Acta Sci. Pol., Agricultura 13(3) 2014, 67-80

YIELD AND ENERGY EFFICIENCY OF BIOMASS PRODUCTION OF SOME SPECIES OF PLANTS GROWN FOR BIOGAS

Władysław Szempliński, Adam Parzonka, Tomasz Sałek
University of Warmia and Mazury in Olsztyn

Abstract. The most often used substrate in agricultural biogas plants is maize. Due to an increase in the area of maize acreage and the necessity of use proper crop rotation in the plant cultivation, alternative raw materials should be looked for. Apart from the high biomass yield, alternative plants for biogas production should be characterized by a favourable energy efficiency index. The favourable value of this index can be obtained by reduction of energy outlays incurred for biomass production and high energy efficiency in the yield. The aim of this study was to compare the yield and energy efficiency of biomass production of some species of plants grown under different conditions of energy outlays. The study was conducted in the years 2009-2011 at the Production and Experimental Station at Bałcyny near Ostróda (53°35' N; 19°51' E) of the University of Warmia and Mazury in Olsztyn. The study was based on the strict two-factorial experiment established in soil of 4. soil agricultural suitability complex, where three plant species were compared (maize cv. LG 2244, sorghum cv. Sucrosorgo 506, Virginia fanpetals) cultivated according to two technologies – high-input (intensive) and medium-input (with reduced outlays for means of production in relations to the intensive technology). Among the studied plants, the highest efficiency of biomass (21.4 $Mg \cdot ha^{-1}$ d.m.) and energy in yield (390 $GJ \cdot ha^{-1}$) and the most favourable index of energy consumption per unit (1.02 $GJ \cdot t^{-1}$) and energy efficiency (18.4) were provided by maize. Sorghum and *Virginia fanpetals* gave significantly lower yields than maize (by 40 and 54%, respectively) and were not equal in respect of energy discriminants in yield, energy consumption per unit or energy efficiency. The high-input technology provided a significantly higher biomass yield on average for 3 studied species (15.8 $Mg \cdot ha^{-1}$ d.m.) than medium-input (13.6 $Mg \cdot ha^{-1}$ d.m.). In the medium-input technology, reduction in energy outlays by 27%, mainly of mineral fertilization, caused a significant decrease in biomass yield by 14%, but it provided a higher energy efficiency of its production (15.3). The most favourable energy efficiency index of biomass production was obtained by maize cultivated in the medium-input technology (19.7). Lower energy assessment value of sorghum and Virginia fanpetals does not eliminate possibility of using the biomass of these plants as supplementing substrates for biogas production.

Corresponding author – Adres do korespondencji: dr hab. Władysław Szempliński, prof. UWM, Department of Agrotechnology and Crop Management, University of Warmia and Mazury in Olsztyn, M. Oczapowskiego 8/114, 10-719 Olsztyn, e-mail: wladyslaw.szemplinski@uwm.edu.pl

Key words: biomass yield, maize LG 2244, sorghum Sucrosorgo 506, Virginia fanpetals, energy efficiency, production technology,

INTRODUCTION

Maize silage is now the substrate used most frequently in agricultural biogas plants, which results mostly from large availability and efficiency of biomass [Fugol and Szlachta 2010, Podkówka and Podkówka 2010, Gołaszewski 2011] as well as large and constant production of biogas [Strauβ *et al.* 2009]. Production technology and biomass preservation and storage is also relatively well developed [Jasiulewicz 2010]. Although corn is a perfect component for biogas production, alternative raw materials should be looked for. This results from the excessive growth of its acreage, the necessity of using proper crop rotation, as well as ensuring food safety for the country [Podkówka and Podkówka 2010].

Of plant species useful for silage production, especially in conditions of rainfal deficit in the growing period when maize usually gives poor yields, great hope is placed in sorghum, which is tolerant to water shortage. Some studies [Burczyk 2012] indicate that the yields of its new cultivars may exceed the efficiency of maize. Also Virginia fanpetals is suitable for energy production. Although its biomass yield is lower than those of maize and sorghum [Borkowska 1996, Borkowska and Styk 2006] it can constitute the substrate for biogas production [Wojnowska-Baryła and Bernat 2012].

Searching for raw materials for biogas production which would be alternative to corn should be based not only on the biomass efficiency. Plant yield should be only one of criteria for the assessment of usefulness of the given species for biomass production for energy purposes. Also the evaluation of energy outlays incurred for gaining biomass, energy volume contained in it and the energy efficiency index are vital questions [Bujak *et al.* 2010, Tworkowski *et al.* 2010, Stolarski *et al.* 2001]. Agricultural production for energy should be optimized in respect of maximizing energy efficiency [Roszkowski 2008]. Consequently, it should be characterized by favourable ratio of the energy contained in the biomass to the energy needed to its generation [Jadczyszyn *et al.* 2008]. Only in such aspect further stages of biomass conversion to secondary energy carriers will be justified from the ecological and economic point of view [Tworkowski *et al.* 2010].

The energy analysis allows the choice of intensity of the given production technology and comparison of results obtained at different place and time, irrespective of differences in prices of agricultural products and means of production [Węgrzyn and Zając 2008]. Modern technologies of plant production should strive to reduce energy outlays due to the necessity of saving energy and the environment [Harasim 2006], and consequently, the use of energy-saving technologies in agriculture [Niedziółka 2000, Bujak *et al*. 2010]. The problem of energy outlays is particularly important in plant biomass production for energy [Stolarski *et al*. 2001, Harasim 2008], among other things, to reduce production costs and improve the energy efficiency of technologies [Niedziółka 2000, Gorzelany *et al*. 2011].

The aim of this study was to assess the yield of three plant species (maize, sorghum, Virginia fanpetals) grown in conditions of high and medium-input cultivation technologies and to analyse the energy efficiency of their biomass production.

MATERIAL AND METHODS

The study was carried out in the years 2009-2011 in experimental fields of the Production and Experimental Station at Bałcyny near Ostróda (53°35' N; 19°51' E) owned by the University of Warmia and Mazury in Olsztyn. The strict field two--factorial experiment was established in the randomized split-plot design in 2 replications. Three plant species were involved in the study – maize, sorghum and Virginia fanpetals, which were cultivated according to two technologies – high-input (intensive) and medium-input (with reduced outlays for means of production in relations to intensive technology). The plot area was 105 m^2. The experiment was located in slightly diluvial alfisol, formed on light loam, classified as quality class IIIa and agricultural suitability complex 4 (very good rye complex). The humus level of soil had slightly acid pH, and its abundance in availability was moderate.

Tillage under the studied species was performer according to the rules of Good Agricultural Practice. Maize of the cultivar LG 2244 (FAO 230) was sown from 21st to 30th April with a single-seed drill in rows 75 cm apart, with a density of 12 germinating grains per 1 m^2, at a depth of 6 cm. In the high-input technology, mineral fertilization was applied in the following rates: nitrogen – 180 $kg \cdot ha^{-1}$ N (120 kg N – before sowing, 60 kg N – at stage BBCH-12), phosphorus – 53.8 $kg \cdot ha^{-1}$ P and potassium – 116.3 $kg \cdot ha^{-1}$ K – before sowing. Preparation Trophy 768 EC (a.s. – acetochlor, dichloroamid) was applied to control weeds before maize emergences at a rate of 2.0 $dm^3 \cdot ha^{-1}$. In the medium-input production technology, fertilization amounted to: nitrogen – 120 $kg \cdot ha^{-1}$ N, phosphorus – 43.6 $kg \cdot ha^{-1}$ P, potassium – 99.7 $kg \cdot ha^{-1}$ K and was applied once before sowing maize. Weed control was carried out similarly to the high-input technology. During harvest maize was at the wax maturity, and the dry matter content in green forage from both technologies ranged from 34 to 35%.

Sorghum (cultivar Sucrosorgo 506) was sown at the time suitable for its thermal requirements (around the 20th of May) with a single-seed drill in rows with a width of 75 cm, at the density of 25 germinating grains per 1 m^2, at a depth of 2.5–3.0 cm. In the intensive technology fertilization was used at the following rates: nitrogen – 160 $kg \cdot ha^{-1}$ N (100 kg N – before sowing, 60 kg N – at stage BBCH–12), phosphorus – 34.9 $kg \cdot ha^{-1}$ P and potassium – 132.9 $kg \cdot ha^{-1}$ K – before sowing. Weed infestation in the stand was regulated chemically, using the preparation Lumax 537,5 SE (a.s. – terbuthylazine, mesotrione, s-metolachlor) against monocotiledonous and dicotiledonous weeds before emergence at a rate of 2.5 $dm^3 \cdot ha^{-1}$. In the medium-input technology sorghum was fertilized before sowing at the following rates: nitrogen – 100 $kg \cdot ha^{-1}$ N, phosphorus – 21.8 $kg \cdot ha^{-1}$ P, and potassium – 83.0 $kg \cdot ha^{-1}$ K. In 2009 regulation of weed infestation was made mechanically (weeding inter-rows) and in the years 2010-2011, similarly to the high-input technology. Sorghum biomass was harvested at the time of maize harvest, and the dry matter content in it in both technologies ranged from 22 to 25%.

The plantations of Virginia fanpetals in both production technologies were established vegetatively from root cuttings in 2007 (from 20th to 30th April). Plants were sown in rows with a row spacing of 70 cm, and 45 cm apart in a row (density of 32 thousand plants per 1 ha), at a depth of 6-8 cm. In the years of the study (2009-2011) Virginia fanpetals was in the period of full productivity. In the high-input technology fertilization was applied in the following rates: nitrogen – 150 $kg \cdot ha^{-1}$ N (80 kg N – in early spring together with phosphorus-potassium fertilizers, 70 kg N – after plant emergences), phosphorus – 43.6 $kg \cdot ha^{-1}$ P and potassium – 124.6 $kg \cdot ha^{-1}$ K. In the medium-input technology single early spring fertilization was applied at the following rates: nitrogen – 100 kg·ha^{-1} N, phosphorus – 26.2 kg·ha^{-1} P, potassium – 66.4 kg·ha^{-1} K. Weed control was not used in the years of the study. Virginia fanpetals biomass was harvested at the time of maize harvest, and the dry matter content in it in both technologies amounted to about 39%.

The energy assessment of biomass production technologies was conducted using calculations made on large-area farms. The following sets of machines and tools were used in cultivation practices: ploughing – JD8100 + Kverneland BB100, seedbed preparing with the tillage unit – JD8100 + KP600, presowing fertilization – JD5720 + Amazone Za-m Max 2000, single-seed sowing – U914 + Variasem, mechanical cultivation – C360 + Wielorak, chemical protection – JD6620 + Krukowiak Goliat, biomass harvest – JD7200 + T088 + JD6620. The use of materials and the means of production (seeds, fertilizers, plant protection preparations) were in accordance with the methods. Fuel consumption was determined with the full tank method.

The following converters were adopted in calculations of accumulated energy outlays: 1 kg N – 77 MJ, 1 kg P – 34.4 MJ, 1 kg K – 12.1 MJ, 1 kg of the active substance of plant protection preparation – 300 MJ, 1 kg of diesel oil – 48 MJ [Banasiak 1999, Wójcicki 2000]. Energy outlays of the tractors and machines used in the production process were calculated by multiplying the material consumption per unit by the energy equivalent amounting to 112 MJ·kg^{-1} of biomass. Human labour was calculated using the equivalent 40 MJ·rbh^{-1} [Pawlak 1989]. The amount of outlays incurred for materials was calculated assuming their real use in the study and indexes of energy consumption used in drawn energy calculation [Anuszewski 1987, Wielicki 1989, Wójcicki 2000, Harasim 2006]. The gross energy value of biomass yield determined by adiabatic combustion in the bomb calorimeter was for maize – 18.2, sorghum – 17.7, Virginia fanpetals – 18.3 MJ·kg^{-1}. In the energy assessment of biomass production technology were determined as follows: energy gain – as the difference between the energy value of yield and the total energy spent on its gaining, the energy consumption per unit – as the ratio of the total energy outlays on the unit of dry matter yield, the energy efficiency index – as the ratio of the energy value of yield and energy outlays incurred for its generating.

The weather conditions differed considerably in the years of the study (Table 1). Total precipitations over the years 2009-2011 ranged from 563.2 to 623.2 mm and they were similar to the mean total precipitation from the long-term period (595.8 mm). Total precipitations during the plant growing period (April-September) over the years 2010-2011 exceeded by 11.6 and 13.0% the long-term value for that period amounting to 376.7 mm, whereas in 2009 they were lower by 7.1% from the long-term total. Mean daily air temperatures in the years of the study stayed in the range from 7.2-8.0ºC, and in the period April-September, from 14,7 to 15,3ºC and exceeded the long-term value for that period (13.7ºC).

The results were analysed statistically according to the experimental design using the analysis of variance ANOVA with the STATISTICA 8.0® software. Synthesis was performer in the mixed model, treating years as a random factor. To assess the significance of differences between the treatment means, Tukey's multiple comparison test was used at the significance level $P \leq 0.05$.

Table 1. Moisture and thermal conditions of biomass production
Tabela 1. Warunki wilgotnościowe oraz termiczne produkcji biomasy

Years Lata	Plant rest Spoczynek roślin	Spring growth Wzrost wiosenny			Summer growth Wzrost letni			Autumn Okres jesienny	Total/ Mean Suma/ Średnio
	December-March grudzień – marzec	April kwiecień	May maj	June czerwiec	July lipiec	August sierpień	September wrzesień	October-November październik – listopad	
Total precipitation – Suma opadów, mm									
Long-term* Wielolecie	113.7	35.2	56.7	68.3	81.3	78.1	57.1	105.4	595.8
2009	128.3	3.7	89.6	133.1	82.2	25.7	15.6	99.3	577.5
2010	80.9	9.4	105.5	73.7	87.8	99.3	45.0	121.6	623.2
2011	97.9	33.7	41.5	56.2	171.9	83.6	38.9	39.5	563.2
Mean daily air temperature – Średnia temperatura dobowa powietrza, °C									
Long-term Wielolecie	-1.6	6.6	12.4	15.7	16.5	18.2	12.6	5.5	7.2
2009	-0.9	9.7	12.2	14.7	18.9	18.5	14.7	5.6	8.0
2010	-2.9	7.9	12.0	15.7	20.8	19.3	12.2	4.8	7.2
2011	-3.1	9.7	13.6	17.5	18.0	18.1	14.6	5.9	7.5

* long-term period comprises the years 1961-2001 – wielolecie dotyczy lat 1961-2001

RESULTS AND DISCUSSION

The plant species which are suitable for energy production are characterized by a high energy potential, and therefore providing large biomass yields. Its highest efficiency can be obtained only from the so-called purposeful crops, that is production plantations established specifically to this purpose [Gołaszewski 2011]. The studied species differed in the degree of dry matter accumulation in yield. In the 3 years cycle of the study, maize proved to be unrivalled in dry matter efficiency, with the yield amounting on average to 21.4 Mg·ha^{-1} (Table 2). Large dry matter yield of maize in the present study is also confirmed in the studies of other authors [Harasim 2008, Szempliński *et al*. 2009, Szempliński and Dubis 2011, Księżak *et al*. 2012], where maize gave yields from 14.9 to 25.0 t·ha^{-1}. Dry matter yields of sorghum, on average for 3 years, amounted to 12.9 Mg·ha^{-1}, and of Virginia fanpetals – 9.9 Mg·ha^{-1} and they were significantly lower than maize yields (by 40 and 54%, respectively). From the previous studies [Śliwiński and Brzóska 2006, Sowiński and Liszka-Podkowa 2008, Burczyk 2012, 2013, Księżak *et al*. 2012] it follows that the dry matter yield of sorghum ranges from 12.5 to 28.1 Mg·ha^{-1}. Virginia fanpetals yields in the previous studies [Borkowska 1996, Borkowska and Styk 2006, Kuś *et al*. 2008, Kuś and Matyka 2009] ranged from 8.9 to 18.0 Mg·ha^{-1}, which indicates that in the present study they stayed in the lower limit of the yields obtained by other authors.

Table 2. Biomass yield of the studied energy plant species, Mg·ha^{-1} D.M.
Tabela 2. Plon biomasy badanych gatunków roślin energetycznych, Mg·ha^{-1} s.m.

Study years Rok badań	Maize Kukurydza zwyczajna			Sorghum Sorgo zwyczajne			Virginia fanpetals Ślazowiec pensylwański			Mean Średnia		Mean Średnia
	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	
2009	22.1	19.0	20.6	13.9	12.7	13.3	11.2	9.3	10.3	15.7	13.7	14.7
2010	18.9	16.7	17.8	12.8	10.4	11.6	12.2	10.9	11.6	14.6	12.7	13.7
2011	26.6	25.2	25.9	15.2	12.3	13.8	9.3	6.3	7.8	17.0	14.6	15.8
Mean Średnia	22.5	20.3	21.4	14.0	11.8	12.9	10.9	8.8	9.9	15.8	13.6	–

LSD – NIR
species – gatunek 0.55
technology – technologia 0.39
years – lata 0.41
interaction – interakcja:
years × species – lata × gatunek 0.88
years × technology – lata × technologia ns – ni
species × technology – gatunek × technologia ns – ni
years × species × technology – lata × gatunek × technologia 1.23

W – high-input technology – technologia wysokonakładowa
S – medium-input technology – technologia średnionakładowa
$\bar{x}$ – mean – średnia

Plant yield is the outcome of their genetic potential, the arrangement of soil and climate conditions, the level of cultivation technology and the interaction of those factors [Gołaszewski 2011]. In the present study, agrobiomass yields were significantly different in the years of the study. Statistically the highest yield (on average for all the species – 15.8 Mg·ha^{-1} d.m.) was obtained in 2011, where the highest precipitation in the summer period was observed (Table 1). In the other years, with less rainfall, the yields were significantly smaller (the differences ranged from 7.0% in 2009 to 13.3% in 2010). In all the years maize gave definitely best yields – 17.8-25.9 Mg·ha^{-1} d.m. The yields of sorghum ranged from 11.6 to 13.8 Mg·ha^{-1}, and Virginia fanpetals – from 7.8 to 11.6 Mg·ha^{-1} d.m. Even in the favourable year (2011), where maize obtained the highest dry matter yield (25.9 Mg·ha^{-1}), sorghum yields were lower by 47%, and of Virginia fanpetals – by 70%. It is stressed in the literature that the yield in the years are determined by the weather conditions during the growing period, and the total precipitation is of greater importance in this respect than mean daily air temperatures [Sulewska 2004, Chmura *et al*. 2006, Szempliński *et al*. 2009]. Water demand shows a connection with species, its transpiration index and the plant developmental stage, and it growth along with their development. It usually comprises the period from the shoot elongation stage to flowering [Chmura *et al*. 2006]. The results of this experiment do not confirm the opinion that sorghum is more tolerant to water deficit in the growing period than maize [Sowiński and Liszka-Podkowa 2008, Burczyk 2012].

The high-input technology, on average for 3 species, provided the biomass yield of 15.8 Mg·ha^{-1} d.m. In the medium-input technology the dry matter yield was significantly lower (by about 14%). This relationship was observed in all the years of the study, but the differences did not statistically confirmed. In the medium-input technology the outlays of accumulated energy were lower than in the intensive, but the technologies did not significantly differentiate the biomass yield of individual plant species. Maize responded to a reduction of energy outlays in the medium-input technology by 21% (Table 3) with a decrease in dry matter yield by about 10% (Table 2). In sorghum reduction in energy outlays by 27% resulted in a decrease in dry matter yield by 16%, and in Virginia fanpetals reduction in energy outlays for production technology by 34% resulted in a decrease in yield by 19%. The species differed among the years of the study in dry matter yields, which is indicated by the interaction years × species. Maize obtained significantly the highest dry matter yield in 2011, sorghum in 2009 and 2011 and Virginia fanpetals in 2010. Interaction years × species × technology indicates that maize and Virginia fanpetals in all the years showed significantly higher yields in the high-input technology, and sorghum only in two out of the three years of the study.

Table 3. Energy outlay for biomass production of studied energy plant species, $GJ \cdot ha^{-1}$
Tabela 3. Nakłady energii na produkcję biomasy badanych gatunków roślin energetycznych, $GJ \cdot ha^{-1}$

Study years Rok badań	Maize Kukurydza zwyczajna			Sorghum Sorgo zwyczajne			Virginia fanpetals Ślazowiec pensylwański			Mean Średnia		Mean Średnia
	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	
2009	23.9	18.8	21.4	21.0	15.3	18.2	19.5	12.8	16.2	21.5	15.6	18.6
2010	23.9	18.8	21.4	21.0	15.3	18.2	19.5	12.8	16.2	21.5	15.6	18.6
2011	23.9	18.7	21.3	21.4	15.8	18.6	19.5	12.8	16.2	21.6	15.8	18.7
Mean Średnia	23.9	18.8	21.3	21.1	15.5	18.3	19.5	12.8	16.2	21.5	15.7	–

for explanation, see Table 2 – objaśnienia pod tabelą 2

Technologies differed in energy outlays incurred for biomass production of the studied energy plant species. Production of maize biomass was the most energy-consuming (21.3 $GJ \cdot ha^{-1}$). Production of sorghum and Virginia fanpetals biomass was less energy-consuming, by 3.0 and 5.1 $GJ \cdot ha^{-1}$, respectively (Table 3). Lower energy outlays incurred for biomass production of Virginia fanpetals in comparison with maize and sorghum result not only from less mineral fertilization, but also from the fact that as a perennial plant, energy outlays of technology connected with tillage and establishment of plantation were spread out over the adopted 20 years' period of its use. This means that maize was produced most intensively. In the study by Gorzelany *et al*. [2011] and Harasim [2008] energy outlays incurred for silage maize cultivation were considerably higher (24.3 $GJ \cdot ha^{-1}$).

Energy efficiency calculated for the biomass yield is the product of the yield of individual species and the energy value of 1 kg of dry matter. In the analysed study, the species differed significantly in the energy efficiency of the biomass yield (Table 4), and the highest efficiency in the 3-year cycle of the study was found for maize (390 $GJ \cdot ha^{-1}$). Sorghum accumulated in the biomass yield on average 228 $GJ \cdot ha^{-1}$ of energy (by 42% less then maize) and Virginia fanpetals – 181 $GJ \cdot ha^{-1}$ (less by 54%). Energy efficiency in the biomass yield was significantly different in the years of the study (Table 4). The highest energy efficiency in yield was obtained in 2011 (on average for 3 species – 286 $GJ \cdot ha^{-1}$), and in the other years these values were lower from 7 to 14%. In all the years, maize accumulated the highest energy efficiency in the biomass yield (from 324 to 471 $GJ \cdot ha^{-1}$). Also in the study by Szempliński and Dubis [2011] the energy efficiency of maize biomass yield (417 GJ·ha^{-1}) was higher than in sorghum (235 GJ·ha^{-1}). Different results were obtained by Burczyk [2012, 2013], where the energy efficiency in the dry matter yield of sorghum ranged from 452 to 528 GJ·ha^{-1}, and of maize – from 424 to 513 GJ·ha^{-1}. In the study by Harasim [2008] maize grown for silage provided biomass with energy value amounting to 229 GJ·ha^{-1}. The energy efficiency in the biomass yield of Virginia fanpetals obtained in the present study is similar to the earlier study by Borkowska and Styk [2006], where the energy volume in the biomass yield stayed in the range from 174 to 334 GJ·ha^{-1}.

Of the two production technologies, the high-input technology ensured higher energy efficiency in the biomass yield (286 GJ·ha^{-1}). In the medium-input technology this value was significantly lower by 13.6% (Table 4). Also in the years of the study the technologies significantly differentiated the energy efficiency of the biomass yield. In the high-input technology, energy efficiency in the years ranged from 265 to 308 GJ·ha^{-1}, and in the medium-input technology it was significantly lower from 13.0% in 2009 to 14.3% in 2011 (Table 4). Technologies differentiated the efficiency of energy contained in the yield of studied plant species. In the high-input technology, the energy value of maize biomass yield was significantly higher than in medium-input technology, by 11.1%, similarly in sorghum – by 18.2% and in Virginia fanpetals – by 22.8% (Table 4).

Table 4. Energy efficiency in the biomass yield of studied energy plant species, GJ·ha^{-1}
Tabela 4. Wydajność energii w plonie biomasy badanych gatunków roślin energetycznych, GJ·ha^{-1}

Study years Rok badań	Maize Kukurydza zwyczajna			Sorghum Sorgo zwyczajne			Virginia fanpetals Ślazowiec pensylwański			Mean Średnia		Mean Średnia
	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	
2009	402	346	374	246	225	235	205	170	188	284	247	266
2010	344	304	324	227	184	205	223	199	211	265	229	247
2011	484	459	471	269	218	243	170	115	143	308	264	286
Mean Średnia	410	369	390	247	209	228	199	162	181	286	247	–

LSD – NIR

species – gatunek	7.01
technology – technologia	5.20
years – lata	6.22
interaction – interakcja:	
years × species – lata × gatunek	13.09
years × technology – lata × technologia	18.23
species × technology – gatunek × technologia	14.53
years × species × technology – lata × gatunek × technologia	15.38

for explanation, see Table 2 – objaśnienia pod tabelą 2

In the literature [Szczukowski *et al*. 2006, Gołaszewski 2011] it is stressed that intensive production for biogas production requires plant species with a high biomass productivity from the area unit. Such species should be characterized by a high energy balance, that is the difference between the energy contained in the biomass and the energy needed for its generation. In the present study, the highest energy gain in the biomass yield (Table 5) was provided by maize (368 GJ·ha^{-1}). The other species were not competitive as compared with maize, since energy gain in sorghum yield was less by 43%, and in Virginia fanpetals – by 55%. In the study by Szempliński and Dubis

[2011], among 9 studied plant species, maize, which accumulated 377 GJ·ha^{-1} of energy, and sorghum – only103 GJ·ha^{-1}, was definitely the best in respect of the gain of accumulated energy contained in the dry matter yield.

Energy gain in the biomass yield was different in the year of the study. The highest value was obtained in 2011 (267 GJ·ha^{-1}), and in the other years those values were smaller from 7.5 to 14.6% (Table 5). Maize in all the years of the study ensured the highest energy gain in the biomass yield and was competitive for the other species. Due to a high dry matter yield, the high-input technology also ensured a higher energy gain in yield than the medium-input technology, and the difference accounted for 14,3%. All species ensured higher energy gain in the intensive technology than in medium-input technology. In the medium-input technology the energy gain in the dry matter yield of maize was lower by 9.1%, sorghum – by 14.6%, and Virginia fanpetals – by 17.2%.

Table 5. Energy discriminants of biomass yield of studied energy plant species
Tabela 5. Wyróżniki energetyczne plonu biomasy badanych gatunków roślin energetycznych

Study year Rok badań	Maize Kukurydza zwyczajna			Sorghum Sorgo zwyczajne			Virginia fanpetals Ślazowiec pensylwański			Mean Średnia		Mean Średnia
	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	$\bar{x}$	W	S	
Energy gain in biomass yield – Zysk energii w plonie biomasy, GJ·ha^{-1}												
2009	378	327	353	225	209	217	185	157	171	263	231	247
2010	320	285	303	206	169	187	204	187	195	243	214	228
2011	460	440	450	248	202	225	151	102	127	286	248	267
Mean Średnia	386	351	368	226	193	210	180	149	164	264	231	–
Energy consumption per unit – Energochłonność jednostkowa, GJ·Mg^{-1} D.M.												
2009	1.08	0.99	1.04	1.51	1.20	1.36	1.74	1.38	1.56	1.44	1.19	1.32
2010	1.26	1.13	1.20	1.64	1.47	1.56	1.60	1.17	1.39	1.50	1.26	1.38
2011	0.90	0.74	0.82	1.41	1.28	1.35	2.10	2.03	2.06	1.47	1.35	1.41
Mean Średnia	1.08	0.95	1.02	1.52	1.32	1.42	1.81	1.53	1.67	1.47	1.27	–
Energy efficiency index – Współczynnik efektywności energetycznej												
2009	16.8	18.4	17.6	11.7	14.7	13.2	10.5	13.3	11.9	13.0	15.5	14.2
2010	14.4	16.2	15.3	10.8	12.0	11.4	11.4	15.6	13.5	12.2	14.6	13.4
2011	20.3	24.5	22.4	12.6	13.8	13.2	8.7	9.0	8.9	13.9	15.8	14.8
Mean Średnia	17.2	19.7	18.4	11.7	13.5	12.6	10.2	12.6	11.4	13.0	15.3	–

for explanation, see Table 2 – objaśnienia pod tabelą 2

Plant species differed in the energy consumption per unit (Table 5). The production of 1 Mg of maize dry matter (1.02 GJ·Mg^{-1}) was the least energy consuming, due to the highest biomass yields. In comparison with maize, the energy consumption per unit of sorghum production was higher by 39%, and the most energy consuming was Virginia fanpetals biomass production (increase by 64%). Energy consumption of production of 1 Mg of dry matter was slightly differentiated in the years of the study and it ranged from 1.32 GJ·Mg^{-1} in 2009 to 1.41 GJ·Mg^{-1} in 2011. In the years of the study, the energy consumption per unit of maize dry matter production ranged from 0.82 to 1.20, of sorghum – from 1.35 to 1.56, and of Virginia fanpetals – from 1.39 to 2.06 GJ·Mg^{-1}. In the study by Szempliński and Dubis [2011], the energy consumption per unit of green forage maize production was 0.99, and of sorghum – 2.36 GJ·Mg^{-1}. In the study by Harasim [2008] the energy consumption of silage maize production amounted to 1.94 GJ·Mg^{-1}.

The comparison of biomass production energy consumption indicates that in the intensive technology 1.47 GJ of energy was spent on production of 1 Mg of dry matter, and in the medium-input technology by 0.20 GJ (13.6%) less energy. Energy consumption per unit of biomass production in the medium-input technology in maize and sorghum was smaller by 12-13%, and in Virginia fanpetals by as much as 22%. The medium-input technology proved to be more favourable in respect of biomass production, which confirmed the thesis of Bujak *et al*. [2010] that growing outlays for cultivation technology, by means of higher rates of mineral fertilizers, causes an increase in energy outlays and results in worsening of energy consumption per unit.

The energy efficiency of production compares energy contained in the final product, which is biomass, with the accumulated energy outlays incurred for its production, contained in materials, energy carriers, human labour, as well as machines, tools and devices [Wójcicki 2000, Harasim 2006]. Comparison of energy efficiency indexes of the studied plant species indicates (Table 5) that in the 3 years cycle of study the most favourable energy efficiency was provided by maize (18.4). This means that 1 GJ of energy spent on cultivation of this plant resulted in more than 18-fold energy increase in biomass yield. This index obtained a distinctly lower value in sorghum (12.6) and the lowest in Virginia fanpetals (11.4). Weizsäcker *et al*. [1999] report that in field crop production, the energy efficiency index ranges from 2 to 10 and it assumes the most favourable value in comparison with other branches of agricultural activity. Due to the high energy efficiency of field production, plant biomass production has a growing importance on the market of renewable energy materials. In the present study, the energy efficiency index of silage maize was very high and similar to those in the study by Szempliński and Dubis [2011] and twice more favourable than in the study by Harasim [2008]. The index of energy efficiency in sorghum was more favourable than in the study by Szempliński and Dubis [2011]. The energy efficiency index of biomass production of the studied plant species was changing in the years of the study, which was undoubtedly affected by the level of their yield. Biomass was the most efficiently produced in 2011, when 1 GJ of energy spent on cultivation resulted in almost 15-fold energy effect in the dry matter yield. In the other years the energy efficiency of biomass production was less and ranged from 4 to 10%.

Of the compared biomass production technologies, the medium-input technology obtained more favourable index of energy efficiency (15.3) than the high-input technology (13.0), and the difference was almost 18%. This means that technologies with less energy outlays were characterized by a higher efficiency index in each of the studied plants. In the case of maize, this index was higher by more than 14%, in sorghum – by 15%, and in Virginia fanpetals – by 23%. These relationships occurred in all the years of the study (Table 5). Bujak *et al*. [2010] claim that the energy consumption of plant production should always be considered together with the effects of production. Less-input, energy saving production technologies are justified when they do not result in a large decrease in yield. From the point of view of the energy efficiency of a given technology, a decrease in efficiency will be justified only when its value expressed in energy units will be less than the energy saving obtained as a result of reducing outlays incurred for this technology.

CONCLUSIONS

1. The highest efficiency of the substrate for biomass production of the studied plant species was ensured by maize (21.4 $Mg \cdot ha^{-1}$). The other taxons gave significantly lower yields – sorghum by 40%, and Virginia fanpetals – by 54%. This relationship of yield remained in all the years of the study.

2. The high-input technology ensured a significantly higher biomass yield of the studied species. In the medium-input technology a reduction of energy outlays, mostly mineral fertilization, resulted in a decrease in ensured yield by10%, sorghum – by 16%, and Virginia fanpetals – by 19%.

3. Biomass was the most favourably produced in the medium-input technology that ensured lower energy consumption per unit, and therefore higher energy efficiency, than the intensive technology.

4. Maize cv. LG 2244 was the taxon that ensured the most favourable indexes of energy consumption per unit and energy efficiency. Its biomass was the most favourably produced in moderate-input technology.

5. Sorghum (cultivar Sucrosorgo 506) and Virginia fanpetals gained less favourable discriminants of energy consumption per unit and energetic efficiency in the yield and were not equal to maize in respect of those characters. Lower results of energy evaluation did not exclude the possibility of their use as supplementing substrates for biogas production.

REFERENCES

Anuszewski R., 1987. Metoda oceny energochłonności produktów rolniczych. Zag. Ekon. Rol. 4, 16-26.

Banasiak J., 1999. Agrotechnologia. Wyd. Nauk. PWN Warszawa – Wrocław.

Borkowska H., 1996. Wpływ nawożenia azotowego i potasowego na wysokość i jakość plonów zielonki ślazowca pensylwańskiego (*Sida hermaphrodita* Rusby). Univ. Marie Curie-Skłodowska, Sect. E, 51, 63-70.

Borkowska H., Styk B., 2006. Ślazowiec pensylwański (*Sida hermaphrodita* Rusby). Uprawa i wykorzystanie. Wyd. AR Lublin.

Bujak K., Frant M., Harasim A., 2010. Efektywność energetyczna produkcji roślinnej w płodozmianie 4-polowym w zależności od uproszczeń w uprawie roli i poziomu nawożenia mineralnego. Acta Agroph. 15(1), 23-31.

Burczyk H., 2012. Przydatność jednorocznych roślin, uprawianych do produkcji biomasy na potrzeby energetyki zawodowej. Probl. Inż. Rol. 1(75), 59-68.

Burczyk H., 2013. Przydatność poplonu ozimego oraz kukurydzy i sorgo w plonie wtórnym do produkcji biomasy dla biogazowi. Probl. Inż. Rol. 2(80), 87-97.

Chmura K., Chylińska E., Dmowski Z., Nowak L., 2006. Rola czynnika wodnego w kształtowaniu plonu wybranych roślin polowych. Infrastruktura i Ekologia Terenów Wiejskich PAN Kraków 9, 33-44.

Fugol M., Szlachta J., 2010. Zasadność używania kiszonki z kukurydzy i gnojowicy świńskiej do produkcji biogazu. Inż. Rol. 1(119), 169-174.

Gołaszewski J., 2011. Wykorzystanie substratów pochodzenia rolniczego w biogazowniach w Polsce. Post. Nauk Rol. 2, 69-94.

Gorzelany J., Puchalski Cz., Malach M., 2011. Ocena kosztów i nakładów energetycznych w produkcji kukurydzy na ziarno i kiszonkę. Inż. Rol. 8(133), 135-141.

Harasim A., 2006. Przewodnik ekonomiczno-rolniczy w zarysie. IUNG-PIB Puławy.

Harasim A., 2008. Ocena ekonomiczna i energetyczna różnych systemów produkcji pasz objętościowych. Pam. Puł. 47, 97-109.
Jadczyszyn J., Faber A., Zaliwski A., 2008. Wyznaczanie obszarów potencjalnie przydatnych do uprawy wierzby i ślazowca pensylwańskiego na cele energetyczne w Polsce. Studia i Raporty IUNG-PIB 11, 55-65.
Jasiulewicz M., 2010. Potencjał produkcji biogazu w Polsce. [In:] Ekoenergetyka – zagadnienia technologii, ochrony środowiska i ekonomiki, Wyd. GWSA Gdańsk, 81-102.
Księżak J., Bojarszczuk J., Staniak M., 2012. Produkcyjność kukurydzy i sorga w zależności od poziomu nawożenia azotem. Polish J. Agron. 8, 20-28.
Kuś J., Faber A., Stasiak M., Kawalec A., 2008. Produkcyjność wybranych gatunków roślin uprawianych na cele energetyczne w różnych siedliskach. [In:] Studia i Raporty IUNG-PIB, Uprawa roślin energetycznych a wykorzystanie rolniczej przestrzeni produkcyjnej w Polsce, 11, 67-80.
Kuś J., Matyka M., 2009. Wydajność wybranych gatunków roślin uprawianych na cele energetyczne w zależności od jakości gleby. Fragm. Agron. 26(4), 103-110.
Niedziółka I., 2000. Energochłonność i opłacalność produkcji ziarna kukurydzy. Inż. Rol. 8(19), 133-139.
Pawlak J., 1989. Organizacyjne i ekonomiczne aspekty mechanizacji produkcji roślinnej w indywidualnych gospodarstwach rolniczych. PWRiL Warszawa.
Podkówka Z., Podkówka W., 2010. Substraty dla biogazowi rolniczych. Wyd. AgroSerwis Warszawa.
Roszkowski A. 2008. Efektywność energetyczna różnych sposobów produkcji i wykorzystania biomasy. Studia i Raporty IUNG PIB 11, 101-112.
Sowiński J., Liszka-Podkowa A., 2008. Wysokość i jakość plonu kukurydzy i sorga cukrowego na glebie lekkiej w zależności od dawki azotu. [In:] Problemy agrotechniki oraz wykorzystania kukurydzy i sorgo, Michalski T. (ed.), Wyd. UP Poznań, 250-252.
Stolarski M., Szczukowski S., Tworkowski J., 2001. Efektywność energetyczna produkcji biomasy wierzby w systemie Eko-salix. Fragm. Agron. 28(1), 62-69.
Strauβ Ch., Vetter A., Nehring A., 2009. Entwicklung und Vergleich Standortangepasster Produktionssysteme für Energiepflanzen. Internationale Wissenschaftstagung Biogas Science, Erding, 47-56.
Sulewska H., 2004. Wymagania środowiskowe kukurydzy i możliwości jej uprawy w Polsce. [In:] Technologia produkcji kukurydzy, Dubas A. (ed.), Wyd. Wieś Jutra Warszawa, 16-23.
Szczukowski S., Kościk B., Kowalczyk-Juśko A., Tworkowski J., 2006. Uprawa i wykorzystanie roślin alternatywnych na cele energetyczne. Fragm. Agron. 3, 300-315.
Szempliński W., Bogucka B., Wróbel E., 2009. Przydatność mieszańców kukurydzy o zróżnicowanej wczesności do uprawy na kiszonkę w warunkach województwa warmińsko-mazurskiego. Acta Sci. Pol., Agricultura 8(1), 57-68.
Szempliński W., Dubis B., 2011. Wstępne badania nad plonowaniem i wydajnością energetyczną wybranych roślin uprawianych na cele biogazowe. Fragm. Agron. 28(1), 77-86.
Śliwiński B.J., Brzóska F., 2006. Historia uprawy sorgo i wartość pokarmowa tej rośliny w uprawie na kiszonkę. Post. Nauk Rol. 1, 25-37.
Tworkowski J., Kuś J., Szczukowski S., Stolarski M., 2010. Uprawa roślin energetycznych. Monografia. Nowoczesne technologie pozyskiwania i energetycznego wykorzystywania biomasy. Wyd. Instytut Energetyki Warszawa.
Weizsäcker E.U., Lovins A.B., Lovins L.H., 1999. Mnożnik cztery. Podwojony dobrobyt – dwukrotnie mniejsze zużycie zasobów naturalnych. Raport dla Klubu Rzymskiego. Wyd. Rolewski Toruń.
Węgrzyn A., Zając G., 2008. Wybrane aspekty badań efektywności energetycznej technologii produkcji biomasy roślinnej. Acta Agroph. 11(3), 799-806.
Wielicki W., 1989. Analiza efektywności energetycznej w rolnictwie. Post. Nauk Rol. 1, 69-86.

Wojnowska-Baryła I., Bernat K., 2012. Produkcja biogazu w procesach fermentacji i ko-fermentacji. Program strategiczny – Zaawansowane technologie pozyskiwania energii. CBEO UWM Olsztyn, www.imp.gda.pl/BF2012/prezentacje/p111.pdf (access: 26.11. 2013).

Wójcicki Z. 2000., Wyposażenie techniczne i nakłady materiałowo-energetyczne w rozwojowych gospodarstwach rolniczych. IBMER Warszawa.

PLONOWANIE I EFEKTYWNOŚĆ ENERGETYCZNA PRODUKCJI BIOMASY WYBRANYCH GATUNKÓW ROŚLIN UPRAWIANYCH NA CELE BIOGAZOWE

Streszczenie. Najczęściej wykorzystywanym substratem w biogazowniach rolniczych jest kukurydza. Ze względu na wzrost powierzchni jej zasiewów i konieczność stosowania w uprawie roślin poprawnego zmianowania należy szukać dla niej surowców alternatywnych. Rośliny alternatywne do produkcji biogazu, poza wysokim plonem biomasy, powinny charakteryzować się korzystnym współczynnikiem efektywności energetycznej. Korzystną wartość tego wskaźnika można uzyskać przez zmniejszenie nakładów energii ponoszonych na produkcję biomasy i wysoką wydajność energii w plonie. Celem badań było porównanie plonowania i efektywności energetycznej produkcji biomasy wybranych gatunków roślin uprawianych w różnych warunkach nakładów energetycznych. Badania przeprowadzono w latach 2009-2011 w Zakładzie Produkcyjno-Doświadczalnym w Bałcynach k. Ostródy (53°35' N; 19°51' E), należącym do Uniwersytetu Warmińsko-Mazurskiego w Olsztynie. Podstawą opracowania było ścisłe doświadczenie dwuczynnikowe, założone na glebie 4. kompleksu przydatności rolniczej, w którym porównywano trzy gatunki roślin (kukurydza zwyczajna odmiana LG 2244, sorgo zwyczajne odmiana Sucrosorgo 506, ślazowiec pensylwański) uprawiane według dwóch technologii – wysokonakładowej (intensywnej) i średnionakładowej (o zmniejszonych nakładach na środki produkcji w stosunku do intensywnej). Z badanych roślin najwyższą wydajność biomasy (21,4 $Mg \cdot ha^{-1}$ s.m.) i energii w plonie (390 $GJ \cdot ha^{-1}$) oraz najkorzystniejszy wskaźnik energochłonności jednostkowej (1,02 $GJ \cdot t^{-1}$) i sprawności energetycznej (18,4) zapewniała kukurydza zwyczajna. Sorgo zwyczajne i ślazowiec pensylwański plonowały istotnie niżej niż kukurydza (odpowiednio o 40 i 54%) i nie dorównywały jej wyróżnikami wydajności energii w plonie, energochłonnością jednostkową czy efektywnością energetyczną. Technologia wysokonakładowa zapewniała istotnie większy plon biomasy średnio dla 3 badanych gatunków (15,8 $Mg \cdot ha^{-1}$ s.m.) niż średnionakładowa (13,6 $Mg \cdot ha^{-1}$ s.m.). W technologii średnionakładowej zmniejszenie nakładów energetycznych o 27%, głównie nawożenia mineralnego, powodowało wprawdzie istotny spadek plonu biomasy o 14%, ale zapewniało wyższą efektywność energetyczną jej produkcji (15,3). Najkorzystniejszy wskaźnik efektywności energetycznej produkcji biomasy zapewniała kukurydza uprawiana w technologii średnionakładowej (19,7). Słabsza ocena energetyczna sorgo i ślazowca nie przekreśla możliwości wykorzystania biomasy z tych roślin jako uzupełniających substratów do produkcji biogazu.

Słowa kluczowe: efektywność energetyczna, kukurydza LG 2244, sorgo Sucrosorgo 506, ślazowiec, plon biomasy, technologia produkcji

Accepted for print – Zaakceptowano do druku: 25.07.2014

For citation – Do cytowania:

Szempliński W., Parzonka A., Sałek T., 2014. Yield and energy efficiency of biomass production of some species of plants grown for biogas. Acta Sci. Pol., Agricultura 13(3), 67-80.