Biomass Conversion and Biorefinery (2023) 13:3309–3317
https://doi.org/10.1007/s13399-021-01316-0

ORIGINAL ARTICLE

Green mass to biogas in Ukraine—bioenergy potential of corn and sweet sorghum

Mykola Grabovskyi[1] · **Mykola Lozinskyi**[2] · **Tetiana Grabovska**[3] · **Hynek Roubík**[4]

Received: 2 December 2020 / Revised: 15 January 2021 / Accepted: 18 January 2021 / Published online: 28 January 2021

Abstract

In current times, we heavily rely on the use of fossil fuels, which bring negative impacts on climate change; therefore, it is essential to place more focus on all renewable alternatives, especially bioenergy crops. This study is focused on the quantification and evaluation of biogas production from either corn or sweet sorghum, as well as their combination. The field data were obtained from 2013 to 2016 in central Ukraine. The Buswell equation was used for the calculation of the theoretical biogas and methane potential. The results show that corn and sweet sorghum were intercropping and had higher on 8.5–37.8% of green mass, and 9.5–28.7% estimated yield of biogas compared to the single use of these crops. Due to the higher dry matter content, the specific yield of biogas per unit of applied corn silage was higher by 33.7–50.6% compared to sweet sorghum. However, biogas yield was increased by 9.2–13.0% when using a mixture of corn silage and sweet sorghum compared to sweet sorghum alone. Results of biogas and methane yield per unit area show that the highest rates, 10.2 and 5.9 thousand m^3/ha, were obtained in the combined growing of hybrids of sweet sorghum Dovista and corn Monica 350. Even though theoretical calculations have some limitations, the gathered results provide essential information on the potential of the examined green mass for biogas potential in Ukraine. Such information are crucial to be known for economic and energy reasons.

Keywords Varieties · Hybrids · Dry matter · Methane · Green mass yield

1 Introduction

The formation of the European countries' biofuel market shows that the most important among renewable energy resources is biomass: carbon containing (vegetable biomass, waste of processing industry) and sugar containing (sugar beet, cane, sweet sorghum). Evidently, biomass alone cannot cover the growing needs of modern civilization, but even 6–10% of their satisfaction through the proper utilization of organic matter is noteworthy for including generating electricity, heating homes, fuelling vehicles, and providing process heat for industrial facilities [1, 2].

The equations of Buswell and Mueller [3], as well as Boyle [4], assume a complete conversion of biomass. This results in an

---

✉ Mykola Grabovskyi
nikgr1977@gmail.com

✉ Hynek Roubík
roubik@ftz.czu.cz

Mykola Lozinskyi
lozinskk@ukr.net

Tetiana Grabovska
grabovskatatiana@gmail.com

[1] Department of Technologies in Crop Production and Plant Protection, Agrobiotechnology faculty, Bila Tserkva National Agrarian University, pl. 8/1 Soborna, Bila Tserkva, Kyivska Oblast 09117, Ukraine

[2] Department of Genetics, Breeding and Seed Production of Crops, Agrobiotechnology Faculty, Bila Tserkva National Agrarian University, pl. 8/1 Soborna, Bila Tserkva, Kyivska Oblast 09117, Ukraine

[3] Department of General Ecology and Ecotrophology, Ecology faculty, Bila Tserkva National Agrarian University, pl. 8/1 Soborna, Bila Tserkva, Kyivska Oblast 09117, Ukraine

[4] Department of Sustainable Technologies, Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, Kamýcka 129, 16500 Prague Suchdol, Czech Republic

overestimation of gas yields, and these models assume that substrates are individually fermented and are not part of complex feedstock mixtures as it is usually the case these days. The theoretical gas yields based on the Boyle model can provide useful information and allows the comparison of the potential of different materials based on their composition. This study provides a simple model, which does not require a large number of inputs and can be applied to a large number of feedstock as long as the user has data from the ultimate analyses for the elements of carbon, hydrogen, oxygen, nitrogen, and sulfur [5].

Many substrates of plant origin can be used effectively for biogas production (corn, sugar beet, sweet sorghum, cereals, and legumes). These energy crops have a higher methane output than animal excrement; however, they also have longer hydraulic retention time [6, 7]. The most important parameter in the selection of plant species for biogas production is the amount of energy produced per hectare, which is determined mainly by biomass output and methane productivity [8].

The most useful type of plants for biogas production are those that have a high content of fast-fermenting carbohydrates and a low content of lignin and structural carbohydrates (cellulose and hemicellulose) [9]. In addition, they are easy to store and accessible throughout the year. The technology of growing these crops should be simple; they must be tolerant to weeds, pests, diseases, and droughts and have good winter resistance as well as low nutritional requirements [10]. Not only the genetic characteristics of plants but also the technology of their cultivation has a significant impact on the biomass yield and biogas output potential. Harvesting time and the ripeness phase of crops play an important role in the formation of silage quality and maximum methane output [11].

In comparison to other energy crops, corn for silage has more advantages due to lower costs of cultivation and storage; its methane content is about 52–58% [12–14]. One ton of corn silage can produce 200–400 m^3 of gas [12]. The composition of organic matter and its biodegradability are key determinants of the methane output potential of corn silage [15]. In turn, the composition of corn organic matter depends on several factors: the location of cultivation, climatic conditions, corn hybrid, the duration of the growing season, the technology of cultivation, and the method of corn silage [16].

The widespread use of corn as a monoculture for biogas production has a negative impact on the environment in terms of biodiversity loss, a reduction in food and feed production, increased pest development, and nutrient use [17]. Other crops for biogas production such as sunflower, Miscanthus, millet, hemp, sorghum, and Sudan grass have been proposed as an alternative to corn [18]. However, finding alternative crops to corn or combining corn with other crops should stay among aims, especially for regions were corn is not so traditionally grown crop.

In the arid conditions of southern Ukraine, sweet sorghum is a promising crop for biogas production. Also sweet sorghum is better adapted to the semiarid marginal lands than corn due to its superior drought tolerance and low input requirement. An area of 500 thousand ha of sorghum can yield up to 10.0 t/ha of which it is possible to obtain about 4.4 billion m^3 of methane [19].

In Ukraine, when growing corn for silage in area of 1 million ha, a yield of up to 30 t/ha green mass can be obtained of which it is possible to produce 3.3 billion m^3 of methane per year. With an increase in the yield of green mass to 50 t/ha, the methane yields will amount to 5.6 billion m^3 per year [20]. The share of corn silage mixed with other co-substrates in biogas plants can be 2–99% [21], which is based on improving the yield appropriately. Biogas plants are the most widespread (25%), where the share of corn silage in the mixture is 40–60%. In most cases, corn silage is used with 1–5 substrates. The use of manure as a monosubstrate for biogas production is, in most cases, economically feasible and requires the addition of other substrates [22].

The results obtained by Slovak University of Agriculture in Nitra have confirmed the suitability of combining either sorghum silage or potatoes with corn silage as a co-substrate in biogas devices. The values and specifics of the biogas production were significantly higher in both observed substrate mixtures than in digesting of only liquid manure and slurry [23].

The potential of methane output from corn silage is influenced by several factors, the main ones being the duration of the growing season of hybrids. With the increase of vegetation duration from 97 to 131 days, the specific output of methane per unit mass of dry organic matter of corn silage falls noticeably. At the same time, the output of methane from 1 ton of silage increases by 1.9–2.5 times. The highest output of methane can be obtained by the fermentation of the whole corn plant in biogas plants. Fermentation of the corn grain mixture with cobs, only grains, or only stems without grain and cobs results in a 43–70% decrease in methane output compared to the whole plant. The maximum yield of methane (CH_4) from late-maturing corn hybrids is 7.1–9.0 thousand m^3/ha, for early and medium-early corn—5.3–8.5 thousand m^3/ha [24].

Sweet sorghum has biomass composition similar to corn biomass, but it also has a higher level of productivity [25]. The yield of green mass of sweet sorghum averages 60–80 t/ha and can reach up to 100 t/ha with a content of about 22% of dry matter. Approximately 1000 m^3 of biogas with 54% methane content can be obtained from 1 ton of sorghum silage [26]. The study on corn and sweet sorghum for biogas production has been carried out for a long time in different countries. Nevertheless, there is insufficient information on the feasibility of their joint cultivation as bioenergy crops. Therefore, there is a need for research of biogas and methane output in a single and intercropping way to grow corn and sweet sorghum. Some studies on the selection of plant species for biogas production have been conducted in Europe, but there is no data available to assess the potential of biogas production from different plant species in Ukraine and further East European regions. The lack of available information was also recently confirmed by Mazur et al. [27].

Therefore, this research aims to determine the output of biogas and the productivity of sweet sorghum and corn depending on the varietal composition and sowing method.

2 Materials and methods

2.1 Site description

The field data were obtained in 2013–2016 at the research field of Bila Tserkva National Agrarian University, located 80 km from Kyiv (49° 46′ 14.8” N, 30° 04′ 22.0″ E). The soil of the experimental plot was typically leached black soil. Agrochemical characteristics of the soil are as follows: the content of humus is 2.7–3.2%, nitrogen 90–120 mg/kg, mobile phosphorus 130–160 mg/kg, and exchangeable potassium 120–130 mg/kg. The climate of the area is moderately continental with an average rainfall of 538 mm, a mean annual temperature of 8 °C, while the average annual relative humidity is about 77%.

Meteorological conditions in the years of research are almost typical for all meteorological indicators for this region. Deviations of air temperature and precipitation from average long-term values did not approach critical, except for 2012 and 2015, when there were periods that negatively affected the growth and development of plants and the productivity of corn and sweet sorghum.

2.2 Experimental design and field layout

The research was carried out according to the following scheme: sweet sorghum and corn varieties and hybrids (factor A), (1) Silosne 42, (2) Dovista, (3) Monica 350, and (4) Bistritsa 400; and method of sowing (factor B), (1) one-species and (2) intercropping. The sowing area was 56.0 m^2, the accounting area was 33.6 m^2, and the experiment was carried out in three repetitions. The replicating variants were randomized.

In autumn, plowing was carried out to a depth of 23–25 cm, and in spring there are two cultivations, the first to a depth of 10–12 cm and the second before sowing to a depth of 7–8 cm. The sowing of corn and sweet sorghum was carried out in the first part of May with a row distance for both crops of 70 cm by seeder Klen-2.8. Row ratio in combined crops of corn and sweet sorghum is 2:2. Intercropping sowing was performed by the selection of disks in the seeder.

2.3 Yield parameters

The dry matter content was determined by sampling plants weighing up to 1 kg, which were then thoroughly crushed. Two pieces of 10 g each were taken from the crushed samples. The pieces were there after dried to a dry weight in a drying cabinet at a temperature of + 105 °C until constant weight reached. Before harvesting, samples were taken to determine the structure of the crop (the ratio of leaves, stems, panicles, and kernels).

2.4 Harvesting

Determination of the yield of green mass of corn and sweet sorghum was performed in the waxy ripeness phase of grain. The calculation of the yield of green mass was determined by weighing the plants from the accounting area. The yield per hectare (kg) was extrapolated from the net plot.

2.5 Chemical quality of biomass

The determination of the chemical quality indices of corn green mass and sweet sorghum was carried out in the laboratory of analytical researches, Institute of bioenergy crops and sugar beets. The chemical analysis was performed according to the following standards: sampling methods – State standard of Ukraine ISO 6497:2005, determination of total nitrogen was performed using the Kjeldahl method - State standard of Ukraine ISO 5983–2003, phosphorus according to State standard of Ukraine ISO 6491:2004, potassium according to State standard of Ukraine ISO 7485:2003, carbon according to State standard of Ukraine B.2.1-16:2009.

2.6 Data analysis

All data were analyzed with the SAS software (Version 7.2) after first undergoing an ANOVA to determine statistical significance for the treatment effects ($P = 0.05$ or less). Significant differences between individual means were determined using the least significant difference test (LSD).

3 Results

The analysis of the structural elements of corn and sweet sorghum shows that the intercropping cultivation of these crops reduces the proportion of panicles, kernels, and leaves, and the proportion of stems increases, compared to single cropping system. Thus, in single cropping system, sowing of corn hybrid Monica 350 and Bistritsa 400, the proportion of kernels is 42.1 and 41.4% and for intercropping cultivation with sweet sorghum is 40.4–40.5% and 40.6–40.7% (Table 1).

Table 1 Content of leaves, stems, kernels, and panicles in the green mass of corn and sweet sorghum (waxy ripeness phase of grain) (average 2013–2016)

Variety, hybrid	Content*							
	Leaves		Stems		Kernels		Panicles	
	g	%	g	%	g	%	g	%
Silosne 42 (sweet sorghum)	68.7	11.2	428.6	70.1	–	–	114.5	18.7
Dovista (sweet sorghum)	86.7	11.8	514.3	70.1	–	–	132.2	18.0
Monica 350 (corn)	153.2	14.4	462.5	43.5	447.8	42.1	–	–
Bistritsa 400 (corn)	165.0	14.8	489.1	43.8	462.3	41.4	–	–
Silosne 42 + Monica 350	59.8	11.2	451.7	73.3	–	–	104.4	17.0
	147.3	14.0	478.1	45.5	425.0	40.5	–	–
Silosne 42+ Bistritsa 400	63.4	10.2	452.6	73.2	–	–	102.7	16.6
	157.0	14.1	502.5	45.3	450.1	40.6	–	–
Dovista + Monica 350	82.4	11.4	520.3	71.7	–	–	122.5	16.9
	150.2	14.2	480.7	45.4	427.6	40.4	–	–
Dovista + Bistritsa 400	83.5	11.4	525.1	72.0	–	–	120.8	16.6
	156.1	14.0	506.0	45.4	453.5	40.7	–	–
LSD ($P \leq 0.05$)	6.9		9.5		8.7		2.1	

[*] In intercropping crops, the first line is for sweet sorghum, the second is for corn

In single-sowing crops of sweet sorghum Silosne 42, the share of the panicles was 18.7%, of the Dovista hybrid 18.0%, and intercropping with corn 16.6–17.0% and 16.6–16.9%. The content of corn and sweet sorghum leaves is also higher in single crops, 11.2–11.8% and 14.4–14.8%; because of other components, it is reduced in intercropping crops on 0.8–0.9% in sweet sorghum and on 0.2–0.8% in corn.

The dry matter content varied depending on the crop and sowing method presented in Table 2.

The highest values of this index were in plants of corn hybrids, 30.7 and 32.2%, which is higher than in sweet sorghum on 7.4–9.9%. With the intercropping sowing of these crops, the dry matter content of the whole plant remained practically the same compared to the one-species crops.

The highest dry matter was in corn kernels, 62.5-63.0%, and sweet sorghum panicles, 60.3–61.1%. In the corn stems, the dry matter content was in the range of 26.0–27.1%, and in the sweet sorghum 20.1–21.4%.

The yield of the green mass of sweet sorghum exceeds corn. Thus, on average during the years of research, sweet sorghum in a single crop provides a yield of green mass 67.8–76.1 t/ha, which is 11.6–24.0 t/ha higher than that of corn (Table 3).

Table 2 The content of dry matter in leaves, stems, kernels, and panicles of corn and sweet sorghum (waxy ripeness phase of grain) (average 2013–2016)

Variety, hybrid	Content of dry matter, %				
	Leaves	Stems	Kernels	Panicles	The whole plant
Silosne 42 (sweet sorghum)	28.2	20.4	–	60.3	22.3
Dovista (sweet sorghum)	30.1	21.2	–	60.8	23.4
Monica 350 (corn)	29.6	26.6	62.5	–	30.7
Bistritsa 400 (corn)	30.4	27.1	63.0	–	32.2
Silosne 42 + Monica 350	28.0	20.1	–	60.7	22.4
	29.5	26.4	62.8	–	30.5
Silosne 42+ Bistritsa 400	28.4	20.5	–	60.5	22.6
	30.1	27.5	63.5	–	32.0
Dovista + Monica 350	30.4	21.2	–	60.3	23.2
	29.3	26.0	63.0	–	30.4
Dovista + Bistritsa 400	30.6	21.4	–	61.1	23.6
	30.5	27.3	62.8	–	32.5
LSD ($P \leq 0.05$)	0.3	0.4	0.3	0.2	0.6

[*] In intercropping crops, the first line is for sweet sorghum, the second is for corn

Table 3 Yield of green mass of corn and sorghum sugar, t/ha

Variety, hybrid	2013	2014	2015	2016	Average
Silosne 42 (sweet sorghum)	71.8	73.9	45.9	79.5	67.8
Dovista (sweet sorghum)	80.2	82.7	51.2	90.1	76.1
Monica 350 (corn)	53.6	57.5	40.3	57.0	52.1
Bistritsa 400 (corn)	57.8	61.2	43.2	62.7	56.2
Silosne 42 + Monica 350	80.7	84.9	53.2	88.5	76.8
Silosne 42+ Bistritsa 400	83.6	87.5	55.3	92.4	79.7
Dovista + Monica 350	86.6	91.0	57.0	95.9	82.6
Dovista + Bistritsa 400	89.5	93.6	59.0	99.9	85.5
LSD ($P \leq 0.05$)	2.8	2.7	2.4	3.3	3.1

In the intercropping sowing of these crops, on average, the yield of green mass was higher than in the single sowing on 9.0–30.5 t/ha. The highest level of green mass yield was noted under the intercropping sowing of hybrids corn Bistritsa 400 and sweet sorghum Dovista—85.5 t/ha.

When replacing the hybrid Bistritsa 400 with Monica 350, the yield decreases by 3.4 to 82.6 t/ha. The use as a component of sweet sorghum Silosne 42 provides a yield of green mass 76.8–79.7 t/ha, which is on 5.6–5.8 t/ha less than the variants where the Dovista hybrid was sown.

In our study, the yield of green mass of corn and sweet sorghum depended on the hydrothermal conditions of the growing season. Thus, in the more favorable 2013–2014 and 2016, it was higher on 24.6–43.2% compared to 2015.

The regression dependence between the estimated biogas output and the yield of green mass and the dry matter content of corn and sweet sorghum are shown in Figs. 1 and 2.

The correlation-regression analysis revealed differences in the formation of polynomial trends, which have high values of the determination coefficient ($R^2 = 0.83$–0.88). It shows a close correlation between the studied indices. Theoretical regression lines of the dependence of the green mass yield and the estimated output of biogas in single-species crops of corn and sweet sorghum have almost the same orientation, but depending on the dry matter content of corn and sweet sorghum and estimated output of biogas, intercropping crops take a middle place.

In the waxy ripeness phase, the nitrogen content of sweet sorghum was 1.09–1.14%, phosphorus 0.32–0.39%, potassium 1.11–1.16%, and carbon 38.06–38.59%. In corn hybrids, nitrogen, phosphorus, and carbon were higher on 0.27–0.29%, 0.04–0.12%, and 1.21–1.27%, respectively, and potassium on 0.17–0.23%. According to the content of these elements, the mixture of corn and sweet sorghum occupies an intermediate position between these crops (Table 4).

The minimum values for the estimated output of biogas and methane, based on the content of nutrients in the green mass, are noted in the sweet sorghum Silosne 42–103.1 and 59.8 l × kg of silage weight. It was the maximum in the corn hybrid Bistritsa 400–155.3 and 90.0 l × kg (Fig. 3).

3.1 Biogas output

The biogas output was calculated based on the Buswell and Mueller [3] equation derived from the stoichiometry balance between the quantities of organic matter (expressed by the formula $C_aH_bO_cN_d$) to be biodegraded and the gaseous products resulting from its anaerobic biodegradation (Eq. 1):

$$C_aH_bO_cN_d + \left(a - \frac{b}{4} - \frac{c}{2} + \frac{3d}{4}\right) * H_2 0 \rightarrow \left(\frac{4a + b - 2c - 3d}{8}\right) * CH_4 + \left(\frac{4a - b + 2c + 3d}{8}\right) * CO_2 + d * NH_3 \qquad (1)$$

This equation describes the complete degradation of all the carbon present in the substrate, also considering the fraction of organic matter that commonly is not transformed, that is, the carbon necessary to the microorganism metabolism (5–10% of the inlet carbon), the portion slowly degradable (lignin, cellulose) that has not enough time to be digested, and the not biodegradable fraction.

This general balance and, in particular, its expression as the maximum theoretical biogas and methane-specific production were applied to the considered samples. For biogas Eq. 2 and for methane Eq. 3:

$$Biogas \left(\frac{m^3}{kg_{vs}}\right) = a * \frac{22.415}{12a + b + 16c + 14d} \qquad (2)$$

$$Methane \left(\frac{m^3}{kg_{vs}}\right) = \frac{\left(\frac{4a + b - 2c - 3d}{8}\right) * 22.415}{12 + b + 16c + 14d} \qquad (3)$$

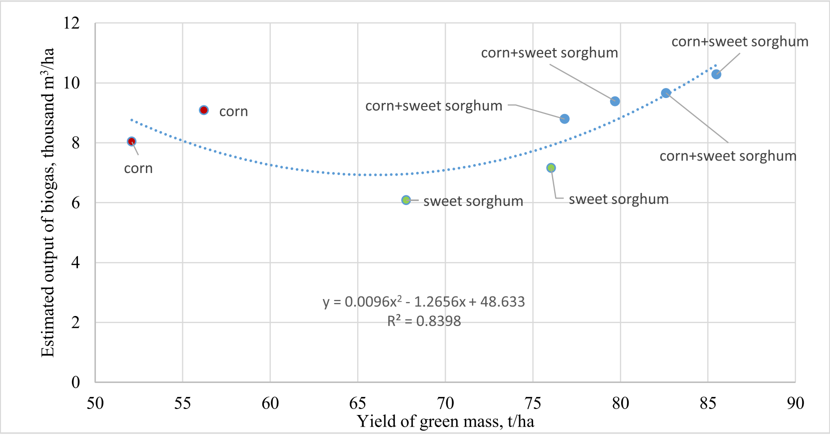
In co-growing these cereal crops, the best variant was Dovista + Monica 350. The estimated output of biogas and methane from the unit of the applied mixture of corn and sweet sorghum silage was 138.2 and 80.4 l × kg.

Converted to 1 ha of sown area, biogas and methane outputs of sweet sorghum were 7.0–8.4 and 4.1–4.9 thousand m^3/ha, corn 5.7–6.5 and 3.3–3.7 thousand m^3/ha, and in the intercropping cultivation of these crops 9.1–10.2 and 5.3–5.9 thousand m^3/ha (Fig. 4).

4 Discussion

The theoretical study can support the increased application of anaerobic technology as a sustainable waste treatment option and a viable alternative to other energy production processes [28].

Fig. 1 Regression dependence between the yield of green mass and estimated output of biogas in single and intercropping crops of corn and sweet sorghum



The existing models vary concerning their objectives and complexity. There are comparatively simple models developed exclusively to calculate the maximum biogas rate, which will theoretically be produced from organic substances. Another also still comparatively simple type of models for calculating a biogas rate includes degradation or digestion rates because not every component of the substrate is degradable at the same conversion rate [28].

Simple ways to calculate the biogas production of organic matter are the models of Buswell and Mueller [3], Boyle [4], Baserga [29], Keymer and Schilcher [30], or Amon et al. [16]. These time-independent models are based on data for basic elements or components of organic matter and result only in values for the production of methane and carbon dioxide. Since the models are time independent, no prediction of required retention time is possible. This is particularly useful, as it allows us to estimate the theoretical biogas and methane potential, which provides a way to evaluate the technical and economic feasibility of the process and the substrates. It also serves well, as preliminary work for laboratory-scale and pilot-scale research [31].

Biogas and methane output calculated by Buswell equations higher than the one gained in reality by anaerobic digestion of biomass are being consumed during the process and converted into microorganisms. All the theoretical calculations are based upon the assumption that the substrate is completely degraded or organic material completely oxidized to form methane. This assumption is ideal because the degradation depends on so many factors among which are temperature, ph, particle size, and mixing rate. Assumption or empirical estimation accounts for these factors.

To investigate the kinetics of biogas production, the whole biogas process has to be considered: the growth of microorganisms, degradation of substrate, and the formation of products. Substrate degradation and gas production change over the retention time, whereby growth requirements for microorganisms change permanently. The kinetics of bacterial growth provides the basis of the degradation process and is strongly dependent on growth requirements and the medium [32].

Nevertheless, the calculation of the theoretical output of biogas is a useful way of indicating materials with bioenergy potential, especially in Ukraine, where there is insufficient scientific information on this topic. The mathematical models

Fig. 2 Regression relationship between dry matter content and estimated output of biogas in single and intercropping crops of corn and sweet sorghum

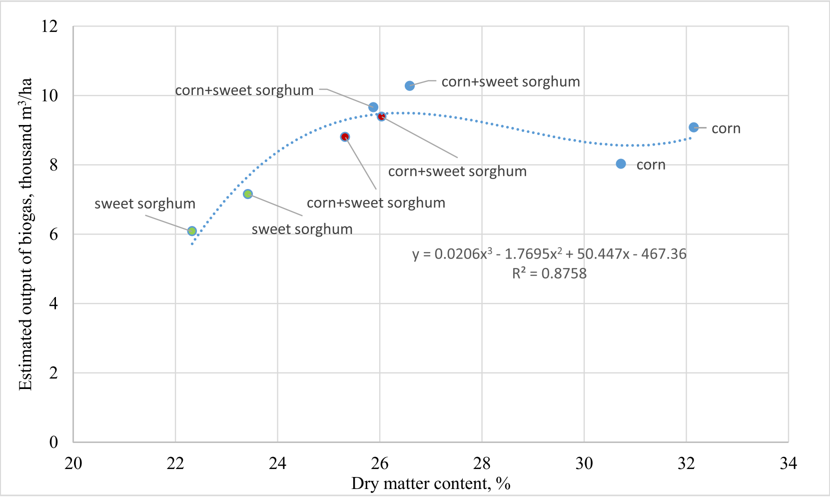


Table 4 Content of dry matter, nitrogen, phosphorus, potassium, and carbon in the green mass of corn and sweet sorghum in the phase of waxy ripeness of the grain, %

Variety, hybrid	Dry matter	N	P	K	C
Silosne 42 (sweet sorghum)	22.3	1.09	0.32	1.11	38.06
Dovista (sweet sorghum)	23.4	1.14	0.39	1.14	38.59
Monica 350 (corn)	30.7	1.38	0.44	0.88	39.33
Bistritsa 400 (corn)	32.2	1.41	0.43	0.97	39.80
Silosne 42 + Monica 350	25.3	1.21	0.36	0.93	37.87
Silosne 42+ Bistritsa 400	26.0	1.23	0.37	1.01	37.81
Dovista + Monica 350	25.9	1.28	0.37	0.96	38.01
Dovista + Bistritsa 400	26.6	1.29	0.36	1.03	37.96

can indicate digester performance capabilities, and hence, research efforts are currently focused on the development of advanced models with higher accuracy levels [5]. Future directions could also go via application of an artificial neural network for estimations of the methane production from various substrates [33].

Corn straw can be an appropriate substrate for the biogas plant. With the methane productivity reaching 201–207 m^3/Mg of fresh mass, this material is a significantly better substrate than that typically used in Europe corn silage (approximately 105 m^3/Mg fresh mass) [13].

The results of our research are in line with those results observed in other studies, such as the one by Abeuov [34] in which yields of the green and dry weight of intercropping crops of corn and sweet sorghum were higher by 27.2% and 15.3%, respectively, compared to one-species crops of corn, or in line with the study by Mazur et al. [27], where silage corn was evaluated as the most important crop for biogas production.The use of intercropping crops of sweet sorghum with corn hybrids of different maturity groups contributes to a yield increase of 57.4% and a dry matter harvest of 30.8% compared to one-species corn crops [35]. Therefore, intercropping of corn and sweet sorghum is a promising alternative for sustainable biogas production, which was also confirmed by Samarappuli and Berti [36] in North Dakota, USA.

Corn hybrid, vegetation period, and hybrid influence on average green mass yield were substantial. There was a significant correlation between the length of the growing season (days from sowing until harvesting) and the organic dry matter content at harvest. A high correlation between organic dry matter content of fresh and ensiled samples was noted; similar results were reported in the study by Bartusevics and Gaile [37].

The yield of methane from corn was 1700–7000 m^3/ha, meaning about 6–16% higher than in the case of sorghum; such results are in agreement with those obtained by Hermuth et al. [38]. Klimiuk et al. [39] even found biogas yield higher about 20%. In this study by Klimiuk et al. [39], a 3-year yield of methane per hectare was 5774.21 m^3/ha (Goliath, rows 25 cm). In the case of corn, Kára et al. [40] determined the average methane output per ton of dry matter as 306 m^3/t, higher on 14.7% in comparison with our experimental data (266.78 m^3/t, the best methane output).

Sorghum was characterized by higher average biogas productivity (about 12%), higher methane content in biogas (about 10%), and higher methane productivity (about 43%). It can, therefore, be stated that sorghum represents an alternative plant to corn for biogas production [41].

Due to higher dry matter content, nitrogen, phosphorus, potassium, and carbon, the estimated output of biogas and methane in corn was higher on 4.1–11.2% compared to the use of sweet sorghum and its mixtures with corn.

There is not enough research in Ukraine to determine the possible output of biogas from different types of substrates;

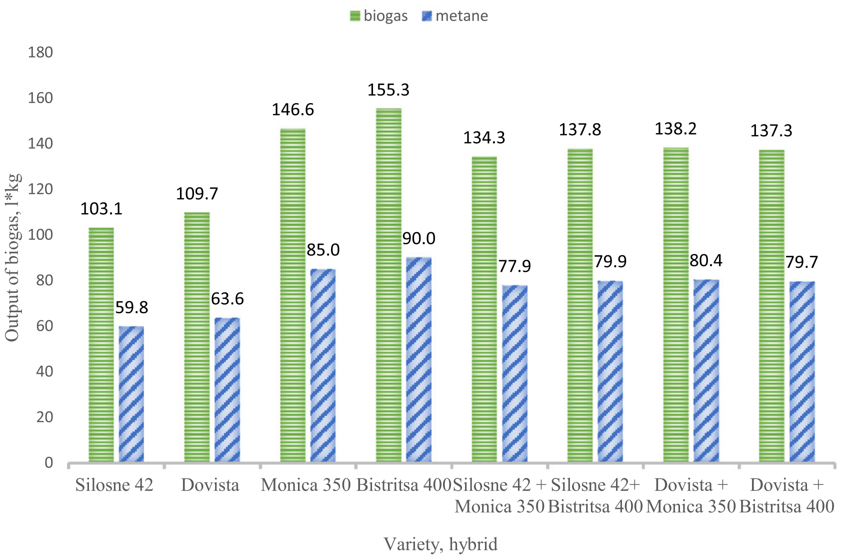
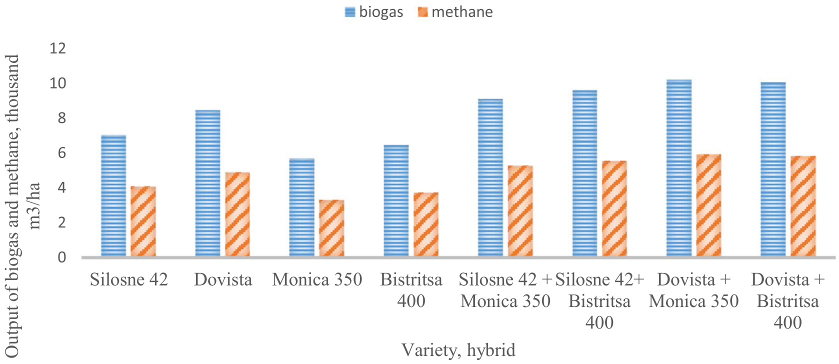


Fig. 3 Estimated output of biogas and methane per unit of input green mass of corn and sweet sorghum, l × kg

Fig. 4 Estimated output of biogas and methane based on the content of nutrients in a green mass of corn and sweet sorghum, thousand m^3/ha



although the number of biogas plants is increasing annually and by the end of 2019, their number was 23, with an installed capacity of electricity production of 56.7 mW. This leads to the continuation of studies of the output of biogas from various types of substrates, including plant origin.

5 Conclusion

It is essential to determine the bioenergy potential of the main crops for each target area, which in the case of Ukraine is corn and sweet sorghum. Therefore, in this paper, biogas production from different varieties and hybrids of corn and sweet sorghum and their mixtures have been done. The results indicate that the productivity of intercropping crops of corn and sweet sorghum is higher than in one-species of these crops: by the yield of green mass on 8.5–37.8%, and biogas output on 9.5–28.7% from 1 ha compared to one-species crops. The maximum yield of green mass and the yield of biogas from 1 ha were obtained on the joint cultivation of hybrid sweet sorghum Dovista and corn hybrid Bistritsa 400–85.5 t/ha and 10.3 thousand m^3/ha. Due to the higher dry matter content, the specific output of biogas per unit of applied corn silage was higher on 33.7–50.6% compared to sweet sorghum and on 9.2–13.0% with a mixture of these crops. When calculating the biogas and methane output per unit area, the highest rates 10.2 and 5.9 thousand m^3/ha were obtained in the co-cultivation of hybrids sweet sorghum Dovista and corn Monica 350. Therefore, based on this research, it is recommended to cultivate intercropping crops of corn and sweet sorghum, which provide high yields of green mass and output of biogas and methane per hectare. At the same time, it is necessary to conduct follow-up research to determine the output of biogas and methane from the green biomass of these crops on laboratory-scale and pilot-scale level followed by research directly in the biogas plants.

Acknowledgments We are thankful to the Czech Development Cooperation support, which allowed this scientific cooperation to start. Furthermore, this research was supported by the Internal Grant Agency of the Faculty of Tropical AgriSciences, Czech University of Life Sciences Prague, project number [20205008].

Author Contribution Mykola Grabovskyi: supervision, methodology, investigation, and writing—original draft. Mykola Lozinskyi: formal analysis and data curation. Tetiana Grabovska: methodology, formal analysis, and visualization. Hynek Roubík: conceptualization, validation, resources, and writing, review and editing, project administration, and funding acquisition.

References

1. Kaletnik GM, Pryshlyak VM (2010) Biofuels: efficiency of their production and consumption in the agro-industrial complex of Ukraine. Ki.ev. 327 p
2. Toklu E (2017) Biomass energy potential and utilization in Turkey. Renew Energy 107:235–244. https://doi.org/10.1016/j.renene.2017.02.008
3. Buswell AM, Mueller HF (1952) Mechanism of methane fermentation. Ind Eng Chem №44(3):550–552
4. Boyle WC (1977) Energy recovery from sanitary landfills. In: Schlegel HG, Barnea J (eds) Microbial energy conversion. Pergamon Pres, New York, pp 119–138
5. Achinas S, Euverink GJW (2016) Theoretical analysis of biogas potential prediction from agricultural waste. Resour-Effic Technol №2(3):143–147. https://doi.org/10.1016/j.reffit.2016.08.001
6. Luna-deRisco M, Normak A, Orupold K (2011) Biochemical methane potential of different organic wastes and energy crops from Estonia. Agron Res 9(1–2):331–342
7. Mahnert P, Linke B (2009) Kinetic study of biogas production from energy crops and animal waste slurry: effect of organic loading rate and reactor size. Environ Technol 30(1):93–99. https://doi.org/10.1080/09593330802246640
8. Kacprzak A, Krzystek L, Ledakowicz S, Księżak J (2010) Evaluation of biochemical potential (BMP) of various energy crops. In: Proceedings of the 3-rd international conference on engineering for waste and biomass valorisation, Beijing, China, p. 5 2010
9. Bassam N (1998) Energy plant species-their use and impact on environment. London. 200 p
10. Scholz V, Ellerbrock R (2002) The growth productivity, and environmental impact of the cultivation of energy crops on sandy soil in Germany. *Biomass Bioenergy* №23:81–92
11. Heiermann M, Plöchl M, Linke B, Schelle H, Herrmann C (2009) Biogas crops – part I: specifications and suitability of field crops for anaerobic digestion. Agric Eng Int CIGR J Vol. XI:1087–1093
12. Dubrovskis V, Plume I, Bartusevics J, Kotelenecs V (2010) Biogas production from fresh maize biomass. Engineering for Rural Development, Jelgava, pp 220–225
13. Mazurkiewicz J, Marczuk A, Pochwatka P, Kujawa S (2019) Maize straw as a valuable energetic material for biogas plant feeding. Materials (Basel) №12:3848

14. Meyer-Aurich A, Lochmann Y, Klauss H, Prochnow A (2016) Comparative advantage of maize- and grass-silage based feedstock for biogas production with respect to greenhouse gas mitigation. Sustainability 8(7):617
15. Bartuševics J, Gaile Z (2010) Effect of silaging on chemical composition of maize substrate for biogas production. In Annual 16-th International Scientific Conference Proceedings: Research for rural development, Jelgava, Latvia, Vol. 1. pp. 42–47 19–21 May 2010
16. Amon T, Amon B, Kryvoruchko M, Zollitsch W, Mayer K, Gruber L (2007) Biogas production from maize and dairy cattle manure – Influence of biomass composition on the methane yield. Agric Ecosyst Environ №118:173–182
17. Schittenhelm S (2010) Effect of drought stress on yield and quality of maize/sunflower and maize/sorghum intercrops for biogas production. *J Agron Crop Sci* №196:253–261
18. Serra P, Giuntoli J, Agostini A, Colauzzi M, Amaducci S (2017) Coupling sorghum biomass and wheat straw to minimise the environmental impact of bioenergy production. J Clean Prod 154:242–254. https://doi.org/10.1016/j.jclepro.2017.03.208
19. Royik MV, Hanzhenko OM, Tymoschuk VL (2014) Concept of biogas production from bioenergy plants in Ukraine. Bioenergetics 2:6–8
20. Geletukha GG, Zheleznaya TA, Kucheruk PP, Oleynik EN, Triboy AV (2015) Bioeneregetika in Ukraine: current state and prospects for development. Part 2. Ind Heat Eng Vol. 37(№ 3):65–73
21. Masse L, Masse DI, Beaudette V, Muir M (2005) Size distribution and composition of particles in raw and anaerobically digested swine manure. Trans ASAE №48(5):1943–1949
22. Weiland P (2003) Production and energetic use of biogas from energy crops and wastes in Germany. Appl Biochem Biotechnol №109(1–3):263–274
23. Kažimírová V, Gaduš J, Giertl T (2018) Verification of suitability of substrate composition for production and quality of biogas. Acta Technologica Agriculturae №3:115–118
24. Amon T, Kryvoruchko V, Amon B, Bodiroza V, Zollitsch W, Boxberger J (2006) Biogas Production from Energy Maize. Landtechnik №2:86–87
25. Mahmood A, Ullah H, Ijaz M, Naeem AS, Honermeie B (2013) Evaluation of sorghum cultivar for biomass and biogas production. Aust J Crop Sci №7(10):1456–1462
26. Podkówka W, Podkówka Z, Kowalczyk-Ju'sko A. Pasyniuk P 2012 Agricultural biogas renewable energy source. Theory and practical application. Wydawnictwo PWRiL pp. 147–152 2012
27. Mazur VA, Pantsyreva HV, Mazur KV, Myalkovsky RO, Alekseev OO (2020) Agroecological prospects of using corn hybrids for biogas production. Agron Res 18:177–182 (in press)
28. Gerber M, Span R (2008) An analysis of available mathematical model for anaerobic digestion of organic substances for production of biogas. International Gas Union Research conference, Paris. №1. 1294–1324 2008
29. Baserga U (1998) Landwirtschaftliche Co-Vergärungs-Biogasanlagen. FAT-Berichte Nr. 512, Eidg. Forschungsanstalt für Agrarwirtschaft und Landtechnik, Tänikon, Schweiz
30. Keymer U, Schilcher A (2003) Biogasanlagen: Berechnung der Gasausbeute von Kosubstraten. Bayrische Landesanstalt für Landwirtschaft
31. Roati C, Fiore S, Ruffino B, Marchese F, Novarino D, Zanetti MC (2012) Preliminary evaluation of the potential biogas production of food-processing industrial wastes. Am J Environ Sci 8(3):291–296
32. Velázquez-Martí B, Meneses-Quelal OW, Gaibor-Chavez J, Niño-Ruiz Z (2003) Review of mathematical models for the anaerobic digestion process, anaerobic digestion. J Rajesh Banu, IntechOpen 2018. https://doi.org/10.5772/intechopen.80815
33. Kowalczyk-Juśko A, Pochwatka P, Zaborowicz M, Czekała W, Mazurkiewicz J, Mazur A, Janczak D, Marczuk A, Dach J (2020) Energy value estimation of silages for substrate in biogas plants using an artificial neural network. Energy 202:117729
34. Abeuov SK (2014) Polyspecific crops, especially unity and contradictions. Potential Mod Science 6:10–13 (in Russian; Polividovye posevy, osobennosti edinstva i protivorechij)
35. Drozdova OV (2015) Productivity and chemical composition of green mass of intercropping crops of different corn and sorghum hybrids. Sci Tech Bull №114:69–73
36. Samarappuli D, Berti MT (2018) Intercropping forage sorghum with maize is a promising alternative to maize silage for biogas production. J Clean Prod 194:515–524
37. Bartusevics J, Gaile Z (2012) Maize production for biogas in Latvia. Proceedings of the International Scientific Conference on Renewa, 51–56 p 2012
38. Hermuth J, Janovská D, Strašil Z, Usťak S, Hýsek J (2012) *Sorghum bicolor* (L.) Moench: possibilities of utilization in Czech Republic conditions. VÚRV. Praha, 47 p
39. Klimiuk E, Pokój T, Budzyński W, Dubis B (2010) Theoretical and observed biogas production from plant biomass of different fibre contents. Bioresour Technol №101:9527–9535
40. Kára J, Pastorek Z, Přibyl E (2007) The production and utilization of biogas in agriculture. VÚZT. Praha. 120 p
41. Kuglarz K, Bury M, Kasprzycka A, Lalak-Kańczugowska J (2019) Effect of nitrogen fertilization on the production of biogas from sweet sorghum and maize biomass. Environ Technol №15:1–11