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Energy and economic potential of maize straw used for biofuels production

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Abstract. The paper presents the energy and economic comparison of two technologies of maize straw utilization: solid biofuel production (briquettes) and methane fermentation. The research experiments have shown that maize straw is the material which can be efficiently implemented in both technologies. Maize straw usage as briquettes can generate more energy (10.956 GJ Mg^{-1}) than methane fermentation (9.74). In Europe, biogas is used in co-generation units for production of electric and heat energy. Due to higher price of electricity, economic profitability of maize straw usage for biogas production is over twice higher (182 USD) than in case of briquettes production (96 USD).

1 Introduction

Nowadays, the plant biomass is considered to be the oldest source of energy. It can be obtained both from conventional agricultural sector, as well as from forest crops, however, more often comes straight from the energy crops used in order to produce electricity and heat [1]. It is obtained from the herbaceous plants with high yields (mallow, Jerusalem artichokes), woody plants (willow, poplar), grasses (i.e. miscanthus) or from plant production (straw, hay). The structure of existing sources of biomass from crop production mainly includes the use of wheat and rye straw. And this resulted directly from a decline in cattle numbers in Poland. Currently, the straw for energy demands is applied in the unprocessed form i.e. in the form it has been harvested or processed into the form of briquettes and pellets. However, new possibility of energy production from plant biomass is a maize straw. Maize has a high yield potential ratio, 12-15 Mg of dry mass of the whole plants from 1 ha. This factor makes possible to use it not only for biogas production (fresh mass, silage) or bio-ethanol (grain) but also for direct combustion [2].

Maize straw (the main subject of this paper) is characterized by a variable humidity resulting from various development phases and harvest deadlines. In order to improve the maize straw energy properties it should be additionally dried. Niedziółka showed [3] that the average calorific value of the maize straw was in fresh state 6.5 MJ kg^{-1}, whereas dried reached 15.5 MJ kg^{-1}. Furthermore, raw and unprocessed straw is a material with low energy value, due to decreased concentration of energy per unit volume. Therefore, the most common method of maize straw management in Poland is production of pellets intended for thermal energy production. This process allows to obtain the pellets with considerably better density compared with initial one. Thus, the pellets provide longer combustion time in comparison with incompact biomass [4]. Another advantageous feature of use of processed biomass from plant production for energy purposes is reduction of transportation costs, and moreover the ability of automatization of the combustion process.

Maize is a widely cultivated plant. Except for being a good feed for animals, it can be considered as a raw material for food or chemical industry. Along with an increase of energy production from the plant biomass, the interest in maize cultivation intended for energy purposes including the biogas production, has also raised [5]. Until now, commonly used feedstock for biogas plants was the maize silage as a substitute improving the energy efficiency of biogas plants [6]. Thus, it became kind of stimulator for fermentation process and facilitated the utilization of sewage sludge [7] and slurry [8]. Due to the production costs of the substrate, presence of crop monocultures and providing the food for domestic animals, the importance of maize silage as a feedstock for biogas plants gradually decreases. Therefore, we are looking for new directions of maize use or application of new herbaceous plants. More recently, there have been attempts to use a maize straw as a structural material for composting of the sewage sludge [9-10]. A new trend of management in agricultural biogas plants is application of the maize straw, thus eliminating the methane production from the maize silage. In this case there is lack of conclusive determination of costs of the total energy production from the maize silage and straw.

Within last years, it has been observed also dynamic development of advanced technologies of artificial intelligence (neural networks) for optimization of production and treatment of agricultural biomass and biowaste. Those activities were usually close to energetic and environmental problems, following often the idea promoted by European Union: "waste-to-energy". The development of IT systems and implementation of large computing power of the computers has significantly contributed to neural networks implementation. High influence on the development of artificial neural networks had a technical evolution in the field of neuro-processors construction, which are analog hardware applications. In recent years, the artificial neural networks have been used in agricultural engineering [11-12], eco-energetics [13-14] and environmental engineering [15-16]. The obtained rewarding results in terms of classification and prediction were used to construct the expert systems working in real-time, effectively supporting the decision-making processes in many sectors of agriculture, food processing and biofuel production [17-18]. This even resulted in development of the first agricultural equipment and machinery based on the methods of artificial intelligence, and therefore, without constant supervision and manual. Moreover, also in terms of application of maize straw, the appropriate measures have been taken in order to use the neural networks to produce biogas from maize silage and straw [19].

2 Aim and the range of research

The aim of this study was to analyze the energy potential and economic balance of maize straw used as new biofuels source (biogas and briquettes – the most popular methods of energetic biomass utilization in Central Europe). The analyzes have included use of maize straw as a substrate for biogas and briquettes production. One of the important analytical aspect was to compare the energetic efficiency as well as price of raw material with other kinds of substrates, typically used for biogas and solid biofuel production.

3 Materials and methods

The research and basic physical analyzes were made in the Industrial Institute of Agricultural Engineering. The biogas experiment for estimation of energetic value of maize straw during fermentation was made in Laboratory of Ecotechnologies, at the Institute of Biosystems Engineering, Poznan University of Life Sciences (PULS). Heat of combustion tests of maize straw was estimated in the Institute of Technology and Life Sciences.

The research material (maize straw) was collected from PULS experimental farm located in Złotniki, near Poznań, in autumn 2014, during maize harvest for grain. The dry matter content was made according to Polish standard norm PN-75C-04616/01 (drying by 24 h in 105°C), whereas organic dry matter according to PN-Z-15011-3 norm (samples combustion in 525°C for 3 hours) [20-21].

The heat of combustion was made on the dried straw, initially crushed by rotor mill. For analysis, the calorimeter was used according to the Polish standard and European norm PN-EN ISO 9831. The analysis consisted of the total combustion of 1 g sample in pure oxygen atmosphere with 2.8 MPa pressure in calorimeter submerged in water of 2.7 dm^3 volume. The combustion heat was calculated automatically by internal calorimeter calculation program.

The biogas production tests were made in Laboratory of Ecotechnologies, the biggest Polish biogas laboratory with over 250 different fermenters. The analyzes were done according to the German norms DIN 38414/S8 and VDI 4630 - standardized biogas guidance issued by the Association of German Engineers in Dresden.

The biogas production experiments (both in meso- and thermophilic fermentation) were conducted in the set of multi-chamber biofermenter (Fig. 1) constructed in the Laboratory of Ecotechnologies. On the basis of obtained results, available information concerning installation, presented assumptions, economic analysis of briquettes production from the solid fraction of digestate, was performed.

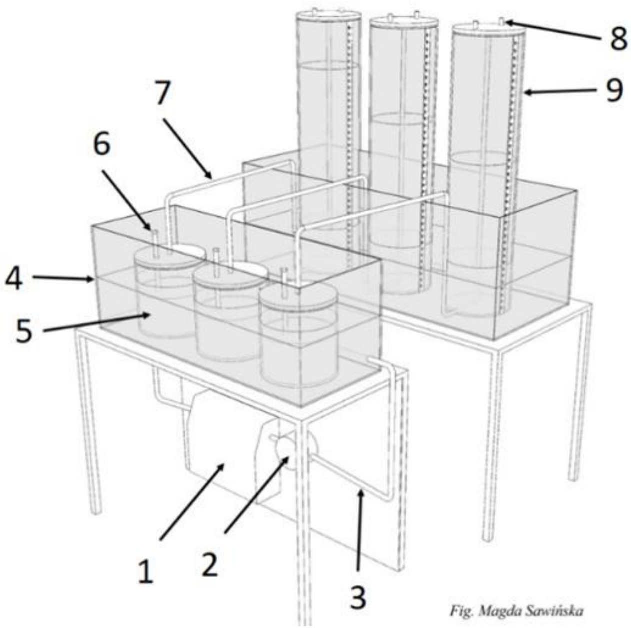

Figure 1. Scheme of biofermentor for biogas production research (3-chamber section): 1 – water heater with temperature regulator, 2 – water pump, 3 – insulated conductors of calefaction liquid, 4 – water coat, 5 – biofermentor with charge capacity 2 dm3, 6 – sampling tubes, 7 – biogas transporting tube, 8 - gas sampling valve, 9 – biogas volume-scale reservoir

The biogas production was conducted in the glass biofermenters (capacity of 2 dm^3). The maize straw samples were fermented in inoculum i.e. liquid fraction of post-fermented pulp from the typical biogas plant working in Działyń, near Poznań. The temperatures of fermentation were: 39°C±1 (mesophilic fermentation) and 55°C±1 (thermophilic fermentation) in order to link this experiment with working conditions of methane fermentation process occurring on typical biogas plants in Europe. The volume of produced biogas (as well as composition: CH_4, CO_2, H_2S and NH_3) was checked once a day (each 24 hours) and introduced to the calculation program. This program automatically calculated the total production of biogas and biomethane per ton of fresh or dry matter.

The energy value of biogas produced from maize straw fermentation bases on methane content in the gas (biogas is the mixture of CH_4 and CO_2). The calculation of maize straw energy value in methane fermentation process was made by the following formula:

$$E = V_{CH4} \cdot We_{CH4}$$

where:

E – amount of energy produced from material [MWh];

V_{CH4} - volume of methane produced from 1 Mg of substrate [m^3];

We_{CH4} – energy value of methane [0,00917 MWh $\cdot m^{-3}$]

In case of combustion of biogas in co-generation unit for production of electric and heat energy (situation present in over 97% all biogas plants in Europe), the calculated amount of energy has to be recalculated by coefficients:

η_e = 0,4 (electric efficiency of co-generation unit);

η_t = 0,48 (thermal efficiency);

The price of maize, straw as well as other substrates for briquettes and biogas production were taken from the actual market data (September-October 2015) published by Polish agricultural agencies. The price for electric and heat energy was taken from the Polish Energy Regulatory Office (www.ure.gov.pl).

4 Results and Discussion

4.1 The energy efficiency

The research results showed that the dry matter (TS) of the fresh maize straw amounted 77.8%, while the dry organic matter was 89.8%. In turn, the heat of combustion of the analyzed briquettes sample had value of 16.142 MJ•kg^{-1}, while the calorific value amounted 14.245 MJ•kg^{-1} (tab. 1).

Table 1. The parameters of the tested material (maize straw and briquettes)

Substrate	Values
Total Solids (maize straw) [%]	77.8
Volatile Solids (maize straw) [%]	89.8
Heat of combustion (briquettes) [MJ·kg^{-1}]	16.142
Heating value (briquettes) [MJ·kg^{-1}]	14.245

The analysis of basic maize straw parameters shows that this material has high content of organic dry matter (over 89.5%) which is favorable for energetic use as solid biofuel (i.e. briquettes) and promising for methane fermentation. The heat of combustion was also high (16.142 MJ kg^{-1}) and real heating value amounted 14.245 MJ kg^{-1}. This value is similar to other popular species of straw.

Table 2. The biogas and biomethane production from 1 Mg of maize straw

Sample	CH_4 content [%]	Biogas yield [m^3 Mg^{-1}]	Methane yield [m^3 Mg^{-1}]
Maize straw	51.9	442.1	229.6

The experiment with maize straw fermentation has proved very high biogas production efficiency. This efficiency is over twice higher than maize silage – the most popular substrate for biogas plants in Europe. However, high biogas and biomethane potential is related to much higher dry matter content (tab. 1) comparing to typical maize silage (32%).

The analysis of maize straw energy transformation, made using two technologies (briquettes production and biogas fermentation), let us to develop simplified energy balance for those methods. This balance is shown in table 3.

Table 3. Energetic balance of methane fermentation and briquette production of 1 Mg of maize straw dry matter

Energy type	MWh Mg^{-1}	GJ Mg^{-1}
Methane fermentation of maize straw		
Total content in biogas, including:	2.71	**9.74***
- electric energy (for sale)	0.97	-
- heat energy (for sale)	-	4.21
Briquettes production from maize straw		
Heat of combustion of maize straw	-	14.245
Energy of maize straw drying	-	0.55
Energy for briquettes production	0.162	-
Energy in briquettes	-	13.695
Losses during combustion (furnace efficiency 80%)	-	2.739
Net energy from maize straw briquettes	**-**	**10.956**

* calculated by coefficient that 1 MWh = 3.6 GJ

The total amount of energy content in biogas produced from 1 Mg of maize straw is 9.74 GJ and this value is a little bit smaller than net energy which can be used by combustion of briquettes. However, it has to be highlighted that over 97% of European biogas plants use biogas for production of electric and heat energy in cogeneration units. Thus, the real energy value from energy transformation of maize straw by combustion of produced biogas is 0.97 MWh of electric energy and 4.21 of heat. About 15% of energy is lost, mainly in the form of heat.

4.2 Economic analysis

The real economic profitability from energetic use of maize straw in both analyzed technologies is presented in tables 4 and 5.

Table 2 presents the results of biogas and biomethane production from 1 Mg of maize straw by fermentation process. After biogas production, it is combusted in co-generation unit with 40% of electric and 48% of thermal efficiency (as shown in Materials and Methods chapter). The amount of electric energy production from 229.6 m^3 of CH_4 was 0.97 MWh, however heat production was 1.17 MWh (4.21 GJ). In order to obtain the profits from the energy sold, those values were multiplied by Polish electric energy price (150 USD MWh^{-1}) and heat energy price (12.5 USD GJ^{-1}).

Table 4. Profits of transformation of 1 Mg maize straw dry matter by methane fermentation process into electric and thermal energy, including cost of material

Parameter	Value (USD)
Profit from energy sold:	
- electric	146
- heat	53
Total profit	199
Cost of 1 Mg of maize straw	17
Net total profit	**182**

The economic calculations of maize straw energetic usage profitability show that net total profit is 182 USD for 1 Mg of used material. This high value is related to the level of electric energy price in Poland. Due to the European Union climate policy and decarbonization of European economies (CO_2 taxation) electric energy is expensive.

Table 5. Profits of transformation of 1 Mg maize straw dry matter by briquettes production (electric energy price = 150 USD MWh^{-1} and heat energy price = 12.5 USD GJ^{-1})

Parameter	Value (USD)
Energy costs for briquettes production	24
Profit from briquettes combustion	137
Total profit	113
Cost of 1 Mg of maize straw	17
Net total profit	**96**

The economic analysis for briquettes production shows much lower profit comparing to maize straw usage as substrate for biogas production. This is related mainly to the fact that heat energy price in Poland is several times lower comparing to electric energy price. In consequence, even transformation of maize straw for solid biofuel (briquettes) can generate more energy from 1 Mg of biomass, this is heat energy, cheaper than electric energy. That is why transformation of maize straw by methane fermentation is more profitable under Polish conditions, which are similar to these present in the whole Central Europe.

5 Conclusions

Based on the aforementioned analysis, the following conclusions were made:

1. Maize straw is the material which can be efficiently transformed into solid biofuel and biogas.

2. Use of maize straw as briquettes can generate more energy (10.956 GJ Mg^{-1}) than methane fermentation (9.74).

3. In Europe, biogas is used in co-generation units for production of electric and heat energy. Due to higher price of electricity, economic profitability of maize straw usage for biogas production is over twice higher than in case of briquettes production.

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