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Extrusion pretreatment of maize straw – case study for a Polish biogas plants

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A b s t r a c t. One of the most commonly used substrates in biogas plants is maize silage, however, the application of mono-fermentation technology under Polish economic conditions has a tendency to rapidly bankrupt the investor. The lack of profitability of investments based on this material has encouraged investors to search for other, more economically favourable biomass sources *i.e.* maize straw. The aim of the research was to compare the energetic potential of untreated maize straw and extruded maize straw used for biogas production and furthermore, to determine the amount of electricity and heat generated as well as the amount of heat produced from direct combustion. The results obtained confirmed the substantial energy potential of maize straw. It has been proven that using the extrusion method as a pretreatment before the fermentation process, enables the producer to increase biogas and methane production respectively by 7.50 and 8.51%. However, the use of an extruder machine in biogas plants in Poland is economically unjustified due to its high energy consumption. Moreover, it has been shown, that the use of maize straw in the methane fermentation process enables it to generate (in Poland) a higher income than is the case of using this material in a direct combustion process.

K e y w o r d s: maize straw, extrusion, methane fermentation, biogas, energetic potential

INTRODUCTION

Climate change and the potent emissions of pollution generated from conventional electricity and heat production systems, have resulted in the use of an increased share of renewable energy sources (RES) in the national energetic systems and in transport (Mesarić and Krajcar, 2015; Zhang *et al.*, 2010). These changes have become especially noticeable in the last decade (Borenstein, 2015).

The need to change the direction of current energy policy has significantly influenced the development of new environmentally friendly technologies (Caceres *et al.,* 2015; Papadias *et al.,* 2012; Parpurello *et al.,* 2015). One of the methods proposed to fulfil the targets set by the European Union, is to use a biomass for energy generation purposes (Czekała *et al.,* 2015; Dach *et al.,* 2014; Igliński *et al.,* 2012; Lewicki *et al.,* 2014). This is mainly due to the large area of agricultural land (approx. 14.6 million ha) (Central Statistical Office, 2016) along with well-developed cattle and swine breeding as well as poultry farming (Piwowar *et al.,* 2016). However, due to the high price of maize silage (approx. 30 EUR Mg^{-1} fresh matter) (Dach *et al*., 2014), the risk related to monoculture cultivation and the low level of financial support from the government (compared with RES support in Germany), potential biogas investors are looking for alternative substrates which may be used in energy production (Dach *et al.,* 2014). One very important reason for the positive economic balance of investment (in Poland) is also the implementation of innovative technologies, the use of the heat produced in heat and power co-generation (*CHP*) and the management of digested pulp, as a high quality organic fertilizer (Czekała *et al.,* 2012, 2015; Dach *et al.,* 2014).

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In the last few years, there has been a notable increase in the use of non-food materials and agricultural waste for energy production (White *et al.,* 2013). This is related to the low cost of purchase resulting in an increase in the economic profitability of the potential investment. One of these materials is maize straw, which has a lower cost in the range of 12-17 EUR Mg^{-1} FM than maize silage and is characterized by a high methane yield (Mo and Pilarski, 2011). Moreover, this substrate does not have a wider application in Polish agriculture and industry (Przybył *et al.,* 2013). Maize straw usually remains in the fields as a crop residue.

It is also worth noting that the pretreatment of the substrate before anaerobic digestion is becoming more frequent. This allows for an increase in the efficiency of biogas production, especially from lignocellulosic substrates – resistant to decomposition (Rafique *et al.,* 2010; Zhang *et al.,* 2016). There are four kinds of pretreatments: physical (using high temperature and pressure) (Ahring *et al.,* 2015; Kratky and Jirout, 2015; Ruffino *et al.,* 2015; Tedesco *et al.,* 2016; Theuretzbacher *et al.,* 2015b), chemical (with the use of acids or alkali) (Gu *et al.,*2015; Li *et al.,* 2015; Liu *et al.,* 2015), biological (*i.e.* the application of appropriate bacterial consortia or fungi and yeast) and mixed (a combination of physical, chemical and biological treatments) (Lamsal *et al.,* 2010; Reilly *et al.,* 2015; Theuretzbacher *et al.,* 2015a). Currently, in Poland the most popular choice is the mechanical pretreatment of the substrate material. One possible solution may be the use of extrusion in order to increase the biogas production efficiency of the substrate. This technology is commonly used in other branches of industry *i.e.* food industry, plastics and/or metals moulding (Rodriguez *et al.,* 2017), and the devices are widely available (Lehmann Maschinenbau, 2012).

In the extrusion process, the substrate is heated, mixed and pulverized, which causes the lignin and cellulose fibres to break apart. Furthermore, the sudden decrease in pressure causes the evaporation of intracellular water, which additionally increases the efficiency of the disintegration of the material (Lehmann Maschinenbau, 2012).

The research aim was to define and compare the energy potential of the untreated maize straw and extruded maize straw used in biogas production (for electricity and heat generation) as well as heat from direct combustion. The range of research experiments included the determination of the physicochemical parameters the substrates used and research into the methane fermentation of untreated maize straw and extruded maize straw. In addition, the heat of combustion and the calorific value of the tested materials were determined. The revenue per Mg of substrate used for biogas and biomass boiler utilization was also estimated, taking into account the national RES support scheme.

MATERIALS AND METHODS

The maize straw used in the research experiments was obtained from Przybroda Agricultural-Orchard Experimental Farm belonging to the Poznań University of Life Sciences (PULS). The fermentative inoculum was the separated liquid fraction (after dry mass separator) taken from the operating agricultural biogas plant in Działyń (Poland).

In order to select the appropriate proportions between the tested substrate and inoculum, the following parameters were examined: total solids (TS) – PN-75 C-04616/01, volatile total solids (VS) – PN-Z-15011-3, pH PN-90 C-04540/01. These parameters enabled the subsequent calculation of biogas efficiency calculated based on the Mg of fresh matter, total solids and volatile total solids of the substrate.

The pretreatment of the tested material was carried out in the Department of Thermal Technology and Food Process Engineering at the University of Life Sciences in Lublin. In the experiment, a device made by the staff of the Department was used. The material was treated at a temperature of 140°C and high pressure. The rotation speed of the screw conveyor set at 70 rpm. The extruder was driven by a 10 kW motor. The starting humidity of the tested material was set at a level of 25%. Samples (2 kg) were collected from the exit of the extruder at the outlet opening. Control and treated samples were collected in plastic (polyethylene) containers and stored at 4°C until analysis.

The research concerning the methane efficiency of the substrates in batch culture technology was carried out in the Laboratory of Ecotechnologies at the Institute of Biosystems Engineering (PULS) on the basis of internal procedures, based on adapted standards: DIN 38 414-S8 and VDI 4630, commonly used in Europe. The detailed methodology of the performed research was presented by Cieślik *et al.* (2016). The fermentation set-up consisted of 21 biofermentors. Each individual biofermentor (made from glass) had a volume of 1.8 dm^3. The process was carried out under mesophilic conditions at 39±1°C. The biogas produced in each fermentor chamber was transported via teflon pipe to the gas storage system (volume 4 dm^3). These reservoirs were made from plexiglass as an inverted cylinder immersed in water. Between the water and gas areas, there was a liquid barrier preventing the dissolution of CO_2 in the water. The volume of biogas produced was read at equally spaced 24-h intervals. The tested gases were methane, carbon dioxide, ammonia, hydrogen sulphide and oxygen as a control, and the results were recorded with an accuracy of 0.01 dm^3. Measurements were made using Geotech's GA5000 certified gas analyser (certificates ATEX II 2G Ex ib IIA T1 Gb (Ta = -10°C do +50°C), CSA certificates and UKAS ISO 17025 calibration). The ranges of gases detected by the analyser were: 0-100% CH_4, 0-100% CO_2, 0-25% O_2, 0-10 000 ppm H_2S and 0-1 000 ppm NH_3.

The research concerning the heat of combustion was carried out in the Section of Wood Chemistry and Forest Products at Poznan University of Life Sciences according to Polish norm PN-81/G-04513. Based on literature data, the heat of combustion was calculated, taking into account the hydrogen content at a level of 5.3% (Herkowiak *et al.,* 2018; Kołodziej and Matyka, 2012). The substrate was fragmented, next three 1-gram samples were taken, in order to define the heat of combustion using calorimeter KL-12Mn.

The heat of combustion and the calorific value of the tested fuels were determined using the calorimeter method. The measurement of the heat of combustion was based on the complete combustion of the substrate sample placed in a calorimeter bomb immersed in water. Measurement was performed under clean oxygen conditions. The calorific value (by calorimetric method) was determined in accordance with PN-81/G-04513. Using formulas (1) and (2) the parameter values were determined (Czekała *et al*., 2018):

$$Q_s^a = \frac{C(D_t - k) - c}{m}, \quad (1)$$

where: Q_s^a – average calorific value of the fuel analysed (J g^{-1}), C – heat capacity of the calorimeter (J g^{-1}), D_t – overall increase of the main period temperature (K), k – correction for environmental heat exchange (K), c – correction sum for the additional heat effects (J), m – fuel sample mass (g).

Calorific value (Q_w) in the analytical state was calculated using the following equation:

$$Q_w^a = Q_s^a - 24.42^{(1)}(W^a + 8.94^{(2)} H_a), \quad (2)$$

where: Q_w^a – calorific value of the analysed biofuels in the analytical state (J g^{-1}), W^a – moisture content of the test sample (%), H_a – hydrogen content of the test sample (%), [1]heat of evaporation of water at temperature 25°C, which corresponds to 1% of the water in the fuel (J kg^{-1}), [2]factor of hydrogen to water conversion (-).

Knowing the methane volume that may be obtained from 1 Mg of the substrate, it is possible to calculate the amount of obtainable electricity and heat. Therefore, in order to calculate the amount of energy produced, it is necessary to introduce a methane calorific value of 0.009968 MWh m^{-3} (9.968 kWh m^{-3}). Expression of the efficiency factor in MWh is due to the fact that the megawatt hour is a basic unit of settlement of the RES energy producers in Poland. The relevant formulas are given below.

The amount of electricity produced in the co-generation of heat and power (CHP) may be calculated by the following equation:

$$E_E = V_{CH_4} We_{CH_4} \eta_e, \quad (3)$$

where: E_E – amount of electricity produced in CHP (MWh Mg^{-1} FM), V_{CH_4} – produced methane volume (m^3 Mg^{-1} FM), We_{CH_4} – methane calorific value (0.009968 MWh m^{-3}), η_e – electrical efficiency of co-generation unit (for the purposes of these calculations 42% efficiency was assumed for the unit offered by PAKTOMA, Polish manufacturer of modern co-generation units for biogas plants).

Amount of heat produced in CHP was calculated in accordance with the following equation:

$$E_{H(CHP)} = V_{CH_4} We_{CH_4} \eta_{t(CHP)}, \quad (4)$$

where: $E_{H(CHP)}$ – amount of heat produced in *CHP* (MWh Mg^{-1} FM), $\eta_{t(CHP)}$ – heat efficiency of co-generation unit (for the purposes of these calculations 45% efficiency was assumed for the unit offered by PAKTOMA, Polish manufacturer of modern co-generation units for biogas plants).

In practice, the amount of heat produced is given in gigajoules (GJ). Knowing that 1 GJ equals 0.274 MWh, the generated heat expressed in MWh can be converted according to the following equation:

$$E_{H(CHP)(GJ)} = \frac{E_{H(CHP)}}{0.274}, \quad (5)$$

where: $E_{H(CHP)(GJ)}$ – amount of heat produced in *CHP* (GJ Mg^{-1} FM).

The amount of heat produced in the direct combustion of the substrate is shown by Eqs (6) and (7):

$$E_{HD(GJ)} = C_V \eta_{t(s)}, \quad (6)$$

where: $E_{HD(GJ)}$ – amount of heat produced in direct combustion (GJ Mg^{-1} FM), C_v – calorific value (GJ Mg^{-1} FM), $\eta_{t(s)}$ – heat efficiency of stove (-) (for the purposes of these calculations 85% efficiency was assumed for the unit offered by PAKTOMA, Polish manufacturer of modern co-generation units for biogas plants).

$$E_{HD(MWh)} = E_{HD(GJ)} 0.274, \quad (7)$$

where: $E_{HD(MWh)}$ – amount of heat produced in direct combustion (MWh Mg^{-1} FM).

In the economic calculations, two systems (resulting from the amendment of the Renewable Energy Act of 22 June 2016) supporting the production of renewable energy in agricultural biogas plants were included. For these installations, support is provided in the form of so-called "blue certificates" obtainable due to the production of 1 MWh. This type of certificate of origin is listed on the Polish Power Exchange, and its price depends on the supply and demand of energy produced in such installations. According to the data of the Polish Power Exchange of 31.01.2018 the "blue certificate" price was 76.44 EUR MWh^{-1} (Polish Power Exchange, 2017). In addition, agricultural biogas plants in Poland can receive support for energy production in high-efficiency co-generation (yellow certificate – 27.68 EUR MWh^{-1}) for the sale of "black energy" (approx. 40.4 EUR MWh^{-1}) and for the sale of heat produced (approx. 6.0 EUR GJ^{-1}) (Table 1). It should be added that the sale price of "black energy" applies to the amount of electricity generated in co-generation. This price is announced quarterly by

Table 1. Prices EUR of certificate of origin and heat as determined by the Polish Power Exchange and Energy Regulator Office of 31 January, 2018 (Energy Regulatory Office, 2017; Energy Regulatory Office, 2018; Polish Power Exchange, 2017)

Parameter	Price	Unit
Electricity price	40.41	EUR MWh^{-1}
Blue certificate price	76.44	EUR MWh^{-1}
Yellow certificate price	27.68	EUR MWh^{-1}
Heat price	6.02	EUR GJ^{-1}
Euro exchange rate	4.1541	PLN

the Energy Regulatory Office. The profit from the sale of electricity and heat produced in the co-generation from 1 Mg FM of the substrate was calculated as follows:

$$I_{TC} = I_E + I_H, \quad (8)$$

where: I_{TC} – total income from the certified electricity and heat sale (EUR Mg^{-1} FM), I_E – income from the electricity sale (EUR Mg^{-1} FM), I_H – income from the heat sale (EUR Mg^{-1} FM).

The income generated from the sale of electricity depends on the amount of energy produced (reduced by 5% of the plant's own consumption), electricity sales prices and green and yellow certificates. The income from the sale of electricity may be calculated from Eqs (9) and (10):

$$I_E = ((E_E\ 0.95) - E_{EX})\ SP_E, \quad (9)$$

where: E_E – amount of electricity produced in *CHP* (MWh Mg^{-1} FM), E_{EX} – energy consumed for the work of the extruder (MWh Mg^{-1} FM), SP_E – electricity selling price (EUR MWh^{-1}), 0.95 – electricity sales ratio reduced by the amount of energy used for the needs of the installation itself.

$$SP_E = SP_{BE} + SP_{BC} + SP_{YC}, \quad (10)$$

where: SP_{BE} – "black energy" price (EUR MWh^{-1}), SP_{BC} – "blue certificate" price (EUR MWh^{-1}), SP_{YC} – "yellow certificate" price (EUR MWh^{-1}).

Revenue generated from the sale of heat produced by the combustion of biogas may be estimated from the following equation:

$$I_H = E_{H(CHP)(GJ)}\ SP_H\ 0.80, \quad (11)$$

where: I_H – income from the heat sale (EUR Mg^{-1} FM), $E_{H(CHP)(GJ)}$ – amount of heat produced in CHP (GJ Mg^{-1} FM), SP_H – selling price of heat (EUR GJ^{-1}), 0.80 – heat sales ratio reduced by the amount of heat used for own demands of the installation under mesophilic technology (Oleszek *et al.,* 2016).

The reform of the RES support system in Poland envisages auctions for the purchase of a specified amount of energy, by the Polish government, for renewable energy producers. The winners of the auction offering the lowest selling price for electricity, will be guaranteed a15-year contract from the auction date. Additionally, Polish law has included provisions for the separation of auctions for energy produced from certain types of renewable energy sources, *i.e.* for producers using only agricultural biogas. Moreover, separate categories for installations below or over 1MV capacity have been included. The new support system for agricultural biogas energy ensures that the reference price (*i.e.* the maximum price for 1 MWh, for which the generated electricity can be sold by the producers) from RES in 2016-2018 for installations using only agricultural biogas will be not less than 129.70 EUR MWh^{-1}. Accordingly, the total income from the sale of electricity and heat produced in co-generation in the auction system can be calculated according to Eq. (12):

$$I_{TA} = ((E_E\ 0.95) - E_{EX})\ C_R, \quad (12)$$

where: I_{TA} – total income from the electricity and heat sold in the auction system (EUR Mg^{-1} FM), C_R – reference price (EUR MWh^{-1}), 0.95 – electricity sales ratio reduced by the amount of energy used for the needs of the installation itself.

At present, it is difficult to predict what price for 1 MWh of energy will be offered to owners of agricultural biogas plants in the conducted auctions. For this reason, the reference price was used for the economic calculation as the selling price of the electricity.

In the case of using maize straw in the direct combustion process in a specially adapted oven, it is possible to obtain additional income from the sale of heat to the district heating network. This parameter is calculated from the following equation:

$$I_{H(DC)} = E_{HD(GJ)}\ SP_H, \quad (13)$$

where: $I_{H(DC)}$ – total income from the sale of heat produced by direct straw combustion (EUR Mg^{-1} FM).

RESULTS AND DISCUSSION

The basic physical and chemical parameters, which are necessary to estimate the energetic potential of the substrate were: pH, total solids and volatile solids content.

Untreated and extruded maize straw were characterized by a high TS and VS content of 92.80 and 93.67%, as well as 89.20 and 95.42%, respectively (Table 2).

The methane fermentation process of untreated maize straw under mesophilic conditions was performed for 34 days (Fig. 1). It is worth emphasizing that in the case of technologies commonly implemented in biogas plants, which use maize silage as the main substrate, the process is

Table 2. Physical and chemical parameters of inoculum and extruded and untreated maize straw

Sample	pH	Total solids (TS) (% FM)	Volatile total solids (VS) (% TS)	References
Inoculum	7.85	2.80 ± 0.027	71.02 ± 1.778	(-)
Untreated maize straw	9.55	92.80 ± 0.339	89.20 ± 1.376	(-)
Extruded maize straw	6.37	93.67 ± 0.214	95.42 ± 0.117	(-)
Maize silage	3.77	37.24	90.79	(Li *et al*., 2015)

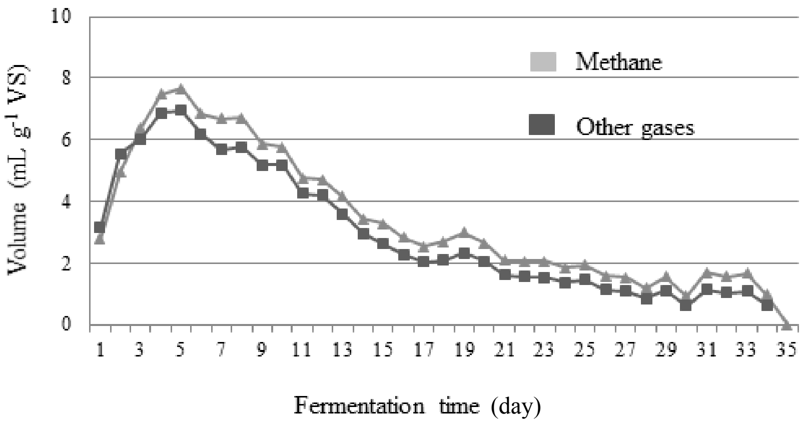

Fig. 1. Daily dynamics of biogas production for tested untreated maize straw in the methane fermentation process.

similar – about 35 days (Dach *et al.,* 2014). The long duration of maize straw decomposition is due to the complex structural composition of the substrate (McKendry, 2002; Zheng *et al.,* 2014). It is characterized by a high content of tightly bounded lignin and cellulose fibres, which are difficult for microorganisms to consume, and a small share of simple sugars and starch (Cieślik *et al.,* 2016; Irlbeck *et al.,* 1993; Russell, 1986). Figure 1 shows the daily dynamics of biogas production for tested untreated maize straw.

During the methane fermentation process of untreated maize straw (Fig. 1) notable peaks of biogas production were observed (between the 3rd and 6th day of fermentation), which were the result of the fermentation of small amounts of easily accessible carbohydrates. Also, in view of the packed structure and high degree of polymerization, the biodegradation process is characterized by a long duration (Cieślik *et al.,* 2016; McKendry, 2002; Mosier *et al.,* 2005; Zhang *et al.,* 2010). Figure 2 shows the change in the daily dynamics of biogas and methane production from extruded maize straw.

In the case of the fermentation of extruded maize straw, the intensive production of biogas during the first 9 days of the process was observed (Fig. 2). The change in the daily dynamics of biogas production for the tested extruded maize straw, compared to the untreated sample, results from cellulose, hemicellulose, lignin and protein depolymerization in the substrate (Camire, 1998; Karunanithy and Muthukumarappan, 2010). Additionally, the fragmentation of the material allowed for an increase in the area available for fermentation bacteria, and this resulted in an improvement of the efficiency of the hydrolysis and methanogenesis process (Bougrier *et al.,* 2006; Hjorth *et al.,* 2011).

The investigated maize straw was characterized by a relatively high biogas efficiency at the level of 407.75 m^3 Mg^{-1} FM, due to the low humidity of the substrate (Table 3). This result is comparable with the results of other research experiments related to maize straw fermentation (Cieślik *et al.,* 2016; Lewicki *et al.,* 2014). In the case of the use of substrate extrusion, an increase in biogas and methane production was observed, by 7.50 and 8.51% respectively. This study confirmed the results obtained by Hjorn *et al.* (2011) and Brückner *et al.* (2007), which proved that using extrusion for agricultural substrates (*e.g.* maize straw) as a pretreatment before the fermentation process, can increase methane efficiency from 8 up to 70%. The percentage of methane content in the gas produced was about 51%, which is characteristic for substrates with a high share of the carbohydrates fraction.

One of the most important parameters, which are characteristic for materials with potential energy applications, is combustion heat. This parameter determines the amount of heat emitted during the combustion of a fuel mass unit in an oxygen atmosphere, with the assumption that the end products are oxygen, nitrogen, carbon dioxide, sulphur oxides, water in a liquid state and ash. The second parameter is the calorific value reduced by the amount of heat, which is required for water evaporation. Comparing these two results, produces information about the possible energy

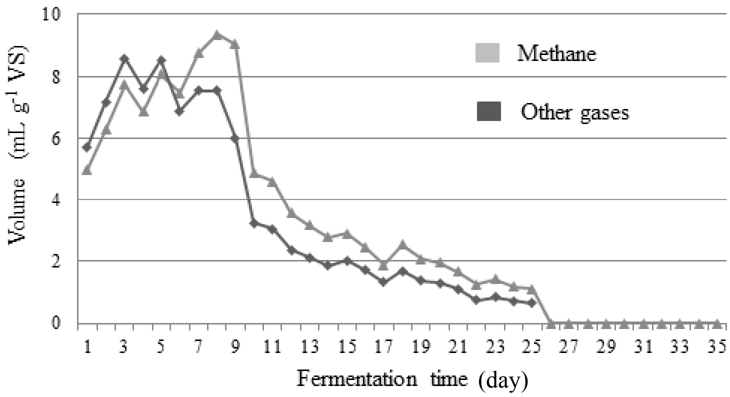

Fig. 2. Daily dynamics of biogas production for tested extruded maize straw in the methane fermentation process.

Table 3. Biogas efficiency of maize straw in mesophilic fermentation

Sample	Fresh matter		Volatile solids		References
	Cumulated methane	Cumulated biogas	Cumulated methane	Cumulated biogas	
	(m^3 Mg^{-1} FM)		(m^3 Mg^{-1} VS)		
Untreated maize straw	207.75 ± 7.14	407.81 ± 16.55	237.30 ± 10.23	465.82 ± 23.70	(-)
Extruded maize straw	225.42 ± 4.14	438.40 ± 9.63	252.47 ± 4.88	491.00 ± 11.35	(-)
Maize silage	130.88	218.40	387.10	645.96	(Li *et al*., 2015)

yield calculated per unit mass of the substrate. The following Table 4 shows results of combustion heat and calorific value analyses of maize straw.

The untreated maize straw used in research, was characterized by a heat of combustion and calorific value respectively at the levels 16.90 and 15.58 MJ g^{-1} FM (Table 4). These values are comparable with results, which were obtained by other researchers. According to McKendry (2002), the heat of combustion of the substrate is heavily dependent on the moisture content. According to Mani *et al.* (2004) during research concerning the energy efficiency of maize with a moisture content of approx. 9.41%, the results indicated a calorific value with a level of approx. 16.2 MJ kg^{-1} FM.

On the basis of the results obtained for the biogas efficiency and calorific value of maize straw, an economic analysis of the profitability of the development of this substrate for energy purposes on the Polish market was conducted. On the basis of the existing system based on certificates of origin and an auction system, the income obtained from methane fermentation or direct incineration was calculated (Table 5).

Based on this calculation, it is apparent that the maize straw extrusion process prior to the fermentation process results in an increase of electricity production by 8.51% from 1 t of the substrate. This is due to the increased methane yield from the methane fermentation process, as demonstrated by other researchers and described in a previous section (Hjorth *et al.,* 2011). In the currently operating systems supporting the production of energy from agricultural biogas in Poland, the extrusion of maize straw may be economically unjustified due to the high energy consumption of the extruder (0.492 MWh Mg^{-1} FM). The use of this kind of substrate pretreatment results in a decrease of total income from the sale of electricity and heat by 59.56 EUR Mg^{-1} FM (for the system of certificates of origin) and 54.44 EUR Mg^{-1} FM (in the case of the auction system) (Table 5).

Table 4. Heat of combustion and calorific value of maize straw

Substrate	Moisture content (%)	Heat of combustion (J g^{-1})	Calorific value (J g^{-1})
Untreated maize straw	7.20 ± 0.339	16 900 ± 330	15 567 ± 255

Table 5. Possible income from the sale of electricity and heat produced from 1 Mg of fresh maize straw

Parameters	Methane fermentation				Direct combustion
	Maize straw				
	Untreated		Extruded		Untreated
Electricity and heat					
Electricity (MWh Mg^{-1})	0.870		0.944		-
Heat (MWh Mg^{-1})	0.932		1.011		3.575
Heat (GJ Mg^{-1})	3.401		3.690		13.048
Extrusion energy consumption (MWh Mg^{-1})	-		0.492		-
Income					
	Certificate of origin system	Auction system	Certificate of origin system	Auction system	Sale in both systems
Electricity (EUR Mg^{-1})	33.39	-	16.35	-	-
Blue certificate (EUR Mg^{-1})	63.16	-	30.92	-	-
Yellow certificate (EUR Mg^{-1})	22.87	-	11.20	-	-
Auction (EUR Mg^{-1})	-	109.40	-	56.82	-
Heat (EUR Mg^{-1})	16.37	16.37	17.77	17.77	78.52
Amount (EUR Mg^{-1})	135.80	125.77	76.24	71.33	78.52

At the same time, it has been shown that under current conditions, it is more profitable for functioning biogas plants to retain the certificate of origin system, where the income from 1 Mg of material for the installation is higher by approximately 5-10 EUR MWh^{-1} than is the case for the auction system. However, it is important to bear in mind the volatility of the “blue certificates” price on the energy market, which depends on the supply and demand of electricity produced from agricultural biogas. In the case of winning the auction, the investor is guaranteed that the energy produced from agricultural biogas will be purchased at a fixed price for a period of 15 years, which in the longer term may prove to be a more advantageous solution.

The use of untreated maize straw in the direct combustion process seems to be economically unreasonable. The significantly higher income resulting from the utilization of the substrate for biogas is due to the possibility of selling heat and electricity. Increasing the calorific value of the straw by mechanically breaking up the material is associated with an additional cost of energy consumption, which may increase the difference in the income from Mg of the fresh weight.

CONCLUSIONS

1. Maize straw has a lower biogas potential (at the level 439.45 m^3 Mg^{-1} TS) in comparison with maize silage (586.47 m^3 Mg^{-1} TS) but it may be used as an alternative substrate in the methane fermentation process and as a fuel in biomass stoves.

2. The validity of using maize straw as a substrate in biogas plants was confirmed by a significantly higher income from the use of 1 Mg of the material in contrast to its direct combustion.

3. Using the extrusion process for biogas substrates increases biogas and methane efficiency in the fermentation process by 7.50 and 8.51% respectively, and reduces fermentation time by approximately 8 days.

4. Despite the increased efficiency of the fermentation process, the use of extrusion in Poland is economically unjustified due to the high energy consumption of the pretreatment process.

5. Under current economic conditions prevailing in the market for renewable energy produced from biogas in Poland, the use of the certificate of origin system allows for the generation of a higher income from 1 Mg of maize straw than is the case with the auction system.

Conflict of interest: The Authors declare they have no conflict of interest.

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