Energy Properties Potential of Novel *Miscanthus* Hybrids in the Plantation Establishment Phase

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Summary

Miscanthus × *giganteus* J.M. Greef, Deuter ex Hodk., Renvoize (*M. giganteus*) is currently one of the most important energy crops in terms of the cultivation of dedicated crops. However, restricting biomass production to a sterile triploid hybrid may result in insufficient energy efficiency under various agroecological conditions. Therefore, current researches are focused on developing novel hybrids with higher tolerance to abiotic stresses, such as salinity or drought. Increasing the utilization of energy crops, i.e., the potential is achieved by increasing biomass yield and improving its energy properties under certain conditions. In this study, the biomass of five new *Miscanthus* hybrids (*M. sacchariflorus x M. sinensis*) and *M. giganteus* was used as control. The energetic properties were studied during the first two years of the cultivation period. Following the determination of biomass yield in fresh weight, dry matter content was also determined using standard methods, as well as the main energetic properties. Statistical data processing compared the energy potential of the new hybrids with each other and with that of the control hybrids. The results confirmed that there were specific changes in the energy properties of the new genotypes and the control hybrids during the establishment phase. In parallel with the increase in yield, it has a positive effect on energy efficiency and results from different genetic sources and adaptation to environmental conditions.

Key words

Miscanthus x giganteus, novel hybrids, energy properties

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Introduction

The European bioeconomy and circular economy strategies aim at food security and sustainable management of natural resources, reducing dependence on non-renewable resources, mitigating and adapting to climate change, creating jobs and maintaining European competitiveness (EEA, 2018). One of the main guidelines of these strategies is the use of biomass for various purposes, from fuels to advanced bioproducts and the production of isolates (Lewandowski et al., 2019). Such a form of resource management significantly increases the demand for biomass in the industry. The growing demand for agricultural- or forest-based biomass and biomaterials can be met either by increasing productivity per cultivated area (higher yield per hectare) or by expanding the area used. Higher yields are usually associated with intensive management (e.g. through higher use of water, pesticides and fertilizers, and mechanization), which affects soil, water, and air quality, as well as biodiversity (EEA, 2018). The expansion of arable land in agriculture as well as deforestation have negative impacts on the biodiversity of wildlife and protected areas, but also on their carbon storage potential.

To avoid this, it is necessary to implement the increase of biomass production through the principle of environmental protection. Another way to meet these requirements is the careful selection, development and cultivation of energy crops. Such a development model should provide a climate-specific crop that can achieve the highest yields and industrial qualities considering the cultivated area (Robson et al., 2019). However, even with the introduction of these crops, such an increase in production requires the maximum use of all available agricultural land. Therefore, a compromisable strategy for biomass production is to grow biomass crops on lower quality agricultural land, known as marginal land, where no competition with the cultivation of feed and food crops is expected (Lewandowski et al., 2016). Marginal lands are usually characterized by abiotic stressors such as drought, flooding, stoniness, steep slopes, wind exposure, and suboptimal orientation, and have low nutrient content and/or are contaminated. In these challenging environments, a crop must not only be resilient but also have a high yield-to-energy ratio (typically 20-50) to achieve significant carbon savings. (Tóth et al., 2016; Clifton-Brow et al., 2019).

One of the crops that is becoming increasingly important from this point of view is *Miscanthus x giganteus* (*M. giganteus*). Its remarkable adaptability to different environments makes *M. giganteus* suitable for cultivation in a range of European and North American climates (Lewandowski et al., 2016). Although *M. giganteus* has shown high potential over the last 25 years, its commercial cultivation has not reached a significant level, mainly due to its infertility (a sterile trihybrid), which requires a high initial investment in vegetative propagation. In recent years, great efforts have been made to identify new genotypes and hybrids adapted to different agroclimatic conditions, with higher productivity and stability, but also reducing the cost of plantation establishment (Lewandowski et al., 2016; Clifton-Brown et al., 2017). Genotypes of the genus *Miscanthus*, as well as their hybrids, grow rapidly, reach an average height of 3 to 4 m, and after reaching full maturity form massive biomass (sometimes more than 40 t DM ha^{-1}) that is rich in cellulose and lignin (Anderson et al., 2011; Brosse et al., 2012; Kotrla and Prčík, 2019). However, the establishment of the plantation and its maturation depends on the local climatic conditions as well as on the marginal land.

Although *Miscanthus* hybrids are characterized by favorable properties for the production of second-generation biofuels and bioproducts, the biomass of *M. giganteus* grown on about 25,000 hectares in the European Union (EU28) (Bioenergy Europe, 2019) is currently mainly used by direct combustion. Combustion is used in a variety of services to convert the chemical energy stored in biomass into heat, mechanical energy or electricity, and various process plants are used in this process (Bilandžija et al., 2018). Together with the yield potential of the energy crop, its energetic characteristics allow determining the energy production potential. Although lower amounts of biomass are produced in the establishment phase of *Miscanthus* plantations with a poor leaf-to-stem ratio, a detailed examination of the main energetic properties could provide preliminary data on the potential for growing certain hybrids under specific agroclimatic conditions.

Based on the above, the aim of this study was to investigate the dynamics of improvement in yield and energy characteristics of 5 novel *Miscanthus* hybrids and *M. giganteus* as control, grown in Croatia. To observe these dynamics, the observations and analyses were performed on the biomass harvested in March 2019 and 2020. To quantify these traits, the data were compared with previous studies on *M. giganteus* biomass grown under similar agroclimatic conditions.

Materials and Methods

Materials

In this study, the biomass of 5 new *M. sacchariflorus x M. sacchariflorus* (GRC 10 - 15) hybrids was used, as well as *M. giganteus* (GRC 9) that was used as a control hybrid. Biomass was harvested in March 2019, after the first year of vegetation, and in March 2020, after the second year of vegetation, at the experimental station Šašinovec (45°50'59.3" N, 16°11'26.2" E), Croatia, at the Faculty of Agriculture, University of Zagreb. The plantation was established in May 2018 on marginal soil with low pH (ph in H_2O 4.7) and consequently limited NPK content. These new hybrids were carefully selected for their performance on marginal, contaminated, and unused/abandoned soils under the H2020 BBI-DEMO project No. 745012 "GRowing Advanced industrial Crops on marginal lands for biorEfineries - GRACE". After harvesting, the yield and moisture content of the fresh weight was determined. Before laboratory analyses, the biomass was dried, milled, and processed according to the method EN ISO 14780:2017.

Methods

Proximate analysis of biomass included ash content (EN ISO 18122:2015) by oven-dry sample combustion in a crucible at 500 °C until constant weight; coke and volatile matter content (EN 15148:2009) by sample combustion in a crucible at 900 °C for 7 minutes; fixed carbon content was calculated (EN ISO 17225-1:2014), and the higher heating value (EN 14918:2010) was determined in an adiabatic bomb calorimeter IKA C200, by determination of the heat energy released from a combusted sample.

Elemental analysis (C, H, N, and S) was performed by using Vario Macro Elemental Analyzer (Elementar Analysensysteme GmbH, Germany) through the combustion of each biomass sample. After combustion in a controlled atmosphere, combustion products (CO_2, H_2O, SOx, and NOx) were analyzed. The analysis was carried out according to EN ISO 15104:2011 method, while oxygen (O) content was calculated following the EN ISO 15289:2011 method.

Statistical analysis of the data was performed by using a one-way ANOVA with Tukey's multiple comparison test ($P < 0.05$). Statistical analysis and graphical representation were done using R (R Development Core Team, 2008), R Studio (RStudio, Inc., 2018) and 'multcompview', 'lsmeans', 'multcomp', 'devtools,' 'ggpubr' and 'ggplot2' packages.

Results and Discussion

In order to use and ensure the highest possible energy yield from the agricultural unit of land, it is important to quantify, in the first place, the possibility of biomass production. Each of the hybrids studied exhibited certain quality traits at selection, but to assess their suitability for different conditions, yield dynamics should be closely monitored during the establishment phase of the plantation. Table 1 shows the increase in dry matter (DM) yielded per hectare by the hybrids studied after the first and second years of vegetation.

Table 1. DM yield dynamics of investigated *Miscanthus* hybrids throughout the plantation establishment phase

Hybrid ID	Yield (t DM ha^{-1})	
	2019	2020
GRC 9	0.95a±0.39	2.81a±1.34
GRC 10	0.40a±0.20	3.24a±2.69
GRC 11	0.40a±0.15	2.69a±1.55
GRC 13	1.08a±0.93	7.40ab±1.39
GRC 14	0.38a±0.10	4.30a±3.74
GRC 15	0.80a±0.55	11.19b±2.35
P	NS	**

Note: *** = $P < 0.001$, ** = $P < 0.01$, * = $P < 0.05$, NS = not significant

After the relatively low, but expected, yields in the first harvest in 2019, which ranged from 0.37 t DM ha^{-1} (GRC 14) to 1.07 t DM ha^{-1} (GRC 13), the second harvest, conducted in 2020, showed a significant increase in the yield of GRC 15 biomass (11.19 t DM ha^{-1}) ($P<0.01$), whereas other hybrids were still quite low in their yields, compared to matured plantations described in the previous studies at similar locations. Therefore, the expected yield of the *M. giganteus* biomass DM per hectare, in a full maturity field, is expected to range from 21.90 t to 44.62 t (Bilandžija et al., 2017b). However, by comparing those yield dynamics with juvenile *Miscanthus* plant yield regression (Shepherd et al., 2020), it is expected for all hybrids to reach full yield potential by the end of the fourth year in general. In a Croatian warmer climate, however, it is expected that hybrids will reach it in earlier years.

Biomass to energy conversion efficiency is determined by its energy properties, where higher heating value (HHV) is the most common assessment to describe gross compositional properties impacting biomass-to-energy conversion (Jurišić et al., 2014). HHV depends on a complex of biological traits of biomass, including moisture, ash, fixed carbon (FC), volatile matter, coke content, as well as elemental composition (Bilandžija et al., 2017a). High coke and FC contents are desirable traits of biomass and have a positive impact on its energy efficiency, while high ash content has a negative impact. The major challenge for the combustion of *Miscanthus* biomass is a low ash melting temperature, which not only reduces the conversion efficiency but also leads to other technical problems such as damage to boiler surface (Iqbal et al., 2017). In Table 2, the data related to the proximate analysis of novel hybrids is shown.

As mentioned before, the ash content of biomass, used as a solid biofuel has a direct negative impact both on energy conversion efficiency and technical durability. Ash content of all investigated hybrids, after the first year, did not exceed 5.74 % (GRC 13), with no significant differences found. In the second year, ash content changed and was statistically different between the investigated hybrids. GRC 9 (*M. giganteus*) had the lowest ash content (2.40 %), while GRC 11 had the highest (7.22 %) ($P<0.001$). By reaching its maturity, due to the increased nutrient circulation and decreased leaf proportion, it is expected for biomass to achieve lower contents of ash; that has been the case for all of the hybrids, except the above-mentioned GRC 11 hybrid. The previous studies, on *Miscanthus* biomass cultivated in similar locations, showed that the ash content of mature *Miscanthus* biomass ranged from 1.20 % (Kričkaet al., 2017) and 1.86 % (Bilandžija et al., 2018), to 2.01 (Voća et al., 2021), which is significantly lower than the biomass investigated in this study, but with reaching its full maturity, the significant drop in the ash content is expected to occur. Other studies conducted on *Miscanthus* biomass reported ash contents lower than in investigated hybrids, with 1.40 % (Conrad et al., 2019) and 1.50 % (Lisy et al., 2020), while Ivanyshyn et al. (2018) reported something increased content of 3.67 %.

Coke content is a favorable component of a solid biofuel which increases its energy conversion rate. In biomass harvested after the first vegetation year, there were no significant differences between the coke content in investigated hybrids; they ranged between 15.80 % and 18.50 %. After the second vegetation year, the coke content dropped, with GRC 11 having significantly the highest content (16.52 %), while other hybrids did not show statistical differences (13.61 % to 14.53 %) ($P<0.001$). In previous studies, the coke content of mature biomass cultivated in similar locations was from 11.24 % (Kričkaet al., 2017) and 11.91 % (Jurišić et al., 2014), to 12.14 % (Voća et al., 2021). All investigated hybrids had significantly higher coke contents, while a drop with maturity was noticed; therefore, it is expected that with full maturity, the coke content will decrease proportionally.

Fixed carbon (FC) represents the amount of carbon bound in the biomass by photosynthesis and represents a solid residue after the release of volatile matter (García et al., 2012). The increase in FC increases the heating value, so thus improves the quality of the biomass.

Table 2. Proximate analysis of the novel *Miscanthus* hybrids during the plantation establishment phase

Hybrid ID	March, 2019				March, 2020			
	AC (% db)	CK (% db)	FC (% db)	VM (% db)	AC (% db)	CK (% db)	FC (% db)	VM (% db)
GRC 9	4.68a±0.11	15.80a±1.81	10.39a±1.44	76.91c±0.03	2.40a±0.02	13.61a±0.38	11.22b±0.38	79.87c±0.38
GRC 10	5.52a±0.78	17.99a±0.90	13.28ab±0.19	75.54a±0.10	3.93bc±0.13	14.45a±0.79	10.53ab±0.90	78.96bc±0.79
GRC 11	4.70a±0.53	17.31a±1.36	12.83ab±1.82	76.64b±0.09	7.22d±0.36	16.52b±0.40	9.30a±0.63	76.82a±0.40
GRC 13	5.74a±0.40	17.26a±0.81	12.38ab±1.72	76.49b±0.03	3.67b±0.10	14.53a±0.47	10.86b±0.54	78.47b±0.47
GRC 14	5.03a±0.83	18.50a±0.52	13.20ab±0.13	75.70a±0.00	4.15c±0.04	13.85a±0.39	9.70ab±0.43	79.36bc±0.39
GRC 15	5.41a±0.19	18.20a±0.23	13.85b±0.28	76.95c±0.04	4.02bc±0.13	13.99a±0.33	9.97ab±0.21	79.12bc±0.33
P	NS	NS	*	***	***	***	**	***

Note: AC = ash content; CK = coke; FC = fixed carbon; VM = volatile matter; % db = % dry basis; significance: *** = $P < 0.001$, ** = $P < 0.01$, * = $P < 0.05$, NS = not significant

FC in this study ranged from 10.39 % (GRC 9) to 13.85 % (GRC 15) after the first vegetation year ($P < 0.05$), and from 9.30 % (GRC 11) to 11.22 % (GRC 9) after the second vegetation year ($P<0.01$). In previous studies, FC content reported values of 8.74 % (Bilandžija et al., 2018), 10.14 % (Voća et al., 2021), 10.41 % (Bilandžija et al., 2017b) and 12.90 % (Conrad et al., 2019). FC content decreased during the second vegetation year in all investigated hybrids; since it showed significantly lower ranges in the previous studies, its decrease is expected to continue in the following year. With lower FC content, biomass could become more convenient for conversion to bioproducts. However, its content in investigated hybrids is still within a desirable level for energy production.

In both harvest years, volatile matter (VM) content was found to be significantly different between hybrids ($P<0.001$). After the first vegetation year, VM content ranged from 75.54 % (GRC 10) and 75.70 % (GRC 14) to 76.91 % (GRC 9) and 76.95 % (GRC 15). This data is significantly lower than in the previous studies, where VM content was reported to be 81.46 % (Voća et al., 2021), 85.70 % (Conrad et al., 2019), 88.01 % (Bilandžija et al., 2018) to 89.81 % (Jurišić et al., 2014).

Together with biomass proximate properties, the complex chemical composition of carbon, hydrogen, oxygen, nitrogen, sulfur represents an important indicator of fuel quality. The results obtained from the ultimate analysis of the investigated hybrids are shown in Table 3.

Table 3 shows that the carbon content in all *Miscanthus* hybrids in the first harvest was not statistically different, and it ranged from 48.39 % (GRC 11) to 49.74 % (GRC 15). In the second year, however, significant differences were found, where GRC 11 had the lowest carbon content (48.40 %), while GRC 9 had the highest content (50.70 %) ($P<0.001$). Moreover, there were no significant changes in carbon content between the first two harvest years, except a slight increase in GRC 9. The carbon content is proportional to the heating value of biomass; thus, an increase benefits the biomass quality. In the previous studies, the carbon content of mature biomass ranged from 46.50 % (Bilandžija et al., 2017a) and 49.75 % (Jurišić et al., 2014) to 51.52 % (Voća et al., 2021). Compared to the investigated hybrids in this study, these carbon contents were similar, as well as in accordance with *Miscanthus* solid biofuel specifications (ISO EN 17225-1:2021), where carbon content typically varies from 46.00 % to 52.00 %.

Hydrogen content increases the heating value of a fuel, and its increase improves the quality of the raw material itself. After the first year, hydrogen content was not significantly different between the hybrids, with a mean of 3.92 %. In the second year, its proportion increased, with a statistically significant difference between the hybrids ($P<0.001$); GRC 11 had the lowest content of hydrogen (5.59 %), and GRC 13 had the highest (5.79 %). The results are in line with the previous studies, where the hydrogen content ranged from 3.57 % (Bilandžija et al., 2017a) and 6.09 % (Voća et al., 2021) to 6.17 % (Krička et al., 2017), following standardized normative (ISO EN 17225-1:2021), where hydrogen content varies from 5.00 % to 6.50 % in *Miscanthus* biomass.

The nitrogen content of the investigated biomass ranged from 0.74 % (GRC 9) to 1.54 % (GRC 10) in the first harvest ($P < 0.05$), with a slight increase in the second harvest, where GRC 9 had 1.02 % of nitrogen, while GRC 11 had 2.60 % ($P<0.001$). Nitrogen content was significantly higher in both harvests compared to the previous studies, where the highest content was found to be 0.74 (Krička et al., 2017) and 0.18 % (Voća et al., 2021), while the lowest was 0.20 % (Bilandžija et al., 2017a). Nitrogen content negatively affects the energy efficiency of biomass; however, in these cases, the content in hybrids GRC 9, 11, 13, 14, and 15 in the first harvest, as well as in GRC 9 and 15 in the second harvest is rather low and in accordance with *Miscanthus* solid biofuel specifications (ISO EN 17225-1:2021), where nitrogen content typically varies from 0.10 % to 1.50 % for all hybrids. However, there is increased content of nitrogen in GRC 10 in both harvests, as well as for GRC 11, 13, and 14 in the second harvest, when compared to normative values.

As sulfur forms gaseous components, sulfur dioxide (SO_2) and sulfur trioxide (SO_3), from an ecological point of view, its lowest possible content is important (García et al., 2012). In the first harvest, sulfur content was not significantly different between hybrids, and it ranged from 0.10 % to 0.12 %.

Table 3. Ultimate analysis of the novel *Miscanthus* hybrid during the plantation establishment phase

Hybrid ID	March, 2019					March, 2020				
	C (% db)	H (% db)	N (% db)	S (% db)	O (% db)	C (% db)	H (% db)	N (% db)	S (% db)	O (% db)
GRC 9	48.86a±1.05	3.92a±0.02	0.74a±0.11	0.10a±0.01	45.81ab±0.52	50.70c±0.02	5.76c±0.01	1.02a±0.07	0.20a±0.00	42.30abc±0.11
GRC 10	49.59a±0.90	3.90a±0.04	1.54b±0.35	0.13a±0.01	44.84a±1.33	49.82ab±0.02	5.77c±0.00	2.50de±0.09	0.42c±0.04	41.47a±0.03
GRC 11	48.39a±0.36	3.91a±0.03	1.30ab±0.53	0.12a±0.04	45.18ab±0.55	48.40a±0.53	5.59a±0.04	2.60e±0.08	0.34b±0.00	43.05c±0.65
GRC 13	49.37a±0.71	3.93a±0.01	1.03ab±0.14	0.12a±0.00	45.56ab±0.55	49.81ab±0.09	5.79c±0.01	2.32d±0.09	0.31b±0.00	41.75ab±0.17
GRC 14	49.70a±0.66	3.91a±0.01	1.40ab±0.16	0.12a±0.00	45.19ab±0.09	49.34ab±0.07	5.77c±0.02	1.96c±0.11	0.34b±0.00	42.57bc±0.17
GRC 15	49.74a±0.04	3.91a±0.01	0.78a±0.06	0.10a±0.00	46.82b±0.33	49.78ab±0.30	5.69b±0.03	1.33b±0.08	0.21a±0.01	42.96c±0.24
P	NS	NS	*	NS	*	***	***	***	***	***

Note: C = carbon; H = hydrogen; N = nitrogen; S = sulphur; O = oxygen; % db = % dry basis; significance: *** = $P < 0.001$, ** = $P < 0.01$, * = $P < 0.05$, NS = not significant

In the second year, its proportion slightly increased, reaching a maximum of 0.42 % (GRC 10), while GRC 9 had the lowest content (0.20 %) ($P<0.001$). Previous studies showed somewhat lower contents, ranging from 0.07 % (Bilandžija et al., 2017a., Voća et al., 2021) to 0.29 % (Kričkа et al., 2017). Sulfur levels in *Miscanthus* biomass, according to normative levels (ISO EN 17225-1:2021) range from 0.02 % to 0.60 %.

Oxygen is an element which presence in the fuel is undesirable since it can take part in the combustion process, by replacing a share of the oxygen from the air. Investigated hybrids had a higher oxygen content in the first harvest, from 44.84 % (GRC 10) to 46.82 % (GRC 15) ($P < 0.05$). In the second harvest, GRC 10 also showed the lowest content of oxygen (41.47 %), while GRC 11 showed the highest content (43.05 %) ($P<0.001$). This decrease is favorable, due to an increase in the energy potential of biomass. Previous studies showed data in oxygen content that ranged from 42.14 % (Voća et al., 2021) and 45.68 % (Jurišić et al., 2014) to 49.31 % (Bilandžija et al., 2017a), while standardized normative (ISO EN 17225-1:2021) limits its value to a range from 40.00 % to 45.00 %, within which the investigated hybrids fit.

In order to evaluate and assess biomass-to-energy efficiency and potential, it is crucial to determine a higher heating value (HHV) of biomass fuels (Dashti et al., 2019). The results of higher and the lower heating values are shown in Table 4.

Table 4. Higher and lower heating values of the novel *Miscanthus* hybrids during the plantation establishment phase

Hybrid ID	March, 2019		March, 2020	
	HHV* (MJ kg^{-1})	LHV (MJ kg^{-1})	HHV (MJ kg^{-1})	LHV (MJ kg^{-1})
GRC 9	17.94a±0.06	17.08a±0.06	18.37bc±0.05	17.11bc±0.05
GRC 10	18.12a±0.22	17.27a±0.21	18.76d±0.03	17.50d±0.03
GRC 11	17.75a±0.04	16.89a±0.04	17.76a±0.06	16.54a±0.06
GRC 13	18.01a±0.09	17.15a±0.10	18.50c±0.02	17.24c±0.02
GRC 14	18.12a±0.28	17.26a±0.29	18.40bc±0.03	17.14bc±0.03
GRC 15	18.01a±0.07	17.14a±0.07	18.28b±0.15	17.03b±0.15
P	NS	NS	***	***

Note: HHV = higher heating value: LHV = lower heating value; *all data is expressed on dry basis; significance: *** = $P < 0.001$, NS = not significant

The HHV of fuel is equal to the amount of heat released when a unit mass of the fuel is burnt completely, accounting for the enthalpy of condensation of liquid water as a combustion product under standard conditions. LHV differs from the HHV by the magnitude of the latent heat of vaporization (condensation) of water vapor from fuel gases generated from the moisture and hydrogen contained in the fuel. Fuels with higher HHV/LHV will have the highest possible energy output (Xu and Yuan, 2015; Uzun et al., 2017). The hybrids investigated in this study did not have significantly different HHVs in the first harvest, ranging from 17.75 MJ kg^{-1} (GRC 11) to 18.12 MJ kg^{-1} (GRC 10 and 14).

In the second year, these values slightly increased, reaching 18.76 MJ kg^{-1} (GRC 10) (P<0.001); the data are higher than in the previous studies conducted on the mature *Miscanthus* biomass in similar locations, which had HHVs from 17.64 MJ kg^{-1} (Voća et al., 2021) and 17.48 MJ kg^{-1} (Krička et al., 2017) to 18.20 MJ kg^{-1} (Bilandžija et al., 2017a). LHVs followed the same dynamics, respectively. According to standardized normative for *Miscanthus* solid biofuel (ISO EN 17225-1:2021), a typical higher heating value is reported to be 19.00 MJ kg^{-1}, ranging from 17.00 MJ kg^{-1} to 20 MJ kg^{-1}.

Conclusions

To determine the maturation dynamics of the new *Miscanthus* hybrids, a series of biomass analyses was conducted in relation to their energy potential. The results of the ultimate analyses (CHNSO) of the biomass of four hybrids as well as *M. giganteus* were in agreement with the results of previous studies, except for the hydrogen content. The data of primary analyses (ash, coke, fixed carbon, and volatiles) and HHV were also comparable with the previous studies on the mature *Miscanthus* plantations grown in similar climatic locations. The yield was found to be the only characteristic significantly different from the mature *Miscanthus* plantations.

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