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Evaluation of selected *Miscanthus* genotypes for biogas production as a possible solution of regional bioenergy

Hodnotenie vybraných genotypov *Miscanthus* na produkciu bioplynu ako možného riešenia regionálnej bioenergie

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ABSTRACT

Plantations of fast-growing crops represent local agroecosystems providing provisioning services in the form of phytomass that can be utilized for energy and/or non-energy purposes. Permanent grasses such as *Miscanthus* are identified as potentially suitable sources of raw materials for the output of second-generation biofuels. The experiments focused on the production ability of the perennial energy grass *Miscanthus* were performed in the region of SW Slovakia. It was confirmed that the studied genotypes (*Miscanthus sinensis* Tatai and *Miscanthus* × *giganteus*) exceeded the cost-efficient level of biomass production. The above-ground biomass of the studied genotypes was ensiled and afterwards fed to the experimental fermenters to evaluate the biogas production. The experiments with individual silage mixtures lasted 600 hours. The total amount of biogas produced from *M.* × *giganteus* and *M. sinensis* Tatai silage mixture was 273 dm^3 and 328 dm^3, respectively. The average share of methane in the biogas of both studied samples of silage mixtures was 51%. On the basis of the 10-year average yields of the studied *Miscanthus* genotypes achieved in our conditions, it is possible to produce 8 181 m^3/ha (*M.* × *giganteus*) and 11 248 m^3/ha (*M. sinensis* Tatai) of biogas from the silage mixtures. The achieved production represents sufficient and stable amount of biogas and its use can be economically efficient and sustainable in the long run in SW Slovakia.

Keywords: anaerobic digestion, bioenergy, biogas, biomass, *Miscanthus* × *giganteus*, *Miscanthus sinensis* Tatai

ABSTRAKT

Plantáže rýchlorastúcich rastlín predstavujú lokálne agroekosystémy poskytujúce zásobovacie služby vo forme fytomasy využiteľnej na energetické a/alebo neenergetické účely. Trvalé trávy ako *Miscanthus* sú identifikované ako potenciálne vhodné zdroje surovín na výrobu biopalív druhej generácie. Experimenty zamerané na produkčnú schopnosť trvácej energetickej trávy *Miscanthus* boli realizované v regióne JZ Slovenska. Potvrdilo sa, že študované genotypy (*Miscanthus sinensis* Tatai a *Miscanthus* × *giganteus*) prekročili ekonomicky efektívnu úroveň produkcie biomasy. Nadzemná biomasa študovaných genotypov bola silážovaná a následne privedená do experimentálnych fermentorov na vyhodnotenie produkcie bioplynu. Pokusy s jednotlivými silážnymi zmesami trvali 600 hodín. Celkový objem vyprodukovaného bioplynu zo silážnej zmesi *M.* × *giganteus* a *M. sinensis* Tatai bol 273 dm^3 a 328 dm^3. Priemerný obsah metánu v bioplyne oboch študovaných vzoriek silážnych zmesí bol 51%. Na základe 10-ročných priemerných výnosov študovaných genotypov *Miscanthus* dosiahnutých v našich podmienkach je možné vyrobiť 8 181 m^3/ha (*M.* × *giganteus*) a 11 248 m^3/ha (*M. sinensis* Tatai) bioplynu z tzv. silážne zmesi. Dosiahnutá produkcia predstavuje dostatočné a stabilné množstvo bioplynu a jeho využitie môže byť na JZ Slovenska ekonomicky efektívne a dlhodobo udržateľné.

Kľúčové slová: anaeróbna fermentácia, bioenergia, bioplyn, biomasa, *Miscanthus* × *giganteus*, *Miscanshus sinensis* Tatai

INTRODUCTION

A policy focused on the promotion of bioenergy as a path to sustainable energy production and aimed at gaining a growing understanding of the importance of ecosystem services for the well-being of human society have emerged over the last decade. Reasons for the study of the implications of bioenergy cultivation for ecosystem services has changed from academic interest to the need to design sustainable bioenergy countries (Dale et al., 2016). Tilman et al. (2009) and Manning et al. (2014) confirmed that if society is to obtain the potential benefits of growing energy plants, a key requirement is that scientifically validated environmental principles be put in place to ensure that the best use of bioenergy is adopted. The relevance of integrating ecosystem services into the analysis of the consequences of land-use change towards energy-producing plants is based on an awareness of their value to society (Porter et al., 2009; Gasparatos et al., 2011). In recent years, several studies have shown that the transition from land use focused on agricultural crops to targeted energy crops may have a positive impact on provisioning services (biomass production) (Milner et al., 2016; Dauber and Miyake, 2016; Chimento et al., 2016).

An approval was reached at the EU level on a new directive on renewable energy for the next decade in 2018. The new policy includes a legally binding Europe-wide target of 32% share of renewable energy by the year 2030 (EU DIRECTIVE 2018/2001, 2018).

Plants absorb carbon dioxide through photosynthesis, convert it into biomass, and when the plants transpire, some of the carbon from the carbon dioxide is returned to the atmosphere, the rest remains in the form of biomass. It is a cycle that repeats in a short time (every year). The use of fossil fuels causes the sudden release of large amounts of CO_2 into the atmosphere. Biofuels could help minimize the dependence on and burning of fossil fuels and thus reduce CO_2 emissions (Kitani et al., 1989). Biofuels and bio-products made from plant biomass thus represent an environmentally friendly way of mitigating global change. In addition, the production of biofuels together with bio-products can provide new occasions in rural areas from a socio-economic point of view. According to (Stevens and Verhé, 2004), the transition to alternative industrial raw materials and ecological processes for the production of biofuels from renewable biomass sources is one of the most important tasks in the 21st century.

Second-generation biofuels are obtained in two different ways: by biochemical and thermochemical conversion. The thermochemical conversion technologies include for instance pyrolysis, liquefaction, torrefaction and gasification. The biochemical conversion represents the conversion of the cellulosic and hemicellulosic elements of the biomass feedstock to a mixture of fermentable sugars by enzymatic or acid hydrolysis. This is followed by the fermentation of sugars to alcohol, especially ethanol, by microorganisms. Biochemical conversion technologies include for instance enzymatic saccharification and fermentation (Sims et al., 2010; Singh et al., 2020).

The expansion in the cultivation of fast-growing energy crops in Slovakia is related to the development of biogas crops since January 2010 when Act no. 309/2009 Coll. on the promotion of renewable energy sources and high-efficiency cogeneration came to force (Act No. 309/2009, 2009). About 113 biogas crops are cultivated in Slovakia, and maize silage is most used as a feedstock for biogas production (Chodkowska-Miszczuk et al., 2017). Feedstock from perennial crops such as *Miscanthus* is, however, considered to be more environmentally sound. As reported by (Ericsson et al., 2009), due to effective production of biomass, *Miscanthus* may have an important place in the sustainable agricultural biomass production of energy crops in the near future. The species can be also suitable for more arid areas due to its water use efficiency (Clifton-Brown and Lewandowski, 2000; Cadoux et al., 2012).

The aim of this study was to point out the possibility of biogas production in the rural areas from the *Miscanthus* biomass. The working hypothesis was that the achieved yields of cultivated *Miscanthus* stands provide sufficient and stable amount of biomass in the required quality and its use can be economically efficient and sustainable in the long run in SW Slovakia.

MATERIALS AND METHODS

Plant material

Miscanthus is a perennial grass native to East Asia (Chund and Kim, 2012). It consists of many species but only a few taxa are used for energy purposes. The species *Miscanthus sacchariflorus*, *Miscanthus floridulus* and *Miscanthus sinensis* are used for breeding. The basic number of chromosomes is n = 19. *Miscanthus* × *giganteus* GREEF et DEU is a vital triploid hybrid of *Miscanthus sacchariflorus* (diploid) and *Miscanthus sinensis* (tetraploid). It has 57 somatic chromosomes. *Miscanthus* × *giganteus* triploids are sterile (without the ability to pollinate and self-pollinate) (Syntaxonomy of *Miscanthus* × *giganteus*, 2022).

Miscanthus sinensis Tatai, a triploid hybrid (with 57 chromosomes) was bred by cross-pollination of the *Miscanthus sinensis*. This species has been optimized for the conditions of the Hungarian climate (Pintér, 2016). Rhizomes branch off and grow below the soil surface. They produce roots and aboveground stems from the nodes. The seedlings have several stems.

Individual species of perennial energy grass *Miscanthus* and its hybrids have fast growth and achieve an average height of 3 – 4 m. They produce massive above-ground biomass (more than 20 t/ha) with a high content of cellulose and lignin (Nielsen, 1987) stated the general characteristics of perennial energy grasses including the following characteristics related to *Miscanthus*: energy grasses are perennial plants with a long production ability of 15 – 20 years; they also grow on low-quality soils; in the first year of cultivation, dry biomass yields reach about 6 t/ha; yield in the following years (from the 3rd year) is approximately 15 – 40 t/ha.

Research area

The experimental fields of fast-growing energy crops are located in the Nitra Region in the cadastral area of the Kolíňany village, SW Slovakia (Figure 1).

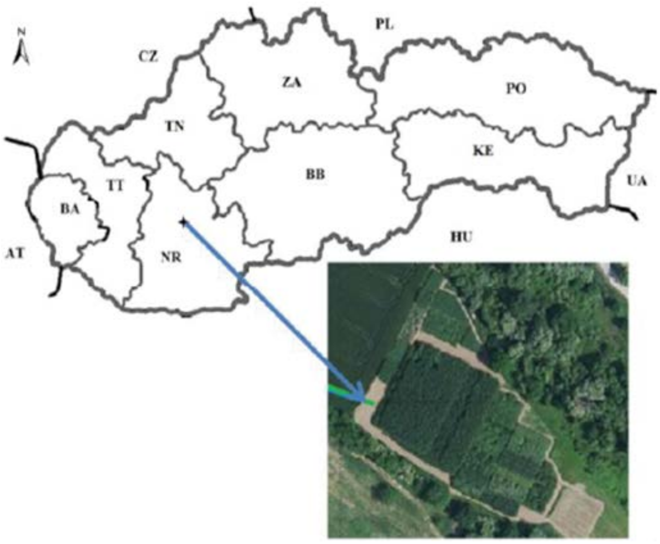

Figure 1. Location of the experimental fields of fast-growing crops in Kolíňany, Nitra Region

Selected properties of the research locality are shown in Table 1.

The research plot of the *Miscanthus* stands was established in 2009. *Miscanthus* × *giganteus* GREEF et DEU was planted by hand in the form of roots. The planting material was obtained from Hannes Stelzhammer Austria.

Table 1. Selected properties of the research locality

Location	13 km north of Nitra
Altitude	199 m above sea level
GPS location	48° 21' 21.6752115" N 18° 12' 23.8327789" E 1
Ø annual air temperature / during the growing season	11.0 °C / 15.4 °C
Ø annual total precipitation / during the growing season	594.22 mm / 429.88 mm
Soil	gley fluvisol, medium-heavy soil

The fresh weight of the roots at planting ranged from 1.67 g to 3.54 g, the length of the roots ranged from 50 to 85 mm. *Miscanthus sinensis* Tatai was planted by hand in the form of seedlings. The seedlings were prepared in vitro in Power-H Kft, Hungary. For the detailed methodology of the research plot establishment see study of Kotrla (Kotrla et al., 2019).

Destructive determination of biomass production

The destructive determination of the *Miscanthus* above-ground biomass production was carried out during the winter period. After the cutting of the selected genets (n = 20), the total weight of the individual plant was determined. The harvested biomass samples were transported to the laboratory. The samples were oven-dried at 105 °C to a constant weight and the dry weight of the samples was determined. The total dry mass (Dw) was retrieved as follows:

$$\% \, DW = \frac{DW}{FW} \times 100$$

where DW represents the dry weight and FW is the fresh weight of the biomass samples.

The moisture content of *M.* × *giganteus* varied from 19% to 22% and *M. sinensis* Tatai varied from 20% to 24% depending on the time of harvest.

Ensiling of the Miscanthus biomass

The biomass samples of the studied *Miscanthus* genotypes used for the biogas production were harvested in October 2018. The samples were ensiled the same way as maize. Three different silage samples were prepared for the experiment: *M.* × *giganteus*, *M. sinensis* Tatai and maize. Prior to the ensiling, the harvested biomass samples were cut to the length of 8 to 12 mm, which is considered the optimal length for the maize silage. During the ensiling, the silage mass was compressed to provide anaerobic conditions. The fermentation process of the silage takes approximately 90 days. Afterwards, the samples were fed to the fermenters for biogas production.

The biomass samples were handled in the experimental facility of the Slovak University of Agriculture located in Kolíňany. A sample of maize silage that is the usual input component of the experimental biogas station was used for comparison with the *Miscanthus* samples. A fermentate consisting of cattle manure and pig slurry was applied as inoculum.

Biogas production

The experimental fermenters were proposed and assembled by the researchers of the Slovak University of Agriculture in Nitra. The main task was to perform comparative tests of the different mixtures of biomass inputs for biogas production according to methodology of Giertl et al. (2022). The structural arrangement of the fermenters is shown in Figure 2.

Four replicates were performed from each sample. Replicates were selected at random design from the entire volume of silage biomass. Each replicate lasted 600 hours. A biomass used as fermentate consist of cattle manure and pig manure was used as inoculum. The experiments were realized as follows:

1) 4 × 600 h: 97 liters of inoculum from a biogas plant in co-fermentation with 3 kg of *M.* × *giganteus* silage,

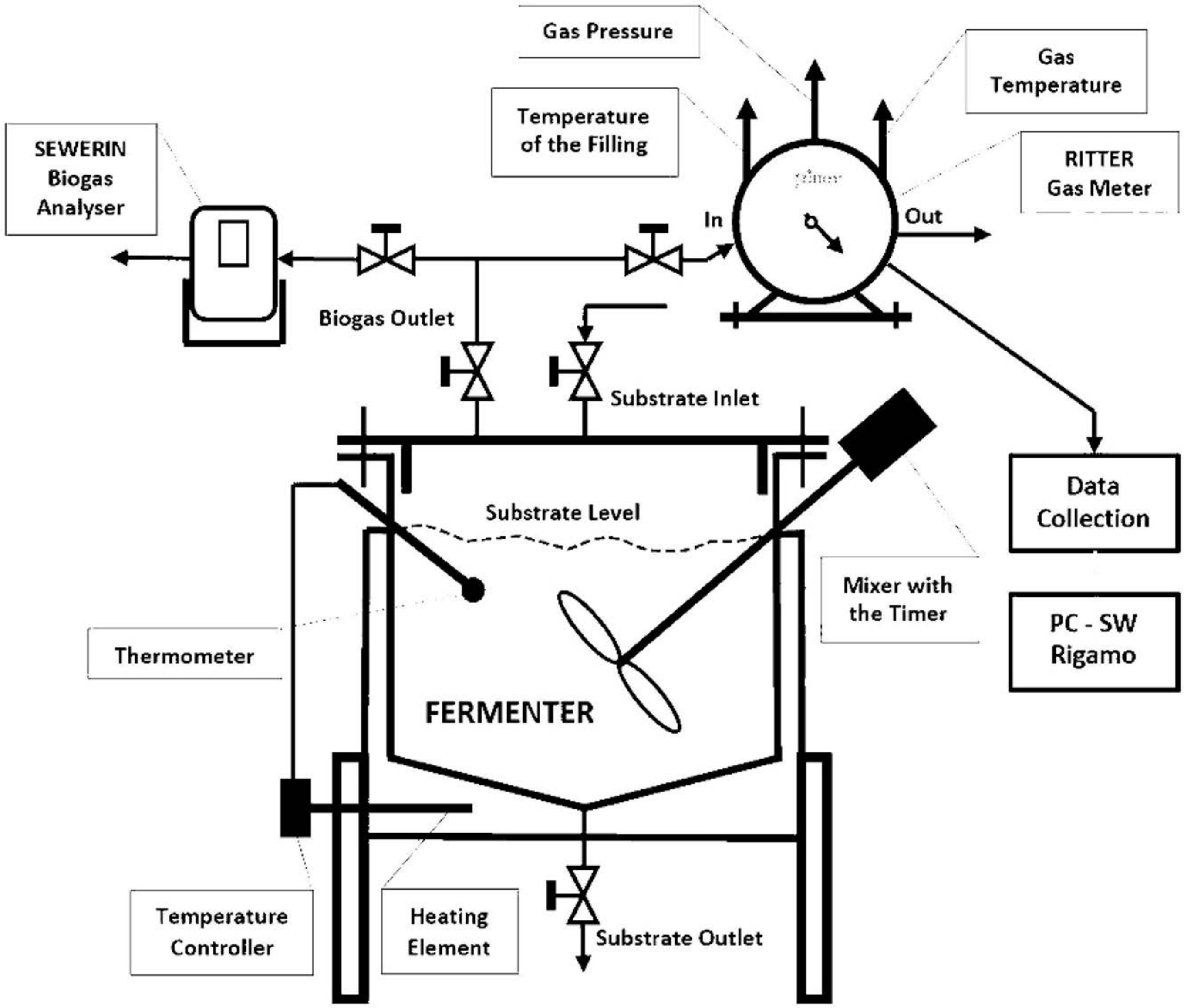

Figure 2. Technological scheme of the experimental equipment for the biogas production

2) 4 × 600 h: 97 liters of inoculum from a biogas plant in co-fermentation with 3 kg of *M. sinensis* Tatai silage,

3) 4 x 600 h: 97 liters of inoculum from a biogas plant in co-fermentation with 3 kg of maize silage,

4) 4 × 600 h: 97 liters of inoculum.

RESULTS AND DISCUSSION

The average 10-year yield (2011 – 2020) of *M. × giganteus* and *M. sinensis* Tatai was 27.00 t/ha and 30.90 t/ha of dry matter (DM), respectively in our research conditions. Both genotypes reached a level of biomass production that can be considered economically efficient already in the second year after the planting (Table 2). The economically efficient yield represents 12.00 t of DM per ha in the conditions of Slovakia (Porvaz et al., 2008). The average yields confirmed the reported average yield of *M. × giganteus* of more than 20.00 t/ha DM for Slovakia (Gubišová, 2013). The advantage of *Miscanthus* cultivation compared to standard annual crops, such as maize is that it can be cultivated on marginal land, although lower yields have to be taken into account. However, Wagner et al. (2018) found out that the cultivation of *Miscanthus* for biogas production on marginal land makes economic and environmental sense based on the Life-Cycle Assessment and complementary Life-Cycle Cost Analysis. Cultivation of *Miscanthus* is considered uneconomic if the biomass yield is lower than 11.00 t/ha DM. The authors also reported that the costs of *Miscanthus*-based biogas generation and utilization are considerably lower than those of maize.

Table 2. Production of the above-ground dry matter of *Miscanthus* genotypes in individual growing periods (Mandalová et al., 2017; Kotrla and Prčík, 2020)

Growing period	Dry yield of the *Miscanthus* genotypes [t/ha]	
	M. sinensis Tatai	*M. × giganteus*
2010	10.80	11.10
2011	16.90	18.10
2012	22.60	27.10
2013	24.10	30.30
2014	26.30	30.90
2015	25.80	30.10
2016	30.28	37.12
2017	25.90	26.57
2018	33.40	36.40
2019	31.60	33.50
2020	33.33	39.34

Similar yields (36.54 t/ha DM) comparable with our results are reported by (Porvaz et al., 2015), who studied the production parameters of the *M. × giganteus* in the environmental conditions of the East Slovak lowland. The yields in South Europe varied between 25.00 and 30.00 t/ha DM (Angelini et al., 2009) and reach up to 44.00 t/ha when the irrigation was applied (Clifton-Brown et al., 2001; Cosentino et al., 2007; Danalatos et al., 2007; Mantineo et al., 2009).

We have obtained impressive yields already in the first year after the planting exceeding 10.00 t/ha in both genotypes. According to literature, the *Miscanthus* yield of biomass should be around 5.90 t/ha in the first year of cultivation and between 8.00 t/ha and 13.00 t/ha in the second and third year of cultivation (Arnoult and Brancourt-Hulmel, 2015). Results of biomass production show that it is possible to consider *Miscanthus* as a suitable plant for energy purposes.

The pH value of the studied samples of silage was 4.9 (*M. × giganteus*) and. 4.6 (*M. sinensis* Tatai). Important parameters that need to be known when designing a biogas plant include the volume of biogas produced and the composition of the biogas. Figure 3 shows the cumulative biogas production of the studied materials during the entire fermentation period. The silage of *M. × giganteus* and *M. sinensis* Tatai produced similar amounts of biogas during the whole experiment.

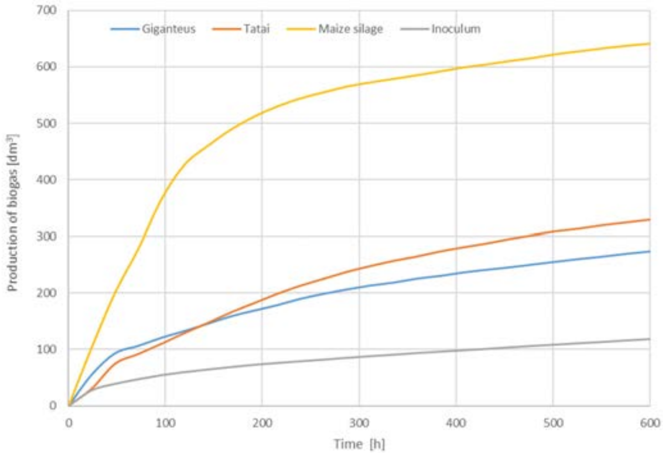

Figure 3. Accumulated biogas production of various types of biomass

The total volume of biogas produced from *M. × giganteus* and *M. sinensis* Tatai silage was 273 dm^3 and 328 dm^3, respectively. The DM content of the silage was 30%. For comparison, maize silage produced in total 641 dm^3 of biogas and the inoculum produced 118 dm^3 of biogas. After conversion to 1 t of silage biomass, it is possible to produce 91 m^3 and 109 m^3 of biogas from *M. × giganteus* and *M. sinensis* Tatai silage, respectively. Compared to maize silage, *M. × giganteus* produced 58% less biogas and *M. sinensis* Tatai 49% less biogas.

Significant biogas production from the *Miscanthus* silage was recorded in the first of 72 hours. The maximum flow of biogas from maize silage was reached after 48 hours of biogas production (4.4 dm^3/h). Compared to the maize silage, the biogas flow from the *M. × giganteus* and *M. sinensis* Tatai silage was lower by 47% and 55%, respectively at the time of maximum flow. After 240 hours, the biogas flows reached similar values in all three silage mixtures (Figure 4).

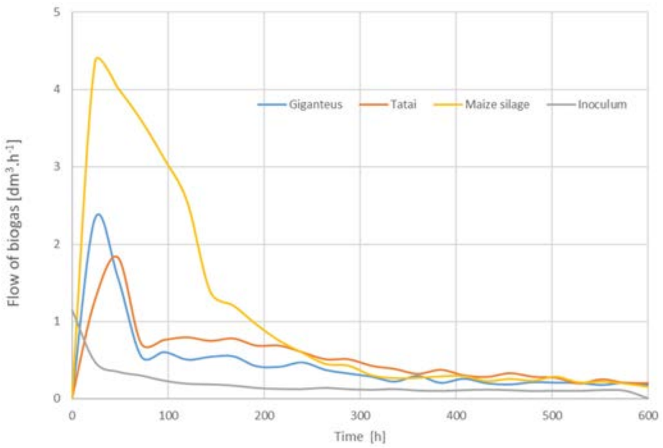

Figure 4. Biogas flow of various types of biomass

According to (Kupryś-Caruk and Podlaski, 2019), biogas production from *M. × giganteus* is 337 m^3/t DM. Our results show that it is possible to produce biogas in a volume of 303 m^3/t and 364 m^3/t DM from *M. × giganteus* and *M. sinensis* Tatai silage various mixture, respectively. If we take into account the average 10-year yields of *M. × giganteus* and *M. sinensis* Tatai achieved in our region, it is possible to achieve an average biogas production of 8 181 m^3/t (*M. × giganteus*) and 11 248 m^3/t (*M. sinensis* Tatai). These results are much higher than the value of 4 803 m^3/t reported by (Mangold et al., 2019).

Also the composition of biogas during fermentation was examined in this study. The main components of biogas were CH_4 (48 – 75%) and CO_2 (30 – 50%). Minor elements of the biogas were registered too: H_2O (1 – 10%), N_2 (0 – 5%), O_2 (0 – 2%), H_2 (0 – 1%), NH_3 (0 – 1%) and H_2S (0 – 1%). Gaduš (2019) reports that the content of major and minor elements of biogas depends on the composition of the biomass input and on the course of the fermentation The average content of methane in biogas produced from *M. × giganteus* and *M. sinensis* Tatai was recorded at the level 51%. The average methane content in biogas from maize silage was almost equal (52%). The average content of methane in inoculum biogas was 44% (Figure 5). Similar results of the average methane content in *M. × giganteus* silage reported (von Cossel et al., 2019) (55.1%) and (Kupryś-Caruk and Podlaski, 2019) (55%).

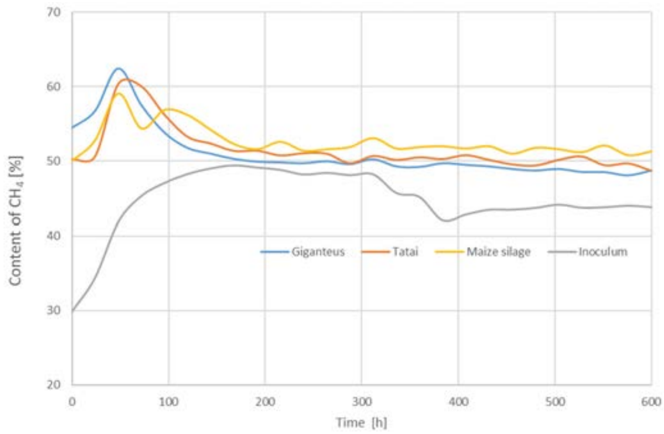

Figure 5. Content of methane in the biogas of various types of biomass

Carbon dioxide is the second major component of biogas. The CO_2 content in the biogas fluctuated significantly during the first 72 hours. One of the causes is the change in the methane content of the biogas. The course of the CO_2 content was similar in the biogas of *M. × giganteus*, *M. sinensis* Tatai and maize silage across the whole study and its average content was at the level of 44% (Figure 6).

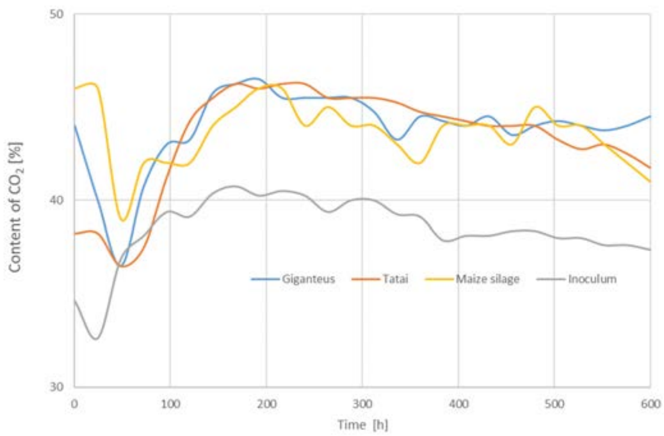

Figure 6. Carbon dioxide content in the biogas of various types of biomass

The content of hydrogen sulphide (H_2S) in biogas is undesirable (Figure 7). H_2S causes corrosion and mechanical wear that drastically increases maintenance costs (Wellinger et al., 2013). H_2S content of the *M. ×*

giganteus biogas was the lowest, reaching 200 ppm at the beginning of the experiment. Subsequently, the H_2S content kept on decreasing continuously until the end of the experiment. Its average content was recorded at the level of 95 ppm. The H_2S content of the *M. sinensis* Tatai biogas reached 650 ppm at the beginning of the experiment and also gradually decreased, averaging at 220 ppm. The highest H_2S content was measured in the maize silage biogas. At the beginning of the experiment, it reached the highest value of 1100 ppm. Its average content during the experiment was 430 ppm.

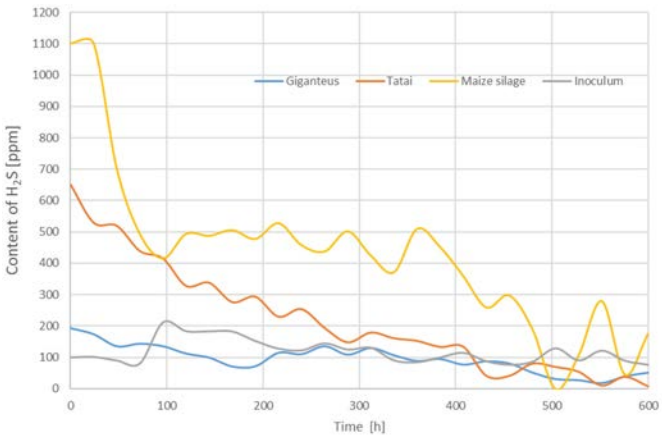

Figure 7. Hydrogen sulfide content in the biogas of various types of biomass

CONCLUSIONS

The findings of study realized on the basis of the analysis of the biomass production of the two *Miscanthus* genotypes showed the suitability of this energy grass for bioenergy utilization. In the second year since the establishment of the stand, the production of dry matter exceeded the limit of economic efficiency. *M. × giganteus* and *M. sinensis* Tatai can be used as an alternative source of input biomass for biogas crops. The total amount of biogas produced from *M. × giganteus* and *M. sinensis* Tatai silage mixture was 273 dm^3 and 328 dm^3, respectively. Based on the 10-year average yields of the studied *Miscanthus* genotypes achieved in our conditions, it is possible to produce 8 181 m^3/ha (*M. × giganteus*) and 11 248 m^3/ha (*M. sinensis* Tatai) of biogas from the silage mixtures. The biogas production was lower compared to the maize silage. However, the advantage is that it can be grown on land that is not suitable for crop production. The average methane content in the biogas of both monitored samples of silage types was 51%. A comparison of the methane content in the *Miscanthus* and maize silage suggests that maize silage can be easily replaced by *Miscanthus*. The use of the obtained results in practice will make it possible to produce so much biomass on low-quality agricultural land with an area of 100 ha, which would be sufficient for the year-round operation of a cogeneration unit with an electrical power of approximately 300 kW (360 kW heat power). This is enough to provide electricity in around 90 households without using quality agricultural land for energy purposes.

ACKNOWLEDGEMENTS

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REFERENCES

Act No. 309/2009 Coll. on the promotion of renewable energy sources and high-efficiency cogeneration and on the amendment of certain laws as amended.

Angelini, L.G., Ceccarini, L., Nassi o Di Nasso, N., Bonari, E. (2009) Comparison of *Arundo donax* L. and *Miscanthus × giganteus* in a long-term field experiment in Central Italy: Analysis of productive characteristics and energy balance. Biomass and Bioenergy, 33 (4), 635-643. DOI: https://doi.org/10.1016/j.biombioe.2008.10.005

Arnoult, S., Brancourt-Hulmel, M. (2015) A Review on *Miscanthus* biomass production and composition for bioenergy use: genotypic and environmental variability and implications for breeding. Bioenergy Research, 8 (2), 502-526. DOI: https://doi.org/10.1007/s12155-014-9524-7

Cadoux, S., Riche, A.B., Yates, N.E., Machet, J.M. (2012) Nutrient requirements of *Miscanthus × giganteus*: conclusions from a review of published studies. Biomass and Bioenergy, 38, 14-22. DOI: https://doi.org/10.1016/j.biombioe.2011.01.015

Clifton-Brown, J.C., Lewandowski, I. (2000) Water use efficiency and biomass partitioning of three different *Miscanthus* genotypes with limited and unlimited water supply. Annals of Botany, 86 (1), 191-200. DOI: https://doi.org/10.1006/anbo.2000.1183

Clifton-Brown, J.C., Lewandowski, I., Andersson, B., Basch, G., Christian, D.G., Kjeldsen, J.B., Jørgensen, U., Mortensen, J. v., Riche, A.B., Schwarz, K.U., et al. (2001) Performance of 15 *Miscanthus* genotypes at five sites in Europe. Agronomy Journal, 93, 1013-1019. DOI: https://doi.org/10.2134/agronj2001.9351013x

Cosentino, S.L., Patanè, C., Sanzone, E., Copani, V., Foti, S. (2007) Effects of soil water content and nitrogen supply on the productivity of *Miscanthus × giganteus* Greef et Deu. in a Mediterranean environment. Industrial Crops and Products, 25 (1), 75–88. DOI: https://doi.org/10.1016/j.indcrop.2006.07.006

Dale, V.H., Kline, K.L., Buford, M.A., Volk, T.A., Tattersall Smith, C., Stupak, I. (2016) Incorporating bioenergy into sustainable landscape designs. Renewable and Sustainable Energy Reviews, 56, 1158–1171. DOI: https://doi.org/10.1016/j.rser.2015.12.038

Danalatos, N.G., Archontoulis, S. v., Mitsios, I. (2007) Potential growth and biomass productivity of *Miscanthus × giganteus* as affected by plant density and N-fertilization in central Greece. Biomass and Bioenergy, 31 (2-3), 145-152. DOI: https://doi.org/10.1016/j.biombioe.2006.07.004

Dauber, J., Miyake, S. (2016) To integrate or to segregate food crop and energy crop cultivation at the landscape scale? Perspectives on biodiversity conservation in agriculture in Europe. Energy, Sustainability and Society, 6 (1), 1-11. DOI: https://doi.org/10.1186/s13705-016-0089-5

Ericsson, K., Rosenqvist, H., Nilsson, L.J. (2009) Energy crop production costs in the EU. Biomass and Bioenergy, 33 (11), 1577-1586. DOI: https://doi.org/10.1016/j.biombioe.2009.08.002

EU Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast) (Text with EEA relevance).

Gaduš, J. (2019) Prospects for the development of biogas use in the EU and Slovakia [in Slovak]. Available at: http://www.agroporadenstvo.sk/index.php?pl=107&article=1576 (Accessed 2 March 2022).

Gasparatos, A., Stromberg, P., Takeuchi, K. (2011) Biofuels, ecosystem services and human wellbeing: Putting biofuels in the ecosystem services narrative. Agriculture, Ecosystems & Environment, 142 (3-4), 111-128. DOI: https://doi.org/10.1016/j.agee.2011.04.020

Giertl, T., Pauková, Ž., Hauptvogl, M., Prčík, M., Gaduš, J. (2022) Evaluation of the Biomass of *Arundo donax* L. in the Context of Regional Bioenergetics. Polish Journal of Environmental Studies, 31 (4), 3043–3049. DOI: https://doi.org/10.15244/pjoes/145413

Gubišová, M. (2013) Množenie *Miscanthus giganteus* v in vitro Kultúre. Centrum výskumu rastlinnej výroby Piešťany: Piešťany, Available at: https://www.vurv.sk/fileadmin/VURV/Viac/PUblikacna_cinnost_VURV/Metodicka_prirucka_Mnozenie_Miscanthus_giganteus_v_in_vitro_kulture.pdf (Accessed 2 March 2022)

Chimento, C., Almagro, M., Amaducci, S. (2016) Carbon sequestration potential in perennial bioenergy crops: the importance of organic matter inputs and its physical protection. GCB Bioenergy, 8 (1), 111-121. DOI: https://doi.org/10.1111/gcbb.12232

Chodkowska-Miszczuk, J., Kulla, M., Novotný, L. (2017) The role of energy policy in agricultural biogas energy production in Visegrad countries. Bulletin of Geography, 35, 19-34. DOI: https://doi.org/10.1515/bog-2017-0002

Chung, J.-H., Kim, D.-S. (2012) *Miscanthus* as a potential bioenergy crop in East Asia. Journal of Crop Science and Biotechnology, 15 (2), 65-77. DOI: https://doi.org/10.1007/s12892-012-0023-0

Kitani, O., Hall, C.W. (1989) Biomass Handbook. New York: Gordon and Breach Science Publ. ISBN 9782881242694.

Kotrla, M., Pauková. Ž., Prčik, M. (2019) Impact of different fertilization regimes on the biomass production of perennial grass *Miscanthus × giganteus* in Slovakia. Applied Ecology and Environmental Research, 17 (6), 15233-15244. DOI: http://dx.doi.org/10.15666/aeer/1706_1523315244

Kotrla, M., Prčík, M. (2020) Evaluating the effects of climatic parameters on growth and biomass production of *Miscanthus* in climate conditions of southern Slovakia. Polish Journal of Environmental Studies, 29 (1), 669-675. DOI: https://doi.org/10.15244/pjoes/99975

Kupryś-Caruk, M., Podlaski, S. (2019) The comparison of single and double cut harvests on biomass yield, quality and biogas production of *Miscanthus × giganteus*. Plant, Soil and Environment, 65 (7), 369-376. DOI: https://doi.org/10.17221/97/2019-PSE

Mandalová, K., Kotrla, M., Prčík, M. (2017) Regional disparities in the cultivation and use of biomass of fast-growing plants in the conditions of Slovakia [in Slovak]; Slovenská poľnohospodárska univerzita: Nitra; ISBN 978-80-552-1704-8.

Mangold, A., Lewandowski, I., Hartung, J., Kiesel, A. (2019) *Miscanthus* for biogas production: Influence of harvest date and ensiling on digestibility and methane hectare yield. GCB Bioenergy, 11 (1), 50-62. DOI: https://doi.org/10.1111/gcbb.12584

Manning, P., Taylor, G., Hanley, M.E. (2014) Bioenergy, food production and biodiversity – an unlikely alliance? GCB Bioenergy, 1-18. DOI: https://doi.org/10.1111/gcbb.12173

Mantineo, M., D'Agosta, G.M., Copani, V., Patanè, C., Cosentino, S.L. (2009) Biomass yield and energy balance of three perennial crops for energy use in the semi-arid Mediterranean environment. Field crops research, 114 (2), 204-213. DOI: https://doi.org/10.1016/j.fcr.2009.07.020

Milner, S., Holland, R.A., Lovett, A., Sunnenberg, G., Hastings, A., Smith, P., Wang, S., Taylor, G. (2016) Potential impacts on ecosystem services of land use transitions to second-generation bioenergy crops in GB. GCB Bioenergy, 8 (2), 317-333. DOI: https://doi.org/10.1111/gcbb.12263

Nielsen, P.N. (1987) Vegetativ formering af elefantgræs, *Miscanthus sinensis "Giganteus"*. Tidsskr. Planteavl, 91, 361-368.

Pintér, C. (2016) Harvesting system established for the utilisation of *Miscanthus sinensis* 'Tatai' "energy cane" in biomass power plants. Acta Agraria Debreceniensis, 69, 143–150. DOI: https://doi.org/10.34101/actaagrar/69/1803.

Porter, J., Costanza, R., Sandhu, H., Sigsgaard, L., Wratten, S. (2009) The value of producing food, energy, and ecosystem services within an agro-Ecosystem. AMBIO: A Journal of the Human Environment, 38 (4), 186-193. DOI: https://doi.org/10.1579/0044-7447-38.4.186.

Porvaz, P., Mati, R., Kotorová, D., Jakubová, J. (2008) Cultivation of Chinese silver grass (*Miscanthus sinensis* Anderss.) for energy purposes [in Slovak]; SCPV - Ústav agroekológie: Michalovce,; ISBN 978-80-88872-93-1.

Porvaz, P., Gaduš, J., Tóth, Š., Polák, M., Kron, I. (2015) Alternative use of Chinese silver grass *Miscanthus × giganteus* for energy purposes [in Slovak]; NPPC – VÚA, Michalovce: Michalovce.

Sims, R.E.H., Mabee, W., Saddler, J.N., Taylor, M. (2010) An overview of second generation biofuel technologies. Bioresource Technology, 101 (6), 1570-1580. DOI: https://doi.org/10.1016/j.biortech.2009.11.046.

Singh, A., Nanda, S., Berruti, F. (2020) A review of thermochemical and biochemical conversion of *Miscanthus* to biofuels. Biorefinery of Alternative Resources: Targeting Green Fuels and Platform Chemicals, 195-220, Available at: https://link.springer.com/chapter/10.1007/978-981-15-1804-1_9.

Stevens, C. v., Verhé, R. (2004) Renewable bioresources: scope and modification for non-food applications. John Wiley and Sons Ltd: Chichester, ISBN 0-470-85446-4.

Syntaxonomy of *Miscanthus* × *giganteus* (2022) Greef et Deu Available online: https://eurekamag.com/research/002/508/002508384.php (accessed on 24 March 2022).

Tilman, D., Socolow, R., Foley, J.A., Hill, J., Larson, E., Lynd, L., Pacala, S., Reilly, J., Searchinger, T., Somerville, C., et al. (2009) Beneficial biofuels—the food, energy, and environment trilemma. Science, 325 (5938), 270-271. DOI: https://doi.org/10.1126/science.1177970.

von Cossel, M., Mangold, A., Iqbal, Y., Lewandowski, I. (2019) Methane yield potential of *Miscanthus* (*Miscanthus* × *giganteus* (Greef et Deuter)) established under maize (*Zea mays* L.). Energies, 12 (24), 4680. DOI: https://doi.org/10.3390/en12244680.

Wagner, M., Mangold, A., Lask, J., Petig, E., Kiesel, A., Lewandowski, I. (2018) Economic and environmental performance of *Miscanthus* cultivated on marginal land for biogas production. GCB Bioenergy, 11 (1), 34-49. DOI: https://doi.org/10.1111/gcbb.12567.

Wellinger, A., Murphy, J., Baxter, D. (2013) The biogas handbook: science, production and applications. Woodhead publishing, p. 476. DOI: https://doi:10.1533/9780857097415