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JERUSALEM ARTICHOKE (*HELIANTHUS TUBEROSUS* L.) AS ENERGY RAW MATERIAL

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Jerusalem artichoke is suitable for use in biorefineries due to the very high biomass production and low soil, climate and cultivation requirements. Tubers of this species can be used for the production of methane fermentation or bioethanol. The aboveground part can be used for the production of biomethane, as well as in the direct combustion process or for the production of briquettes and pellets. Of the cultivars tested, Albik and Violet de Rennes proved to be the most useful for energy purposes. An important advantage of Jerusalem artichoke is its resistance to adverse climatic conditions (drought, frost), resistance to diseases and pests and the possibility of self-renewal.

Keywords: *Jerusalem artichoke, energy efficiency, heating efficiency, cultivars, biogas, bioethanol*

INTRODUCTION

Renewable energy sources (RES) are playing an increasingly important role in Europe's energy balance. One of the most important energy plants is Jerusalem artichoke, characterized by low climate and soil requirements, high production potential and multifunctionality. Jerusalem artichoke (*Helianthus tuberosus* L.) is an herbaceous species belonging to the Asteraceae family, resistant to most pests and diseases, resistant to frost, drought and therefore can be grown on most soils with a small amount of fertilizer. The climate in the countries of Central and Northern Europe ranges from moderate in the south to subarctic in the north (Bergh et al., 2003). Jerusalem artichoke can be grown commercially in colder regions, even in the Nordic countries (Slimestad et al., 2010). Due to the rich chemical composition, high ability to bind solar energy and transform it into an organic substance, Jerusalem artichoke can partially or completely replace the shortage of energy materials. *Helianthus tuberosus* plants underground produce tubers rich in inulin (14-25% fresh weight), while above ground they produce significant air biomass and can grow up to 3 m in height (Nottingham, 2007a). Potential yields of fresh biomass are over 100 tons per hectare of area ($t{\cdot}ha^{-1}$) per year, including about 40 $t{\cdot}ha^{-1}$ fresh tubers and over 60 $t{\cdot}ha^{-1}$ fresh lignocellulosic air biomass (Sawicka and Skiba 2007, Sawicka 2016). Currently, Jerusalem artichoke is grown primarily for the production of inulin and used as dietary fiber in food production (Flamm et al., 2001). Inulin is a linear polysaccharide consisting of d-fructose bound by (2 → 1), which is terminated by a d-glucose molecule bound by fructose (2 → 1) (Barclay and Ginic-Markovic, 2010). Biomass from the Jerusalem artichoke plantation can be used to produce electricity or heat, as well as to produce liquid or gaseous fuel. Based on the existing Jerusalem artichoke plantations, you can create local, dispersed energy centers located in small towns – instead of district heating based mainly on coal. Creating a local biomass system (electricity + heat) is very economically efficient (90% efficiency), fully ecological and activating rural areas by creating new jobs, full use of land and circulation of capital in the local system, which creates a local "circle" economy" (Gunnarsson et al. 2014, Sawicka 2016). When using large-scale biomass in local energy centers, the most reasonable form, for economic reasons, should be unprocessed biomass transported over short distances (50 km).

The traditional use of Jerusalem artichoke tubers is to use them as animal feed or for the production of products such as purified inulin, syrup with high fructose content or for fermentation into bioethanol or other biochemical substances through the use of microorganisms (Li et al., 2013, Sawicka 2016). The potential use of Jerusalem artichoke for the sustainable production of biofuels and biochemistry does not interfere with food production, because it is considered a non-food plant due to poor inulin digestibility, compared to other carbohydrates (Cheng et al., 2009, Zhuang et al., 2011, Li et al., 2013, Gunnarsson et al. 2014, Sawicka 2010, 2016), because only few microorganisms produce inulinase – an enzyme capable of hydrolyzing inulin, the stage of hydrolysis required to break down inulin into its monosaccharides: fructose and glucose before fermentation (Sangeetha et al.., 2005). The aerial part of *Helianthus tuberosus*, depending on the chemical composition, lignocellulosic, can be used as a solid biofuel for the production of heat and energy through combustion, as well as for the production of transport biofuels (biogas, bioethanol) or for biochemical production (Menon and Rao, 2012; Sheldon, 2011, Philp et al., 2013). Second-generation bioethanol production from lignocellulosic raw materials has already been widely evaluated and studied in recent decades (Suurs and Hekkert, 2009). Numerous plant biomass raw materials with high cellulose content (30-45% of dry matter) were compared, e.g. wheat, rice, corn or cane straw (Carroll and Somerville, 2009, Sawicka et al., 2018). The lignocellulose composition of Jerusalem artichoke is characterized by a lower content of cellulose and hemicellulose than other preferred raw materials for the production of bioethanol. However, by examining the genetic variability of cellulose and hemicellulose sources, as well as the impact of harvesting time on biomass composition, it is possible to determine the most optimal, appropriate plant material and harvesting date to obtain high cellulose content in aboveground parts (> 30%). All potential products should be considered in the concept of biorefineries with Jerusalem artichoke. It was found that the protein content in both air and bulbous biomass exceeds 10% of dry matter (Kosaric et al., 1984, Li et al., 2013), and in the concept of the biorefinery this protein can be extracted or hydrolyzed to its amino group with acid components for numerous nutritional applications (Young and Pellett, 1994). Some aboveground biomass components, such as pectin, are too difficult to extract in polymeric form from lignocellulosic biomass and therefore have no applications other than anaerobic digestion. Recent findings suggest that uronic acids can be fermented by metabolically modified yeast or E. coli to ethanol or other fermentation products (Edwards and Doran-Peterson, 2012, Bont and Teunissen, 2013). It has been found that the content of uronic acid in the aboveground biomass of Jerusalem artichoke exceeds 10% of dry matter (Gunnarson et al., 1985, Lindberg et al., 1986), therefore the fermentability of uronic acids would increase the potential of bioethanol in this type of biomass (Dwards and Doran-Peterson, 2012). A lot of research has been carried out (Gunnarson et al., 2014, Kosaric et al., 1984, Matías et al., 2013, Slimestad et al., 2010) on the evaluation of aboveground biomass yield and tubers of different Jerusalem artichoke cultivars and comparing their chemical composition. However, detailed changes in the composition of aboveground biomass and tubers during cultivation in central and northern Europe are not known. Knowledge about changes in the composition of Jerusalem artichoke biomass will be used to determine the optimal harvest period depending on the intended application. This species is increasingly sought after and popular. Therefore, the research carried out evaluated the potential of Jerusalem artichoke biomass, its calorific and energy value, and estimated the potential for bioethanol and biogas production.

MATERIAL AND METHODS

The research was carried out in 2015-2017 in Poland (51°38′N, 22°54 E) on lessive, slightly acidic soil (WRB 2014). The experiment was carried out using the randomized block method, in triplicate. Four cultivars were tested, including two Polish: Albik, Rubik, French: Violet de Rennes and one Lithuanian: Sauliai. The plot area to be harvested was 40 m^2. The experience was set up annually, in mid-April, with 40000 cast pcs. ha^{-1}. All agrotechnical operations were carried out in accordance with the requirements of this species. The collection of aboveground mass was carried out at the end of the last decade of October. At the time of harvest, the yield of fresh weight of the aerial parts was determined and samples of the aerial parts were taken from 20% of plants in each plot to determine dry matter content and calorific value. The moisture content of the raw material was determined by the drying-weighing method. The crushed biomass was dried to constant weight at 60°C and then for 1 hour at 105°C. The heat of combustion and the calorific value of the aerial parts of Jerusalem artichoke were determined in accordance with PN-ISO 1928: 2002. The measurements were made in six replications. The tested samples were dried to the same humidity in order to obtain comparable calorific values, and the adopted test method was to be used only for comparative purposes of the obtained results. The calorific value of the material under test was calculated on the basis of the combustion heat, humidity, hydrogen and ash content in the analytical state (moisture content of the material after preparation of the sample for analysis) and in the working state (humidity of the material as finished fuel) and dry ash. The heat of biomass combustion was followed by Sawicka (2018). Tubers were harvested in early spring. After harvest, tuber yield, dry matter content and tubular bioethanol and biomethane production indicators were determined according to Kotowski (2007).

The soil pH was determined potentiometrically. Analysis of macroelements was performed using the atomic absorbtion spectrometry (ASS). Humus content was determined by the Tiurin method modified by Simakow (Wójcikowska-Kapusta, Niemczuk, 2006). In soil, the following was determined: granulometric composition - areometric method. Soil analyzes were carried out in accordance with ISO 10694: 1995.

Statistical treatment of the results was performed using ANOVA analysis of variance. The significance of sources of variation was tested by the Fischer-Snedecor F test, and $LSD_{0.05}$ was assessed by the Tukey test.

The weather pattern in the years of the study was varied, as illustrated in Table 1. In 2015, the first half of the growing season was moist and warm, June, August and September – with poor drought, and October, which determined the fall of the aboveground mass – wet. In 2016, the beginning of vegetation (April-May) was moist and cool, June and July – dry, in August and October it was dry, and in September there was extreme drought. In 2017, the May-June period turned out to be wet and cool, and the remaining months, except August – were dry or dry and warm. In all years, the most optimal conditions, in terms of temperature and humidity, were in April and May, while extremely dry conditions occurred in September (table 1).

Table 1. Sielianinov's coefficient values (k) according to meteorological station in Uhnin

Year	Month								Mean
	IV	V	VI	VII	VIII	IX	X	XI	
2015	2.2	1.4	0.9	1.3	0.6	0.5	2.4	1.3	1.3
2016	4.1	1.3	0.9	0.5	1.1	0.2	1.3	1.4	1.4
2017	0.7	1.9	1.9	0.7	1.2	0.3	0.2	1.0	1.0
Mean	2.3	1.5	1.2	0.8	1.0	0.3	1.3	1.1	1.2

Ranges of values of Sielianinov index were classified according to Skowera et al. (2014) as: extremely dry − $k \le 0.4$; very dry − $0.4 < k \le 0,7$; dry − $0.7 < k \le 1.0$; fairly dry − $1.0 < k \le 1.3$; optimum − $1.3 < k \le 1.6$; fairly humid − $1.6 < k \le 2.0$; wet − $2.0 < k \le 2.5$; very humid − $2.5 < k \le 3.0$; extremely humid − $k > 3.0$.

The field experiment was carried out on soils whose humus surface levels were built of light sandy formations - light loamy and / or strong loamy sands (WRB 2014) with acidic or slightly acidic reaction (pH 5.1-5.9) and average carbon content in organic compounds. The abundance of these soil levels in available phosphorus and potassium was high to very high, while in magnesium – low to high (table 2).

Table 2. Characterization of soils according to agronomic categories

Years	Percentage content of fraction in diameter, mm			Soil texture (according to PTG)	Organic matter ($g \cdot kg^{-1}$)	pH_{KCl}
	1-0,1	0,1-0,02	<0,02			
2015	57	24	19	pgm	15.3	5.5
2016	62	25	13	pgl	15.9	5.9
2017	65	21	14	pgl	12.4	5.1
Mean	61.3	23.3	15.3	-	14.5	5.5

pgm – strong loamy sand; pgl – loamy sand

RESULTS AND DISCUSSION

The average dry matter yield was at the level of 22.3 t · ha^{-1} and was significantly diversified, both by cultivars and years of research (Table 3). The Albik cultivar yielded a 18.2% higher dry matter yield than the Sauliai cultivar, 11.7% higher than the Rubik cultivar and 10.1% higher than the Violet de Rennes cultivar (Table 3).

Table 3. Dry matter yield and electricity and calorific value of Jerusalem artichoke depending on the cultivars, and years

Experimental Factors		Yield of dry matter ($t \cdot ha^{-1}$)	The value of electricity ($MWh \cdot ha^{-1}$)	Calorific value ($GJ \cdot ha^{-1}$)
Cultivars	Albik	24.8	44.1	387.0
	Rubik	21.9	38.9	341.4
	Violet de Rennes	22.1	39.4	345.0
	Sauliai	20.3	36.2	317.1
	LSD p0.05	1.1	2.6	17.4
Years	2015	25.1	44.7	391.8
	2016	19.1	34.0	297.9
	2017	22.7	40.4	353.7
	LSD $p_{0.05}$	0.9	2.0	13.1
Mean		22,3	39.7	347.8

Sauliai cultivar defined in Lithuania as medium late (Baronytė 2013), in Poland it was characterized by early flowering and the end of the vegetation period 3-4 weeks earlier than other cultivars tested in the experiment. Slimasted et al. (2010) in Norway, they proved that late cultivars had the most preferred tuber shape, but were characterized by low energy efficiency, while the highest yield (28.7 t ha^{-1}) and the number of tubers per plant was obtained in early cultivars. According to Piskier (2009), the average yield of energy obtainable from Jerusalem artichoke is 88.4 GJ · ha^{-1} and is not dependent on the cultivar. The high share of varietal variation in own and other authors' research (Kuś et al. 2006, Skiba 2015, Lakić et al. 2018) in the overall dry matter yield variability indicates a potential possibility of improving this characteristic through selection.

Habitat conditions, irrespective of experiment factors, significantly shaped dry matter yield and energy indicators (Table 3). The highest dry matter yield of aerial parts and the highest values of energy indicators were obtained in the most favorable cultivation of Jerusalem artichoke, moist and warm 2015, while the lowest values were obtained in 2016, with a long dry period during the most intense period of plant growth. The influence of climatic conditions on the yield is confirmed by the works of Kuś et al. (2006), Piskier (2009), Sawicka (2010, 2016), Sawicka and others (2009, 2018), Skiba (2015). The heat of combustion of *H. tuberosus* above ground mass, depending on the cultivar, ranges from 18.1 to 26.1 GJ t^{-1}. Assuming that, on average, 1 ton of dry matter is equivalent to only 15 GJ of chemical carbon energy content (at 20% above-ground moisture), productivity from 1 hectare can be calculated. The calorific value of the aerial parts of Jerusalem artichoke was on average 347.8 GJ · ha^{-1}, while the energy value of *H. tuberosus* aboveground mass was 39.7 MWh·ha^{-1}, and depending on the cultivar ranged from 36.2 to 44.0, and depending on meteorological conditions from 34.0 to 44.7 MWh·ha^{-1}. According to Niedziółka (2006), the energy value, as one of the basic thermophysical parameters of solid biofuels, ranges from 6-8 MJ·kg-1 for Jerusalem artichoke biomass with humidity 50-60% to 15-17 MJ·kg^{-1} for dried biomass, whose humidity is 10-20%, up to 19 MJ·kg^{-1} for completely dried biomass. Genetic features of the studied cultivars significantly shaped energy value and calorific value. The most of these units was produced by Albik, while the least by Sauliai. Rubik and Violet de Rennes cultivars produced significantly greater energy and heating value than the Sauliai cultivar, and were also homogeneous in this characteristic. Genetic variability, according to Sawicka and Michałek (2005), Gunnarsson et al. (2014), Skiba (2015) is a factor that differentiates not only the yield of dry matter of plants, but also its derivatives. Meteorological conditions in the years of the research also modified both the dry matter yield of the above-ground parts of Jerusalem artichoke as well as its energy and heating value. The highest value of this feature was obtained in the optimum in terms of thermal humidity in 2015, and the least in the dry, 2016 (Table 3). The dependence of the raw material productivity for obtaining renewable energy on environmental conditions is confirmed by Sawicka and Michałek (2005), Sawicka (2010, 2016), Sawicka and Kalembasa (2013), Gunnarsson et al. (2014), Skiba (2015). According to Sawicka (2016), from 1 hectare, on better soils, approximately 30 t·ha^{-1} dry bulbous sunflower mass per year is obtained. On weaker soils, on larger areas and in worse production conditions, production from 1 ha may decrease to 10-20 tonnes of dry matter (Kuś et al. 2006, Piskier 2009). In the conducted tests, an average of 22.3 tons of dry aboveground mass was obtained, which, calculated on the heat of combustion, gave an annual productivity of 1 hectare of Jerusalem artichoke in the amount of 347 GJ·ha^{-1}.

The average dry tuber yield in the experiment was 10.6 t·ha^{-1}, and depending on the cultivar – from 9.5 to 12.4 t·ha^{-1}. Albik turned out to be the most fertile, while Violet de Rennes was the least fertile; with the Rubik cultivar being homogeneous in this respect. The Lithuanian cultivar Sauliai came in second in the ranking of cultivars and yielded significantly higher than the Rubik and Violet cultivars of De Rennes (Table 4). The volume of calculated biomethane and bioethanol production indicators showed similar dependence on varietal characteristics as tuber dry matter yield. Albik turned out to be the one with the highest biomethane and bioethanol productivity, while the one with the lowest – Violet de Rennes. The Rubik cultivar proved to be homogeneous in this respect (Table 4).

Table 4. Tuber dry matter yield and bioethanol and biogas efficiency from Jerusalem artichoke tubers (2015-2017)

Cultivars	Yield of dry matter of tubers (t·ha^{-1})	Production of biomethane m^3·ha^{-1}	Production of bioethanol (l·ha^{-1})
Albik	12.4	6944	4216
Rubik	9.6	5393	3274
Violet de Rennes	9.5	5326	3233
Sauliai	10.8	6037	3665
LSD $p_{0.05}$	0.6	326	198
Mean	10.6	5925	3597

Biogas is the most effective biofuel in terms of production efficiency per hectare of energy crops. Not only tubers, but also fresh mass of aerial parts, collected several times during the growing season, can be used as a raw material for biogas production, both after wilting and ensilage (Grzybek 2007). Johannsen et al. (2015) believe that Jerusalem artichoke is an excellent plant for biorefineries, due to high biomass production and limited cultivation requirements. In their opinion, the potential possibilities of Jerusalem artichoke as a plant for the biorefinery and its products are high, as carbohydrates in tubers have the potential to produce platform chemicals, e.g. succinic acid. Jerusalem artichoke is mentioned as one of the most efficient species for the production of bioethanol. The high content of inulin in tubers *Helianthus tuberosus* easily hydrolyzing to includes and d-fructose puts it in a series of valuable raw materials for alcoholic fermentation, which is biologically simpler than the fermentation used for starch raw materials (Sirisansaneeyakul et al. 2007). According to Sawicka and Skiba (2009), from 1 ha of Jerusalem artichoke, 8-9 liters of ethanol can be obtained at spring harvest. 100 kg^{-1} tubers. Only about 3.8 liters are obtained from the same number of tubers with autumn equipment. Research (Chabbert et al. (1983), Nakamur et al. (1996), Curt et al. (2006), Kays and Nottingham (2007b), Godin et al. (2013), Sawicka (2010), Sawicka et al. (2016, 2017) have shown that fermenting tubers of Jerusalem artichoke can spend from 3060 to 11,000 l·ha^{-1} bioethanol, which is considered high yield in comparison with e.g. 6470 l·ha^{-1} from sugar cane (Goldemberg and Guardabassi, 2010, Gunnarsson et al. 2014), or 4180 l·ha^{-1} from corn (Goldemberg and Guardabassi, 2010).

Jerusalem artichoke stalks are also used in the spirits industry. 100 kg of spirit can be obtained from 100 kg of aerial parts. On average, 2834 dm of bioethanol can be obtained from 1 ha of sunflower, using stems and 7554 l from tubers (Sawicka and Skiba 2007, Skiba & Sawicka 2008). Butanol and dimethylfuran can also be obtained from biomass of this species. Attempts have also been made to use *Helianthus tuberosus* for the production of methyl and butylacetyl alcohol (Sirisansaneeyakul et al. 2007). On the suitability of plants for intensive cultivation for bioenergy purposes, according to Bartoszewicz-Burcza (2012), Małuszyńska and others (2013), Johannsen et al. (2015) and Sawicka (2016), decide: energy efficiency of the crop, i.e. the ratio of energy contained in biomass to the energy needed to produce it, as well as the type of biomass carbohydrates (lignin-cellulose or starch), due to the different efficiency of the thermochemical process or biological processing (Sawicka and Michałek 2005, Barbaś and Sawicka 2008). Jerusalem artichoke, as an energy plant, generates low production costs and can be used for the production of biofuels or directly used for combustion (heating or electricity production). Due to the rich chemical composition, the large capacity of binding solar energy and converting it into an organic substance, Jerusalem artichoke may partially or completely replace the shortage of energy materials, as well as allow the extension of the range of manufactured products (Kuś et al. 2006, Czeczko 2011, Danilčenko et al. 2017. Sawicka 2016, 2018).

CONCLUSIONS

1. Due to the high yielding potential and versatile utility value of biomass, Jerusalem artichoke has a chance to become an alternative source of energy. Tubers can be used for the production of bioethanol or for methane fermentation; the aboveground part can be used for the production of biomethane, in the direct combustion process or for the production of briquettes and pellets. The estimated biomass potential of this species indicates the existence of significant biofuels resources, which can be an important element in Poland's fuel and energy balance.
2. The late Albik cultivar showed the highest yield of biomethane and bioethanol from tubers, while the lowest - Rubik and Violet de Rennes. Albik and Violet de Rennes were characterized by the highest dry matter yield and the highest energy and heating value of aerial parts, the other cultivars proved to be less useful for energy purposes.
3. The yielding potential of *Helianthus tuberosus* can be increased through the use of more efficient cultivars, allowing to obtain a high level of tuber yields and above-ground mass and their high energy value. Cultivars with a high yield of dry matter and inulin should be preferred for this purpose, which will allow to obtain a higher than average domestic yield of bioethanol and biogas yield, especially on weak soils.
4. Climatic conditions determined the yield of dry matter of above-ground parts as well as energy indicators. Optimal supply of plants with water was conducive to obtaining a large dry matter yield and high energy value, while dry or dry periods did not favor achieving high levels of these indicators.

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