Energy Use Efficiency of Biogas Production Depended on Energy Crops, Nitrogen Fertilization Level, and Cutting System

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Abstract

The paper evaluates the relation between energy input (E_i) and output (E_o) of biogas production from six energy crops: maize, sorghum, sunflower, triticale, reed canary grass (RCG), and Virginia mallow (VM), cultivated in three different nitrogen fertilization levels. Furthermore, in the case of RCG, the impact of cutting system was examined. The results showed that raised N fertilization dose (in the range of 40–120 kg ha⁻¹ and 80–160 kg ha⁻¹, depending on the crops) increased biomass yield and methane productivity (MP) but simultaneously caused also the increase in E_i . Nonetheless, the application of higher N doses did not cause drastic decrease in energy use efficiency (EUE). The E_i was significantly lower for perennials than for annual crops. For this reason, EUE for RCG harvested in two cuts (5.0–5.2 GJ GJ⁻¹) was close to EUE for maize (5.7–6.8 GJ GJ⁻¹), despite the much lower MP (2027–2903 m³ ha⁻¹ and 4409–5692 m³ ha⁻¹, respectively) and E_o (73–105 GJ ha⁻¹ and 159–205 GJ ha⁻¹, respectively). Furthermore, the collection of RCG in more than two cuts turned out to be unjustified, due to increase in E_i and, simultaneously, decrease in MP.

Keywords Bioenergy · RCG · Sida · EUE · Methane · Fermentation · Digestion · Balance

Introduction

One of the main requirements for energy crop cultivation is the lack of the competition with food and feed production in arable land areas [1]. For this reason, high biomass yield of properly selected species, and thus, high productivity of energy from unit of cultivation area, is very important. In addition to the right selection of species, appropriate agrotechnical measures are applied, such as increased fertilization doses or more frequent mowing of perennials and grasses. All these measures, however, result in an increase in energy input on cultivation, which in consequence may result in lower energy efficiency. However, we should strive to ensure that the energy input (E_i) and energy output (E_o) ratio, i.e., the so-called energy use efficiency (EUE), is as high as possible.

At present, there is no complete assessment of the energy efficiency of biogas production from the tested species, which would justify the use of higher doses of nitrogen fertilizers [2]. Jankowski et al. [3] even assessed energy efficiency of biogas production from crops grown in Poland, but E_o was calculated based on calorific value of biomass, not on its biogas yield. They also did not evaluate neither the impact of various nitrogen fertilization levels, nor cutting frequency.

Some studies on the influence of nitrogen fertilization on the energy efficiency of biomass production intended for combustion have showed that an increase in the level of fertilization resulted in a decrease in EUE. Lewandowski and Schmidt [4] recorded a significant increase in E_i on the cultivation of reed canary grass (RCG), triticale, and miscanthus along with an increase in the level of nitrogen fertilization and, in consequence, a significant decrease in EUE, despite an increase in biomass yields. Szempliński et al. [5] stated that high-input technology with high level of nitrogen fertilization provided a significantly higher biomass yield but simultaneously caused the decrease in EUE. The importance of the species was also highlighted. The authors reported that much lower energy input (E_i) was noted for cultivation of multi-annual species—Virginia mallow (VM)—than for cultivation of maize and sorghum

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(16.2; 21.3 and 18.3 GJ ha⁻¹, respectively). Nevertheless, due to the differences in biomass yield, the EUE was still the highest for maize.

The study on energy efficiency of biogas production calculated based on biogas and methane yield was conducted by Barbanti et al. [6]. The authors noticed low energy efficiency of biogas production from maize, despite high biomass and methane yield. It was due to the high E_i for maize cultivation. Meanwhile, other tested crops, alternative to maize, such as sorghum, arundo, and switchgrass, deserved attention in view of a low need of energy for cultivation. Their E_o , which was lower than of maize, resulted from lower biodegradability in the methane fermentation process. Therefore, the improvement of their chemical composition is highly recommended.

There are very few studies on the influence of nitrogen fertilization on energy efficiency of biogas production from energy crops, and furthermore they reduce the role of nitrogen fertilization level to a positive effect on biomass yield. The effect of N level on the quality of biomass and therefore also on biogas yield was neglected. Meanwhile, it has been found that differentiated doses of nitrogen fertilization can affect not only the biomass yield but also the chemical composition of biomass and its biodegradability and, consequently, the biogas production efficiency [7–11]. Oleszek and Matyka [1] proved that elevated level of nitrogen fertilization increased biogas yield, due to positive changes in chemical composition of biomass, mainly decrease in lignin content, and improvement of digestibility.

Considering that both yield and biomass quality were influenced by nitrogen fertilization and more frequent harvest, a hypothesis was made that both nitrogen fertilization and cutting frequency have a significant impact on the biogas and methane productivity and, consequently, on E_o . In addition, due to the high E_i for production of nitrogen fertilizer and cutting, the EUE of biogas production may significantly decrease with increasing N level and number of cuts. Moreover, it was assumed that perennial crops will have a higher EUE, due to lower E_i for their cultivation.

Materials and Methods

Field Experiment

Field experiment was described in detail by Oleszek and Matyka [12]. Briefly, the tested crops were cultivated in Experimental Station of Institute of Soil Science and Plant Cultivation in Osiny, Lublin Province, Poland, in 2012–2014, in a randomized complete block design in “split-plot” system, in four replicates. Nitrogen fertilization, in the form of

ammonium nitrate, was applied in low, medium, and high doses. In the case of maize (*Zea mays* L., var. Ulan) and sorghum (*Sorghum bicolor* L., var. Rona 1), 80, 120, and 160 kg N ha⁻¹ were applied, and in the case of sunflower (*Helianthus annuus* L. var. Kornelka), triticale (*x Triticosecale* Wittm. ex A. Camus. var. Leontino), RCG (*Phalaris arundinacea* L. var. Bamse), and VM (*Sida hermaphrodita* L.), 40, 80, and 160 kg N ha⁻¹ were applied. Perennials were cut repeatedly: VM was harvested in a two-cut system (VM IIC), while RCG both in a two-cut (RCG IIC) and a three-cut system (RCG IIIC). After harvest, biomass yield from four plots was determined. Raw material was combined, fragmented and ensiled in 5-L plastic barrels, and stored in the dark. The silages were subjected to analysis of dry matter (DM) and organic dry matter (ODM) content for calculation of dry and organic dry yield of silages. The DM and ODM were determined using a gravimetric method after drying at 105 °C and 550 °C, respectively [13].

Biogas and Methane Productivity

Based on biomass yield, silage yield was calculated, taking into account 12% losses during ensiling [14]. Next, biogas productivity (BP) and methane productivity (MP) per hectare were estimated, using biogas yield (BY) and methane yield (MY) of tested crops reported previously by Oleszek and Matyka [1], according to Formulas 1 and 2:

$$BP = Y \times BY \quad (1)$$

$$MP = Y \times MY \quad (2)$$

where BP is the biogas productivity (m³ ha⁻¹), BY is the biogas yield (m³ t⁻¹), MP is the methane productivity (m³ ha⁻¹), MY is the methane yield (m³ t⁻¹), and Y is the silage yield (t ha⁻¹).

Energy Output and Input

Energy gained from methane production, so-called energy output (E_o), was calculated according to the following formula [15]:

$$E_o = MP \times 36 \times 10^{-3} \quad (3)$$

where E_o is the energy output (GJ ha⁻¹), MP is the methane productivity (m³ ha⁻¹), and 36 is the methane calorific value (MJ m⁻³).

Calculation of energy input (E_i) includes the energy demand for biomass cultivation, harvest, and transport of biomass as well as energy consumption by anaerobic digester operation. Coefficients of cumulated energy consumption (CCEC) used in the calculation based on literature [16–22] were presented in Table 1.

Table 1 Coefficients of cumulated energy consumption (CCEC) used in energy input (E_i) calculation

Source of energy input	CCEC
Cultivation, harvest, and transport of biomass	
Fuels	
Diesel	45 MJ kg ⁻¹
Raw materials	
Fertilizers	
Nitrogenous	40 MJ kg ⁻¹ N
Potassic	10 MJ kg ⁻¹ K
Phosphorous	14 MJ kg ⁻¹ P
Calcium	6 MJ kg ⁻¹ Ca
Plant protection products	300 MJ kg ⁻¹ (of active substance)
Other	
Seeds	16 MJ kg ⁻¹
Silage films	86 MJ kg ⁻¹
Fixed assets	
Operation of tractors and machines	112 MJ kg ⁻¹
Spare parts	80 MJ kg ⁻¹
Materials for repairs	30 MJ kg ⁻¹
Labor	40 MJ MH ^{-1a}
Biogas plant operation	
Heat	110 MJ t ^{-1b}
Electricity	66 MJ t ⁻¹

^a MH man-hour, ^b Based on [22] “tonne” refers to substrate with a 10% dry matter content

In the calculation of E_i for cultivation, harvest, and transport of biomass, four main energy streams were defined: fuel (diesel), fixed assets (machines, tools, spare parts), raw materials (fertilizers, plant protection products, seeds and cuttings, silage films, etc.), and labor.

The data regarding agricultural technology, the duration of particular steps of cultivation, and the consumption of raw materials were taken from documentation of the field experiments. In the case of perennial plants, a 17-year period of plantations usage was established in order to determine the average annual energy expenditure for establishing and closing of plantation.

The E_i for biogas plant operation, such as the electricity and heating requirements, was determined according to the method implemented previously by Berglund and Börjesson [22]. The base electricity and heating demand are given in Table 1 and expressed in MJ per tonne of substrate added to the digester. The “tonne” refers to 1 t of substrate with a 10% dry matter. Therefore, the value of E_i for biogas plant operation has been calculated taking into account the dry matter content in tested biomass and biomass yield per hectare and finally expressed in GJ ha⁻¹.

Energy Use Efficiency (EUE)

Energy use efficiency (EUE) was expressed as the ratio of E_o and E_i :

$$EUE = \frac{E_o}{E_i} \quad (4)$$

where EUE is the coefficient of energy use efficiency (GJ GJ⁻¹), E_o is the energy output (GJ ha⁻¹), and E_i is the energy input (GJ ha⁻¹).

Statistical Analysis

The statistical analysis was performed in STATISTICA 12. In order to explain the influence of species of energy crops, nitrogen fertilization level and cutting system and year on the biomass yield, methane productivity and EUE, one-way and two-way ANOVA, as well as Tuckey’s post hoc test were applied.

Results and Discussion

Biomass Yield

The tested crops differed in biomass yield (Table 2). The highest yield of fresh biomass was obtained for maize (67.7 ± 4.0 t ha⁻¹), sunflower (67.3 ± 2.1 t ha⁻¹), RCG harvested in two-cut system (61.4 ± 2.8 t ha⁻¹), and sorghum (57.3 ± 3.1 t ha⁻¹). Significantly lower biomass yield was stated for triticale and VM (41.6 ± 2.7 and 45.4 ± 1.8 t ha⁻¹, respectively). The higher yield of RCG in the case of two-cut system than three-cut system indicates the lack of legitimacy of harvesting this crop in three cuts. The year of cultivation did not influence significantly on the biomass yield (Table 2), despite the slightly different weather conditions in 2012–2014 (Table 3).

In 2012, average monthly sums of precipitation during vegetation period were close to the long-term average. Slight deficit of precipitations occurred in April and May, but it could have been partially offset by a larger number of them in the remaining months. Mean air temperature was higher than long-term one, particularly in July and August. The weather conditions in 2013 were characterized by a high variability during the growing season. In the initial months (April–June), the amount of rainfall was much higher than the long-term average. On the contrary, significant deficit of precipitation was noted in the following months (July–August). It should be assumed that this deficiency, combined with high air temperature, resulted in the increase in the rate of evapotranspiration, which could deteriorate the growth and biomass accumulation. In 2014, both air temperature (especially in

Table 2 Fresh biomass yield depending on the species and nitrogen fertilization level

Characteristics	Fresh biomass yield* (t ha ⁻¹)
Species	
Maize	67.7 ± 4.0 d**
Sunflower	67.3 ± 2.1 d
Sorghum	57.3 ± 3.1 cd
Triticale	41.6 ± 2.7 a
RCG IIC	61.4 ± 2.8 cd
RCG IIIC	54.6 ± 2.9 bc
Virginia mallow	45.4 ± 1.8 ab
<i>p</i> Value	0.0000
<i>F</i>	14.45
Nitrogen fertilization level	
N I	52.4 ± 2.6 a
N II	54.7 ± 2.2 a
N III	62.4 ± 2.5 b
<i>p</i> Value	0.0003
<i>F</i>	9.14
Year	
2012	55.7 ± 9.8 a
2013	53.3 ± 10.5 a
2014	60.5 ± 11.0 a
<i>p</i> Value	0.1203
<i>F</i>	1.35
Species × nitrogen fertilization level	
<i>p</i> Value	0.7527
<i>F</i>	0.69
Species × year	
<i>p</i> Value	0.2615
<i>F</i>	1.81

*Fresh biomass yield for species is the average yield from all plots of the same species, regardless of fertilization level and year of cultivation, $n = 36$ (3 N levels × 3 years × 4 plots); fresh biomass yield for nitrogen fertilization level is the average yield for the same nitrogen fertilization level, regardless of species and year of cultivation, $n = 84$ (7 species × 3 years × 4 plots); fresh biomass yield for year is the average yield from all plots collected in particular year, regardless of species and nitrogen fertilization level, $n = 84$ (7 species × 3 N levels, × 4 plots)

**Values with the same letters do not differ significantly in the Tukey test, at $p > 0.05$

April and July) and the precipitations were significantly higher than the long-term mean, which favored plants growth. The deficit of precipitation occurred only in September, which could not have a significant impact on the biomass accumulation process.

Generally, increasing in nitrogen fertilization level caused the increase in the fresh biomass yield, although significant differences were observed only between the lowest and the highest N level of VM and RCG IIIC, as well as after application the highest nitrogen dose in the case of RCG IIC (Table 2).

The effect of nitrogen fertilization level was slightly different in the case of dry matter and organic dry matter yield of the tested silages, due to the differences in their DM and ODM contents. The highest dry silage yield was noted for maize, grown at the highest level of nitrogen fertilization (20.5 t ha⁻¹), and the lowest one was observed for VM fertilized with the lowest nitrogen dose (6.4 t ha⁻¹) (Fig. 1).

The rise in nitrogen fertilization level caused the increase in the dry silage yield of maize, RCG IIC, RCG IIIC, and VM. In the case of sunflower and triticale, the lowest dry silage yield was observed at the medium level of fertilization. The opposite effect was obtained for sorghum, where the medium level of N fertilization caused the highest dry silage yield.

There are numerous reports in the literature on biomass yields of tested crops that have been compared with the results of present study (Table 4). According to the Polish Central Statistical Office, the average yield of maize grown for fodder in 2012 amounted to 49.9 t ha⁻¹, which was much lower than fresh biomass yield of maize obtained in this study (67.7 ± 4.0 t ha⁻¹) [23]. Gorzelany et al. [24] stated the fresh biomass yield of maize of 54 t ha⁻¹. Matyka and Książak [25] noted the maize biomass yield in a wide range from 41 to 97 t ha⁻¹, depending on the year of cultivation, nitrogen fertilization level, and localization. Much higher fresh biomass yield of maize was obtained by Barbanti et al. [6] (95.7 t ha⁻¹), which could have resulted from the use of a high nitrogen fertilization level (250 kg ha⁻¹), another climate zone (44° 33' N, 11° 21' E, Italy), and a variety adapted to it (Clip, FAO 700). These authors investigated also the yield of sorghum, which also was much higher than the yield obtained in present study (94.9 and 57.3 ± 3.1 t FM ha⁻¹, respectively). However, fresh biomass yield of the sorghum was closed to the results noted by Matyka and Książak [25] (44–85 t ha⁻¹ depending on the year, nitrogen fertilization level, and region of Poland). In the 5-year study of Burczyk [26], the fresh biomass yield of maize and sorghum was 64.0 and 84.8 t ha⁻¹, respectively, when 120 kg N ha⁻¹ was used. However, the author emphasizes that the amount of precipitation in individual years of the study greatly influenced on the yield of both plants.

The yield of fresh biomass of sunflower obtained in present study (67.3 ± 2.1 t ha⁻¹) was similar to the results of Demirel et al. [36], who obtained a yield of 60.4, 72.6, and 71.8 t ha⁻¹, depending on the stage of maturity at harvest (flowering, milk, and full maturity, respectively). A slightly lower yield of sunflower biomass (from 42.6 to 51.4 t ha⁻¹ depending on the cultivar) was obtained by Güney et al. [37], who applied nitrogen fertilization in the dose of 100 kg ha⁻¹.

The yield of fresh biomass of triticale (from 37.2 to 46.9 t ha⁻¹ depending on the level of nitrogen fertilization) was comparable with the results obtained by other authors. González-García et al. [38] recorded a yield of 37 t ha⁻¹. The results of the previous studies on RCG cultivation proved that the yields of fresh and dry matter of these crops depend

Table 3 Weather conditions in 2012–2014 compared to the long-term period

	Month								
	I–III	IV	V	VI	VII	VIII	IX	X–XII	
Year	Precipitation (mm)								Sum
2012	94	35	39	78	81	84	26	143	578
2013	100	45	70	113	47	11	58	78	521
2014	110	68	171	99	56	106	16	105	729
1951–2006	86	41	54	75	81	67	54	117	569
Year	Temperature (°C)								Mean
2012	−1.0	9.8	15.7	17.1	20.8	18.7	14.1	3.5	8.7
2013	−2.1	8.2	15.2	18.2	19.3	19.3	11.8	5.9	8.6
2014	2.0	10.2	13.4	15.7	20.6	18.4	14.7	5.1	9.5
1951–2006	−1.0	8.1	13.8	17.1	18.7	17.9	13.3	3.6	8.1

strictly on the number of cuts. Kandel et al. [39] and Staršil [40] found a higher yield of dry matter of RCG from two cuts, compared with a single cut (16.0 and 12.0 and 10.1 and 7.8 t ha^{−1}, respectively). This fact is also confirmed by Księżak and Faber [41], who pointed to the lodging and rotting of plants as the reason for lower yields. Geber [43] reported higher yield of fresh biomass from two harvests compared with three and four cuts (86.8–100.3, 63.5–65.5, and 58.8–60.4 t FM ha^{−1}, respectively, depending on the height of the cut). These results are consistent with the results of the present study and confirm that there is no justification for harvesting this species in more than two cuts.

There are no reports in the literature on the influence of the number of cuts on the biomass yield of Virginia mallow. Most of the work concerns the cultivation of this crop for solid biomass, where it is harvested only once, at the end of the growing season. In the studies of Kuś and Matyka [44], at plant density of 20,000 plants per hectare and nitrogen fertilization of 75 kg ha^{−1}, the yield of dry matter of VM was

Fig. 1 Silage yield depending on species and nitrogen fertilization level. RCG IIC, reed canary grass harvested in two-cut system; RCG IIIC, reed canary grass harvested in three-cut system; VM IIC, Virginia mallow harvested in two-cut system

16.4 t ha^{−1} and 18.0 t ha^{−1}, on light soil on heavy soil, respectively. Borkowska et al. [45] report that in their studies, the average yield from 8 years of cultivation exceeded 11 t DM ha^{−1}. Biomass was harvested in November, after the end of the growing season, at a humidity of about 30%. Šiaudinis et al. [47], who conducted research on the yield of VM in the climatic conditions of Lithuania, received an average yield from a single harvest of 6 t DM ha^{−1}.

In the studies on the assessment of energy efficiency of biogas production from crops preserved by ensiling, silage yield is particularly important, as silage is the form of the substrate from which biogas is directly obtained. Differences in the yield of fresh biomass and silage result from losses caused by ensiling, such as silage juice leachate, evaporation, cellular respiration, the activity of plant enzymes, lactic fermentation, and sometimes also from the action of *Clostridium* bacteria and aerobic microorganisms [48]. According to Burczyk [14], these losses amount to 12% while according to Kacprzak et al. [10], even 25% of fresh weight.

Assuming the above value of ensiling losses, Kacprzak et al. [10] obtained maize silage and sorghum yields of 24 and 19 t DM ha^{−1} respectively, which is higher than silage yields resulted from present investigation. Oslaj et al. [28] obtained a yield of maize silage of 24–30 t ha^{−1}, depending on the cultivar and FAO number. Similar studies were conducted by Negri et al. [29] recording a yield of dry matter of silage in the range of 14.96–26.12 t ha^{−1}, increasing with the FAO number. The yield of dry matter of maize silage obtained in the present study is within the above range. According to Negri et al. [29], the yield of triticale silage amounted to 14.58 t DM ha^{−1}, i.e., about twice as much as in present work. However, neither Oslaj et al. [28] nor Negri et al. [29] indicated how they determined the silage yield and whether they took into account any losses during the ensiling process.

Available literature data confirm the positive effect of nitrogen fertilization on biomass yield. Księżak et al. [27], after applying nitrogen fertilization in the doses of 80, 120, and

Table 4 Comparison of biomass yield, biogas (BP) and methane productivity (MP), energy input (E_i) and output (E_o), as well as energy use efficiency (EUE) obtained in present and other studies

	Biomass yield	Biogas productivity (BP)/methane productivity (MP)	Energy output (E_o)	Energy input (E_i)	Energy use efficiency (EUE)	References
Maize	66.1–69.4 t fresh biomass ha^{-1} 20.5–23.3 t dry mass of silage ha^{-1} , depending on N level	7540–10,138 (BP) and 4409–5692 (MP) m^3 ha^{-1} , depending on N level	156–205 GJ ha^{-1} , depending on N level	28.8–33.8 GJ ha^{-1} , depending on N level	5.0–6.1 GJ GJ^{-1} , depending on N level	Present study
Maize	49.9 t fresh biomass ha^{-1}					[23]
Maize	54 t fresh biomass ha^{-1}		37.8 GJ ha^{-1} (based on heating value)	24.3 GJ ha^{-1} (only biomass cultivation)	1.5 GJ GJ^{-1}	[24]
Maize	41 to 97 t fresh biomass ha^{-1} , depending on the year of cultivation, nitrogen fertilization level, and localization					[25]
Maize	95.7 kg fresh biomass ha^{-1} 27.8 t dry biomass ha^{-1} (250 kg N ha^{-1})	8400 $\text{m}^3 \text{ha}^{-1}$ (MP)	286 GJ ha^{-1}	39 GJ ha^{-1}	7.4 GJ GJ^{-1}	[6]
Maize	64 t fresh biomass ha^{-1} (120 N ha^{-1})					[26]
Maize	59.2, 63.1, and 65.3 t fresh biomass ha^{-1} (80, 120, and 160 kg N ha^{-1} , respectively)					[27]
Maize	24 t dry mass of silage ha^{-1}					[10]
Maize	24–30 t dry mass of silage ha^{-1} , depending on the cultivar and FAO number	11,411–16,447 (BP) and 6996–9441 $\text{m}^3 \text{ha}^{-1}$ (MP)				[28]
Maize	14.96–26.12 t dry mass of silage ha^{-1} , increasing with the FAO number	7513–14,804 $\text{m}^3 \text{ha}^{-1}$ (BP)				[29]
Maize		7500–10,200 $\text{m}^3 \text{ha}^{-1}$ (MP)				[30]
Maize		7492 $\text{m}^3 \text{ha}^{-1}$ (BP)				[7]
Maize		4500 $\text{m}^3 \text{ha}^{-1}$ (MP)				[31]
Maize	15–18 t dry mass of silage ha^{-1} , depending on the soil, climate, and fertilization		111–171 GJ ha^{-1}		From 7 to 25 GJ GJ^{-1} , depending on cultivation scenario	[32]
Maize	8.0 t dry biomass ha^{-1}		86.9 GJ ha^{-1}			[33]
Maize			459.3 and 428.0 GJ ha^{-1} (300 and 150 kg N ha^{-1} , respectively) (based on heating value)			[34]
Maize	23.8 t dry biomass ha^{-1} (180 kg N ha^{-1})			21.7 GJ ha^{-1}		[35]
Maize	21.4 t dry biomass ha^{-1}		390 GJ ha^{-1} (based on heating value)	21.3 GJ kg^{-1}	18.4 GJ GJ^{-1}	[5]
Sorghum	From 54.1 to 61.9 t fresh biomass ha^{-1} From 10.2 to 11.1 t dry mass of silage, depending on N level	4887.5–5880.0 $\text{m}^3 \text{ha}^{-1}$ (BP) and 2782.6–3180.4 $\text{m}^3 \text{ha}^{-1}$ (MP)	100–112 GJ ha^{-1} , depending on N level	29.8–35.3 GJ ha^{-1} , depending on N level	3.2–3.8 GJ GJ^{-1} , depending on N level	Present study
Sorghum	94.9 t fresh biomass ha^{-1}	4600 $\text{m}^3 \text{ha}^{-1}$ (MP)	158 GJ ha^{-1}	21 GJ ha^{-1}	12.2 GJ GJ^{-1}	[6]
Sorghum	79.1, 81.7, and 86.1 t fresh biomass ha^{-1} (80, 120, and 160 kg N ha^{-1} , respectively)					[27]
Sorghum						[25]

Table 4 (continued)

	Biomass yield	Biogas productivity (BP)/methane productivity (MP)	Energy output (E_o)	Energy input (E_i)	Energy use efficiency (EUE)	References
Sorghum	44–85 t ha ⁻¹ depending on the year, nitrogen fertilization level, and country region					[26]
Sorghum	84.8 t fresh biomass ha ⁻¹ (120 kg N ha ⁻¹)					[10]
Sorghum	19 dry mass of silage ha ⁻¹					[5]
Sorghum	12.9 t dry biomass ha ⁻¹		228 GJ ha ⁻¹ , based on heating value	18.3 GJ kg ⁻¹	12.6 GJ GJ ⁻¹	
Sunflower	From 62.9 to 70.4 t fresh biomass ha ⁻¹ , From 11.1 to 13.3 t dry mass of silage ha ⁻¹ , depending on N level	1680–1749 m ³ ha ⁻¹ depending on the level of nitrogen fertilization	60.5–62.9 GJ ha ⁻¹ , depending on N level	27.4–32.6 GJ ha ⁻¹ , depending on N level	1.9–2.2 GJ GJ ⁻¹ , depending on N level	Present study
Sunflower	60.4, 72.6, and 71.8 t fresh biomass ha ⁻¹ , depending on the stage of maturity at harvest (flowering, milk, and full maturity, respectively)					[36]
Sunflower	from 42.6 to 51.4 t ha ⁻¹ depending on the cultivar (100 kg N ha ⁻¹)					[37]
Sunflower		2600–4550 m ³ ha ⁻¹ (MP)				[30]
Triticale	From 37.2 to 46.9 t fresh biomass ha ⁻¹ , depending on N level	1574.9–1981.7 m ³ ha ⁻¹ (BP) and 971–1059 m ³ ha ⁻¹ (MP) depending on the level of nitrogen fertilization	35.0–38.1 GJ ha ⁻¹ , depending on N level	22.9–29.9 GJ ha ⁻¹ , depending on N level	1.3–1.6 GJ GJ ⁻¹ , depending on N level	Present study
Triticale	37 t fresh biomass ha ⁻¹					[38]
Triticale	From 8 to 15 t dry biomass ha ⁻¹ and from 7 to 18 t dry biomass ha ⁻¹ (depending on the location, from 0 to 140 kg N ha ⁻¹)		54–280 GJ ha ⁻¹	3.4–11.6 GJ ha ⁻¹	17–39 GJ GJ ⁻¹	[4]
Triticale	15 t dry biomass ha ⁻¹	1700–3500 m ³ ha ⁻¹ (MP)				[30]
Triticale	14.6 t dry biomass ha ⁻¹	7246 m ³ ha ⁻¹ (BP)				[29]
RCG	53.2–72.7 and 45.9–64.9 t fresh biomass ha ⁻¹ , for two- and three-cut system, depending on N level	5009 and 3093 (BP) and 2453 and 1517 m ³ ha ⁻¹ (MP) for two- and tree-cut system, respectively	73.0–104.5 and 41.1–71.8 GJ ha ⁻¹ , for two-cut and three-cut system, depending in N level	17.2–24.6 and 17.8–25.6 GJ ha ⁻¹ , for two-cut and three-cut system, depending on N level	4.2–4.4 and 2.3–2.8 GJ GJ ⁻¹ , for two-cut and three-cut system, depending on N level	Present study
RCG	12.0 and 16.0 t fresh biomass ha ⁻¹ from one-cut and two-cut system, respectively	3735 and 5430 m ³ ha ⁻¹ (MP) for one-cut and two-cut system				[39]
RCG	7.8 and 10.0 t fresh biomass ha ⁻¹ from one-cut and two-cut system, respectively					[40]
RCG	86.8–100.3, 63.5–65.5, and 58.8–60.4 t FM ha ⁻¹ , from two-cut, three-cut, and four-cut system, respectively, depending on the height of the cut					[41]

Table 4 (continued)

	Biomass yield	Biogas productivity (BP)/methane productivity (MP)	Energy output (E_o)	Energy input (E_i)	Energy use efficiency (EUE)	References
RCG		3000 m ³ ha ⁻¹ (MP) (two-cut system)				[42]
RCG		910–1870 m ³ ha ⁻¹ (MP) (three-cut system)				[8]
RCG	From 2 to 12 t dry biomass ha ⁻¹ , depending on location and fertilization		2–129 GJ ha ⁻¹	2–8 GJ ha ⁻¹ , depending on N level	2–36 GJ GJ ⁻¹	[4]
VM	From 39.8 to 50.7 t fresh biomass ha ⁻¹ , from 6.5 to 9.6 t dry mass of silage ha ⁻¹ , depending on N level	1561.7–3336.5 (BP) and 928.0–1407.4 m ³ ha ⁻¹ (MP), depending on N level	33.4–50.7 GJ ha ⁻¹	16.7–22.2 GJ ha ⁻¹ , depending on N level	2.0–2.3 GJ GJ ⁻¹ , depending on N level	Present study
VM	16.4 t ha ⁻¹ and 18.0 t dry biomass ha ⁻¹ , on light soil and on heavy soil, respectively (at plant density of 20,000 plants per hectare and nitrogen fertilization of 75 kg ha ⁻¹)					[43]
VM	11 t ha ⁻¹ (30% humidity, harvest at November)					[44]
VM	4.1, 6.0, and 8.1 t dry biomass ha ⁻¹ (0, 60, and 120 kg N ha ⁻¹)		65 and 128 GJ ha ⁻¹ (based on heating value) depending on the applied dose of nitrogen fertilization			[45]
VM	from 7.1 to 9.2 t dry matter ha ⁻¹ (from 40 to 160 kg N ha ⁻¹)					[8]
VM	from 9.3 to 11.2 t ha ⁻¹ (from 100 to 150 kg N ha ⁻¹)		181 GJ ha ⁻¹	16.2 GJ ha ⁻¹	11.4 GJ GJ ⁻¹	[5]
VM			166.3 GJ ha ⁻¹ (based on heating value)			[46]

160 kg ha⁻¹, obtained fresh biomass yields of maize and sorghum at the level of 59.2, 63.1, and 65.3 t ha⁻¹ and 79.1, 81.7, and 86.1 t ha⁻¹, respectively. Gołębiewska and Wróbel [49] investigated the effect of diversified nitrogen fertilization doses, increasing every 30 kg ha⁻¹ within the range from 0 to 270 kg ha⁻¹, on the yield of two maize cultivars intended for ensiling. The results of the study showed a regular increase in fresh biomass yield up to 240 kg ha⁻¹. The authors add, however, that significantly higher yield compared with the control was recorded only after the application of nitrogen at the dose of at least 90 kg ha⁻¹. Kacprzak et al. [9], in the studies on VM, obtained the increase in the silage yield from 16.7 to 22.9 t ha⁻¹ and from 31.3 to 46.5 t ha⁻¹, under the influence of increasing nitrogen fertilization doses (from 40 to 120 kg ha⁻¹), in the first and second year of cultivation, respectively. Massé et al. [8] observed an increase in the yield of dry matter of VM from 7.1 to 9.2 t ha⁻¹ under the influence of an increase in fertilization dose from 40 to 160 kg N ha⁻¹.

According to Borkowska et al. [45], VM reacts positively to an increase in nitrogen fertilization, although no significant increase in yield between 100 and 200 kg N ha⁻¹ was observed in light soils with poor water retention. Šiaudinis et al. [47] found, however, a statistically significant increase in the yield of VM (4.1, 6.0, 8.1 t DM ha⁻¹) under the influence of increasing nitrogen fertilization doses (0, 60, and 120 kg ha⁻¹, respectively). Szempliński et al. [5] recorded a significant increase in the yield of dry matter of VM from 9.3 to 11.2 t ha⁻¹ with an increase in fertilization level from 100 to 150 kg N ha⁻¹.

Lewandowski and Schmidt [4] conducted the research on the energy efficiency and nitrogen application in the cultivation of energy crops, depending on the location, and recorded a significant increase in triticale yield from 8 to 15 t DM ha⁻¹ and from 7 to 18 t DM ha⁻¹, together with an increase in nitrogen fertilization from 0 to 140 kg ha⁻¹.

The research on the yield and fertilization of sunflower seeds was conducted by Wilczewski et al. [50]. The authors

observed the 14.6% increase in dry matter yield after the application of 45 kg N ha⁻¹ in comparison with the control and a 7% increase in the yield between 45 and 90 kg N ha⁻¹.

Biogas and Methane Productivity and Energy Output

Many studies showed that in the case of energy production from biogas, the most important is its yield per unit area, also called as biogas productivity (BP) [2, 7, 30]. In the literature, there are numerous reports concerning research on biomass yield optimization aimed at maximizing biogas and methane productivity per hectare. However, the results of these studies very often indicated a discrepancy between high biomass yield and its best quality that meets the requirements for substrates for biogas production. Available literature data on improvement of BP showed that earlier harvest dates often result in better BY and MY but are nevertheless associated with lower biomass yield. Delaying the harvest date results in an increase in biomass yield but poses a risk of lignification and reduction of methane fermentation efficiency [2, 42].

The results of present study indicated that the majority of the tested plant species showed an increase in BP, MP, as well as E_o with the increase in the dose of nitrogen fertilizer, which resulted both from the increase in biomass yield and BY and MY [1]. The exception was sorghum, for which the highest values of BP, MP, and E_o were recorded at the medium level of nitrogen fertilization. In the case of maize and triticale, no directly proportional increase in BP, MP, and E_o was observed, as the lowest values of these parameters were observed in the case of medium nitrogen fertilizer level (Figs. 2 and 3).

High biomass yield and efficiency of methane fermentation process caused the highest BP, MP, and E_o that was observed for maize, followed by sorghum and RCG IIC. The lowest values of BP, MP, and E_o were recorded for triticale (Figs. 2 and 3). It is worth noting the higher BP and MP of RCG IIC, despite slightly lower BY and MY, in comparison with the

Fig. 2 Productivity of biogas (BP) and methane (MP) per unit area. RCG IIC, reed canary grass harvested in two-cut system; RCG IIIC, reed canary grass harvested in three-cut system; VM IIC, Virginia mallow harvested in two-cut system

Fig. 3 Energy output (E_o) depending on plant species and nitrogen fertilization level. RCG IIC, reed canary grass harvested in two-cut system; RCG IIIC, reed canary grass harvested in three-cut system; VM IIC, Virginia mallow harvested in two-cut system

RCG IIIC [1]. This relationship can be explained by a much higher dry matter yield of RCG IIC silage.

The BP and MP from maize silage varied between 7540 and 10,138 and 4409 and 5692 m³ ha⁻¹, respectively, depending on the level of nitrogen fertilization. Significantly higher values of BP and MP were obtained by Oslaj et al. [28] (11411–16,447 and 6996–9441 m³ ha⁻¹, respectively), and significantly higher methane productivity was also reported by Amon et al. [30] (7500–10,200 m³ ha⁻¹) (Table 4). The BP from maize obtained in present study was similar to the results recorded by Goliński and Jokš [7] (7492 m³ ha⁻¹) as well as to the lower limit of the results achieved by Negri et al. [29] (7513–14,804 m³ ha⁻¹). Moreover, comparable MP was found by Gröblichhoff et al. [31] (4500 m³ ha⁻¹). Kacprzak et al. [10], Matyka and Księżak [25], and Barbanti et al. [6] compared the productivity of biogas from maize and sorghum. All authors unanimously confirm the increased competitiveness of maize. Barbanti et al. [6] recorded MP of maize and sorghum of 8400 and 4600 m³ ha⁻¹, which was associated with E_o of 286 and 158 GJ ha⁻¹, respectively. These values are significantly higher than those obtained in the present study (156–205 and 100–112 GJ ha⁻¹ for maize and sorghum, respectively, depending on the level of nitrogen fertilization), as well as the values recorded for maize by Gerin et al. [32] (111–171 GJ ha⁻¹) and Wünsch et al. [33] (86.9 GJ ha⁻¹). For comparison, Matyka and Księżak [24], conducting studies in Poland, obtained biogas productivity values similar to the results of this study (8199–12,568 and 6794–11,499 m³ ha⁻¹ for maize and sorghum, respectively, depending on the location and year of cultivation). Similar results were obtained also by Kacprzak et al. [10], who reported BP for these plant species in the range of 7810–8690 and 6426–8455 m³ ha⁻¹, respectively, depending on the level of nitrogen fertilization.

Studies on the MP of triticale and sunflower were conducted by Amon et al. [30]. The results obtained by them (1700–

3500 and 2600–4550 m³ ha⁻¹, respectively) significantly exceeded the values recorded in the present study (971–1059 and 1680–1749 m³ ha⁻¹, respectively, depending on the level of nitrogen fertilization). Negri et al. [29] found the BP from triticale at the level of 7246 m³ ha⁻¹, which resulted mainly from a very high BY (487 m³ t⁻¹ ODM), as well two times higher silage yield (15 t ha⁻¹) than that obtained in present research (7.0–7.8 t ha⁻¹ depending on the level of nitrogen fertilization) (Fig. 2). The BP and MP recorded in present studies for RCG were 5009 and 2453, as well as 3093 and 1517 m³ ha⁻¹, for the two- and tree-cut system, respectively. The MP values obtained for the two-cut system are similar to Gröblichhoff et al. [31] (3000 m³ ha⁻¹) and for the three-cut system to Massé et al. [8] (910–1870 m³ ha⁻¹).

The current research on the productivity of energy from Virginia mallow is limited to its cultivation for solid biomass. There are no results on BP and MP for this plant. Based on yield and heating value, Borkowska et al. [46] obtained the energy productivity (E_o) of 166.3 GJ ha⁻¹ while Šiaudinis et al. [47], 65 and 128 GJ ha⁻¹, depending on the applied dose of nitrogen fertilization.

The results of previous studies on the influence of nitrogen fertilization on E_o have showed the increase in E_o , mainly due to the increase in biomass yield (Table 4). Wunsch et al. [33] proved the increase in the energy efficiency of biogas production from different crops, monoculture maize, ryegrass, and Jerusalem artichoke, and two types of crop rotation including maize, winter cereals, and catch crops, caused by the increase in the level of nitrogen fertilization.

Ning et al. [34] obtained a 7% higher E_o from maize grown at the fertilization level of 300 kg N ha⁻¹ (459.3 GJ ha⁻¹), in

comparison with the cultivation at 150 kg N ha⁻¹ (428.0 GJ ha⁻¹). Significantly higher E_o , compared with the results of present study, resulted from the fact that heat of combustion was used for calculation, instead of biogas yield.

Kacprzak et al. [10], as well as Massé et al. [8], noted the effect of nitrogen fertilization not only on biomass yield but also on BY. Kacprzak et al. [10] recorded an increase in biogas productivity, due to increasing nitrogen fertilizer doses in the case of sorghum (from 6429 to 8455 m³ ha⁻¹) while a decrease in the case of maize (from 8690 to 7810 m³ ha⁻¹). The negative effect of nitrogen fertilization on BY was responsible for the decrease in BP and MP. However, the authors do not give any potential reasons for this negative influence. Massé et al. [8] found a positive effect of nitrogen fertilization on the BP of RCG, due to the fact that the MY decreased only by 9% and the yield increased by 31%.

Energy Efficiency of Biogas Production

The analysis of the cumulative energy demand showed that the cultivation of maize and sorghum had the highest E_i of 28.8–33.8 and 29.8–35.3 GJ ha⁻¹, respectively, depending on the level of nitrogen fertilization (Fig. 4). This resulted from the application of higher doses of nitrogen fertilizer in their cultivation, compared with the cultivation of other plant species, as well as significant energy demand for biomass harvest, which was due to the high biomass yield. The least energy-consuming was the cultivation of VM and RCG IIC and RCG IIIC (16.7–22.2, 17.2–24.6, and 17.8–25.6 GJ ha⁻¹, respectively), as these are perennial species which do not require annual soil tillage and sowing.

Fig. 4 Energy input (E_i) of biomass cultivation. RCG IIC, reed canary grass harvested in two-cut system; RCG IIIC, reed canary grass harvested in three-cut system; VM IIC, Virginia mallow harvested in two-cut system

Fig. 5 Factors of energy use efficiency (EUE) of biogas production from the tested plant species, depending on nitrogen fertilizer level. RCG IIC, reed canary grass harvested in two-cut system; RCG IIIC, reed canary grass harvested in three-cut system; VM IIC, Virginia mallow harvested in two-cut system

The E_i increased together with the increase in nitrogen fertilization. This should be explained by a significant energy demand for nitrogen fertilizer production, as well as higher biomass yield, resulting in the increase in energy demand for the harvesting and transporting of biomass. Among all sources of energy input, materials (including nitrogen fertilizers) accounted for the highest share, while the labor constituted the lowest one (Fig. 4).

It is worth noting that despite a low E_o for RCG IIC, the EUE of this crop significantly exceeded EUE of sorghum. As a result, the energy efficiency of biogas production from the RCG IIC was only slightly lower than from maize. Together with the increase in nitrogen fertilization, there was an increase in the EUE for RCG IIIC and Virginia VM but the decrease for sunflower and triticale. No clear influence of fertilization level on EUE for maize, sorghum, and RCG IIC was found. Biogas production from the RCG IIC and sorghum was the most energy efficient, when they were cultivated at medium nitrogen fertilization doses. On the contrary, cultivation of maize at this fertilizer level resulted in the lowest EUE (Fig. 5).

Szempliński and Dubis [35] recorded an energy intensity of maize cultivation of 21.7 GJ ha^{-1} , with the biomass yield of $23.8 \text{ t DM ha}^{-1}$ and fertilization of 180 kg N ha^{-1} , while Barbanti et al. [6] noted 39 GJ ha^{-1} with a yield of $27.8 \text{ t DM ha}^{-1}$ and fertilization of 250 kg N ha^{-1} (Table 4). Barbanti et al. [6] also reported on the E_i of cultivation of sorghum and perennial grasses, which, at 120 kg N ha^{-1} , amounted to 21 and 15 GJ ha^{-1} , respectively. They also added that, due to such large differences in the energy demand of the crops, the EUE of biogas production from maize was much lower than from sorghum and the grass species. In the research of Gerin et al. [32], the EUE for biogas production from maize ranged from 7 to 25 GJ GJ^{-1} , while in the case of grasses, it ranged from 7 to 14 GJ GJ^{-1} , depending on the cultivation method.

Lewandowski and Schmidt [4] recorded E_i for reed canary grass cultivation in the range of $2\text{--}8 \text{ GJ ha}^{-1}$, depending on the level of nitrogen fertilization. The share of inputs related to the production of nitrogen fertilizers amounted to 61–76%, respectively. However, Szempliński et al. [5] confirmed much lower E_i for the cultivation of VM than for maize and sorghum (16.2 ; 21.3 and 18.3 GJ ha^{-1} , respectively). Moreover, they also recorded a significant decrease in the EUE between the medium-input (lower nitrogen fertilization level) and high-input (higher nitrogen fertilization level) technology of cultivation of these crops.

As Barbanti et al. [6] emphasized, perennial crops are a noteworthy alternative to maize, mainly due to the low energy demand for their cultivation. However, they added also that the improvement in such biomass biodegradability is required, by optimization of harvest time and technology, or by pre-treatment methods, to increase net energy productivity per unit area. Moreover, environmental benefits are also very important and worth mentioning. Perennial crops have the advantage over annuals that they protect the soil against erosion, leaching of nutrients and depletion of organic matter. Börjesson [51] stated that negative environmental effects from current agriculture practices such as erosion, nutrient leaching, and the emission of greenhouse gases may be reduced when annual crops are replaced by dedicated perennial energy crops.

Conclusions

Increasing N fertilization level resulted in the increase in BP, MP, and E_o , but also the increase in E_i , which caused the decrease in the EUE in some species. The application of increased level of nitrogen fertilization did not caused hypothesized, drastic decrease in EUE, despite the significant increase

in E_i , due to high energy demand for fertilizers production. The E_i was significantly lower for perennials. For this reason, EUE of RCG IIC was comparable with EUE for maize, despite the much lower dry silage yield and MP. The harvest of RCG in more than two cuts is unjustified.

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