Polish Journal of Agronomy
2022, 48, 28-36

doi: 10.26114/pja.iung.478.2022.48

The effect of fertilization with the digestate on the quality and chemical composition of selected plants intended for biogas production

[1]Agata Witorożec-Piechnik, [1]Mariusz Matyka, [1]Marek Woźniak, [2]Marta Oleszek

[1]Department of Systems and Economics of Crop Production, Institute of Soil Science and Plant Cultivation – State Research Institute
ul. Czartoryskich 8, 24-100 Puławy, POLAND
[2]Department of Physical Properties of Plant Materials, Institute of Agrophysics PAS
ul. Doświadczalna 4, 20-290 Lublin, POLAND

Abstract. The aim of the studies was to determine the effect of fertilization with mineral fertilizers and the digestate from an agricultural biogas plant on selected plant parameters. In 2016 a three-year two-factor field experiment was established, where the first factor was the fertilization variant and the second factor was the plant species (triticale, maize, sorghum). Fertilization was carried out on two dates: pre-sowing and top-dressing. The first variant consisted of nitrogen fertilization, exclusively mineral; in the second variant, plants were fertilized before sowing with digestate, and then top-dressed with mineral fertilizer; while in the third variant, in both terms, plants were fertilized with digestate. The quality of biomass was examined in terms of its chemical composition and as a raw material for biogas production. Regardless of the applied variant of fertilization, the plants tested were equally well supplied with nitrogen. Fertilization with digestate increased the C:N ratio in the biomass of sorghum (which deviated from the optimal value for effective anaerobic fermentation process), lowered the crude fibre content in the biomass of triticale, but also increased the content of cellulose in triticale. Fertilization with digestate makes it possible to give up mineral nitrogen fertilization, without negative influence on the quality and chemical composition (including crude fibre and lignin fractions) of triticale and maize used as biogas substrates.

Keywords: biogas, mineral fertilization, digestate, triticale, maize, sorghum.

INTRODUCTION

In an era of global warming, caused among other things by environmental pollution, alternative energy sources based on locally available raw materials are being developed to fit into a closed loop economy. Biogas production through anaerobic digestion is a good example of such a model. Plant substrates for biogas plants should be easy to grow, energy efficient, and at the same time, resistant to adverse climatic conditions associated with climate change. Also important is the yield of such crops and their high quality, which can be achieved through optimized fertilization, minimizing the risks associated with environmental pollution. Doyeni et al. (2021) reported that properly applied digestate had minimal influence with no negative effects on soil chemical properties after three years of application. Koszel et al. (2020) reported that digestate determines the fat and protein content in winter rape and affects the content of macronutrients and saturated fatty acids, monounsaturated fatty acids and polyunsaturated fatty acids. Moreover, it has been proven that application of N mineral fertilization may decrease energy-use efficiency of biogas production, due to the high energy input for production of N fertilizer (Oleszek, Matyka, 2020). Koszel et al. (2017) and Alburquerque et al. (2012) confirmed the validity of using the digestate as a substitute for mineral fertilization in winter wheat and winter oilseed rape cultivation. The study of Oleszek and Matyka (2018) proved that increasing the dose of mineral nitrogen fertilizer had an effect on biogas production, methane yield and on the specific rate of their production. In addition, the reduction of acid detergent lignin (ADL) content in the biomass of the studied plants, contributed to an increase in the digestibility of this biomass and shortening its fermentation time. In the literature, it is found that the lignin content of a given biomass is a factor that strongly inhibits the methane fermentation process. The digestate has not yet been studied for such properties.

High yields in biogas production are demonstrated by plant substrates such as forage, which are quickly and efficiently decomposed (Prochnow et al., 2009). The choice of substrates for biogas production is affected by the local availability of biomass, its chemical composition, energy value, ease of fermentation, as well as the possibility of using the digestate (Vasiljević, Karagić, 2014; Podkówka,

Corresponding author:
Agata Witorożec-Piechnik
e-mail: Agata.Witorozec@iung.pulawy.pl
phone +48 81 4786 822

Podkówka, 2010). An important factor in the choice of substrate for a biogas plant is the cost of obtaining it, including transport. It is therefore important to have one's own substrate, such as dedicated crops for example: maize, triticale, and sorghum. Triticale has lower soil requirements than spring wheat and spring barley, and varieties are characterized by greater drought tolerance (Mazurek, 1994). An increase in the area of maize cultivation has been recorded for more than 20 years, which is mainly dictated by improved climatic conditions (Księżak, Zarychta, 2015). As plants of the genus sorghum occur in the zone of warm and hot climates, they manage water more efficiently than maize. Due to their well-developed root system, they tolerate drought better than other crops (Hołubowicz-Kliza, 2007).

The aim of this study was to investigate the effect of mineral fertilization and fertilization with the use of digestate from an agricultural biogas plant on the quality and chemical composition of maize, triticale and sorghum biomass as potential substrates for biogas production.

MATERIAL AND METHODS

The field experiment was three years long (2016–2018) and was located at the Agricultural Experimental Station in Osiny, Lublin Province (N:51°27'58'', E:22°52'6''). The experiment was established on lessive soil, made of light loamy sand, good rye complex 5, class IV b. The area of a single experimental plot was 225 m^2. The first factor of the experiment were the crop species: maize (*Zea mays* L.) variety Respect, sorghum (*Sorghum vulgare* L.), Sucrosorgo 506 and spring triticale (*Triticale*) Dublet C1 in the first year of research, although winter triticale (*Triticale*) Maestozo in the remaining years. The experiment was conducted in a three-field crop rotation, with fields of all plants replicated four times. Varieties dedicated to agricultural biogas plants were selected for the study. The second factor of the experiment was the nitrogen fertilization variant. Three variants of fertilization included mineral and organic (digestate from biogas plant) fertilizers. Each scheme included two dates, pre-sowing and top dressing. Nitrogen fertilization was in the following schemes: N1 only mineral, N2 before sowing digestate and later mineral, N3 only digestate.

The digestate was obtained from an agricultural biogas plant and its dose was determined annually on the basis of its chemical composition, assuming a rate for triticale of 120 kg N ha^{-1}, while for maize and sorghum of 160 kg N ha^{-1} each. Triticale biomass was harvested at the milk-wax stage, maize at grain maturity from late-wax to full-wax, while sorghum after the occurrence of the first frost. In fresh plant material, the content of crude ash (weight method), organic carbon (elementary analyses in 2016 and high temperature combustion with TC detection in 2017 and 2018), total nitrogen, phosphorus (CFA with spectrophotometric detection), potassium, magnesium (FAES method) and calcium (FAES in 2016 and 2018, FAAS method in 2017) was determined annually. In a few cases the selected methods have been changed due to changes in the availability of the selected methods in the laboratory. The content of organic compounds (total protein, crude fat, crude fibre) and crude fibre fractions (NDF, ADF, hemicellulose, lignin) as well as ash were also tested according to weight methods (with one exception of total protein in 2016 – CFA method). The average value and standard deviation were determined for each of the tested variables. The Shapiro-Wilk test was used to assess normal distribution. The verification of the hypothesis assuming uniformity of variance was performed using Brown and Forsythe's test. To compare the magnitude of differences between the tested variants and species, analysis of variance (ANOVA) testing was performed. Tukey's post-hoc HSD test was used to determine the significance of differences between all the tested samples. All the statistical analyses were performed at the significance level $p<0.05$ in Statistica 7 (StatSoft, Tuls, OK, USA).

RESULTS AND DISCUSSION

High content of: protein, fat, as well as starch and sugar, contribute to more efficient biomethane production (Oleszek, Matyka, 2018). The content of crude ash varied between the studied species (from 3.0 to 5.8% DM). There were no significant differences between the fertilization variants for any of the plant species tested. Sorghum contained significantly more ash than maize and triticale, regardless of the applied fertilization variant. The ash content in the biomass of the tested plants was lower than in studies by other authors (Amon, Zollitsch, 2007; Kozłowski et al., 2007; Heiermann et al., 2009; Kacprzak et al., 2010; Księżak et al., 2012; Kacprzak et al., 2012b; Podkówka, Podkówka, 2014; Kraszkiewicz et al., 2017). The high ash content in biomass hinders the energy conversion in technological processes (Cherney, 2006).

Among the plants studied, maize had significantly the highest organic carbon content (47.4±1.7% DM). Significant differences in organic carbon content were observed due to the application of different variants of fertilization, however, for each species of the studied plants, the effect was different. The lowest content of organic carbon for triticale (46.9±1.8% DM) and maize (47.2±1.8% DM) was recorded in the N3 variant, while for sorghum was significantly more of organic carbon in plants grown in N3 variant, then in N1 (46.8±0.9% DM) (Table 1).

The average organic carbon content in the biomass of triticale grown for biogas production in Spain was 44.9% DM, which was lower than that in present study (47.0% DM) (Sanz et al., 2011). In contrast, higher organic carbon content in triticale biomass (49.1% DM) was shown by Oleszek and Matyka (2017). In maize biomass, lower

Table 1. Crude ash, organic carbon (C), total nitrogen, total protein content in dry matter and C:N ratio in the studied plant species, depending on the fertilization variant.

Specification	Fertilization variant			Average
	N1	N2	N3	
Crude ash [% DM]				
Triticale	3.6±0.3 a A	3.6±0.3 a A	3.6±0.4 a A	3.6±0.3 A
Maize	3.0±0.5 a A	3.4±0.5 a A	3.2±0.4 a A	3.2±0.5 A
Sorghum	6.2±0.8 a B	5.5±0.8 a B	5.8±0.9 a B	5.8±0.9 B
Average	4.2±1.5 a	4.2±1.2 a	4.2±1.3 a	
Organic carbon [% DM]				
Triticale	47.1±1.6 a A	47.2± 1.7 a AB	46.9±1.8 b A	47.0±1.6 A
Maize	47.3±1.8 ab A	47.5± 1.8 a A	47.2± 1.8 b B	47.4±1.7 B
Sorghum	46.8±0.9 a B	47.0± 1.1 ab B	47.3±1.3 b B	47.0±1.0 A
Average	47.1±1.4 a	47.2±1.4 a	47.1±1.6 a	
Total nitrogen [% DM]				
Triticale	1.4± 0.3 a A	1.4± 0.2 a A	1.3± 0.2 a A	1.4±0.2 A
Maize	1.2± 0.1 a A	1.3±0.1 a AB	1.2± 0.1 a A	1.2±0.1 B
Sorghum	1.2± 0.3 a A	1.2± 0.3 a B	1.1±0.3 a B	1.2±0.3 B
Average	1.3±0.3 a	1.3±0.2 a	1.2±0.2 a	
Total protein [% DM]				
Triticale	8.5±2.2 a A	9.2±1.2 a A	8.1±1.1 a A	8.6±1.6 A
Maize	7.4± 0.6 a A	8.0±0.8 a AB	7.6±0.9 a AB	7.7±0.8 B
Sorghum	8.1± 1.9 a A	7.3±2.0 a B	6.9±1.8 a B	7.4±1.7 B
Average	8.0±1.7 a	8.2±1.3 a	7.5±1.4 a	
C:N				
Triticale	36.8±11.3 a A	32.9±4.5 a A	36.7±5.0 a A	35.5±7.4 A
Maize	39.1±3.4 a A	36.5±3.0 a AB	39.2± 4.0 a A	38.3±3.5 AB
Sorghum	37.8± 8.2 a A	41.0 ±9.3 ab B	46.0±10.5 b B	41.5±9.0 B
Average	37.9±7.9 a	36.8±6.1 a	40.6±7.8 a	

Results expressed as mean ± standard deviation. Averages denoted by the same capital letter in columns and small letter in rows are not significantly different by Tukey's test for $p < 0.05$.

Nitrogen fertilization: N-1 only mineral in two dates, N-2 before sowing digestate and later mineral, N-3 digestate in two dates.

organic carbon content (47.4% DM) was found than in the studies of other authors (49.9–50.1% DM) (Amon, Zollitsch, 2007; Oleszek, Matyka, 2017). In the work of Kacprzak et al. (2012a) the organic carbon content of maize and sorghum silages was 45.2 and 46.1% DM, respectively, and these values were lower than those obtained in present study. In the study of Oleszek and Matyka (2017), sorghum biomass contained more organic carbon (49.5% DM) than in our study (47.0% DM). The different results were influenced both by the varietal differences of the plants selected for the study and by the location of the experiments on different continents of our globe, which was also related to the meteorological conditions and the different type of substrate in which the studied plants grew. Irrespective of the fertilization variant, the biomass of triticale contained the most nitrogen and total protein. However, no effect of fertilization with digestate was observed on the content of total nitrogen (values from 1.1±0.3 to 1.4±0.3 % DM) and total protein (values from 6.9±1.8 to 9.2±1.2 % DM) in all tested plants (Table 1).

In the study of Sanz et al. (2011), the average content of total nitrogen in triticale biomass was 0.8% DM, which was lower than in present study (1.4%), while Oleszek and Matyka (2017) obtained a similar content (1.5%) of total nitrogen. Kacprzak et al. (2012a) and Oleszek and Matyka (2017) reported nitrogen contents in maize silages of 1.3% DM and in sorghum silages of 1.2% DM. These results were similar to the values obtained in our study. According to Koszel et al. (2017), fertilization with digestate, in relation to mineral fertilization, results in an increase in protein content in wheat grain. Also, the results of the abovementioned authors' study on winter oilseed rape confirmed the higher efficiency of the application of digestate as fertilizer with respect to protein content. Similarly, in the study of Koszel et al. (2018), where the digestate from the biogas plant in Siedliszczki, near Piaski was used to fertilize wheat, a higher protein content in wheat grain was recorded, as well as increase in the content of selected macronutrients (nitrogen by 3.93%, phosphorus by 13.33%, potassium by 9.26%, calcium by 15.38%, and magnesium by 9.52%) compared to fertilization with mineral fertilizers only.

The content of total protein in triticale biomass obtained from present study (Table 1) was similar (8.6% DM) to the values of 8.6–9.5% DM obtained by other authors (Ozduven et al., 2010; Heiermann et al., 2009; Oleszek, Matyka, 2017; Strauß et al., 2019). The amount of total protein in maize biomass from present study (7.7% DM) was within the range of 6.8–8.0% DM, which was obtained in other studies (Amon, Zollitsch, 2007; Księżak et al., 2012; Podkówka, Podkówka, 2014; Oleszek, Matyka, 2017; Strauß et al., 2019). The amount of total protein in maize obtained from our research was lower compared to the values in the National Feed Database (average 11.4% DM); (Śliwiński et al., 2010). The total protein content of sorghum biomass (7.4% DM) was higher than that obtained by Księżak et al. (2012); (7.1% DM), but lower than that found by Śliwinski et al. (2010) (7.7%) and Oleszek and Matyka (2017) (7.9% DM). The content of total protein in the biomass of sorghum grown in Germany was 8.5% DM, which was higher than in present study (Strauß et al., 2019).

The studied species, regardless of the fertilization variant, differed significantly in the ratio of carbon to nitrogen (C:N). It reached the lowest value in triticale (35.5±7.4), and the highest in sorghum (41.5±9.0); (Table 1). No effect of fertilization variant was found on C:N ratio in triticale and maize plants. In the case of sorghum, a significantly higher C:N ratio was recorded in the N3 variant (46.0±10.5), compared to the N1 variant (37.8±8.2). It was influenced by harvest date, the later the date the higher the C:N ratio (Zwart, Langeveld, 2010). Heiermann et al. (2009) obtained a lower C:N value in triticale (30:1) than that obtained in present study (35:1). The average C:N ratio in maize biomass obtained in present experiment (38:1) was similar to the 40:1 value obtained by Amon and Zollitsch (2007). The C:N in the substrate, affects the growth of microorganisms, which translates into the rate of the fermentation process. The optimal C:N ratio should be 10–30:1 (Burton, Turner, 2003; Igoni et al., 2008; Ledakowicz et al., 2010; Podkówka, Podkówka, 2010; Weiland, 2010; Deublei, Steinhauser, 2011). However, in practice, the range of variation in this parameter can oscillate between 20 and 70:1 (Burton, Turner, 2003). A too low C:N ratio leads to an increase in ammonia concentration, which slows down the methanogenesis process and can inhibit biogas production (Weiland, 2010; Igoni et al., 2008; Podkówka, Podkówka, 2010). Conversely, a high C:N ratio carries the risk of reducing the availability of nitrogen necessary for bacterial growth, which may also result in a less efficient fermentation process (Weiland, 2010; Igoni et al., 2008). With a higher C:N ratio, the loss of ammonia (an inhibitor of methanogenesis) slows down, because the available nitrogen can be incorporated into the mass of bacteria carrying out the fermentation process (Burton, Turner, 2003). In present study, the C:N value varied between 32.9 and 46.0:1, a ratio slightly higher than the optimum, which

Table 2. Content of macroelements in biomass (dry matter) of the studied plant species, depending on the fertilization variant.

Specification	Fertilization variant			Average
	N1	N2	N3	
Phosphorus [% DM]				
Triticale	0.23±0.03 a A	0.24±0.01 a A	0.24±0.02 a A	0.23±0.02 A
Maize	0.22±0.03 a A	0.22±0.02 a A	0.22±0.03 a A	0.22±0.03 A
Sorghum	0.24±0.04 a A	0.23±0.04 a A	0.21±0.05 a A	0.23±0.04 A
Average	0.23±0.03 a	0.23±0.03 a	0.23±0.04 a	
Potassium [% DM]				
Triticale	1.11±0.11 a A	0.95±0.42 a A	1.04±0.15 a A	1.03±0.26 A
Maize	0.90±0.19 a A	0.89±0.11 a A	0.87±0.09 a A	0.89±0.13 A
Sorghum	1.95±0.53 a B	1.39±0.27 a B	1.85±0.46 a A	1.84±0.45 B
Average	1.32±0.37 a	1.19 ±0.52 a	1.25±0.51 a	
Magnesium [% DM]				
Triticale	0.11±0.01 a A	0.10±0.02 a A	0.10±0.01 a A	0.10±0.01 A
Maize	0.16±0.04 a A	0.16±0.04 a B	0.14±0.03 a A	0.15±0.04 B
Sorghum	0.33±0.10 a B	0.24±0.12 a C	0.28±0.05 a A	0.30±0.07 C
Average	0.19±0.11 a	0.19±0.09 a	0.17±0.09 a	
Calcium [% DM]				
Triticale	0.15±0.02 a A	0.15±0.04 a A	0.13±0.01 a A	0.14±0.02 A
Maize	0.20±0.04 a A	0.21±0.06 a B	0.19±0.03 a B	0.20±0.04 B
Sorghum	0.41±0.06 a B	0.25±0.10 b C	0.34±0.03 b C	0.36±0.05 C
Average	0.25±0.12 a	0.23±0.09 a	0.22±0.09 a	

Explanations as in Table 1

may suggest nitrogen deficiency in the methane fermentation process. The increase of C:N ratio beyond the optimal values due to the application of digestate fertilization in the case of sorghum is a disadvantageous effect from the biogas production point of view. Nonetheless, in practice, plant substrates are very often combined with N-rich co-substrates, thus, C/N is then at the optimal value.

The analyses showed no significant differences in phosphorus content between the plant species studied. There was no significant differences of fertilization with digestate on phosphorus content (from 0.21±0.05 to 0.24±0.04% DM) in the biomass of the plants studied (Table 2).

The content of phosphorus in maize biomass was 0.22% DM within the range of that obtained by Księżak et al. (2012) and Schattauer and Weiland (2005), where it was 0.15 and 0.24% DM respectively. Also, the average potassium content in maize biomass (0.89% DM) (Table 2) was lower than obtained by these authors (1.12–1.15% DM).

Potassium content varied among the species studied. Sorghum biomass contained significantly more potassium compared to triticale and maize. The content of potassium (from 0.87±0.09 to 1.95±0.53% DM) was not significantly different among the fertilization variants. The least magnesium was found in the biomass of triticale (0.10±0.01% DM), significantly more in the biomass of maize (0.15±0.04% DM), and the most in the biomass of sorghum (0.30±0.07% DM). No effect of fertilization with digestate was observed on magnesium content in the biomass of the plants studied.

The magnesium content in maize (Table 2) was at a similar level as in the studies of other authors (0.12–0.17% DM) (Księżak et al., 2012; Schattauer, Weiland, 2005). In sorghum the magnesium content was slightly higher (0.23–0.26) than reported by Księżak et al. (2012).

On the other hand, a higher calcium content was found in present study (0.20% DM) than in the studies of Schattauer and Weiland (2005) (0.18% DM) and at the same time this value was lower than that obtained by Księżak et al. (2012) (0.24% DM).2

Sorghum biomass contained more phosphorus (0.23% DM), potassium (1.84% DM) and magnesium (0.30% DM) with respect to the results obtained by Księżak et al. (2012), respectively (0.18; 1.62 and 0.26% DM). On the other hand, the calcium content was at a similar level (0.36% DM).

The lowest calcium content, on average for all fertilization variants, was found in the biomass of triticale (0.14±0.02% DM), significantly more in the biomass of maize (0.20±0.04% DM), and the highest in the biomass of sorghum (0.36±0.05% DM). In the biomass of sorghum, significantly more calcium was contained in plants fertilized only with mineral nitrogen (0.41±0.06% DM), than in the case of variants N2 and N3, where fertilization was performed with digestate (0.25±0.10 and 0.34±0.03% DM, respectively) (Table 2).

The highest content of crude fat was found in maize biomass (3.2±0.4% DM). There was no effect of fertilization variants on the content of crude fat in the studied plant species (Table 3).

The average crude fat content in triticale biomass obtained in present study (2.2% DM) was similar to the ones obtained by Heiermann et al. (2009) and Oleszek and Matyka (2017), where it was 1.4% DM and 2.2% DM, respectively. A higher crude fat content was also recorded in maize biomass (3.2% DM) than the values presented by other authors (2.0–3.1% DM) (Podkówka, Podkówka, 2010; Amon, Zollitsch, 2007; Herrmann et al., 2012; Księżak et al., 2012; Oleszek, Matyka, 2017). The crude fat content of maize biomass obtained from our research was lower than that presented in the National Feed Database (Śliwiński et al. 2010), where it averaged 4.4% DM. The crude fat content in sorghum biomass was the same (2.0% DM) as in National Feed Database (Śliwiński et al. 2010). In works: Księżak et al. (2012) and Oleszek and Matyka (2017), the crude fat content in sorghum biomass was 2.7% DM and 3.8% DM, respectively, and these values were higher than those obtained in present study.

Comparing the species, a significantly higher crude fibre content was found in the biomass of sorghum (31.0±3.0% DM) compared to triticale (20.7±2.0% DM) and maize (19.4±2.5% DM) (Table 3).

Statistically significant differences between fertilization variants were found only in the case of triticale. Triticale fertilized only with mineral nitrogen (N1) contained the biggest amount of crude fibre (22.6±1.9% DM), while the one fertilized only with digestate (N3) contained the smallest amount (19.2±0.9% DM). Crude fibre is more difficult to decompose in anaerobic digestion than other components determining the composition of a given kind of biomass.

Plant fibre forms cell walls and its components are cellulose, hemicellulose and lignin. The other components are: undecomposed protein, pectins, water, and ash (FOSS, 2018; Zadernowski, Piłat, 2016). Triticale biomass obtained in present study contained on average 20.7% DM of crude fibre, which is 2.6% more than that obtained by Heiermann et al. (2009). The average crude fibre content of maize biomass from our study (19.4% DM) was within the range of 18.4 to 19.6% DM derived from studies by other authors (Księżak et al., 2012; Podkówka, Podkówka, 2014, 2016; Śliwiński et al., 2010). In contrast, maize biomass in the study of Amon and Zollitsch (2007) contained more crude fibre (25.5% DM) than the value obtained in present study. The crude fibre content of the sorghum biomass from our study (31.0% DM) was consistent with the values in the National Feed Database (Śliwiński et al., 2010), and similar to the value of 31.6% DM that was obtained by Podkówka and Podkówka (2016). More crude fibre (34.8% DM) was contained in sorghum biomass in the study by Księżak et al. (2012).

Table 3. Biomass composition of the studied plant species, depending on the variant of fertilization.

Specification	Fertilization variant			Average
	N1	N2	N3	
Crude fat [% DM]				
Triticale	2.3±0.6 a A	2.2±0.6 a A	2.2±0.4 a A	2.2±0.5 A
Maize	3.1±0.5 a B	3.3±0.5 a B	3.3±0.3 a B	3.2±0.4 B
Sorghum	2.0±0.4 a A	2.0±0.6 a A	2.1±0.4 a A	2.0±0.4 A
Average	2.5±0.7 a	2.4±0.8 a	2.5±0.7 a	
Crude fibre [% DM]				
Triticale	22.6±1.9 a A	20.2±1.2 b A	19.2±0.9 c A	20.7±2.0 A
Maize	18.2±3.3 a A	21.4±1.2 a A	18.6±0.7 a A	19.4±2.5 A
Sorghum	29.7±2.6 a B	31.0±5.8 a B	31.8±2.5 a B	31.0±3.0 B
Average	23.5±5.5 a	24.2±5.4 a	23.2±6.4 a	
Neutral-detergent fibre [% DM]				
Triticale	46.0±1.6 a A	47.1±2.8 a A	45.4±2.7 a A	46.2±3.6 A
Maize	44.0±5.7 a A	47.3±4.4 a A	46.0±4.7 a A	45.5±4.9 A
Sorghum	66.4±7.1 a B	66.8±7.8 a B	67.1±6.2 a B	66.8±5.9 B
Average	52.1±11.6 a	53.7±10.3 a	52.5±11.8 a	
Acid-detergent fibre [% DM]				
Triticale	25.1±3.0 a A	25.6±1.5 a A	26.0±2.8 a A	25.6±2.4 A
Maize	25.6±4.3 a A	27.0±4.6 a A	25.5±2.6 a A	26.0±3.8 A
Sorghum	44.2±3.8 a B	45.1±10.2 a B	44.6±3.8 a B	44.6±3.6 B
Average	31.7±9.8 a	32.5±9.7 a	32.0±9.6 a	
Cellulose [% DM]				
Triticale	21.9±2.4 a A	21.5±1.1 ab A	22.0±2.5 b A	21.4±2.0 A
Maize	21.6±3.6 a A	23.0±4.2 a A	21.6±2.4 a A	22.1±3.4 A
Sorghum	36.3±3.6 a B	36.9±8.4 a B	37.0±3.2 a B	36.8±3.2 B
Average	26.3±7.9 a	27.1±7.7 a	26.9±7.8 a	
Acid-detergent lignin [% DM]				
Triticale	4.1±0.6 a A	4.1±0.6 a A	4.1±0.3 a A	4.1±0.5 A
Maize	4.0±1.3 a A	4.0±0.9 a A	4.0±0.8 a A	4.0±0.9 A
Sorghum	8.0±1.2 a B	8.1±2.0 a B	7.5±1.1 a B	7.9±1.1 B
Average	5.4±2.2 a	5.4±2.1 a	5.2±1.9 a	
Hemicellulose [% DM]				
Triticale	20.8±3.0 a AB	21.5±3.5 a A	19.4±3.7 a A	20.6±3.3 A
Maize	18.4±2.1 a A	20.4±2.8 a A	19.5±3.6 a A	19.4±2.8 A
Sorghum	22.1±3.6 a B	21.7±3.0 a A	22.5±2.8 a B	22.1±2.8 B
Average	20.4±3.2 a	21.2±2.8 a	20.5±3.5 a	

Explanations as in Table 1

The significantly highest content of neutral-detergent fibre (NDF) fraction was characterized by sorghum (66.8±5.9% DM), while no statistically significant differences were found between maize (45.5±4.9% DM) and triticale (46.2±3.6% DM) (Table 3).

The applied variants of fertilization did not differentiate the content of NDF. Analogous relations were found for the content of acid-detergent fibre (ADF), hemicellulose and acid-detergent lignin (ADL). The content of these components depends on the developmental stage of the plant, and more specifically on the grain filling stage. The later the plants are harvested, the higher ADF and NDF content they have (Bocchi et al., 1996). The amount of fibre and its fractions in the studied material is closely related to the plant species and the vegetation stage in which they were harvested, but also to the dose of nitrogen fertilization (Oleszek, Matyka, 2017). ADF and NDF content is an indicator of the digestibility of a given biomass (FOSS, 2018). NDF content in triticale biomass obtained from our experiment (46.2% DM) was lower than that obtained in the study of Ozduven et al. (2010) (60.8% DM). The NDF content of maize biomass obtained from present experiment was similar (45.5% DM) to the values obtained by other authors (45.5–56.2% DM), sorghum biomass from present study contained 66.8% DM NDF, which was similar like to other studies, where the proportion was 53.2–66.8% DM

(Kozłowski et al., 2007; Śliwiński et al., 2010; Heiermann et al., 2009). The ADF fraction consists of cellulose associated with lignins (Truba, 2015). Higher ADF content results in lower fibre digestibility (Jankowska, 2014; KWS Poland; Kotlarz et al., 2010). According to Kozłowski et al., (2007) and Grygierzec (2012), the amount of fibre fraction in forage is closely related to harvest date, plant development stage, morphological structure and habitat conditions. The ADF content, in triticale biomass obtained from present experiment, was lower (25.6% DM) (Table 3), than the average value for triticale in the studies of Heiermann et al. (2009) (31.7% DM) and Ozduven et al. (2010) (37.9% DM).

The ADF content of maize biomass from our study (26.0% DM) was similar to available literature data (25.6 and 26.2% DM) (Podkówka, Podkówka, 2010; Śliwiński et al., 2010). However, sorghum biomass from present experiment contained (44.6% DM) more ADF than in the studies of other authors (31.9–38.0% DM) (Herrmann et al., 2012; Kozłowski et al., 2007).

Lignocellulosic matter consists mainly of cellulose, hemicellulose, and lignin. Irrespective of the fertilization variant, the biomass of sorghum contained the highest amount of cellulose (36.8±3.2% DM). Statistically significant differences in cellulose content depending on the fertilization variant, were found only in the biomass of triticale. Triticale fertilized with mineral nitrogen only (variant N1 21.9±2.4% DM) contained less cellulose than the plants fertilized solely with digestate (variant N3 22.0±2.5) and the latter were also the highest in cellulose among all variants (Table 3).

Cellulose, which is the main component of plant biomass, can account for 30–60% of the dry weight of the feedstock (Bernat et al., 2014). Due to its structure, water-insoluble cellulose has high extensibility and resistance to enzymatic degradation (Oliveira Buanafina, Cogrove, 2014). The cellulose content of the plant is influenced by genetic conditions, nitrogen fertilization, technological aspects of harvesting of the raw material, among others (Rosso et al., 2013; Oleszek, Matyka, 2017). The content of cellulose in triticale biomass obtained from present study was lower (21.4% DM) than in the study of Oleszek and Matyka (2017) (31.2% DM). The average cellulose content of maize biomass from our research was 22.1% DM and was within the range of values obtained by other authors (from 20.0 to 27.7% DM) (Amon, Zollitsch, 2007; Kozlowski et al., 2007; Kacprzak et al., 2010; Kacprzak et al., 2012b; Podkówka, Podkówka, 2014; Oleszek, Matyka, 2017; Strauß et al., 2019). The cellulose content of the sorghum biomass obtained from present study was higher (36.8% DM) than in the studies of other authors, where it ranged from 17.8 to 30.9% DM (Kozłowski et al., 2007; Kacprzak et al., 2012b; Oleszek, Matyka, 2017; Strauß et al., 2019).

Hemicellulose has a backup function and is an important component of plant cell walls (Zadernowski, Pilat, 2016). Triticale biomass from present study contained less hemicellulose (20.6% DM) (Table 3) compared to the results obtained by Oleszek and Matyka (2017) and Strauß et al. (2019) (25.3 and 22.7% DM, respectively).

Hemicellulose in maize biomass from present experiment was less than obtained by other authors (20.0–35.0% DM) (Amon, Zollitsch, 2007; Kacprzak et al., 2010; Księżak et al., 2012; Podkówka, Podkówka, 2014; Oleszek, Matyka, 2017; Strauß et al,. 2019). Also, sorghum biomass obtained from our experiment contained less cellulose (22.1% DM) than in studies by other authors (25.5–26.6% DM) (Kozłowski et al., 2007; Kacprzak et al., 2012b; Strauß et al., 2019). Larger values of hemicellulose, reported in the works of other authors, compared to the results of our study, may be due to the different morphological structure and habitat conditions under which the compared plants grew (Kozłowski et al., 2007; Grygierzec, 2012). Lignin is a hydrophobic polymer found mainly in the xylem of most terrestrial plants. It is the second largest biopolymer on earth and accounts for almost 30% of organic carbon in plant biomass (Oliveira Buanafina, Cogrove, 2014). The content of the ADL (acid-detergent lignin) fibre fraction is an indication of how far plant woodiness has progressed (Kotlarz et al., 2010). The average ADL content of maize biomass (4.0% DM) from the experiment (Table 3) was consistent with values obtained by other authors, which ranged from 3.3–6.0% DM (Amon et al., 2007; Księżak et al., 2012; Kacprzak et al., 2012a; Oleszek, Matyka, 2017; Strauß et al., 2019).

Lignin content in the substrate does not promote its faster chemical and biological degradation (Bernat, Wojnowska-Baryła, 2014). ADL content determines the dynamics of biomass degradation (Shah et al., 2015). An increase in the proportion of lignocellulosic biomass in the digester mixture results in a longer first phase of biogas production and total biomass decomposition time (Bernat, Wojnowska-Baryła, 2014; Oleszek, Matyka, 2018). In a study by Strauß et al. (2019), the average ADL content in triticale was higher (4.8% DM) than the value obtained in present study (4.1% DM). Also, triticale biomass studied by Oleszek and Matyka (2017) contained more ADL (7.5% DM). In sorghum biomass, the average ADL content (7.9% DM) was higher than the values obtained by Kozłowski et al. (2007), Oleszek and Matyka (2017) and Strauß et al. (2019) (2.8–5.9% DM) and at the same time much lower than the 27.9% DM obtained by Kacprzak et al. (2012b).
Significantly lower crude ash, crude fibre, NDF, ADL and cellulose contents in triticale biomass, compared to sorghum biomass, had a statistically significant effect on higher methane production efficiency from triticale than from sorghum. As the lignin content of the biogas plant feedstock increases, a decrease in methane yield is observed (Amon et al., 2007).

CONCLUSIONS

1. In the case of sorghum biomass, fertilization with digestate resulted in lower calcium content and higher C:N compared to mineral fertilizer.
2. As a result of fertilization only with digestate (N3) significantly lowered crude fibre content in triticale biomass was observed, which is an advantageous change from the biogas production point of view.
3. Organic carbon content in the biomass of triticale and maize was significantly lower in N3 variant than in others variants, while in the case of sorghum an opposite relation was observed.
4. Fertilization with digestate makes it possible to replace mineral nitrogen fertilization without a negative effect on the quality and chemical composition of biomass of selected biogas varieties of triticale and maize.

REFERENCES

Alburquerque J.A., de la Fuente C., Campoy M., Carrascoa L., Nájera I., Baixauli C. et al., 2012. Agricultural use of digestate for horticultural crop production and improvement of soil properties. European Journal of Agronomy, 43: 119-128, doi: 10.1016/j.eja.2012.06.001.

Amon T., Amon B., Kryvoruchko V., Zollitsch W., Mayer K., Gruber L., 2007. Biogas production from maize and dairy cattle manure - Influence of biomass composition on the methane yield. Agriculture, Ecosystems & Environment, 118: 173-182, doi: 10.1016/j.agee.2006.05.007.

Amon T., Amon B., Kryvoruchko V., Machmuller A. Hopfner-Sixt K. et al., 2007. Methane production through anaerobic digestion of various energy crops grown in sustainable crop rotations. Bioresource Technology, 98(17): 3204-3212, doi:10.1016/j.biortech.2006.07.007 .

Bernat K., Wojnowska-Baryła I., 2014. Preparation of raw materials for fermentation and co-fermentation. pp. 79-102. In: Conversion of waste from agri-food industry to biogas – a system approach; eds. I. Wojnowska-Baryła i J. Gołaszewski. [in Polish + summary in English]

Bernat K., Wojnowska-Baryła I., Kasiński S. i Szatkowski M., 2014. The methods of pretreatment of lignocellulosic substrates to methane fermentation. Gaz, Woda i Technika Sanitarna, 7: 269-273. [in Polish + summary in English]

Burton C.H., Turner C., 2003. Manure Management: Treatment strategies for sustainable agriculture. Bedford, UK: Lister & Durling Printers, 451 pp.

Cherney J.H., 2006. Ash content of grasses for biofuel. Bioenergy Information Sheet. Nr 5. Cornell University, pp. 1-2.

Deublei D., Steinhauser A., 2011. Biogas from waste and renewable resources. Wiley-VCH Verlag GmbH&Co, 578 pp.

Doyeni M.O., Stulpinaite U., Baksinskaite A., Suproniene S., Tilvikiene V., 2021. The effectiveness of digestate use for fertilization in an agricultural cropping system. Plants, 10(8): 1734, doi: 10.3390/plants10081734.

FOSS, 2018. Oznaczanie włókna w paszach dla zwierząt. Włókno surowe, neutralno-detergentowe oraz kwaśno-detergentowe - normy i możliwości automatyzacji. 33 pp.

Grygierzec B., 2012. The content of basic nutrients and fibre fractions in hay from extensively used *Alopecuretum pratensis* and *Holcetum lanati communities*. Łąkarstwo w Polsce/ Grassland Science in Poland), 15: 53-65. [in Polish + summary in English]

Heiermann M., Ploechl M., Linke B., Schelle H., Herrmann C., 2009. Biogas Crop - Part I: Specifications and suitability of field crops for anaerobic digestion. Agricultural Engineering International: the CIGR Ejournal, Manuscript 1087, vol. XI.

Herrmann C., Heiermann M., Idler C., Prochnow A., 2012. Particle size reduction during harvesting of crop feedstock for biogas production. I: Effects on ensiling process and methane yields. BioEnergy Research, 5: 926-936, doi: 10.1007/s12155-012-9206-2.

Hołubowicz-Kliza G., 2007. Uprawa sorga cukrowego w technologii "mix cropping". Puławy, IUNG-PIB, 10 pp.

Igoni A.H., Ayotamuno M.J., Eze C.L., Ogaji S.O.T., Probert S.D., 2008. Designs of anaerobic digesters for producing biogas from municipal solid-waste. Applied Energy, 85: 430-438, doi: 10.1016/j.apenergy.2007.07.013.

Jankowska J., 2014. Effect of Starane 250 EC herbicide and nitrogen fertilization on the relative nutritional quality of meadow hay. Fragmenta Agronomica, 31(1): 7-17. [in Polish + summary in English]

Kacprzak A., Krzystek L., Ledakowicz S., 2010. Badania biochemicznego potencjału metanogennego wybranych roślin energetycznych. Inżynieria i Aparatura Chemiczna, 4: 32-33.

Kacprzak A., Matyka M., Krzystek L., Ledakowicz S., 2012a. Wpływ stopnia nawożenia i czynników atmosferycznych na wydajność produkcji biogazu z wybranych roślin energetycznych. Inżynieria i Aparatura Chemiczna, 4: 141-142.

Kacprzak A., Michalska K., Romanowska-Duda Z., Grzesik M., 2012b. Energy crops as a valuable material for biogas production. Kosmos Problemy Nauk Biologicznych, 61, 2(295): 281-293. [in Polish + summary in English]

Koszel M., Przywara A., Kachel-Jakubowska M., Kraszkiewicz A., 2017. Evaluation of the use of biogas plant digestate as a fertilizer in field cultivation plants. IX International Scientific Symposium, pp. 181-186, Lublin, doi: 10.24326/fmpmsa.2017.33.

Koszel M., Przywara A., Santoro F., Anifantis A.S., 2018. Evaluation of use of biogas plant digestate as fertilizer in alfalfa and winter wheat. Engineering for Rural Development, pp. 1413-1418, doi: 10.22616/ERDev2018.17.N184.

Kotlarz A., Stankiewicz S., Biel W., 2010. Botanic and chemic composition of hay from semi-natural meadow and its nutritive value for horses. Acta Scientiarum Polonorum, Zootechnica, 9(4): 119-128.

Koszel M., Parafiniuk S., Szparaga A., Bochniak A., Kocira S., Atanasov A.Z., Kovalyshyn S., 2020. Impact of digestate application as a fertilizer on the yield and quality of winter rape seed. Agronomy, 10(6):878, doi: 10.3390/agronomy10060878.

Kozłowski S., Zielewicz W., Lutyński A., 2007. Determining energetic value of *Sorghum saccharatum* (L.) Moench, *Zea mays* L. and *Malva verticillata* L. Łąkarstwo w Polsce/Grassland Science in Poland, 10: 131-140. [in Polish + summary in English]

Kraszkiewicz A., Kachel-Jakubowska M., Niedziolka I., 2017. The chemical composition of ash from the plant biomass in terms of indicators to assess slagging and pollution of surface heating equipment. Fresenius Environmental Bulletin, 26(11): 6383-6389.

Księżak J., Bojarszczuk J., Staniak M., 2012. The productivity of maize and sorghum yields of according level of nitrogen fertilization. Polish Journal of Agronomy, 8: 20-28, doi: 10.26114/pja.iung.076.2012.08.04. [in Polish + summary in English]

Księżak J., Zarychta M., 2015. Uprawa kukurydzy na kiszonkę z całych roślin. W Instrukcja upowszechnieniowa. Puławy, IUNG-PIB, 203, 79 pp.

KWS Polska. Kukurydza na kiszonkę. Uprawa kukurydzy – poradnik, pp. 77-85.

Ledakowicz S., Kacprzak A., Krzystek L., 2010. Konwersja BiOB na paliwa gazowe. pp. 228-243. In: Nowoczesne technologie pozyskiwania i energetycznego wykorzystania biomasy; eds.: P. Bocian, T. Golec i J. Rakowski, Warszawa, Instytut Energetyki.

Mazurek J., 1994. Zalecenia agrotechniczne – pszenżyto ozime. Technologie uprawy roślin. Puławy, IUNG, tom 56, 06, 27 pp.

Oleszek M., Matyka M., 2017. Nitrogen fertilization level and cutting affected lignocellulosic crops properties important for biogas production. BioResources, 12(4): 8565-8580, doi: 10.15376/biores.12.4.8565-8580.

Oleszek M., Matyka M., 2018. Determination of the efficiency and kinetics of biogas production from energy crops through nitrogen fertilization levels and cutting frequency. BioResources, 13(4): 8505-8528, doi: 10.15376/biores.13.4.8505-8528.

Oleszek M., Matyka M., 2020. Energy use efficiency of biogas production depended on energy crops, nitrogen fertilization level, and cutting system. BioEnergy Research, 13: 1069-1081, doi: 10.1007/s12155-020-10147-2.

Oliveira Buanafina M.M., Cogrove D.J., 2014. Cell walls: structure and biogenesis I: Sugarcane: physiology, biochemistry, and functional biology. Wiley Blackwell, 765 pp., doi: 10.1002/9781118771280.ch13.

Ozduven M.L., Onal Z.K., Koc F., 2010. The effects of bacterial inoculants and/or enzymes on the fermentation, aerobic stability and *in vitro* dry and organic matter digestibility characteristics of tritcale silages. Kafkas Universitesi Veteriner Fakültesi Dergisi, 16(5): 751-156, doi: 10.9775/kvfd.2009.1628.

Podkówka Z., Podkówka L., 2016. Use of sugar sorghum (*Sorghum saccharatum*) for biogas production. Nauka Przyroda Technologie, 10(14): 1-8. [in Polish + summary in English]

Podkówka Z., Podkówka W., 2010. Substraty do produkcji biogazu rolniczego. In: Substraty dla biogazowni rolniczych; eds.: Z. Podkówka, W. Podkówka, Warszawa, Agro Serwis, 72 pp.

Podkówka Z., Podkówka W., 2014. Comparison of methods for estimating production of methane from whole plant maize silage. Nauka Przyroda Technologie, 8, 4(45): 1-8. [in Polish + summary in English]

Prochnow A., Heiermann M., Plöchl M., Linke B., Idler C., Amon T., Hobbs P.J., 2009. Bioenergy from permanent grassland – A review. I: Biogas. Bioresource Technology, 100: 4931-4944, doi: 10.1016/j.biortech.2009.05.070.

Rosso L. et al., 2013. Lignocellulosic biomass as feedstoc for biofuels production. Copenhagen: European Biomass Conference and Exhibition.

Sanz M., Mosquera F., Sanchez G., Barreiro M., Aguado P.L. et al., 2011. Biomass potential of triticale and rye in two different phenological stages and energy characterization. 19th European Biomass Conference and Exhibition, Berlin, pp. 569-758, doi: 10.5071/19THEUBCE2011-VP1.3.16 .

Schattauer A., Weiland P., 2005. Parametry procesowe. pp. 10-16. In: Biogaz produkcja wykorzystanie. Leipzig: Institut fur Energetik und Umwelt gGmbH.

Shah A.F., Mahmood Q., Rashid N., Pervez A., Iftikhar A.R., Shah M.M., 2015. Co-digestion, pretreatment and digester design for enhanced methanogenesis. Renewable and Sustainable Energy Reviews, 42: 627-642, doi: 10.1016/j.rser.2014.10.053.

Strauß C., Vetter A., Dickeduisberg M., Von Felde A., 2019. Biogas production and energy cropping. I: Energy from organic materials (Biomass 3, 24). M. Kaltschmitt (ed.), Springer: 124 pp.

Śliwiński B., Furgał-Dierżuk I., Koreleski J., Brzóska F., Kański J., 2010. Tabele składu chemicznego i wartości pokarmowej pasz. Kraków-Balice: Instytut Zootechniki w Krakowie - Państwowy Instytut Badawczy, 102 pp.

Truba M.M., 2015. Wpływ preparatów biologicznych na wartość pokarmową wybranych gatunków traw. Rozprawa doktorska. Siedlce: Uniwersytet Przyrodniczo-Humanistyczny w Siedlcach, 95 pp.

Vasiljević S., Karagić Ð.M.M., 2014. Potential of biogas production by using winter pea mixtures with triticale and oat – poster.

Weiland P., 2010. Biogas production: current state and perspectives. Applied Microbiology and Biotechnology, 85(4): 849-860, doi: 10.1007/s00253-009-2246-7.

Zadernowski R., Pilat B., 2016. Changes in the content dietary fiber in maturing roots of carrots. Zeszyty Naukowe, 61: 45-56.

Zwart K.B., Langeveld J.W.A., 2010. Biogas. In: The Biobased Economy. Biofuels, materials and chemicals in the post-oil Era; eds: Langeveld H., Sanders J., Meeusen M., London, 416 pp.

received – 15 September 2021
revised – 21 November 2021
accepted – 15 December 2021

Author	ORCID
Agata Witorożec-Piechnik	0000-0003-4071-3382
Mariusz Matyka	0000-0001-6269-1175
Marek Woźniak	0000-0003-4968-3933
Marta Oleszek	0000-0002-1155-002X