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Progress in the Production of Biogas from Maize Silage Following Alkaline and Thermal Pre-Treatment

Anna Nowicka, Marcin Zieliński, Marcin Dębowski, Magda Dudek
University of Warmia and Mazury in Olsztyn

1. Introduction

Lignocellulose can be converted into biofuels such as biogas, ethanol or hydrogen. However, it needs to be pre-prepared due to numerous factors limiting the process of lignocellulosic material biodegradation (Hendriks & Zeeman 2009, Zhang et al. 2016).

In recent decades, many pre-treatment processes have been developed which are being continuously tested and improved. Effective pre-treatment should meet several criteria, *inter alia* ensure lignin separation from cellulose, increase the percentage of amorphous cellulose, ensure the greater porosity of substrates, eliminate sugar losses, reduce the formation of inhibitors and minimise the energy costs. In order to increase the efficiency of production of energy from biomass, physical, physico-chemical, chemical and biological treatments are conducted. An important issue is to determine the technological conditions allowing an efficient, economically viable and safe conditioning process. Where the treatment is not effective enough, it may become a cause of the formation of toxic compounds inhibiting the metabolism of methanogenic bacteria (Jönsson et al. 2016, Sindhu et al. 2016, Bechera et al. 2014).

Among the chemical methods of pre-treatment, acid and alkaline treatments are distinguished. The advantage of the alkaline methods is the removal of lignin and acetyl groups which inhibit the saccharification and reduce the availability of cellulose (Pandey et al. 2000). The solubility of hemicellulose and cellulose is lower than that for hydrothermal acid treatment. Alkali treatment results in swelling and increases the biomass porosity. The ester bonds between lignin and xylan are broken, which intensifies the delignification processes (Zheng et al. 2014). The advantages of the application of alkaline treatment also include a lower temperature of the process, as the alkaline treatment can be successfully conducted at room temperature with no need for carrying out the reaction in special vessels. A disadvantage of the method is the long duration of the process, which lasts from several hours to several days. In an alkaline treatment, sodium, potassium, calcium and ammonium hydroxides are most frequently used. The most commonly used sodium hydroxide successfully disrupts the lignin structure and increases the availability of cellulose and hemicellulose (Fox et al. 2003, Hartmann et al. 1999, Delegens 2002, Gregg 1996, Kumar & Wayman 2009). A new method for preparing the substrate which is attracting increasing interest among researchers is microwave and chemical pre-treatment, which combines the advantages of both thermal and chemical methods. Microwave pre-treatment is considerably more effective than pre-treatment using conventional heating (Balat 2011, Du et al. 2016). This is due to an increase in the reaction rate of the occurring processes, which is similar to the microwave treatment supported by the action of chemical agents. Microwave radiation is applied during the treatment using acids, bases or hydrogen peroxide. A substrate subjected to microwave treatment exhibits a fast reaction rate and a high content of glucose in the hydrolysate (Kaur & Phutela 2016, Delegens 2002).

The aim of the presented study was to analyse the simultaneous effects of microwave radiation and sodium hydroxide on the destruction of lignocellulosic plant biomass and on its susceptibility to the anaerobic decomposition in the methane fermentation process.

2. Materials and methods

2.2. Plan of the study

During the study, the effects of microwave-heating-based disintegration of plant biomass (maize silage) were compared to the results obtained during biomass heating in a conventional manner. During the preliminary tests aimed at the determination of parameters of the thermal hydrolysis process depending on the applied heating method, work was carried out to determine the shortest duration and the lowest temperature of the disintegration process at which the highest effectiveness of the anaerobic biomass conversion was obtained. Preliminary tests demonstrated the efficiency of the application of a temperature of 150°C and a duration of 20 minutes.

The study involved the alkaline-thermal treatment of a lignocellulosic substrate at a temperature and for the duration determined in the preliminary tests; the criterion differentiating particular variants was the dose of a chemical agent used. The addition of a 10% solution of NaOH in the amounts of 0.02, 0.05, 0.1, 0.2, and 0.4 $g/g_{d.m}$ was tested. The pre-prepared substrate was subjected to biogas tests in respirometric units.

2.2. Research material

The raw material used in the experiment was maize silage originating from crops cultivated at the research station of the University of Warmia and Mazury. The characteristics of the research material used are presented in Table 1.

Table 1. Characteristics of maize silage applied in the experiment
Tabela 1. Charakterystyka kiszonki kukurydzy użytej podczas eksperymentu

Parameter	Unit	Value
Dry matter	$[mg/g_{d.m.}]$	360.0±11.0
Organic dry matter	$[mg/g_{d.m.}]$	326.0±9.1
Mineral dry matter	$[mg/g_{d.m.}]$	34.0±2.0
Cellulose	$[\%_{d.m.}]$	20.1±0.5
Hemicellulose	$[\%_{d.m.}]$	14.6±0.3
Lignin	$[\%_{d.m.}]$	2.6±0.1

2.3. Pre-treatment of the substrate

The substrate was broken up in a device in the form of a mill with a perforated drum placed in a sealed housing. During the disintegration of the research material, the rotational speed of the drum was 30 rpm. Thanks to mechanical breakage of the substrate, a material with particle sizes ranging from 2 to 5 mm was obtained. The broken up native substrate was hydrated to the level of 90%, which was followed by the thermal and chemical treatment.

Sodium hydroxide was introduced into thermo-reactors at five different doses: 0.02 $g/g_{d.m.}$; 0.05 $g/g_{d.m.}$; 0.10 $g/g_{d.m.}$; 0.20 $g/g_{d.m.}$; 0.40 $g/g_{d.m.}$, and the obtained results were compared to the control sample with no addition of chemical reacting substances. The treatment of the substrate with a chemical agent involved placing the prepared raw material with the addition of NaOH in pressure vessels, and heating it for 20 minutes at a temperature of 150°C.

Thermal hydrolysis was carried out based on two heating technologies. The hydro-thermal microwave treatment was carried out using a Mars-Solvent Extraction system by CEM with the power output regulated up to 1600 W, and the microwave radiation frequency of 2.45 GHz. The tests were carried out in Easy Prep Teflon vessels with a volume of 115 cm^3 (Fig. 1).

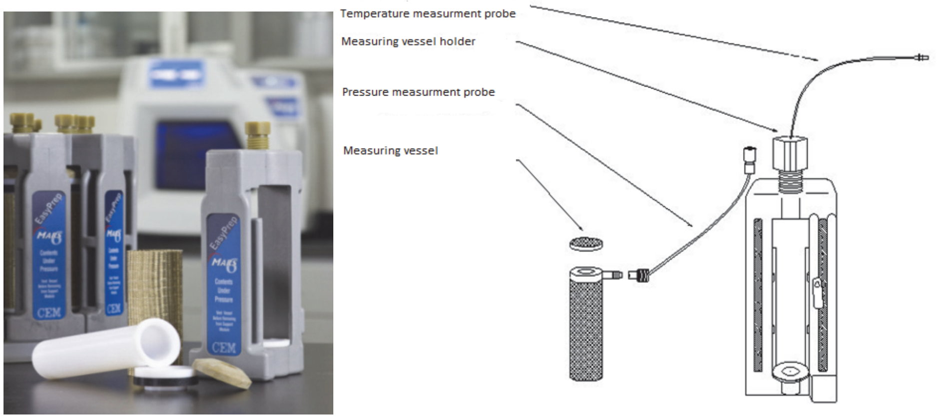

Fig. 1. Utensils for microwave digestion of samples
Rys. 1. Naczynia do mikrofalowej dezintegracji próbek

The thermal hydrolysis under conventional heating conditions was carried out using thermo-reactors of the authors' own design. The thermo-reactors were made of acid-proof steel and designed so the dimensions did not differ from the Easy Prep vessels used during the microwave digestion of samples (Fig. 2). In order to conventionally heat the plant material, a four-station Laboplay O420E oil bath was used, in which silicone oil was the heating medium. The conditions prevailing during the thermal hydrolysis carried out based on both conventional and microwave heating were identical. In order to obtain identical parameters of the course of the process in both devices, the heating duration and the thermal hydrolysis temperature were occasionally controlled.

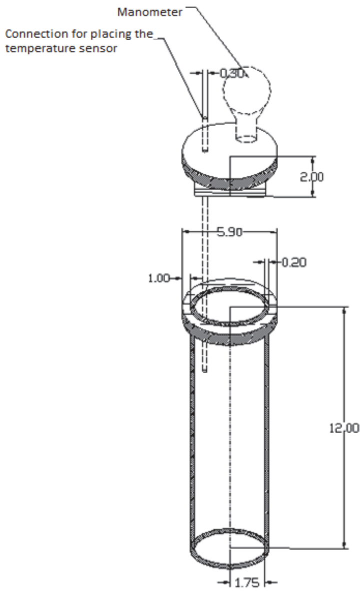

Fig. 2. Utensils for conventional digestion of samples
Rys. 2. Naczynia do konwencjonalnej dezintegracji próbek

2.4. Research procedures

The scope of analyses included the direct and indirect determination of the effectiveness of disintegration process. Directly, the effectiveness of the applied conditioning methods was tested through an analysis of glucose content using a YSI 2300 analyser. The determination of theoretical efficiency of hydrolysis process was tested using an analysis of the chemical oxygen demand (COD) value using the colorimetric method according to Hach (LCK 914), Measurements of the amounts of total carbon (TC), inorganic carbon (IC) and total organic carbon (TOC) were tested using a TOC Shimadzu analyser. Samples for the above determinations were prepared by filtering the thermally and chemically digested plant material through a membrane filter with a pore diameter of 1.2 μm using the method according to Hach (LCK 914).

The following formula (Świątek et al. 2012) was used as a basis for the calculations of the hydrolysis process efficiency:

$$efficiency = \frac{c \times 0.9}{p} \times 100\ [\%] \quad (2.1)$$

where:
c – concentration of reducing sugars [g/dm^3],
p – the contents of cellulose and hemicellulose in the native material [%],
0.9 – conversion factor for simple sugars to polysaccharides.

The effectiveness of hydrothermal depolymerisation was analysed in an indirect manner through respirometric measurements of the decomposition of the digested biomass under conditions of mesophilic methane fermentation. The substrate following the thermal hydrolysis was directed to OxiTop control-and-recording units by WTW, comprising reaction chambers connected to measuring and recording devices. The reaction chambers were inoculated with an inoculum, i.e. anaerobic sludge originating from an agricultural biogas plant fed with maize silage. To 100 cm^3 of the sludge, such an amount of the prepared raw material was added so that the initial load was 5 $g_{o.d.m.}$/l, and the samples were then blown through with nitrogen in order to provide anaerobic conditions. The substrate retention time was 40 days; the necessary duration of measurement was determined based on the amount of biogas being generated. It was assumed that all decomposable matter was processed when three subsequent values of the daily biogas production did not differ by more than 2%. Measurement units analysed changes to partial pressure in the chamber, caused by the production of biogas in anaerobic processes carried out by microorganisms. A measurement unit comprised a reaction chamber and a measuring-and-recording device placed in a thermostatic cabinet with hysteresis not exceeding ±0.5°C. The measurements were carried out at a temperature of 36°C; pressure values in the reaction chamber were recorded every 15 minutes.

An analysis of the quality of the generated biogas was conducted using a 7890A GC gas chromatograph with a TCD detector, in which the measurement was performed through an analysis of changes to electric conduction resulting from changes to thermal conduction of the atmosphere surrounding the thermocouple at the moment when the tested chemical compounds appeared in the carrier gas (helium). The value of changes to thermal conduction was directly proportional to the concentration of the tested biogas components. The chromatograph determined the percentages of biogas components, i.e. methane CH_4, carbon dioxide CO_2, oxygen O_2, hydrogen H_2, and nitrogen N_2.

3. Results

The progress of hydrolysis of maize silage conditioned using NaOH depending on the applied heating method was analysed by determining the amount of glucose released to the solution and calculating the theoretical efficiency of hydrolysis in relation to the polysaccharides contained in the native substrate. In all analysed variants differing in the dose of NaOH, the amount of released glucose (and thus the efficiency of the process) was higher when using microwave heating by at least 14% as compared to the conventional heating. All obtained results were significantly different at the significance level $\alpha = 0.05$. Following the introduction of NaOH dose of 20% into the solution, a large amount of glucose was released and, for the microwave heating, the glucose concentration in the solution was 142±11.25 mg/dm^3, which accounted for 0.75±0.07% of the theoretical efficiency of hydrolysis (Table 2). For conventional heating, the generated amount of 92.1±9.02 mg/dm^3 of glucose accounted for 0.49±0.06% of the theoretical efficiency. The amounts of glucose obtained for the considered dose, were higher by 79% and 39% compared to the sample with no NaOH added, respectively for the microwave and conventional heating. Following an increase in the NaOH dose to 0.4 g/g$_{d.m.}$ in the variant of pre-treatment using microwave radiation, a 40% decrease in glucose concentration was noted in relation to the dose of 0.2 g/g$_{d.m.}$. In the conventional variant, the decrease was by 21% (Fig. 3).

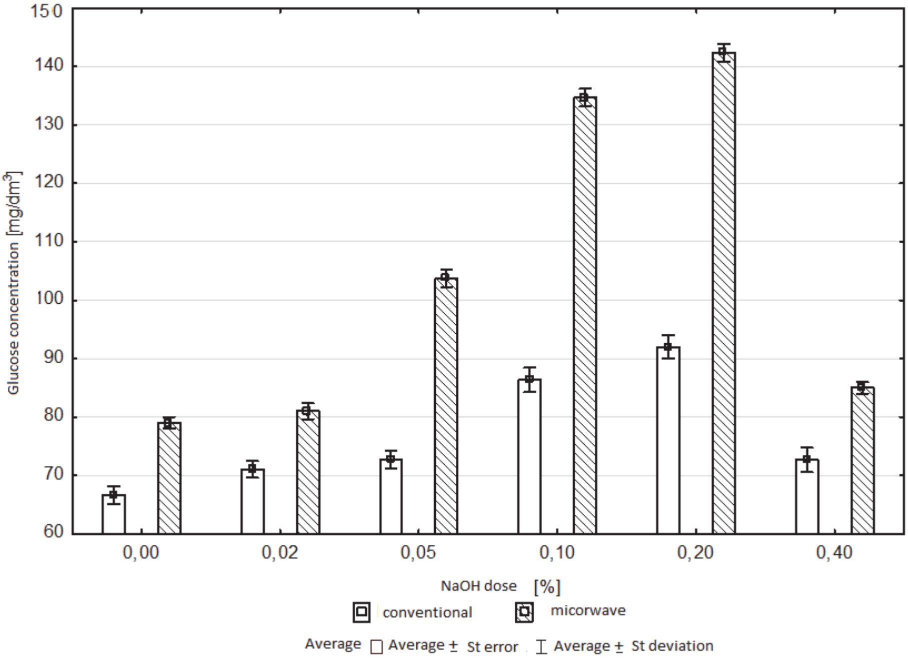

Fig. 3. Concentration of glucose released after maize silage pre-treatment with the addition of NaOH
Rys. 3. Stężenie wydzielonej glukozy po obróbce kiszonki kukurydzy z dodatkiem NaOH

The heating method had a significant effect on the value of the COD of the solution following the process of hydrothermal hydrolysis with the used of sodium hydroxide. In each of the tested variants of the NaOH doses, higher values of the COD were observed when using the microwave heating. The amount of released organic compounds was greater as compared to the tests using the conventional heating by a minimum of 13.9% (at a dose of 0.4 $g/g_{d.m.}$) to a maximum of 31% at a dose of 0.1 $g/g_{d.m}$. A change in the NaOH dose affected, to the greatest extent, the value of the COD of the solution when using microwave heating in the case of an increase from 0.1 $g/g_{d.m.}$ to 0.2 $g/g_{d.m.}$, and the COD value then increased from 17,873±31 mg/dm^3 to 18,620.3±101 mg/dm^3. When analogous doses of NaOH were used for the substrate heated conventionally, the COD value increased by 15.7% from the amount of 13,619±19 mg/dm^3 obtained for the dose of 0.01 $g/g_{d.m}$ to

16,068±28 mg/dm^3 obtained for 0.2 g/g$_{d.m}$. An increase in the dose of sodium base to 0.4 g/g$_{d.m.}$ had no significant effect on the increase in the value of the COD released and the results were not statistically different at the level α = 0.05 (Fig. 4).

Table 2. Theoretical yield of hydrolysis process with the use of NaOH
Tabela 2. Teoretyczna wydajność procesu hydrolizy z użyciem NaOH

NaOH dose [g/g$_{d.m.}$]	Concentration of released glucose [mg/dm^3]	Efficiency [%]
Conventional heating		
0.0	66.7±1.52	0.35±0.01
0.02	71.1±3.0	0.37±0.02
0.05	72.6±4.52	0.38±0.03
0.1	86.3±7.81	0.44±0.04
0.2	92.1±9.02	0.49±0.06
0.4	72.7±7.08	0.37±0.05
Microwave heating		
0.0	79.2±2.82	0.42±0.02
0.02	82.1±6.63	0.43±0.04
0.05	103.7±10.25	0.54±0.07
0.1	134.7±10.35	0.71±0.07
0.2	142.3±11.25	0.75±0.07
0.4	85.2±3.81	0.45±0.02

Another tested parameter which demonstrated the efficiency of the applied method of pre-preparation of the substrate was an analysis of the amounts of total organic carbon, inorganic carbon, and total carbon released to the solution. In the analysed series of the study, an increase dose of NaOH added during the hydrothermal treatment of the raw material resulted in a considerable increase in the contents of carbon compound in the solution (Table 3).

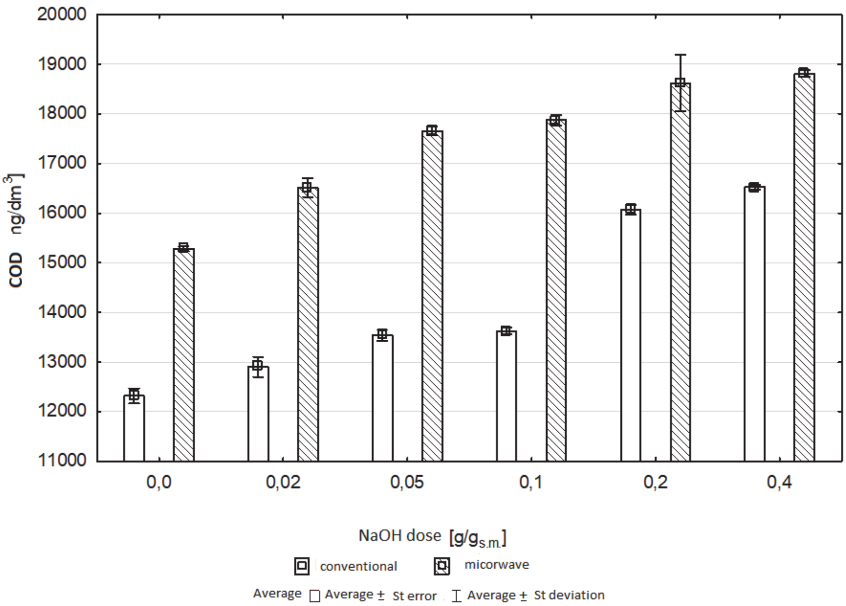

Fig. 4. Value of COD coefficient in the solution after maize silage pre-treatment with the addition of NaOH
Rys. 4. Wartość współczynnika ChZT w roztworze kiszonki kukurydzy po wstępnej obróbce z dodatkiem NAOH

The values of TC, TOC, and IC for the sample heated with microwaves, with no addition of NaOH, amounted to, respectively, 6,313±97 mg/dm^3, 6,145±81 mg/dm^3 and 168±9 mg/dm^3; following the application of the chemical treatment, the values increased, and the highest concentrations of TC, TOC and IC, respectively, (9,178±93 mg/dm^3, 8,780±481 mg/dm^3 and 398±21 mg/dm^3) were noted in the variant with a 0.4 g/g$_{d.m.}$ dose of NaOH. The trend in the results in the variants using the conventional heating method was similar; the contents of TC, TOC and IC in the zero sample amounted to, respectively, 6,293±68 mg/dm^3, 6,145±81 mg/dm^3, and 148±6 mg/dm^3. As in the case of microwave heating, the greatest release of carbon compounds to the solution occurred following the use of the highest NaOH dose (TC amounted to 8,824±120 mg/dm^3, TOC to 8,496±104 mg/dm^3, and IC to 328±19 mg/dm^3). For all analysed doses of NaOH, the results between the use of conventional heating and microwave heating were statistically different at the significance level α = 0.05 Microwave heating contributed to the release of a greater amount of TOC and TC than conventional heating did in each of the variants applied. For total organic carbon, the values obtained using microwave heating were higher from 1.44% (for a dose of 0.02 $g/g_{d.m.}$) to 31.0% (obtained when using NaOH at an amount of 0.1 $g/g_{d.m.}$). For total carbon, these amounts were from 1.81% when using a dose of 0.02 $g/g_{d.m.}$ to 23.27% at a dose of 0.1 $g/g_{d.m.}$.

Table 3. Content of total organic carbon, total carbon and inorganic carbon in the solution after maize silage pre-treatment with an addition of NaOH
Tabela 3. Zawartość całkowitego węgla organicznego, węgla całkowitego i węgla nieorganicznego w roztworze kiszonki kukurydzy po wstępnej obróbce z dodatkiem NAOH

NaOH dose [$g/g_{d.m.}$]	TOC [mg/dm^3]	TC [mg/dm^3]	IC [mg/dm^3]
Conventional heating			
0.0	6,145±81	6,293±68	148±6
0.02	6,241±99	6,421±74	180±18
0.05	7,526±104	7,743±109	217±15
0.1	7,699±112	7,967±115	268±11
0.2	7,996±105	7,971±86	302±17
0.4	8,496±104	8,824±120	328±19
Microwave heating			
0.0	6,145±81	6,313±97	168±9
0.02	8,179±107	8,369±102	190±7
0.05	7,691±105	7,916±81	225±13
0.1	7,810±98	8,111±79	301±10
0.2	8,578±68	8,932±110	354±15
0.4	8,780±81	9,178±93	398±21

The direct susceptibility of the substrate to anaerobic decomposition was assessed by carrying out respirometric tests on the digested substrates with an initial load of the active volume of the reactor of 5 $g_{o.d.m.}/dm^3$. In all discussed variants of this part of the study, the course of the process of biogas production was a first-order reaction. With each considered dose of NaOH, a greater amount of the produced biogas per unit of the substrate weight was obtained thanks to hydrothermal pre-treatment using microwave radiation. The highest effectiveness of biogas production was obtained during the fermentation of maize silage conditioned using microwave radiation with the addition of NaOH in an amount of 0.2 $g/g_{d.m.}$, at the rate of biogas production of 0.146 dm^3/d, with a process efficiency of 1155±34 $dm^3/kg_{o.d.m.}$, and this amount was higher by 11.3% than the sample with the same addition of NaOH, heated conventionally. It was also higher by 29.4% than the sample subjected to no chemical treatment (Fig. 5, Table 4).

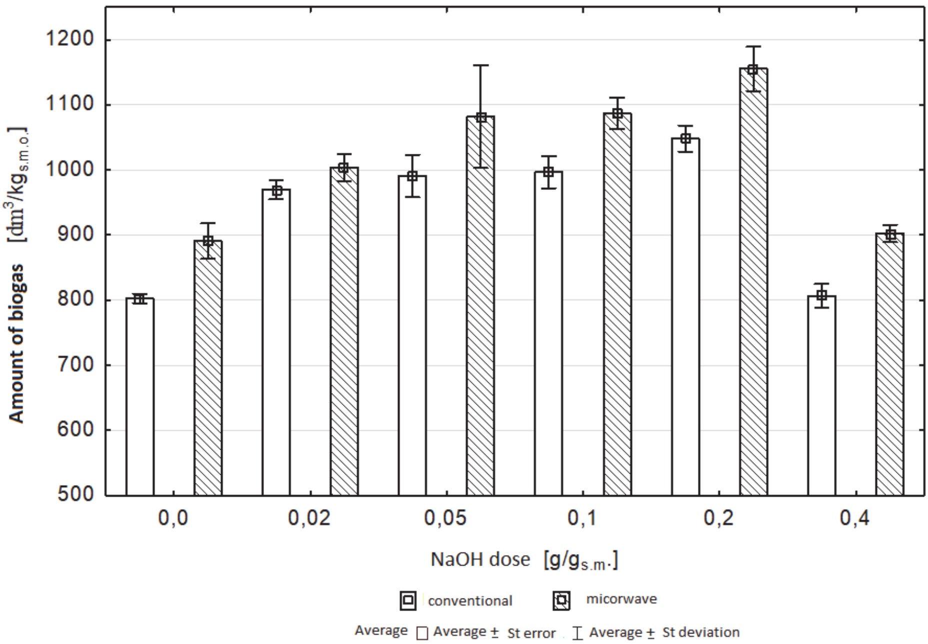

Fig. 5. Biogas production from maize silage pre-treated with the addition of NaOH

Rys. 5. Produkcja biogazu z kiszonki kukurydzy po wstępnej obróbce z dodatkiem NAOH

Increasing doses of NaOH, from 0.02 $g/g_{d.m.}$ to 0.2 $g/g_{d.m}$, using both the microwave heating and conventional heating during hydrothermal depolymerisation, resulted in an increase in biogas production. In both methods of heating, a decrease was observed in the amount of produced biogas, with an increase in NaOH dose to 0.4 $g/g_{d.m.}$. For microwave pre-treatment, the production of biogas decreased by 27.8%, while for the treatment using conventional heating it decreased by 28.8% (Fig. 5).

The percentage of methane in the gaseous products of bacteria metabolism was, irrespective of the applied dose of the chemical agent and the type of heating, at a level of approx. 59%. A statistical analysis indicated no significant differences between the content of methane in the biogas produced following the conditioning of maize silage using various doses of NaOH; similarly, no statistically significant differences were noted between the content of methane produced following the treatment using various types of heating (Fig. 6). The composition of biogas was supplemented with up to 99% carbon dioxide, the residual components accounted for up to 1% of biogas.

Table 4. Biogas production rate in respirometric analysis of maize silage pre-treated with the addition of NaOH
Tabela 4. Współczynnik produkcji biogazu w pomiarach respirmetrycznych kiszonki kukurydzy po obróbce wstępnej z dodatkiem NAOH

NaOH dose [$g/g_{d.m.}$]	Reaction rate constant k [d^{-1}]		The rate of biogas production r [dm^3/d]	
	Conventional heating	Microwave heating	Conventional heating	Microwave heating
0.0	0.29	0.33	0.10	0.13
0.02	0.32	0.23	0.13	0.10
0.05	0.29	0.27	0.14	0.12
0.1	0.19	0.28	0.08	0.14
0.2	0.3	0.28	0.14	0.14
0.4	0.29	0.22	0.10	0.13

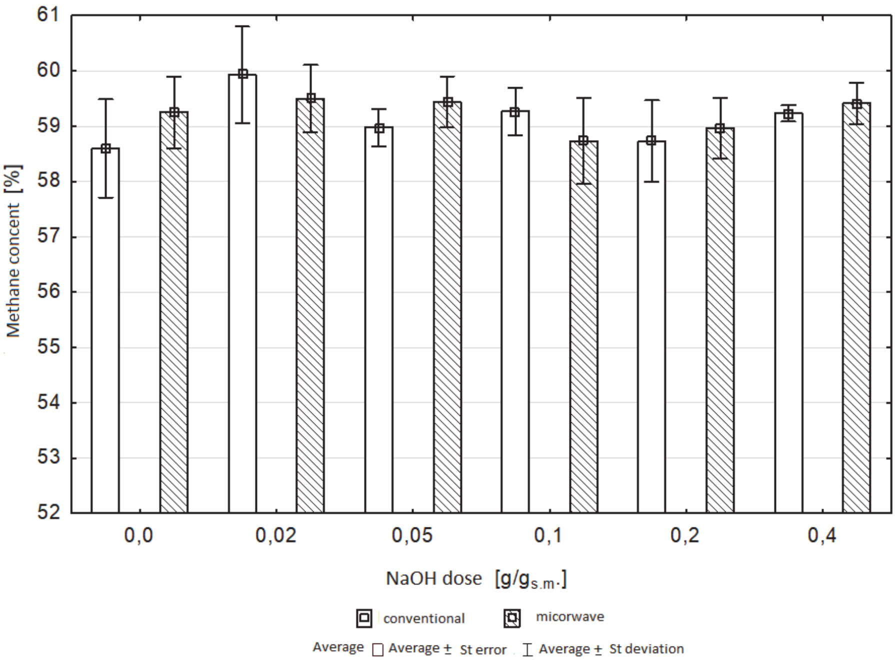

Fig. 6. Percentage content of methane in biogas produced from maize silage pre-treated with the addition of NaOH
Rys. 6. Procentowa zawartość metanu w biogazie z kiszonki kukurydzy poddanej obróbce wstępnej z dodatkiem NAOH

4. Discussion

The presented study aimed to determine the impact of the simultaneous effects of microwave radiation and sodium hydroxide on the destruction of maize silage and its susceptibility to anaerobic decomposition in the methane fermentation process.

The alkaline treatment of plant biomass is usually carried out in the presence of sodium, potassium or ammonium hydroxide (Balat 2011). According to Fengel and Wegner, during alkaline treatment a solvation process occurs which results in a kind of biomass swelling, which renders it more accessible to the action of enzymes and bacteria (Fengel & Wegner 1984). In the author's own study, the chemical reacting substance used for the pre-treatment was sodium hydroxide. In the series with the microwave alkaline treatment of maize silage using the most effective

NaOH dose of 0.2 g/$g_{d.m.}$ (7.1 g/100 g glucose) expressed as an amount of fresh biomass, was released to the solution. The obtained results correspond to the literature data. Hu and Wen (2008) studied the alkaline microwave pre-treatment prior to enzymatic hydrolysis of the switchgrass (*Panicum virgatum*). During the study, the amount of reducing sugars released to the solution was investigated. Based on the obtained data, the most favourable parameters for conducting the treatment in a microwave device were selected. The most sugar was released following microwave pre-treatment with the addition of NaOH at an amount of 0.1 g/g, carried out for 30 minutes at a temperature of 190°C; the amount of the released reducing sugar was 11.4 g/100 g biomass (Hu & Wen 2008).

Alkaline treatment leads to the breakage of the ester bond between lignin and xylan, which intensifies the delignification process – therefore, as claimed by Zheng et al. (2014) and by Liew et al. (2011), the action of the alkaline treatment is more effective where it is applied for the preparation of biomass characterised by a high lignin content of the lignocellulosic complex (Zheng et al. 2014, Liew et al. 2011). As regards the amount of polysaccharides contained in the native substrate, treatment with the addition of NaOH was characterised by low theoretical efficiency of hydrolysis. Such trends in the results could have been due to the low content of lignin in maize silage, as the amount of lignin in the native material was 2.6%. Compared to the literature data characterising the composition of lignocellulosic biomass, the obtained value is very low. As reported by Manlau et al. (2012), the maize stems contain from 3.5 to 10.5% lignin (Monlau 2012). More lignin (from 19 to 25%) is contained in miscanthus (Li et al. 2010), in the sunflower stems – up to 30% (Ruiz et al. 2013), or in coniferous tree shoots – up to 35% (Sun & Cheng 2002). Higher effectiveness of the fermentation process following the application of alkaline treatment is obtained by fermenting biomass with a higher lignin content. Mirahmadi et al. (2010) studied the alkaline treatment of the birch and spruce at a temperature of 100°C and found that alkaline treatment with the addition of NaOH results in an increase in the effectiveness of methane fermentation by 83% for the birch and 74% for the spruce (Mirahmadi et al. 2010).

In the author's own study, it was noted that the amount of biogas produced in respirometric tests increased with an increase in the amount of NaOH added for the pre-treatment; this relationship was maintained to a dose of 0.2 $g/g_{d.m.}$, while following an increase in the dose to 0.4 $g/g_{d.m.}$ the production of biogas decreased. The obtained results developed in the same manner using both types of heating. The obtained results could have been affected by the Na^+ ions formed during the pre-treatment; the literature data indicate the possibility for the inhibition of methane fermentation process due to an excessive amount of these cations. Jabłoński et al. (2014) report that the presence of Na^+ ions in an amount exceeding 3,500 mg/dm^3 is dangerous to the process of methane fermentation, and a concentration exceeding 8,000 mg/dm^3 becomes toxic (Jabłoński et al. 2014).

In the author's own study, in all test variants of the alkaline and thermal pre-treatment, the heating of substrate using microwaves resulted in greater biogas production than from conventional heating. Studies of the use of electromagnetic microwave radiation for the pre-treatment of lignocellulosic biomass indicated that microwave radiation is able to change the ultrastructure of cellulose and lead to the degradation of lignin and hemicellulose in the lignocellulosic complex, thus increasing the susceptibility to the biodegradation process. It was also observed that microwave pre-treatment in the presence of water increased the efficiency of hydrolysis of lignocellulosic structures (Binod et al. 2012).

Reports on the use of microwave treatment in order to intensify the methane fermentation of lignocellulosic biomass do not clearly indicate the efficiency of the method applied. Sapci (2013) investigated the production of biogas from barley straw, spring wheat, winter wheat and oats. As a method of pre-treatment, he used microwave radiation at temperatures of 200°C and 300°C and, following the preparation of the substrate, he carried out methane fermentation under mesophilic conditions for 60 days. The results of that study demonstrated that the microwave treatment did not improve the temperature of the process and resulted in a reduction in biogas production (Sapci 2013). Completely different study results were obtained by Jackowiak et al. (2011), who focused on analysing the process of microwave optimisation of the methane fermentation of wheat straw. During the experiment, four process temperatures were tested: 100°C, 120°C, 150°C and 180°C, with the highest amount of biogas obtained from non-microwave-treated biomass reaching 270 $dm^3/ kg_{o.d.m.}$, which is a result very similar to that obtained by Sapci (277 $dm^3/ kg_{o.d.m.}$) also from wheat straw. However, in Jackowiak's study, the amount of biogas following the microwave treatment increased considerably, with the most effective temperature option (150°C) the efficiency of methane production improved by 28%. As indicated by Sapci, the failure of his study was most probably caused by an increase in the content of dissolved lignin formed at a temperature exceeding 160°C. The compounds generated as a result of lignin dissolution are very reactive and, in many cases, have a toxic effect on bacteria and the archaea. They trigger the inhibition of enzymes responsible for the degradation of the lignocellulosic complex, cellulase, xylanase and glycosidase (Jackowiak et al. 2011, Sapci 2013).

To improve the efficiency of the conversion processes of lignocellulosic materials to energy, it is necessary to learn and understand the mechanism of the action of microwave radiation on the structural components of plants, mainly on the structure of a lignocellulosic complex. Literature reports indicate that low-temperature (< 200°C) microwave treatment is able to increase the energy value of biomass. In low-temperature microwave treatment, the efficiency of the process is, to a large extent, determined by the type of the material subjected to treatment, its physical parameters, structural arrangement, conductivity and dielectric properties. In the conventional thermal treatment, heat is supplied by means of convection and conduction, while the use of microwave radiation results in the energy being supplied directly to the material being heated. The application of microwave technology for heating has many potential benefits as microwaves penetrate the material, accumulate energy and generate heat within the entire volume. The use of microwave energy shortens the duration of additional heating of the material, allows the process to be controlled, and increases energy efficiency. Budarin et al. (2009) studied the process of microwave support of cellulose decomposition; it follows from their study that the interaction between cellulose and microwave radiation is enormous and has a decisive effect on the disintegration of a cellulose molecule. As a result of these interactions, during the low-temperature of microwave treatment, products are generated which, under the conditions of conventional heating, require the use of considerably higher temperatures (> 200°C) (Budarin et al. 2009).

5. Conclusions

The use of microwave heating simultaneously with alkaline treatment resulted in a greater volume of produced biogas. The highest efficiency of biogas production was obtained during the fermentation of maize silage conditioned using microwave radiation with the addition of NaOH in an amount of 0.2 $g/g_{d.m.}$, the process efficiency was 1,155±34 $dm^3/kg_{o.d.m.}$, and this amount was higher by 11.3% than for a sample with the same addition of NaOH heated conventionally, and was 29.4% higher than a sample subjected to no chemical treatment. For both types of heating, a decrease in the amount of produced biogas was observed with an increase in the dose of NaOH to 0.4 $g/g_{d.m.}$. The inhibition of the methane fermentation process at the highest dose of the tested chemical agent could have been caused by the generated inhibition of the methane fermentation process due to an excessive amount of Na^+ ions.

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Postęp produkcji biogazu z kiszonki kukurydzy po wstępnej obróbce alkaliczno-termicznej

Streszczenie

Celem opisanych badań była analiza oddziaływania promieniowania mikrofalowego oraz wodorotlenku sodu na destrukcję lignocelulozowej biomasy roślinnej (kiszonka kukurydzy) oraz określenie podatności wstępnie przygotowanego substratu na beztlenowy rozkład w procesie fermentacji metanowej. W toku prac porównano efekty dezintegracji w oparciu o ogrzewanie mikrofalowe z wynikami uzyskanymi podczas ogrzewania konwencjonalnego. Najwyższą efektywność produkcji biogazu uzyskano podczas fermentacji substratu kondycjonowanego przy pomocy promieniowania mikrofalowego z dodatkiem NaOH w ilości 0,2 $g/g_{s.m.}$, otrzymany wynik był o 11,3% większy od próby ogrzewanej konwencjonalnie i o 29,4% większy od próby nie poddanej obróbce chemicznej.

Abstract

This study analysed the effects of microwave radiation and sodium hydroxide on the destruction of lignocellulosic plant biomass (maize silage) and determined the susceptibility of a pre-treated substrate on anaerobic decomposition in the methane fermentation process. The effects of microwave heating-based disintegration were compared to conventional heating. The highest effectiveness of biogas production was obtained during the fermentation of a substrate conditioned using microwave radiation with the addition of NaOH in an amount of 0.2 $g/g_{d.m.}$, and the obtained result was 11.3% higher than a sample heated conventionally and was 29.4% higher than a sample subjected to no chemical treatment.

Słowa kluczowe:
biogaz, kiszonka kukurydzy, biomasa lignocelulozowa, hydroliza termiczna, promieniowanie mikrofalowe

Keywords:
biogas, maize silage, lignocellulosic biomass, thermal hydrolysis, alkaline treatment, microwave radiation