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High- and low-solids anaerobic digestion in laboratory model fermenter made from silage bags

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A laboratory physical model of a new type of anaerobic fermenter for "dry" and "wet" anaerobic digestion consisting of silage bags was designed. In the model, the experiment based on high-solids discontinuous anaerobic co-fermentation of agricultural substrates was carried out. It was verified that a horizontal fermenter constructed from silage bags is a suitable type of equipment for the production of biogas. The biogas production peaked at 4th day and was completed by 18th day. Within 18 days of discontinuous high-solids process (18.5–20.0 wt. %TS) the intensity of biogas production reached 1.18 $m_N^3 \cdot m^{-3} \cdot d^{-1}$, or 0.0012 $m_N^3 \cdot kg^{-1} \cdot d^{-1}$, and the specific methane production 0.01 $m_N^3 \cdot kg^{-1}$, or 0.07 $m_N^3 \cdot kg_{VS}^{-1}$. After conversion of the modeling process to a semi-continuous low-solids mode (3.5–5. 5 wt. %TS) during the daily dosage of 87 wt % mixture of biscuit meal EKPO-EB with 13 wt % CaO, the intensity of biogas production reached the value 2.42 $m_N^3 \cdot m^{-3} \cdot d^{-1}$, or 0.0105 $m_N^3 \cdot kg^{-1} \cdot d^{-1}$. The fermentation bag appears to be a more efficient device in the semi-continuous "low-solids" Laboratory model: "(2 inches)".

Keywords: mobile biogas plant, high-solids (dry) anaerobic digestion, silage bag, discontinuous mode, semi-continuous mode.

INTRODUCTION

The problem of farmers is frequent and high excess of biological waste (litter, feed and others) which is needed for disposal or use[1–2]. An effective way of material and energy use is an anaerobic digestion[3]. A high-solids (dry) digestion appears to be a suitable solution due to the development of techniques that have recently enabled to process materials of high total solids and fibrous nature[4, 5]. Mostly, high-solids biogas plants are built as the garage type. However, these solutions are unavailable for small farmers, so that it is important to develop alternative types of fermenters capable of processing either solid or semi-fluid substrates efficient on a smaller scale[6–8].

Due to improvements of foreign know-how, in particular[9–11], and of the legislation requirements in the CR, a high increase of interest in biogas technology has been recently noted. A classic technology of low-solids "wet" anaerobic digestion of pumpable substrates is already at a level while any pronounced increase in efficiency is not expected. In contrast, a high-solids technology ("high-solids" or "dry") anaerobic digestion of non--pumpable substrates is still on the mend. Nowadays, there are only 3 high-solids installations in operation in the Czech Republic. It is clear that this technology (its modification) is a useful tool for material-energetic treatment of not only agricultural, alimentary and similar biological waste, but also biological components sorted from municipal solid waste.

The Centre for Environmental Technology, VSB – Technical University of Ostrava, has been involved in a research project, in cooperation with the company Cernin Ltd. The aim of the project is to develop and launch a biogas station, non-demanding for design, low--cost and potentially mobile, suitable for small farms, food production, etc. (electrical power from 50 to 200 kW). The base of the developing technology is a fermenter consisting mainly of silage bags ("fermentation bags"), prepared for the "dry" and "wet" anaerobic digestion. The fermenter will be located in a thermally insulated container. The use of a plastic bag as an anaerobic fermenter is a common practice, particularly in developing countries[12]. In America, Woods End Laboratories[13] tested the production of biogas as an early stage before composting in AG-Bag bags. In Germany[6], they accomplished the extensive experiments of dry anaerobic co-fermentation of manure, hay and silage in AG-Bag silage bags. These silage bags were verified[7]. The results were relatively promising, but fermentation bags were not possible to be used in winter, due to lack of heating.

The original aim of our research was to continue on the basis of references about dry anaerobic digestion carried out in boxing / garage fermenters, etc.[1, 14–16], and carry out the above-mentioned research realized in the AG-Bag bags. The newly developed technology should be able to complete the semi-continuous either by dosing of semi-liquid substrates or composting the digestate in the bag by using forced aeration.

In the first year of the project (2011), a prototype lab model of fermenter was developed at workplaces at VSB - TU Ostrava and in CERNIN Company, Ltd. The model experiments of discontinuous and semi-continuous anaerobic digestion were performed. Simultaneously with the ongoing experiments, the further development of the model fermenter was conducted. The present model fulfills the requirements for the realization of the tests for "dry" and "wet" digestion in the volume of 0.5 m^3.

The development of pilot fermenter with a capacity of 15 m^3 already started, in which the laboratory results will be verified in 2012. For the year 2013, the production of the first operational unit is planned.

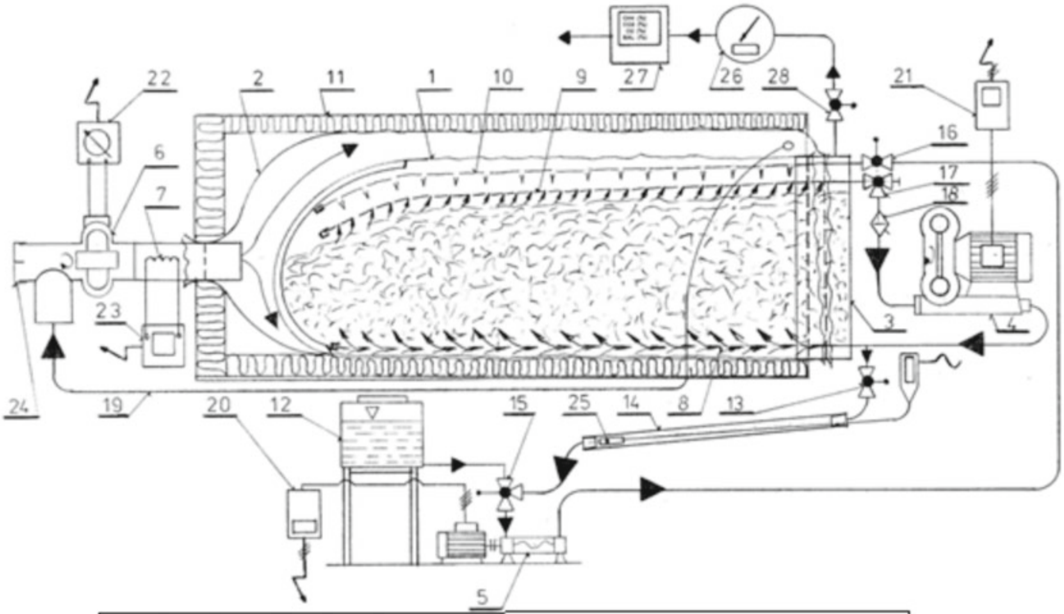
The aim of this paper is to introduce the results of high--solids batch and the further semi-continuous anaerobic co-fermentation of agricultural substrates with the utility for small agricultural farms. The construction of laboratory model of the fermentation bag is also discussed.

MATERIALS AND METHODS

Laboratory model

A laboratory model of a new type of fermenter consists of a steel service front with a short cylindrical extension, internal (fermentation) bag, outer (tempering) bag, heater placed at the end of the model (two electric heaters, air fan, air recirculation duct) and thermal insulation. The model is placed in a shallow concrete trough with a slope 3° toward the front. The blower of biogas placed at the front is used mainly for an occasional balancing of temperature of the batch, partly for the mixing and a potential aeration during composting of the digestate. Biogas is sucked by a perforated hose (2 inch) placed on a semi-liquid or solid batch and pushed into the perforated hose by blower (2 inches) located on the bottom of the bag. The bottom hose serves to drain the process fluid (percolate) to the insulated reservoir with measurements of temperature, pH, redox potential and dissolved oxygen. Percolate is sprayed on the batch as needed with the next perforated hose (0.5 inch). By this hose, it is possible to dose the semi-dilute percolate of the substrates during the semi-continuous mode.

The internal (fermentation) bag with a diameter of 600 mm and the length 3000 mm was made of PE film with thickness of 212 micrometers. The external (heating) bag with a diameter of 800 mm and length 3300 mm was made from the same material and insulated by 20 mm mineral wool. Heating of the batch to 40°C is assured by recirculation of hot air in the space between the inner and outer bag. The maximum air temperature behind the heater (400 W) and the fan is 65 to 75°C. The temperature of air returning from the front of bag by the outer pipeline to the fan is 30 to 35°C (in the



1 – fermentation bag (0.5 m³, 0.212 mm LDPE)	15 – three-way ball valve (DN32)
2 – hot-air bag (0.9 m³, 0.212 mm LDPE)	16 – ball valve for entering of input mixture and percolate (DN20)
3 – technological front with fittings (? 500 mm, steel)	17 – three-way ball valve for biogas recirculation by blower (DN32)
4 – blower of biogas (74 m³.h⁻¹, 15 kPa)	18 – particulate filter
5 – pump of input mixture and percolate (spindle 2.34 m³.h⁻¹, 600 kPa)	19 – pipeline for hot air recirculation
6 – air fan (250 m³.h⁻¹)	20 –pump speed controller of input mixture and percolate
7 – heaters for air heating (2 x 400 W)	21 –speed controller of biogas blower
8 – drain hose for draining of percolate and biogas blowing (DN50)	22 –speed controller of air fan
9 – drain hose for output of biogas (DN50)	23 – thermostat
10 – shower hose to spray percolate and input mixture (DN25)	24 – valve for input of cold air
11 – thermal insulation (mineral wool 80 mm)	25 – probe for measurements of pH / redox potential / dissolved oxygen / conductivity
12 – reservoir of input mixture (0.025 m³)	26 – drum-type gas meter (0.12 m³.h⁻¹)
13 – ball valve to drain percolate (DN32)	27 – analyzer of biogas composition (IR, chemical)
14 – reservoir of percolate (0.003 m³, PMMA)	28 – ball valve for biogas output (DN20)

Figure 1. Laboratory model of the anaerobic fermenter assembled from silage bags

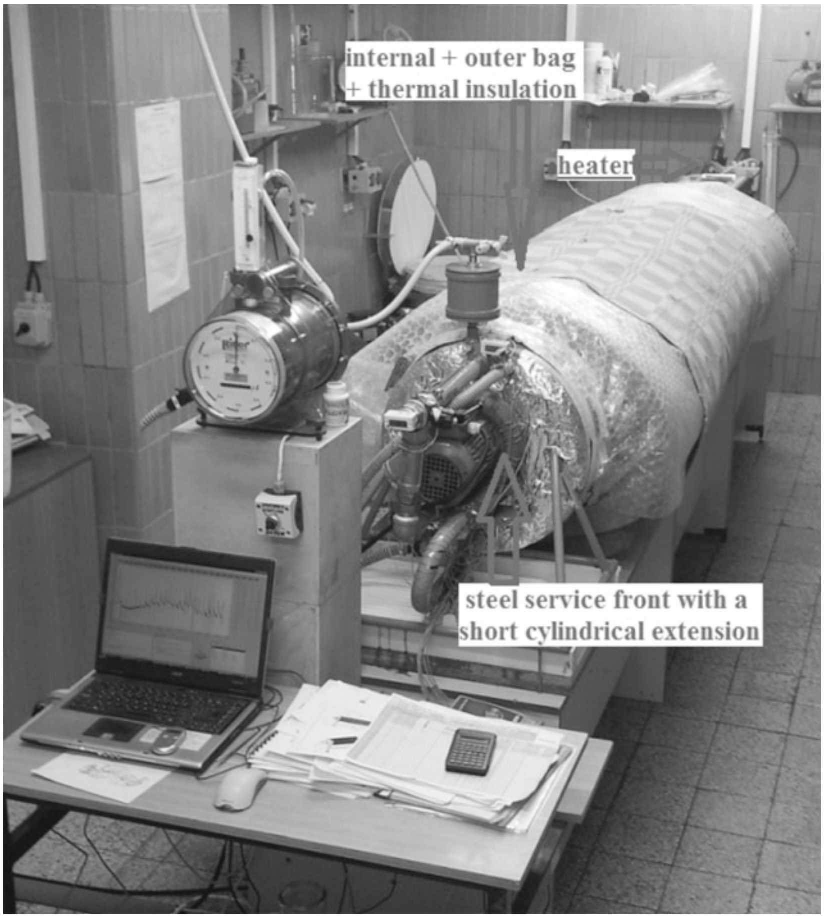


Figure 2. Fermentation bag used for the laboratory test

laboratory at 21°C). An example of the fermenter is shown in Fig. 1. The photo of the model apparatus used during the test is shown in Fig. 2.

Anaerobic digestion test

The principle of the model test was performing the anaerobic co-fermentation of agricultural substrates in a batch mode first. After almost complete stopping of biogas production, the efforts were made to extend the application of the discontinuous process containing microorganisms and enzymes. After that, the process was transferred to a semi-continuous one by dosing daily the easily degradable substrates (biowastes), mainly originated from the food industry. The intensities of biogas and methane production in a batch mode and semi-continuous mode were evaluated.

Feedstock

To verify the feasibility of the high-solids discontinuous anaerobic digestion in the model of the fermentation bag, the batch from a garage biogas plant operated by a company FORTEX-AGS Ltd. Sumperk[17] was used. This biogas plant is using the technology of "dry" anaerobic fermentation from the company BIOFerm GmbH. The batch was non-liquid (stackable). Feeding of fermentation garage plants is done by wheel loaders.

The batch of the weight 234 kg for a model fermenter (the content of 20 wt. % total solids) consisted of 17 wt % corn silage, 9 wt. % grass silage, 6 wt. % cow manure, 1 wt. % corn meal and 67 wt. % solid digestate from the previous fermentation cycle of the station. Digestate was used as inoculum and buffer. A mixture of substrates was mixed with inoculum just before the manual filling of the model.

Bio-enzyme APD BIO GAS prepared by the company Baktoma Ltd. Olomouc was injected into the bag to extend the batch anaerobic digestion process.

For the transition of the process into the semi-continuous mode, a special mixture of easily degradable bio-wastes from the manufacture of confectionery – biscuit meal EKPO-EB from the manufacturer Cervus Ltd. Olomouc in the amount of 1.0 kg per day was used. Mass of 0.15 kg CaO was used daily to regulate pH. The total daily dose of the input mixture was 1.15 kg. The density of the mixture was 1400 kg · m^3. The volume of daily dose of the mixture was 0.82 dm^3.

RESULTS AND DISCUSSION

Discontinuous process

After the fermentation bags were filled and hermetically sealed, the ventilation and air-heating started in the outer bag, and its recirculation. At room temperature 21°C, an average temperature 40°C was reached within two days. During the first 4 days of a discontinuous process, the daily biogas production reached 628 m^3 and the methane content 54 vol %. From that moment, the biogas production was decreasing. On the 11th day of the experiment, the most significant decrease of biogas production was noted, but the methane content continued to increase. On the 18th day of the process, the biogas production was almost zero, however, the highest methane content was obtained (61 vol %). Because the type was not selected properly constant clogging with particles of corn silage-occurred so the recycling process of percolate could not be carried out. This obviously caused a decrease of biogas production at relatively early stage.

During the 18 days of the discontinuous process, the total solids content decreased from 20 wt. % to 18.5 wt. %, and the content of organic dry matter decreased from 15.7 wt. % to 14.1 wt. % and the biogas production achieved an average intensity of 1.18 $m_N^3 \cdot m^{-3} \cdot d^{-1}$, or 0.0012 $m_N^3 \cdot kg^{-1} \cdot d^{-1}$, due to the active volume of fermenter (expressed according to the total weight of batch). Due to the weight of the new substrate, comprising only 1/3 of the batch, the intensity of the biogas production was 0.0036 $m_N^3 \cdot m^{-3} \cdot d^{-1}$. Hoffmann et al.[18] indicate that the dry fermentation can easily reach the intensity of biogas production from 0.002 to 0.004 $m_N^3 \cdot m^{-3} \cdot d^{-1}$. Specific methane production was approximately 0.01 $m_N^3 \cdot kg^{-1}$, or 0.07 $m_N^3 \cdot kg_{VS}^{-1}$.

On the 18th day of the process, 0.1 kg of bio-enzymatic substance Baktoma APD BIO GAS was applied[19, 20]. On the next day a double dose of this substance was used. The assumption that during the first three days the substance would not have an appreciable effect on the process was not confirmed. On the first day after the first application of the substance, an intensive evolution of CO_2 appeared. Consequently, there was a decrease of CH_4 in the biogas. The application of this substance intended to promote biogas stations did not help significantly to extend the discontinuous process. The product had a positive effect on restarting of hydrolysis and acidification, biogas production increased slightly, but methanogenesis was not successful to intensify until the 30th day of the process. It was done to see improvement of discontinuous process. Parameters and results of the discontinuous process are listed in Table 1. The course of the process is depicted in Fig. 3 – fermentation temperature (average of temperatures from 8 different locations in the fermentation bag), daily production of dry biogas under laboratory conditions and methane content in biogas (measured by IR analyzer once per day, verified by gas chromatography).

The process of raw biogas production and its methane content during discontinuous batch digestion of 234 kg in the bag was compared with the corresponding data from the fermentation biogas garage plant Sumperk that

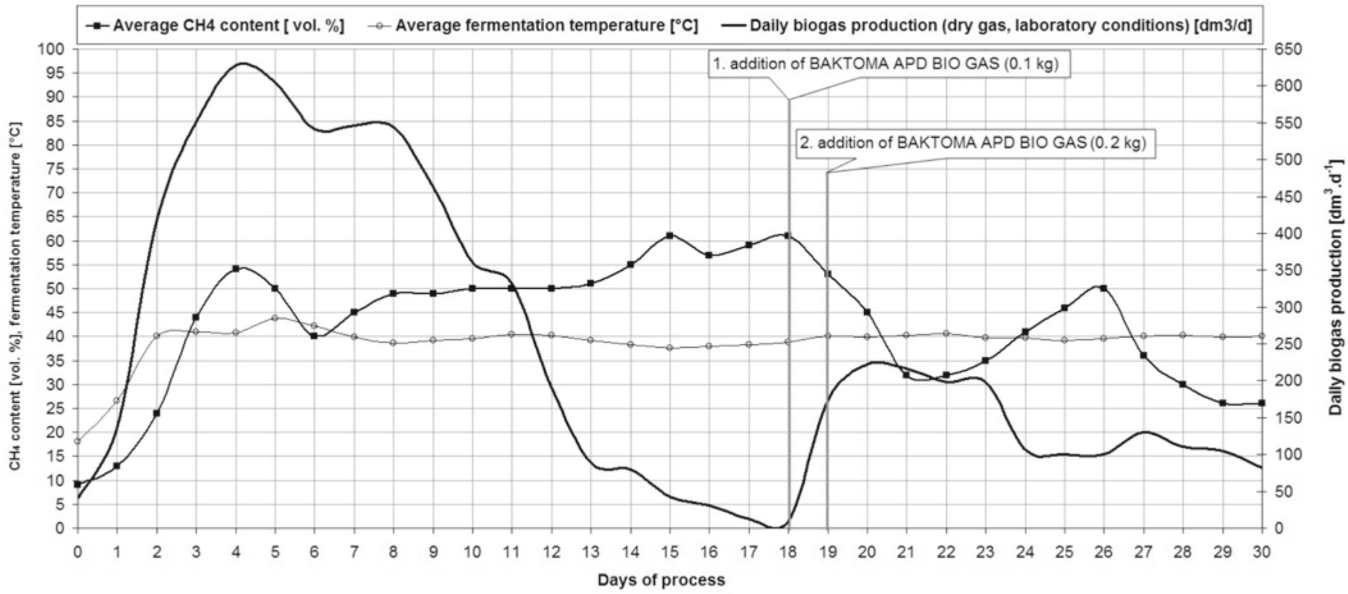


Figure 3. Trend of high-solids discontinuous anaerobic digestion

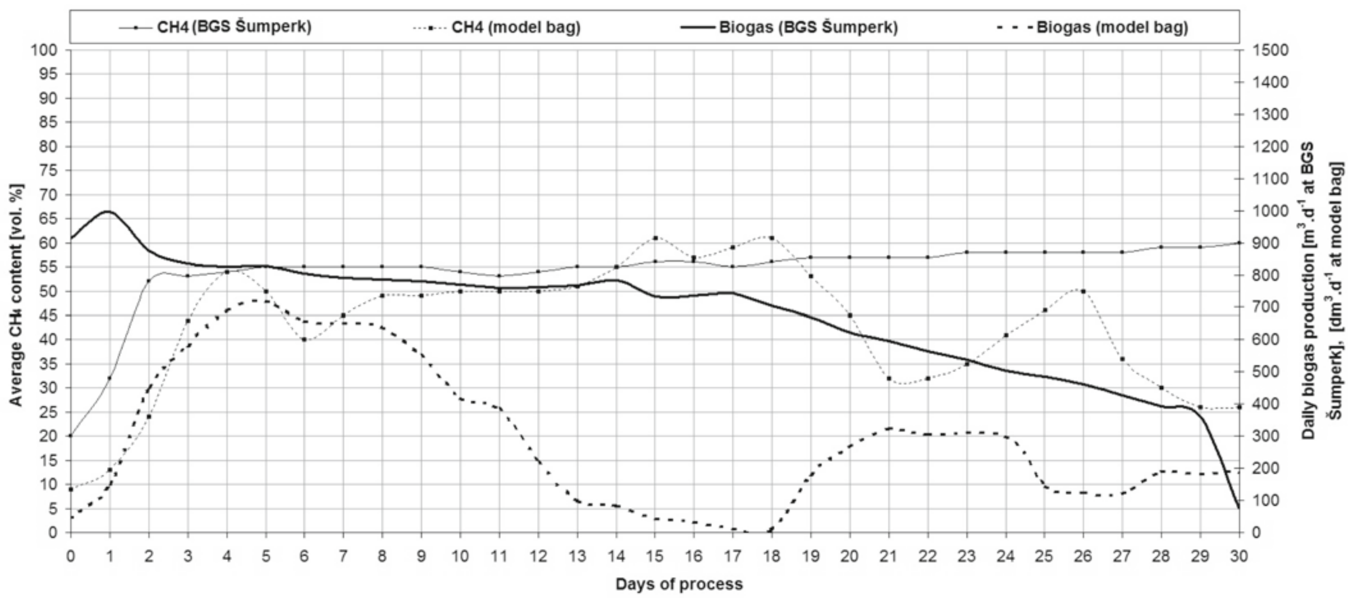


Figure 4. Comparison of the yield of biogas / methane in the bags versus BGS Sumperk

developed 230 tons of the same charge (see Fig. 4). From the figure, it is evident that digestion carried out in the dry garage plant was more intensive and, moreover, for 30 days. This fact seems to have been given by superimposing of the vertical load in the garage and more intensive contact percolate with the batch.

Semicontinuous process

According to the achieved yield of biogas, which seemed insufficient to ensure the effectiveness of model facility, and additional resolution for dry solid suspensions, it was decided to convert the process to semi-continuous by daily dosing of suitable semi-liquid input mixture with a high content of easily degradable total solids. Between 31th to 75th day of the test, the process was stabilized in a semi-continuous mode. Different doses of agricultural or food biowaste were tested. The best result was achieved when biscuit meal was dosed. During this period the total solids content decreased to approximately 10 wt. %, but the total solids content of pumpable volume decreased to approximately 5.5 wt. %. Subsequently the regular daily dose of 1.15 kg of bulk input mixture of biscuit meal EKPO-EB, specified by the manufacturer (Cervus Ltd. Olomouc) for the biogas production (87 wt. %), mixed with calcium oxide (13 wt. %) was utilized. The bulk input mixture was diluted by te process liquid (digestate).

In 60 days of the semi-continuous process (76th to 135th day of the test) the intensity of biogas production 2.42 $m_N^3 \cdot m^{-3} \cdot d^{-1}$, or 0.0105 $m_N^3 \cdot m^{-3} \cdot d^{-1}$ and the specific methane production 0.34 $m_N^3 \cdot kg^{-1}$, or 0.48 $m_N^3 \cdot kg_{VS}^{-1}$ were reached. The total solids content of pumpable volume decreased to 3.5 wt. %. The parameters and results of the semi-continuous process are listed in Table 1. Figure 5 shows the trend of the process – fermentation temperature, daily production of dry biogas under laboratory conditions and methane content in biogas. These results are comparable with the results of anaerobic digestion accomplished in the stirred tank fermenters[21–22].

CONCLUSIONS

Model tests performed on high-solids discontinuous anaerobic digestion of the batch typical for "dry" fermentation by technology of BIOFerm GmbH has confirmed the need for further detailed research to maximize the efficiency of a discontinuous methane production in a horizontal bag. The experience of the tests indicated that the fermenter from the horizontal digester bag is, apparently due to its construction, more suitable for a semi-continuous digestion in the suspension than for a batch digestion in the solid biomass.

In 2012, the research will continue on a pilot scale. For the year 2013, the operating unit is planned. Currently, the developed facility unit is considered to be offered not only to small farmers and food processing companies (canteens, hotels, etc.).

Table 1. Parameters of high-solids mesophilic anaerobic digestion

Parameter	Unit	Discontinuous process *high solids* *20.0 – 18.5 wt. %*	Semi-continuous process *low solids* *5.5 – 3.5 wt. %*
Composition of initial mixtures:	wt. %		–
corn silage		17	–
grass silage		9	–
cow manure		6	–
corn meal		1	–
solid digestate		67	–
biscuit meal EKPO-EB		–	87
calcium oxide		–	13
total solids (105°C)		*20.0*	*93.0*
organic solids (loss on ignition; 550 °C)		*15.7*	*71.1*
Initial pH	–	7.5	7.3
pH of digestate	–	7.8	8.0
Fermentation temperature	°C	39	40
Duration of fermentation test	D	18	60
Residence time	D	18	364
Active reaction volume	m^3	0.241	0.300
Initial loading of fermenter	$kg_{VS}.m^{-3}$	122.5	–
Average loading of fermenter	$kg_{VS}.m^{-3}.d^{-1}$	–	2.736
Average daily production of biogas (dry gas, normal conditions)	$m_N^3.d^{-1}$	0.289	0.727
Average daily production of methane (normal conditions)	$m_N^3.d^{-1}$	0.138	0.391
Average content of methane (dry gas)	vol. %	48	54
Degree of conversion of the input mixture to biogas	%	3.0	82.2
Degree of conversion of the input mixture to methane	%	0.7	23.9
Transfer of the total carbon to biogas	%	14.7	72.7
Specific biogas production according to:			
input mixture	$m_N^3.kg^{-1}$	0.02	0.63
total solids	$m_N^3.kg_{TS}^{-1}$	0.11	0.68
organic solids	$m_N^3.kg_{VS}^{-1}$	0.14	0.89
Specific CH_4 production according to:			
input mixture	$m_N^3.kg^{-1}$	0.01	0.34
total solids	$m_N^3.kg_{TS}^{-1}$	0.05	0.36
organic solids	$m_N^3.kg_{VS}^{-1}$	0.07	0.48
Average intensity of biogas production according to:			
active reacting volume	$m_N^3.m^{-3}.d^{-1}$	1.2	2.42
input mixture	$m_N^3.kg^{-1}.d^{-1}$	0.0012	0.0105

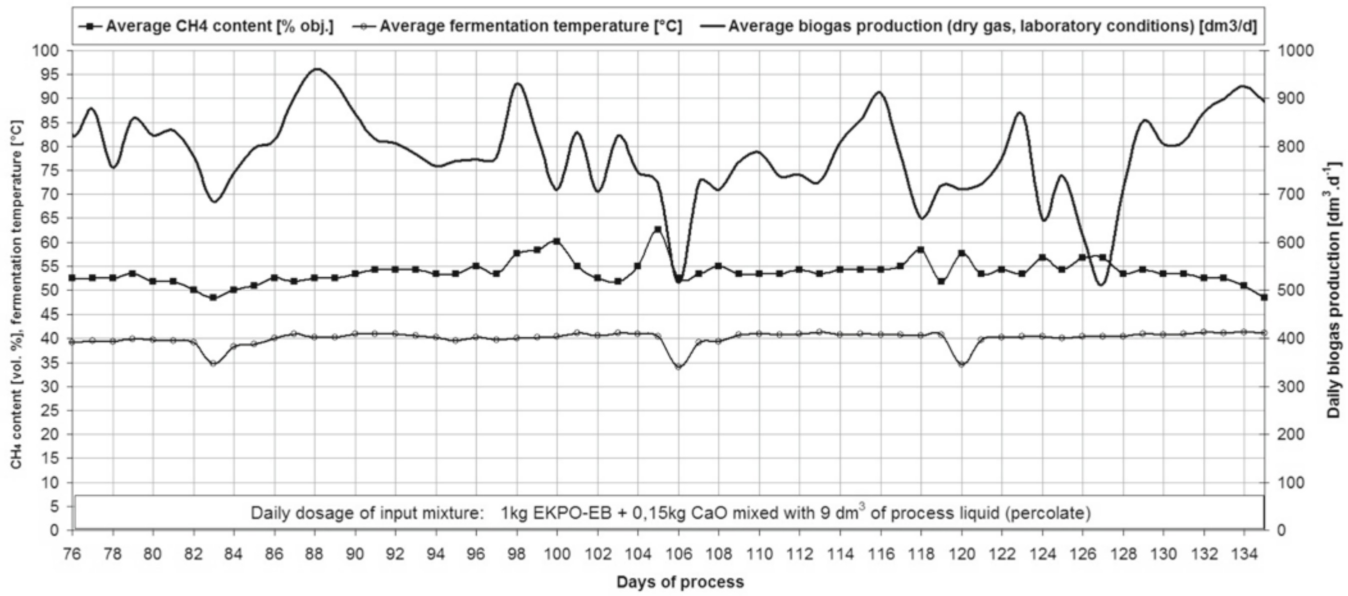


Figure 5. Trend of high-solids semi-continuous anaerobic digestion of EKPO-EB

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