged from 21.2 $Mg \cdot ha^{-1}$ in the control object to 99.4 $Mg \cdot ha^{-1}$ in the object treated with the 30-cm sewage sludge pad (Tab. 3 and Fig. 1). In comparison with the control, significant differences in the biomass yield depending on the pad thickness were noted in the objects treated with the 20- and 30-cm pads ($p=0.0143$ and $p=0.048$). It was also observed that the yield potential of the plant increased in all objects throughout study years, in particular after the third experimental year (Fig. 1). Therefore, the minimum yield was generally obtained in the first year of the experiment (2006), while the maximum value was recorded in the last experimental year (2011). The significant increase in the yield recorded in all the objects after the 3rd experimental year had an impact on the variability of the results obtained in all the objects (V>50%) (Tab. 2).

It is emphasized in the literature that the traditional mineral fertilization in Jerusalem artichoke cultivation can be supported or replaced by sewage sludge (Kołodziej et al. 2010). In our research, the fertilization demands of the Jerusalem artichoke were satisfied by nutrients introduced with the sewage sludge applied for agromelioration into the silty fallow soil. Many authors demonstrated that fertilization of soils with sewage sludge applied in even high doses enhanced the yield potential in different plant species (Kaniuczak et al.

Table 2. Sielianinov coefficient values (k) according to the Meteorological Station in Rzeszów-Jasionka

Years	Months						
	IV	V	VI	VII	VIII	IX	X
2006	1.35 (o)	2.53 (bw)	1.78 (dw)	0.24 (ss)	1.83 (dw)	0.54 (bs)	0.70 (bs)
2007	1.00 (s)	0.83 (s)	1.25 (ds)	1.19 (ds)	1.49 (o)	3.79 (sw)	1.63 (dw)
2008	1.65 (dw)	2.49 (w)	1.61 (dw)	2.04 (w)	0.94 (s)	2.64 (bw)	1.70 (dw)
2009	0.12 (ss)	2.00 (dw)	2.93 (bw)	1.58 (o)	0.77 (s)	0.70 (bs)	3.46 (sw)
2010	1.83 (dw)	4.02 (sw)	2.36 (w)	3.13 (sw)	1.65 (dw)	2.63 (bw)	1.02 (ds)
2011	1.62 (dw)	1.14 (ds)	1.64 (dw)	4.15 (sw)	0.49 (bs)	0.19 (ss)	1.22 (ds)

Values of coefficient k (after Skowera and Puła 2004):
$k \leq 0.4$ Extremely dry (ss); $0.4 < k \leq 0.7$ Very dry (bs); $0.7 < k \leq 1.0$ Dry (s); $1.0 < k \leq 1.3$ Relatively dry (ds); $1.3 < k \leq 1.6$ Optimal (o); $1.6 < k \leq 2.0$ Relatively wet (dw); $2.0 < k \leq 2.5$ Wet (w); $2.5 < k < 3.0$ Very wet (bw); $k \geq 3.0$ Extremely wet (sw).

Table 3. Mean yield of the aboveground parts of the Jerusalem artichoke with variability values over the study years, in relation to the thickness of the sewage sludge pad used (harvest I+II) ($Mg \cdot ha^{-1}$)

Sewage sludge pad (cm)	Mean*	Range		SD	V (%)
		min	max		
0	21.2	8.80	36.0	13.0	61.26
10	31.6	12.8	52.0	18.8	59.55
20	83.8[a]	32.0	140.0	54.8	65.42
30	99.4[a]	27.2	172.0	75.6	76.09

* Legend:
[a] – significant differences relative to the control

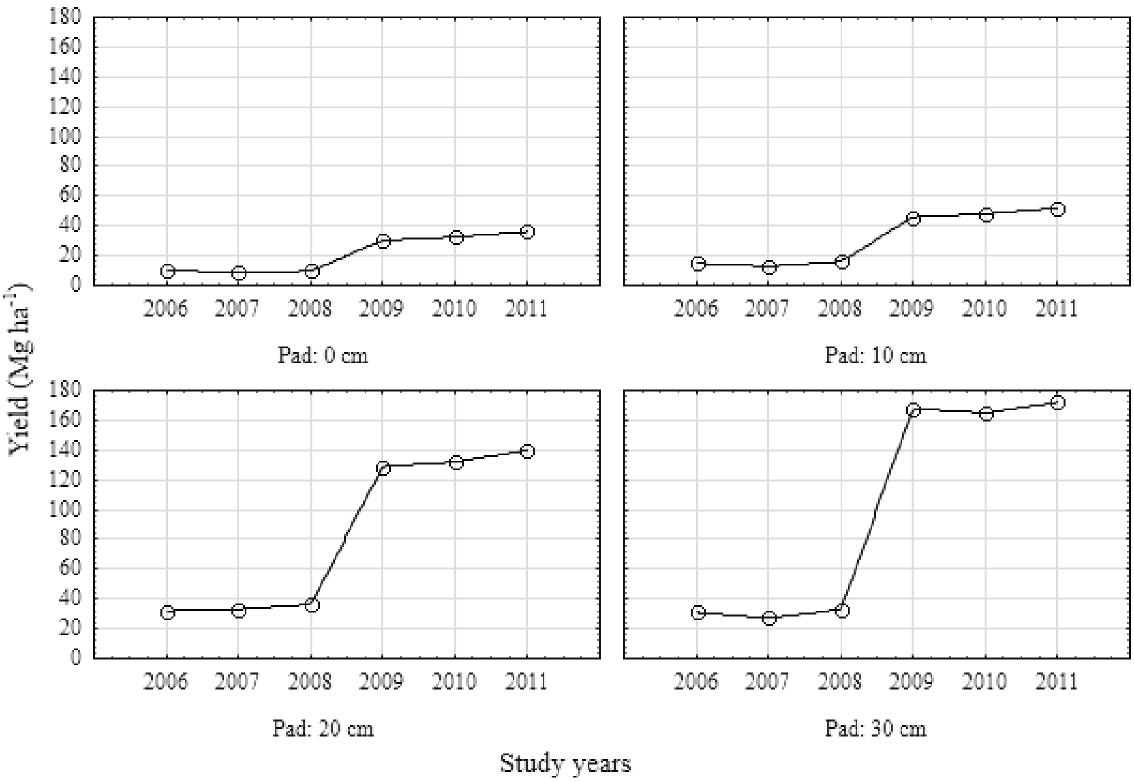

Fig. 1. Yield of aboveground biomass of the Jerusalem artichoke (fresh weight) over the study years in relation to the thickness of the sewage sludge pad (harvest I+II) (Mg·ha^{-1})

2005 a,b, Koncewicz-Baran et al. 2014) and improved yield parameters. Lisowski and Porwisiak (2010) reported that the yield of miscanthus grown with sewage sludge fertilization increased by merely 1% in the first study year and by 81% in the following year, compared with the control, and the biometric parameters were substantially higher.

Different results were reported by Singh and Agrawal (2007), who found various disturbances in the course of photosynthesis induced by excessive accumulation of heavy metals in plants grown in sewage sludge-treated soil, resulting in deterioration of the volume and quality of the Jerusalem artichoke yield (Fig. 1). In a 3-year experiment on cultivation of the Jerusalem artichoke on soil that had been fallowed for 8 years, Piskier (2009) found that fertilization of the plantation with sewage sludge compost resulted in a significant reduction of the yield of Jerusalem artichoke stems, in comparison with mineral and mixed fertilization. The Jerusalem artichoke cultivated on silty fallow soil treated with sewage sludge did not reach a maximum green biomass yield, which can be even 200 Mg ha^{-1}, as reported by Kowalczyk-Juśko et al. (2012). In this study, the maximum yield (172 Mg·ha^{-1}) was achieved in the sixth year of the study in soil with a 30-cm sewage sludge pad introduced prior to the experiment (Fig. 1).

The energy properties of the Jerusalem artichoke aboveground biomass were analyzed as well. The results of these determinations provide basic information about the structure and performance traits of a given material (fuel). The moisture and ash contents are a measure of the amount of ballast in a sample of a given fuel. Determination of HHV and LHV is the basis for assessment of the quality of a given fuel as an energy source. The mean moisture content in the Jerusalem artichoke aboveground biomass in the analytical state obtained over the 6-year study is presented in Table 4.

From the economic and technological points of view, the lowest possible biomass moisture is advisable. This is directly related to energy inputs required for the elimination of moisture in the combustion process and more efficient combustion (Kloc and Karcz 2013). The level of biomass moisture is mainly influenced by the harvesting date. Typically, samples collected in winter are characterized by higher moisture content than those collected in the summer season (Kloc and Karcz 2013, Maj 2015). Stolarski et al. (2008) found that semi-woody and straw biomass acquired in November exhibited a substantially higher moisture level than that obtained in March. As indicated in the study conducted by Komorowicz et al. (2009) and Wróblewska et al. (2009), the mean moisture content of the Jerusalem artichoke aboveground parts is 8.11%. In turn, Kowalczyk-Juśko (2009) reported a moisture level of 9.7% in the Jerusalem artichoke. In the study conducted by Skonecki et al. (2011), the mean moisture content in Jerusalem artichoke biomass was 8.34%, which was similar to that in the giant miscanthus and significantly lower than that in Virginia mallow and basket willow biomass. It was found in the present study that the aboveground biomass of the Jerusalem artichoke obtained during the 6-year study was characterized by the lowest mean moisture of 8.31% in the control object and increased upon the application of the sewage sludge. The highest value was noted in the plant biomass of plants cultivated on soil treated with the 20-cm thick sewage sludge pad (9.21%). The significance of these differences was confirmed statistically (*p=0.002*) (Tab. 4). Moreover, it was found that the moisture content in the Jerusalem artichoke aboveground biomass exhibited

Table 4. Characteristics of the energy value of the Jerusalem artichoke aboveground biomass in relation to the thickness of the sewage sludge pad (mean from the 6 study years)

Parameter	Sewage sludge pad (cm)	Mean*	Range		SD	V (%)
			min	max		
Moisture content W^a (%)	0	8.31	8.06	8.56	0.25	2.96
	10	8.64	8.35	8.93	0.28	3.23
	20	9.21 [a]	8.86	9.56	0.32	3.74
	30	9.02	8.66	9.38	0.35	3.87
Ash content A^a (%)	0	5.44	4.99	5.89	0.36	6.69
	10	5.35	4.84	5.86	0.41	7.71
	20	6.18 [b]	5.57	6.79	0.51	8.29
	30	5.83	5.24	6.42	0.52	8.99
Higher heating value *HHV* (MJ·kg^{-1})	0	15.41	14.93	15.89	0.41	2.67
	10	15.52	14.99	16.05	0.44	2.80
	20	16.02	15.39	16.65	0.54	3.39
	30	15.95	15.34	16.54	0.52	3.25
Lower heating value *LHV* (MJ·kg^{-1})	0	14.19	13.71	14.67	0.41	2.91
	10	14.29	13.77	14.82	0.43	3.03
	20	14.80	14.17	15.43	0.54	3.66
	30	14.72	14.12	15.32	0.52	3.53

* Legends:
[a] – Statistically significant differences relative to the control soil
[b] – Statistically significant differences relative to the soil treated with the 10-cm sewage sludge pad

low variability in all the experimental objects in each year (V<5%) (Tab. 4). Noteworthy, a 1% increase in the biomass moisture results in a ca. 20% reduction of the calorific value (Postrzednik 2011).

The ash content is one of the biomass parameters. Its value is dependent on, e.g. the harvest date (Stolarski et al. 2008). Pure biomass contains low amounts of ash in the range from 0.5 to 12.5%, and higher values indicate contamination of the raw material (Niedziółka and Zuchniarz 2006). The ash content in non-woody solid biofuels is in the range from 4 to 7% (Komorowicz et al. 2009).

In the present study, the mean ash content in the aboveground biomass of the Jerusalem artichoke (samples in the analytical state) grown on soils with the 10- and 20-cm sewage sludge pads was 5.35% and 6.18%, respectively (Tab. 4). The differences were confirmed statistically ($p=0.025$). The ash content in the other experimental objects did not differ significantly (Tab. 4). The variability of this parameter described by the coefficient of variation (V) was <10% in all the experimental objects in each study year (Tab. 4). Stolarski et al. (2008) reported that the mean ash content in biofuels was 4.72%. In the group of the analyzed plants, the authors found the lowest ash content in the wood of the basket willow variety Sprint (on average 2.23%), and the highest content in the biomass of the cup plant, which was 9.57% in November and 7.0% in March. In turn, Skonecki et al. (2011) reported an ash content of 7.79% in Jerusalem artichoke biomass, which was significantly higher than that in the biomass of the Virginia mallow and basket willow and significantly lower than in the biomass of carex grass. Maj (2015) found that the mean ash content in the Jerusalem artichoke was 12.34% at 11.19% moisture and 14.69% at 9.37% moisture. As reported by Kowalczyk-Juśko (2009), the ash content in the aboveground parts of the Jerusalem artichoke was the highest of all energy crops investigated by the author, i.e. on average 5.1% in the air-dry state and 5.6% in the dry state. Sawicka and Kalembasa (2013) reported a higher mean ash content in the aboveground parts of the *Albik* Jerusalem artichoke than in the *Rubic* variety, i.e. 4.43% and 3.90%, respectively. The results obtained in the present study indicate that the ash content in the aboveground parts of the Jerusalem artichoke did not exceed the typical values noted in non-woody solid biofuels and was lower than the typical content determined for brown coal – ca. 7.60% (Komorowicz et al. 2009, Kowalczyk-Juśko 2017). Nevertheless, as indicated by the relationships concerning biomass combustions analyzed by Postrzednik (2011), the lower ash content in the sample, although theoretically more advantageous, may suggest a necessity of deeper drying of the fuel, as the impact of moisture is greater in that case.

The biomass combustion process is accompanied by emission of heat, whose quantity and quality depend on the biomass type, moisture, and species. The higher heating value (HHV) is one of the basic parameters describing the thermophysical properties of solid biofuels and depending on the moisture content in the sample (Kloc and Karcz 2013). A characteristic feature of this parameter is its generally wide range of values, which is associated with the varied composition of organic matter in the biomass depending on the plant species, growing site, or atmospheric conditions (Postrzednik 2011). The higher heating values (HHV) determined in the aboveground biomass of the Jerusalem artichoke in the analytical state in this study and the results of the lower heating value (LHV) are shown in Table 4. The HHV ranged from 15.41 MJ·kg^{-1} in the control object to 16.02 MJ·kg^{-1} in the object treated with the 20-cm sewage sludge pad. The LHV calculated for the Jerusalem artichoke aboveground biomass was therefore the lowest in the control object (14.19 MJ·kg^{-1}) and increased upon the sewage sludge application, reaching the highest value in the object with the 20-cm pad (14.80 MJ·kg^{-1}). However, these differences were not confirmed statistically. With the exception of the object treated with the 30-cm sewage sludge pad, the lowest HHV and LHV value was recorded in 2011 and the maximum value was observed in 2010. Additionally, the values of these parameters exhibited low variability (V<5%) in all the experimental objects (Tab. 4).

The HHV is significantly correlated with the moisture content in the biomass sample. As reported by Maj (2015), the HHV of Jerusalem artichoke biomass with a moisture level of 11.9% is 14.22 MJ·kg^{-1}, whereas the values of this parameter at the 9.37% content is 14.69 MJ·kg^{-1}, which is consistent with the results obtained in this study.

It was reported in previous studies that the LHV usually ranged from 6–8 MJ·kg^{-1} in biomass dried to a moisture level of 50–60% through 15–17 MJ·kg^{-1} in biomass dried to 10–20% moisture to as much as 19 MJ·kg^{-1} in the case of completely dried biomass (Niedziółka and Zuchniarz 2006). For comparative purposes, the LHV of biomass is usually assumed to be 15 MJ·kg^{-1} (Postrzednik 2011). In a group of compared plants, Komorowicz et al. (2009) found that the Jerusalem artichoke was characterized by the lowest LHV, i.e. on average 16.53 MJ·kg^{-1}. The results obtained in this study demonstrate a lower value of this parameter, which is associated with the higher ash content and the higher moisture value in the Jerusalem artichoke biomass, in comparison to the values reported by the authors mentioned above.

Conclusions

1. The yield of the aboveground biomass of the Jerusalem artichoke (*Helianthus tuberosus* L.) increased in relation to the thickness of the sewage sludge pads used. The mean yield of the Jerusalem artichoke biomass ranged from 21.2 to 99.4 Mg kg^{-1}. The Jerusalem artichoke cultivated for 6 years on the silty fallow soil with sewage sludge exhibited significant green biomass production potential, which increased over the study years.
2. The aboveground biomass of the Jerusalem artichoke (*Helianthus tuberosus L.*) grown in the presence of the sewage sludge was characterized by generally favorable parameters of biofuels, such as low moisture and ash contents.
3. The higher heating value (HHV) and lower heating value (LHV) of the Jerusalem artichoke aboveground biomass did not depend on the thickness of the applied sewage sludge pads. However, there was a slight increasing trend in these parameters for 10 and 20 cm pads.
4. The LHV of the biomass of the Jerusalem artichoke (*Helianthus tuberosus L.*) cultivated in sewage sludge-soil was slightly lower than the mean LHV (15 MJ·kg^{-1}) generally adopted for biomass.
5. Technologies associated with cultivation of the Jerusalem artichoke (*Helianthus tuberosus L.*) based on the management of sewage sludge improve the condition of poor-quality soils, in particular fallowed soils, and restore their production values (revitalization).
6. The natural disposal of sewage sludge allows for the secondary utilization of biogenic components and organic matter from these high-nuisance wastes and preservation of mineral resources used for the production of mineral fertilizers as well as non-renewable energy resources. However, due to the large amount of contaminants, such as, e.g. heavy metals introduced into the soil, it is necessary to determine their impact on the soil environment. These issues will be presented in the next publication.

References

Chen, L., Long, X., Zhang, Z., Zheng, X., Rengel, Z. & Liu, Z. (2011). Cadmium accumulation and translocation in two Jerusalem Artichoke (Helianthus tuberosus L.) cultivars, *Pedosphere*, 21(5), pp. 573–580.

Chołuj, D., Podlaski, S., Wiśniewski, G. & Szmalec, J. (2008). A comprehensive assessment of biological suitability seven plant species used for energy purposes, *Studia i Raporty IUNG-PIB*, 11, pp. 81–99. (in Polish)

Czeczko, R. (2011). Comparison of degree of hydration of different parts of Helianthus tuberosus in terms of their usefulness as biofuel, *Ochrona Środowiska i Zasobów Naturalnych*, 49, pp. 521–524. (in Polish)

Decer, S.R., Sheehan, J., Dayton, D.C, Joseph, J., Bozell, J.J, Adney, W.S., Hames, B., Thomas, S.R., Bain, R.L., Czernik, S., Zhang, M. & Himmel, M.E. (2012). Biomass conversion, In: *Handbook of Industrial Chemistry and Biotechnology*, Kent, J.A. (Ed.) Springer Science + Business Media, New York 2012, pp. 1249–1322.

Directive 2008/98/EC of the European Parliament and the Council of 19 November 2008 on waste and repealing certain directives (*Waste framework directive, R1 formula in footnote of attachment II*).

Gizińska-Górna, M., Czekała, W., Jóźwiakowski, K., Lewicki, A., Dach, J., Marzec, M., Pytka, A., Janczak, D., Kowalczyk-Juśko, A. & Listosz, A. (2016). The possibility of using plants from hybrid constructed wetland wastewater treatment plants for energy purposes, *Ecological Engineering*, 95, pp. 534–541.

Gizińska-Górna, M., Janczak, D., Kowalczyk-Juśko, A, Jóźwiakowski, K., Lewicki, A., Marzec, M., Pytka, A., Czekała, W. & Listosz, A. (2017). The parameters of energy biomass plants from hybrid constructed wetland wastewater treatment plants. 3rd International Conference on Energy and Environment: bringing together Engineering and Economics, Porto, Portugal, pp. 97–102.

Faber, A., Stasiak, M. & Kuś, J. (2007). Preliminary evaluation of productivity of the selected energy crops, *Postępy w Ochronie Roślin*, 47(4), pp. 339–346. (in Polish)

Kacprzak, M., Neczaj, E., Fijałkowski, K., Grobelak, A., Grosser, A., Worwag, M., Rorat, A., Brattebo, H., Almas, A. & Singh, B.R. (2017). Sewage sludge disposal strategies for sustainable development, *Environmental Research*, 156, pp. 39–46.

Kaniuczak, J., Niemiec, W., Właśniewski, S., Zamorska, J., Jasiński, T. & Hajduk, E. (2005 a). Selected properties of sewage sludge applied for agromelioration of sandy fallow land, in: *Chosen aspects of organic wastes utilizing and energetic willow biomass production*. (Eds.)

Kaniuczak, J., Hajduk, E., Błażej, J., Niemiec, W. & Jasiński, T. (2005 b). Selected physico-chemical and chemical properties of sandy fallow land before agromelioration with sewage sludge, in: *Chosen aspects of organic wastes utilizing and energetic willow biomass production,* Kaniuczak, J., Kostecka, J. & Niemiec, W. (Eds.). 2005, pp. 79–100. (in Polish)

Kaniuczak, J., Hajduk, E., Zamorska, J. & Ilek, M. (2009). Characteristic of investigated sewage sludge on score usability to natural utilization, *Zeszyty Naukowe Polskiego Towarzystwa Inżynierii Ekologicznej. i Polskiego Towarzystwa Gleboznawczego z siedzibą w Rzeszowie*, 11, pp. 89–94. (in Polish)

Kloc, J. & Karcz, J. (2013). The properties of biomass used in the power industry, *Inżynieria i Aparatura Chemiczna*, 52, 5, pp. 435–436. (in Polish)

Kołodziej, B., Wiśniewski, J. & Bielińska, E. (2010). The effect of using sewage sludge in Jerusalem artichoke culture for energetic purposes, *Zeszyty Problemowe Postępów Nauk Rolniczych*, 556, pp. 407–413. (in Polish)

Komorowicz, M., Wróblewska, H. & Pawłowski, J. (2009). Chemical composition and energetic properties of biomass from selected renewable resources, *Ochrona Środowiska i Zasobów Naturalnych*, 40, pp. 402–410.

Koncewicz-Baran, M., Gondek, K. & Korol, J. (2014). Influence of biological and thermal transformed sewage sludge application on manganese content in plants and soil, *Inżynieria Ekologiczna*, 37, pp. 17–30. (in Polish)

Kowalczyk-Juśko, A. (2003). Jerusalem artichoke, in: *Energetic Plants*, Kościk, B. (Ed.) Wydawnictwo Akademii Rolniczej w Lublinie, Lublin 2003, pp. 96–106. (in Polish)

Kowalczyk-Juśko, A. (2009). Ash from different energy crops, *Proceedings of ECOpole*, 3, 1, pp. 159–164. (in Polish)

Kowalczyk-Juśko, A., Jożwiakowski, K., Gizińska, M. & Zarajczyk, J. (2012). Jerusalem artichoke (*Helianthus tuberosus* L.) as renewable energy raw material. TEKA, *Commission off Motorization and Energetics in Agriculture*, 12, 2, pp. 117–121.

Kowalczyk-Juśko, A., Kupryaniuk, K., Oniszczuk, T., Janczak, D., Smurzyńska A., Jóźwiakowski, K. & Czechlowski, M. (2017). Applicability of Jerusalem artichoke in agricultural biogas plants as maize silage alternative. 3rd International Conference on Energy and Environment: bringing together Engineering and Economics, Porto, Portugal, pp. 91–96.

Kowalczyk-Juśko, A. (2017). The influence of the ash from the biomass on the power boiler pollution, *Journal of Ecological Engineering*, 18, 6, pp. 200–204.

Krzywy, E., Wołoszyk, Cz., Iżewska, A. & Krzywy-Gawrońska, E. (2011). Natural management of sewage sludge, in: *Natural Waste Use. Theoretical and practical basics*, Baran, S., Łabętowicz, J. & Krzywy, E. (Eds.), Powszechne Wydawnictwo Rolnicze i Leśne, Warszawa 2011, pp. 212–246. (in Polish)

Law Gazette 2002 no 134 item 1140. Regulation of the Minister of the Environment of 1 August 2002 on municipal sewage sludge.

Lisowski, J. & Porwisiak, H. (2010). Influence of sludge fertilization on yield of Miscanthus (Miscanthus giganteus), *Fragmenta Agronomica*, 27(4), pp. 94–101. (in Polish)

Maj, G. (2015). Diversification and environmental impact assessment of plant biomass energy use, *Polish Journal of Environmental Studies*, 24, 5, pp. 2055–2061.

Niedziółka, I. & Zuchiniarz, A. (2006). An energetic analysis of selected plant biomass samples, *Motrol Motorization and Power Industry in Agriculture*, 8A, pp. 232–237. (in Polish)

Niemiec, W., Sobolewska, P. & Jasiński, T. (2007). On some selected ways of natural utilisation of sewage sediment, *Zeszyty Naukowe Politechniki Rzeszowskiej*, 240, *Budownictwo i Inżynieria Środowiska*, 42, pp. 63–71. (in Polish)

Polish Standards (1980), *Solid mineral fuels – Determination of moisture content*, PN-80/G-04511. (in Polish)

Polish Standards (2002a), *Solid mineral fuels – Determination of ash content*, PN-80/G-04512: 1980/ Az1 (2002). (in Polish)

Polish Standards (2002b), *Solid mineral fuels – Determination of gross calorific value by the bomb calorimetric method, and calculation of net calorific value*, PN-ISO 1928 (2002). (in Polish)

Piskier, T. (2009). Jerusalem artichoke energy potential, *Problemy Inżynierii Rolniczej*, 1, pp. 133–136. (in Polish)

Postrzednik, S. (2011). Analysis of parameters influencing the energetic usefulness of fuels, *Energetyka,* 7 (685), pp. 395–398.

Prośba–Białczyk, U. (2007). Productivity of Jerusalem Artichoke (Helianthus tuberosus L.) cultivated without fertilization, *Fragmenta Agronomica*, XXIV, 4(96), pp. 106–112.

Rodrigues, M.A., Sousa, L., Cabanas, J.E. & Arrobas, M. (2007). Tuber yield and leaf mineral composition of Jerusalem artichoke (Helianthus tuberosus L.) grown under different cropping practices, *Spanish Journal of Agricultural Research*, 5(4), pp. 545–553.

Sawicka, B. & Kalembasa, D. (2008). Variability in macroelement content in tubers of *Halianthus tuberosus* L. at different nitrogen fertilization levels, *Acta Scientarium Polonorum, Agricultura*, 7(1), pp. 67–82. (in Polish)

Sawicka, B. & Kalembasa, D. (2013). Assessment of the chemical composition of Jerusalem artichoke (Helianthus tuberosus L.) as energy feedstock*, Ecological Chemistry and Engineering A*, 20 (6), pp. 689–699.

Singh, R.P. & Agrawal, M. (2007). Effects of sewage sludge amendment on heavy metal accumulation and consequent responses of Beta vulgaris plants, *Chemosphere*, 67, 11, pp. 2229–2240.

Skonecki, S., Gawłowski, S., Potręć, M. & Laskowski, J. (2011). Physical and chemical properties of plant materials used for biofuels production, *Inżynieria Rolnicza*, 8(133), pp. 253–260. (in Polish)

Skowera, B. & Puła, J. (2004). Pluviometric extreme conditions in spring season in Poland in the years 1971–2000, *Acta Agrophisica,* 3(1), 171–177. (in Polish)

Stolarski, M., Szczukowski, S. & Tworkowski, J. (2008). Biofuels from biomass of perennial energy crops, *Energetyka*, 1 (643), 61, pp. 77–80. (in Polish)

Tworkowski, J. (2012). General characteristics of energy crops, In: *Perennial Plants Energy*, Szczukowski, S. (Ed.), MULTICO Oficyna Wydawnicza, Warszawa 2012, pp. 6–9. (in Polish)

Wang, Ch., Hu, X., Chen, M. & Wu, Y. (2005). Total concentrations and fractions of Cd, Cr, Pb, Cu, Ni and Zn in sewage sludge from municipal and industrial wastewater treatment plants, *Journal of Hazardous Materials,* B119, pp. 245–249.

Wang, X., Chen, T., Ge, Y. & Jia, Y. (2008). Studies on land application of sewage sludge and its limiting factors, *Journal of Hazardous Materials*, 160, pp. 554–558.

Wróblewska, H., Komorowicz, M., Pawłowski, J. & Cichy, W. (2009). Chemical and energetical properties of selected lignocellulosic raw materials, *Folia Forestalia Polonica*, Series B, Issue 40, pp. 67–78.

Wpływ osadów ściekowych na plonowanie i wartość energetyczną nadziemnej biomasy topinamburu (*Helianthus tuberosus* L.)

Streszczenie: Proces oczyszczania ścieków nieodzownie związany jest z powstawaniem osadów ściekowych, które ze względu na swoje właściwości muszą być odpowiednio zagospodarowane. W pracy przedstawiono możliwość zastosowania osadów ściekowych w uprawie topinamburu, jako rośliny energetycznej. W doświadczeniu zastosowano osady ściekowe w formie wkładek o zróżnicowanej miąższości, aplikowane jednorazowo pod poziom darniowo-próchniczy gleby pyłowej. Analizy fizykochemiczne i chemiczne osadów ściekowych oraz gleby, na której zostały zastosowane, przeprowadzono zgodnie z wytycznymi uwzględnionymi w przepisach prawnych. Rezultaty otrzymanych wyników badań porównywano z kontrolą-bez wkładki osadów ściekowych. W pracy przedstawiono wpływ osadów ściekowych na plon oraz parametry energetyczne (zawartość wilgoci, popiołu, HHV, LHV) nadziemnej biomasy topinamburu. Zawartość wilgoci, popiołu oraz HHV i LHV, jako parametrów charakteryzujących biopaliwa, oznaczono zgodnie z Polskimi Normami. Stwierdzono, że plon nadziemnej biomasy topinamburu wzrastał wraz z miąższością zastosowanych wkładek osadów ściekowych, a potencjał plonotwórczy tej rośliny wzmagał się w latach badań. Ponadto stwierdzono, że nadziemna biomasa topinamburu charakteryzowała się generalnie korzystnymi parametrami energetycznymi, charakteryzującymi biopaliwa, takimi jak m.in. niska zawartość wilgoci czy popiołu. Na podstawie przeprowadzonych badań stwierdzono, że zastosowanie osadów ściekowych może być dobrą w stosunku do nawożenia mineralnego alternatywą, w nawożeniu roślin energetycznych.