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Technological and energetic evaluation of maize stover silage for methane production on technical scale

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ABSTRACT

The aim of this study was technological research of maize stover digestion in an agricultural biogas plant and to determine the parameters of digestion under real-life conditions. The authors calculated the electric and thermal power of the cogeneration system in a biogas plant using maize stover. The load of the digestion mixture was maintained at 12% and the volumetric load (BR) at 3.62 kg LOI/m3/day by applying daily amounts of 3.33 Mg of cow slurry and 109.59 kg of maize stover silage into the digestion chamber. The substrates were mixed at a 9:1 ratio. The daily yield of biogas containing 54.0% of methane amounted to 28.71 m3, i.e. 15.50 m3 of methane daily. The annual yield of biogas from the substrates would have amounted to 10,480.6 m^3. This biogas plant using the testing substrates produced 16.5 MWh of electricity and 19.9 MWh of heat per year.

Maize stover silage can be used as a substrate in installations for biogas production. However, due to the high content of dry matter and low volumetric density its share in the digestion mixture should not exceed 10–20% to ensure optimal volumetric load in the digestion chamber of the biogas plant.

1. Introduction

In view of the fact that it is necessary to alleviate the consequences of climate changes as well as due to the increasing demand for energy and the precariousness of future supply of energy generated from fossil fuels, there is growing interest in locally available sources of energy [1,2], such as agricultural biogas [3–5]. The use of biogas for energy production reduces the consumption of fossil fuels, the combustion of which emits greenhouse gases to the atmosphere [6,7]. Many countries developed the renewable energy sector by using biogas [8,9]. There is high potential of biogas in the Polish energy sector [10]. At present agricultural biogas plants generate more than 387 million m^3 of biogas a year. The importance of biogas as a source of energy is growing [9,11,12].

At present silage made from whole maize plants is the most common substrate for biogas production in Central Europe [13]. However, the use of full-value agricultural products for energetic purposes causes their prices to rise and in consequence, it decreases the profitability of biogas production [14]. Therefore, it is necessary to find alternative raw materials to generate energy, e.g. agricultural waste and by-products [15]. Maize stover is a by-product which has not been fully used so far although it is widely available in large amounts.

In the last decade the global production of maize kernels has increased by 40% and at present it amounts to 1030 million tonnes. In 2016 the total production of maize kernels in the EU amounted to 60.3 million tonnes, which was 1.8 million tonnes more than in 2015 [16,17]. In 2015 Poland produced 3.16 million tonnes of maize kernels [18]. The production of maize kernels results in crop residues, such as stalks, leaves, cobs and husks. Crop residues make 47–50% of the yield of dry matter of whole maize plants [19,20]. There are 0.15 kg of cobs, 0.22 kg of leaves, 0.14 kg of husks and 0.5 kg of stalks per 1 kg of dry matter of maize kernels produced [19]. According to our estimates, the annual production of maize stover in Poland may be as high as 4 million tonnes.

For this reason, recently there has been increasing interest in the production of biogas from maize stover [16]. Combined maize production is recommended. It means that one field is used for simultaneous production of feed and biogas substrates, i.e. maize kernels and stover. This solution does not arouse ethical doubts, because there is no conflict between the production of food and energy. Apart from that, the organic matter which is lost from soil when maize stover is taken away from the field can be replenished

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Abbreviations

Mg	megagram
FM	fresh mass
TS	total solids (105 °C)
LOI	loss on ignition (550 °C)
HRT	hydraulic retention time
B_R	organic load ratio
MWh	megawatt hour

by fertilisation with the pulp left after the process of methane digestion [21].

The literature provides the results of studies on the amount of biogas produced from maize stover [13] and the amount of biogas produced from structural elements of the yield of maize stover [16]. Cieślik et al. [3] conducted laboratory investigations in which they compared the efficiency of methane digestion of maize stover ensilaged under thermophilic and mesophilic conditions. Many studies discussed the problem how to increase the amount of biogas produced from maize stover by pre-treatment. Schroyen et al. [22] studied the influence of the duration of pre-treatment with different fungal enzymes on the parameters of digestion and the amount of biogas produced from maize stover. Li et al. [23] conducted research on optimising the kinetics of methane digestion of maize stover. Zhou et al. [24] studied how the mixing of maize stover with cow manure in pre-treatment influenced the biogas yield. Hassan et al. [25] investigated co-digestion of goose manure and maize stover as a method of increasing methane yield and optimising C:N proportions. Zhou et al. [26] studied the co-digestion of maize stover pre-treated with NaOH and food waste. These studies show the results concerning the yield and dynamics of biogas production. These indicators are used to prepare the design and economic estimates of biogas plants [27]. The indicators are determined on the basis of standardised laboratory investigations [28]. However, static laboratory investigations are conducted under ideal technological conditions, which do not reflect the real technical and technological conditions of dynamic digestion in installations for biogas production. Laboratory investigations do not make it possible to imitate the loading of a portion of substrates or draining a portion of digestate from the digestion chamber, which changes the volumetric load of dry matter (Br) in the chamber. Therefore, it is necessary to verify the results of laboratory investigations under real-life conditions to plan the technological process of biogas production correctly.

The literature does not provide data on continuous methane digestion of maize stover or data on the parameters of the process conducted in a biogas plant. Therefore, the aim of this study was to check the technological possibilities of maize stover digestion in an agricultural biogas plant and to determine the parameters of digestion under real-life conditions. The authors also calculated the electric and thermal power of the cogeneration system in a biogas plant using maize stover.

2. Material and methods

In order to achieve the goal of the study the investigations were divided into four stages. At the first stage maize stover was collected and ensilaged and cow slurry was acquired. The second stage of the investigations involved physicochemical analyses of the substrates and laboratory investigations of the yield of biogas and methane from maize stover silage and cow slurry. The results of the laboratory investigations were used to determine the parameters of digestion of the substrate mixture in an agricultural biogas plant. During the third stage the mixture of maize stover silage and cow slurry was continuously digested on a technical scale in a biogas plant for 30 days. At that stage the process parameters specified in the laboratory investigations were verified. The last stage involved calculations of the electric and thermal power of the cogeneration system cooperating with the biogas plant.

2.1. Substrates

A mixture of ensilaged maize stover cultivar PR39A79 (Pioneer, FAO 300) and cow slurry was used as the research material. Maize stover in the form of long chaff, which was lying in a field after kernels had been harvested, was raked by means of a rotary rake and collected into a trailer with a cutting unit. The biomass contained 68% of dry matter. It was ensilaged in a flexible silo. The maize stover silage was dry, loose and inhomogeneous. It contained trace amounts of kernels and stalks cut into pieces of 40–120 mm in length. The husks were not fragmented. There was no decay or mould in the silage.

Dairy cow slurry was collected from a container in a free-stall cowshed. The slurry was homogenous, thick and contained colloidal particles. There were no contaminants or sediments. It smelt of urea, which pointed to automatic digestion. There was no foam on the slurry when it was being mixed.

2.2. Laboratory investigations

The yield of biogas from substrates was investigated in the Technology and Agricultural Biosystems Research Laboratory, Institute of Technology and Life Sciences, Poznań Branch, Poland. The researchers used static biogas digestion – an accredited method based on DIN 38414 Part 8 (Polish Centre for Accreditation, member of ILAC-MRA sign. AB116, PCA/ILAC-MRA). The research facility was equipped with a thermostatic nine-position eudiometric set. The digestion mixture consisted of 380±1 g of the inoculum containing methanogenic microorganisms and 20±1 g of maize stover silage. There was 5% content of the sample in the digestion mixture. The slurry and maize stover silage were examined separately, in 3 replicates. The inoculum of methanogenic populations came from a continuous culture kept in a 140-L laboratory anaerostat with a low-volume flow system of 1 dm^3/d. The incubation temperature was 37 °C.

The biogas volume was read in the eudiometer, according to the production rate. When the gas pressure was equalised in the eudiometric set, the volume and temperature of the biogas as well as the pressure and temperature in the laboratory were registered. The composition of the biogas (CH_4, CO_2, O_2, H_2S) from the eudiometers was analysed by means of a GA 2000 m (Geotechnical Instruments Ltd.). The biogas contamination (N_20, NH_3) was analysed by means of a photoacoustic spectrometer Multi-Gas Monitor 1312 (Innova).

Before measuring the biogas yield the dry matter content was analysed (at 105 °C ± 1 °C) according to EN 12880:2004 and the content of organic dry matter equivalent to loss on ignition (at 550 °C ± 25 °C) EN 12879:2004 was measured in the maize stover silage and cow slurry. The pH value of the substrates of the digestion mixtures and post-digestate was measured with an inoLAB 7131 m with a SenTix probe, using the 1:5 H_2O method according to EN 12176:2004. Before digestion samples of maize stover silage were cut into pieces of 20–30 mm in length and they were homogenised. The silage did not crumble when it was being cut. After fragmentation the mixture was characterised by medium