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High-solids semi-continuous anaerobic digestion of corn silage in bag-type digester

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Abstract: The aim of this paper is to discuss the usability of a newly designed partially stirred horizontal anaerobic bioreactor made from triple layer bag material Sioen B6070 and heated by circulating hot air. For verification of the possibility of processing typical agricultural fibrous substrate at relatively high solids content in this type of reactor, the semi-continuous mesophilic (40 ± 3°C) anaerobic digestion of corn silage of KWS Atletico cultivar was conducted. The reactor with a total volume of 0.7 m^3 provided 0.5 m^3 working volume. Liquid slurry from the 1st stage of the agricultural biogas station Pustejov II was used as inoculum. The silage dosage was performed so that the reactor reached high methane production intensity at low volumetric production of the digestate for 120 days. The average organic loading reached 4.27 kg_{VS} m^{-3} d^{-1} while the average hydraulic retention time decreased to 85 days. The dry biogas production intensity was 3.42 m_N^3 m^{-3} d^{-1} with an average methane content of 52.5 vol%. The specific methane production from corn silage was 0.419 m_N^3 kg_{VS}^{-1}. At the end of the test, the digestate contained 13–14 wt% of total solids (TS) and 82–85 wt% of volatile solids in TS. The bag-type digester with hot air heating can be used by small farmers where there is no viable biogas cogeneration.

Keywords: biogas; bioreactor; corn silage; high-solids anaerobic digestion; horizontal bag-type digester.

1 Introduction

Biomass, e.g. commonly used agriculture fibrous substrate (corn silage) is currently one of the most promising renewable energy sources [1]. Due to its multiple uses, this source delivers about 12% of the worldwide energy demands. The proportion of this energy source rises to 40–50% in many of the developing countries and third-world countries [2]. In the anaerobic digestion process, the biomass is utilized mainly for the production of energy biogas (methane) and simultaneously to produce fertilizers [3].

Anaerobic digestion is a biochemical process without access of air [4–8]. The aim is to transform the organic substrate to material/energy-profitable products. Combining this process with agriculture is very advantageous thanks to huge amounts of biological wastes (leftovers) generated in this area that can be processed together with energy biomass [9–11]. The resulting biogas will find wider use in the future and digestate is very necessary to maintain the quality of agricultural land [12, 13].

High-solids anaerobic digestion allows processing of high-solids, typically fibrous substrates [14], e.g. silages, haylages, harvest residues, feed leftovers. When comparing the high-solids processes to the low-solids processes running in easy flowing biomass suspensions, the comparable biogas and methane yields and biomass degree of stability can be achieved, but the high-solids process leaves a lower volume of the digestate and of the waste water [15–17]. Concentrated digestate requires a different technique for incorporation into soil.

The most often built high-solids biogas stations are of a "garage" (concrete bunker) type. Nevertheless, these reactor structures are still too expensive for small farmers. Thus, it is necessary to develop alternative types of fermenters that are able to efficiently process biomass from low to high solids content on a small scale [18]. For example, Lansing and Moss [19] checked the global growth of market for the small fermenters. Schäfer et al. [15] very well described the function of angled cylindrical reactors in Järna, Sweden. This technology is still very complicated. There is an option to use the silage, compost or similar plastic bag as an anaerobic bioreactor. Regarding the use of plastic bags, we can be inspired in developing countries [20]. In Germany, Jäkel et al. [21] tested the discontinuous dry digestion in the silage bag AG BAG. However, the problem was to keep a sufficient temperature of the batch out of summer months. Rusin et al. [22] and Kasakova and Rusin [23] tried to solve the problem via the recirculation of heated air between the anaerobic bag and an added outer bag. However, the ideal

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solution was proved to be to replace the outer bag for the thermally insulated container [24].

VSB-Technical University of Ostrava, Institute of Environmental Technology in co-operation with CERNIN, Ltd. developed within the TA01020959 research project (see Acknowledgments section) a novel partially mixed horizontal fermenter made from a triple-layer plastic bag and a thermally insulated container. The fermenter is of a simple and low-cost design compared to the “garage” type fermenter and is suitable for e.g. small farmers and biowaste producers.

The aim of this paper is to present the usability of the novel bag-type bioreactor for high-solids semi-continuous mesophilic anaerobic digestion of corn silage at lab-scale.

2 Materials and methods

2.1 Laboratory model

Anaerobic digestion was realized in a lab-scale model of a partially mixed bioreactor made of a triple-layer plastic bag. The bag was made of Sioen B6070 (Sioen Industries NV, Belgium, Ardooie) (polyvinyl chloride (PVC)-polyethersulfon (PES)-PVC foil with a specific weight of 1150 g m^{-2} certified for gas holders of biogas plants), had a diameter of 0.5 m, a length of 3.6 m, and a total volume of 0.7 m^3. The working volume (volume of the anaerobic batch) was set to 0.5 m^3. The bag was stretched out on a short tubular adapter of circular steel cap with a diameter of 0.5 m. The outer casing surrounding the whole bag was built of polystyrene boards of 100 mm thickness, which served as heat insulation. The heating unit for recirculation of warm air around the bag was located at the back of the model. It consisted of two electric heating spirals (1×400 W and 1×400 W backup), an industrial standard tube axial fan (Vents VKMz100 type with a speed controller), flexible aluminum piping for air recirculation (2×4 m length), and a thermostat with an electricity consumption meter. The fan blew the warm air (75°C) on an arched end of the bag. Then, the warm air was flowing in the heat insulation casing along the bag towards the steel cap of the fermenter. The cooled air (40°C) was drawn from the cap via the internal aluminum piping back to the fan and the electric heating spirals heated it again. Air heating was chosen with regard to the large surface area heated, and due to construction simplicity, enabled rapid unfolding and folding of the reactor. No water circulating piping was used. The model bioreactor was located on the laboratory desk in the horizontal position.

To feed the liquid inoculum, a plastic vessel with a volume of 0.03 m^3 was connected to a self-priming pump with an axial rubber impeller (NEREZ Blucina, DN50 type, power consumption 1.5 kW, Czech Republic). The liquid was fed to the steel cap of the bag. To feed the solid corn silage, the same vessel and pump were used after the silage was manually mixed into a small amount of digestate.

Batch stirring was performed in two ways: first of all by the means of recirculation by a pump that was switched on manually three to five tmes a day. The batch was drained by a hose with a 50 mm diameter (positioned at the bottom of the bag and led out at the rear) and returned to the opposite side of the bag (towards the cap), or vice versa. This recirculation was performed daily at 9:00 AM for 15 min before dosing and for 3 min after each dosing of the substrate. The batch was also partially stirred by a continuously running stirrer with two rectangular tinny blades mounted horizontally in the steel cap slightly above its axis. This stirrer with a rotation speed of 23 min^{-1} prevented the foam from leaking into the biogas collecting tank placed above the steel cap. The stirrer was driven by an asynchronous motor of 0.18 kW power input.

The constant batch volume was ensured by an overflow of the digestate through the bent tube (50 mm in diameter) at a constant height (slightly above the stirrer axis). Digestate sampling was done through a valve and hose (60 mm in diameter) beneath the rear of the bag. Once each working day (before morning silage dosing) 2.5 l of digestate was drained out and un-analyzed excess was returned to the bag. Biogas overpressure (10–100 Pa) was checked with a U-type pressure gauge and secured by a liquid-seal. The biogas was collected in the vertical rectangular biogas trap (tinny box of 0.02 m^3 volume connected with the circular steel cap). The biogas production was continuously measured with a drum-type gas flowmeter and the composition was measured with a portable IR/electrochemical analyzer. Figure 1 shows a schematic section of the model bioreactor.

2.2 Feedstock

Liquid digestate (reacting slurry) from the first reactor of the agricultural biogas station Pustejov II, where cattle slurry and agricultural substrates like corn silage and lucerne haylage are processed, was used as inoculum. The inoculum temperature dropped during

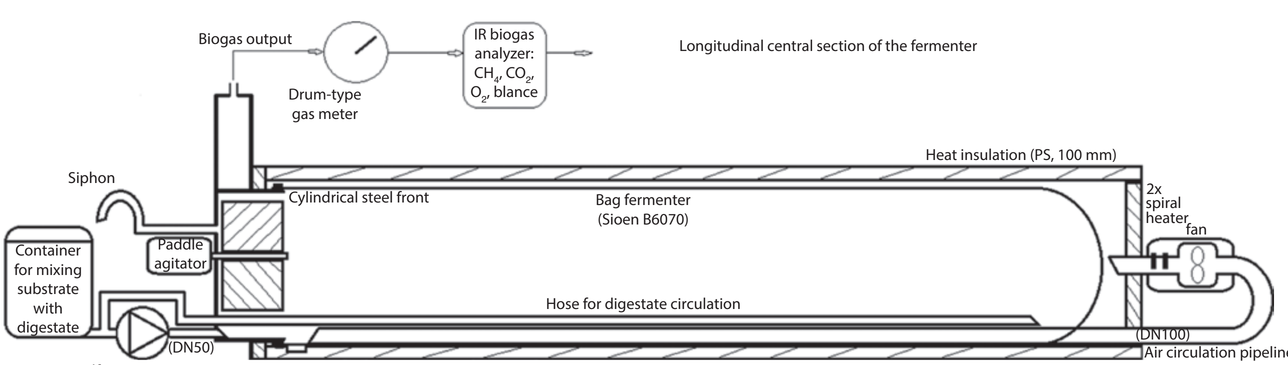

Figure 1: Model bioreactor schema – longitudinal section.

the transport from 40°C to 28°C. This inoculum with a pH value of 7.82 contained in average 6.0% of the total solids (TS), 79.9% of volatile solids in TS (VS_{TS}) and the volatile fatty acid (VFA)/total inorganic carbon (TIC) ratio was 0.22. The C:N ratio was extremely low (5.1:1).

Solid fibrous substrate in the form of corn silage of KWS Atletico cultivar was obtained from the same biogas station. This corn silage was made of the whole crop in the period when the solids content in the chopped material was 30%–35%. Silage was delivered every second week and stored in plastic barrels with internal lids lying on the silage surface to avoid mold growing. Before dosing into the bioreactor, silage was not grinded so the particle size was in the range of 15–20 mm (sometimes up to 50 mm). The silage with a pH of 4.50 contained 30.6% of TS, and 95.6% VS_{TS}. The average parameters of the inoculum and substrate are shown in Table 1. Methods and standards of individual analyses are shown in Table 2.

2.3 Modelling method

The mesophilic (40 ± 3°C) anaerobic digestion was conducted in the semi-continuous mode. The bioreactor was filled with 500 kg of liquid inoculum. Within a couple of hours, an average temperature of 38°C was reached and on the 3rd day, the temperature reached 40°C, as required. At first, the daily dose of corn silage was specified with

Table 1: Inoculum, corn silage and high-solids digestate parameters.

Parameter	Mark (unit)	Inoculum	Corn silage	Digestate
Total solids	TS (%)	6.0	30.6	13.5
Volatile solids	VS ($\%_{TS}$)	79.9	95.6	82.4
Total organic carbon	TOC ($\%_{TS}$)	35.0	44.7	40.5
Carbon	TC ($\%_{TS}$)	35.1	44.8	40.6
Hydrogen	H ($\%_{TS}$)	7.1	6.5	4.1
Nitrogen	TN ($\%_{TS}$)	6.9	1.5	5.8
Sulfur	S ($\%_{TS}$)	0.6	0.1	0.4
Oxygen	O ($\%_{TS}$)	39.2	42.4	41.2
pH-H_2O	pH (–)	7.82	4.50	7.76
Volatile fatty acids (titration to pH 5.0)	VFA (kg m^{-3})	3.21	–	10.1
Total inorganic carbonate (titration, pH 5.0–4.4)	TIC (kg m^{-3})	14.59	–	13.5
Process stability parameter	VFA/TIC (–)	0.22	–	0.75
Volatile fatty acids C2–C5 (24 h after sampling)	VFA (%)	0.08	8.42	0.15
Lipids	CL ($\%_{TS}$)	3.7	3.5	3.1
Simple carbohydrates	CH ($\%_{TS}$)	<0.1	<0.1	<0.1
Starch	ST ($\%_{TS}$)	2.1	23.8	0.3
Crude fiber	CF ($\%_{TS}$)	7.1	24.8	10.6
Ammonia Nitrogen	N_{NH4+} ($\%_{TS}$)	6.6	0.1	3.0
Nitrate nitrogen	N_{NO3-} ($\%_{TS}$)	1.1	<0.1	0.2
Phosphorus	TP ($\%_{TS}$)	1.1	0.3	1.7
Calcium	Ca ($\%_{TS}$)	2.8	0.3	2.1
Potassium	K ($\%_{TS}$)	8.5	1.1	3.3
Magnesium	Mg ($\%_{TS}$)	0.9	0.1	0.8
Arsenic	As (mg kg_{TS}^{-1})	2.3	1.2	<0.5
Cadmium	Cd (mg kg_{TS}^{-1})	0.5	0.9	1.5
Cobalt	Co (mg kg_{TS}^{-1})	3.7	<2.5	3.0
Chrome	Cr (mg kg_{TS}^{-1})	11.3	10.6	22.6
Cuprum	Cu (mg kg_{TS}^{-1})	705	5.0	85.0
Iron	Fe (mg kg_{TS}^{-1})	3400	320	3050
Nickel	Ni (mg kg_{TS}^{-1})	33.2	4.1	33.0
Lead	Pb (mg kg_{TS}^{-1})	16.1	<2.5	8.5
Zinc	Zn (mg kg_{TS}^{-1})	670	40.5	230
Molybdenum	Mo (mg kg_{TS}^{-1})	3.1	<0.5	0.8
Mercury	Hg (mg kg_{TS}^{-1})	0.07	0.01	0.06
Enterococcus	KTJ g_{TS}^{-1}	5×10^1	$<5\times10^1$	6×10^6
Thermotolerant coliforms	KTJ g_{TS}^{-1}	5×10^1	$<5\times10^1$	$<5\times10^1$
Salmonella	Positive /negative	Negative	Negative	Negative
Thermophilic microorganisms	KTJ g^{-1}	4×10^6	3×10^5	2×10^6
Mesophilic bacteria	KTJ g^{-1}	4×10^6	6×10^5	2×10^7
Psychrophilic bacteria	KTJ g^{-1}	3×10^6	3×10^5	2×10^6

Table 2: Methods and standards.

Parameter	Method and standard
Total solids (105°C)	Gravimetric analysis (drying), EN 15934:2012
Volatile solids (550°C)	Gravimetric analysis (loss on ignition), EN 15935:2012
VFA/TIC	Of pH 5.0 and 4.4 according to the Prof. Weiland method
Total organic carbon	Thermal decomposition, CO_2 determination, EN 15936:2012
Carbon	Combustion, CO_2 determination, EN 15104:2011
Hydrogen	Combustion, H_2O determination, EN 15104:2011
Nitrogen	Combustion, NO_2 determination, EN 15104:2011
Sulfur	Combustion, SO_3 determination, EN 15289:2011
Oxygen	Combustion, imputation for O_2, EN 15104:2011
pH-H_2O	Potentiometric analysis, EN 15933:2012
Volatile fatty acids (titration to pH 5.0)	Titration to two end points according to the Prof. Weiland method (HACH Lange manual; HACH-LANGE BIOGAS TIM V02.2: UK, GB – Manchester)
Total inorganic carbonate (titration, pH 5.0–4.4)	
Process stability parameter	
Volatile fatty acids C2–C5 (24 h after sampling)	Capillary isotachophoresis, Villa Labeco application note
Lipids	Total lipids after hydrolysis, extraction, CSN 467092-7
Simple carbohydrates	Sugars extracted by 40% EtOH, hydrolysis, reduction by Luff-Schoorl reagent, ČSN 46 7092-22
Starch	Ewers method, hydrolysis, polarimetry, ČSN 560512-16
Crude fiber	Mergenthaler method, mineralization, CSN EN ISO 6865
Ammonia nitrogen	Conway method with formaldehyde and titration, CSN P CEN/TS 16177
Nitrate nitrogen	Spectrophotometric analysis, CSN P CEN/TS 16177
Phosphorus	Photometric analysis, EN 14672:2005
Calcium	Acid digestion, AAS analysis, EN 16174:2012
Potassium	
Magnesium	
Cadmium	
Cobalt	
Chrome	
Cuprum	
Iron	
Nickel	
Lead	
Zinc	
Arsenic	Acid digestion, AAS analysis, EN 16174:2012
Molybdenum	
Mercury	AAS amalgam technique AMA 254 according to ČSN 757440
Enterococcus	Cultivation at 37°C, counting colonies, ISO 7899-2:1984, according to AHEM 7/2001
Thermotolerant coliforms	Cultivation at 44°C, ČSN ISO 4832, ČSN 75 7835, according to AHEM 7/2001, AHEM 1/2008
Salmonella	Proof test, CEN/TR 15215-1,2,3:2006, ISO 19250:2010, according to AHEM 7/2001, AHEM 1/2008
Thermophilic microorganisms	Cultivation at 55°C, counting colonies, EN ISO 8199:2007
Mesophilic bacteria	Cultivation at 37°C, counting colonies, EN ISO 6222:1999
Psychrophilic bacteria	Cultivation at 20°C, counting colonies, EN ISO 6222:1999

respect to the known load of the first stage bioreactor in the biogas station Pustejov, which corresponded to about 2.5–3.5 kg d^{-1}. Daily dosing was performed after dilution with digestate recirculated from the bag. For trouble-free pumping with the self-priming pump via a short hose, a ratio in the range of 3:1 to 5:1 (five parts by weight of digestate) was sufficient. Gradually, with concurrent control of pH, lower fatty acids, ratio of volatile organic acids concentration and a total concentration of inorganic carbonate (VFA/TIC ratio), and ammonia nitrogen, the daily dose of silage was increased. Dosing up to 3.5 kg of substrate was performed once a day; larger daily quantities were divided into two to three sub-doses that were pumped into the fermenter with an interval of approximately 4 h. Effort was taken to increase the TS content in the reactor above 10 wt% during the shortest time. Thereafter, the TS content was increased slowly up to the known limit for a safe and reliable operation of the pump (approximately 15 wt%). In general, effort was taken to intensify the methane production. Due to the high inlet solids, a minimum daily volume of digestate was produced.

2.4 Analysis

Batch temperature was measured continuously using eight sheathed thermocouples arranged in pairs (left/right) located close to the bottom of the bag at four distances from the cap (0.5 m, 1.0 m, 2.0 m, 3.0 m). The temperature was also checked on a thermometer located in the center of the circular steel cap. Batch suspension (digestate) samples were analyzed using the portable pH-meter EUTECH pH6+. Manual titration of the VFA/TIC ratio using 0.05 M H_2SO_4 to two endpoints (pH 5.0 and pH 4.4) was performed on 20 g samples. The substrate and digestate TS content was measured using an OHAUS MB23 infrared moisture analyzer (10±1 g at 105°C to constant weight). Then, the samples were stored in a refrigerator at a temperature of 2°C–4°C. Once a week, all the batch suspension samples and a fresh substrate sample were subjected to thermogravimetric analysis on a LECO TGA 701 analyzer (LECO, Saint Joseph, USA). There, the TS content and volatile solids content (VS as a loss on ignition at 550°C to constant weight) were specified on 1–2 g samples with an accuracy of ±0.02% relative standard deviation.

Continuous recording of the biogas flow and total volume was done using a drum-type gas flowmeter Ritter TG1/5 (RITTER Apparatebau GmbH & Co. KG, Bochum, Germany) (0.002–0.120 m^3 h^{-1}, ±0.5% accuracy) made of transparent PVC and connected to a PC. Daily biogas production was recorded also manually each morning and it was recalculated to normal conditions, dry gas (0°C, 101.325 kPa).

The raw biogas composition was measured sequentially, every working day (before dosing of the substrate at 9:00 AM) using a portable IR/electrochemical analyzer (Biogas5000: Geotechnical Instruments Ltd, Queensway, UK) type "Biogas" with accuracy of ±3% over 15% CH_4, ±3% over 15% CO_2 and of ±1% below 5% O_2, after calibration. This portable analyzer does not contain H_2 and H_2S sensors.

Once a week, the biogas composition was verified with an Agilent 7890A gas chromatograph (Agilent Technologies, Santa Clara, CA, USA) with a flame-ionization detector. Once a month, the biogas composition was measured every hour for 24 h to correct an average content of methane. The average daily content of methane in biogas corresponded to $0.9 \times CH_4$ value measured in the morning. On completion of the test, an average value of the biogas and methane specific production was calculated. On the last day, the final digestate samples were drained for a complete analysis, especially for checking risk elements (Cd, Pb, Hg, As, Cr, Mo, Ni, Zn, and Cu) contents according to the CZ Regulation no. 271/2009 Coll., as amended.

3 Results and discussion

3.1 Anaerobic digestion test

Digestion of corn silage was conducted for 120 days. The maximum dose of substrate was 12 kg and the average organic loading rate reached 4.27 kg_{VS} m^{-3} d^{-1}. This loading is at the normal upper limit for the wet process [25, 26]. In the long term, it seemed practical to not exceed 5.0 kg_{VS} m^{-3} d^{-1} which is still lower than some others use [27]. Higher doses caused noticeable overloading of the fermenter within the short test period. The hydraulic retention time was lowered from 280 days to 64 days with an average value of 85 days, which is a little longer than is common but should decrease after a longer period. The typical hydraulic retention time for corn silage is 30–90 days [28]. The pH value was stable; it never decreased below 7.65. For the first 45 days, the VFA/TIC ratio was low (up to 0.25) which means almost no overloading, then it increased slowly over 0.50 up to 0.75, which indicated overloading. During the long-term mono-digestion of corn silage (after about 8 months) it would probably be necessary to dose micronutrients, especially Co, Mo, and Se [29].

Due to the horizontal bag fermenter configuration, a two-phase reaction took place, since the paddle stirrer and recirculation pump were not able to maintain the batch fully suspended. There was always a crust in the top part of the bag with the solids content approximately 15–20 wt% TS and a liquid phase with solids content up to 13 wt% TS in the lower part. The process was high-solids only in the crust. During the 120 day test period, an average TS content of 10.3 wt% and average VS content of 77.5 $wt\%_{TS}$ was achieved in the recirculated liquid digestate.

The biogas production intensity calculated from the working volume of the bag increased relatively linearly from 1.52 m_N^3 m^{-3} d^{-1} to 4.86 m_N^3 m^{-3} d^{-1}. The average value was 3.42 m_N^3 m^{-3} d^{-1}. This intensity corresponds to the semi-dry process [30, 31]. The methane content in raw biogas fluctuated from 48 vol% to 59 vol%, but from the 40th day it was relatively stable between 50 vol% and 55 vol%. The average value was 52.5 vol%. This is the normal value of methane content from corn silage [32]. The specific methane production stabilized at 0.123 m_N^3 kg^{-1} (0.419 m_N^3 kg_{VS}^{-1}) and the specific biogas production was 0.234 m_N^3 kg^{-1} (0.800 m_N^3 kg_{VS}^{-1}), which is approximately 2.63 times lower than the biogas production measured by Koutný et al. [32]. The authors state a specific biogas production of 0.617 m_N^3 kg_{VS}^{-1}. However, this is the value from a 26 days batch test, not a long-term average. It is, however, evident that in the bag, the methanization was inhibited by ammonia reaching 4–5 kg m^{-3}.

The progress of the digestion temperature, pH and VFA/TIC ratio is shown in Figure 2. The progress of TS content in the reactor, digestate solids loss on ignition at 550°C, organic loading rate, the daily production of biogas and the average dry methane content are shown in Figure 3. Average process parameters for the entire period of the test are shown in Table 3.

The average power consumption of the air heating system was 7.980 kWh d^{-1} (0.666 kWh m^{-3} of the batch and day) and the average net calorific value of the biogas was 8.958 kWh d^{-1}. The ratio of produced and consumed energy

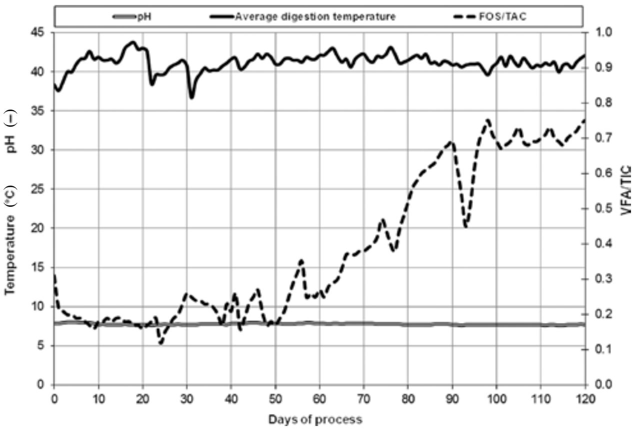

Figure 2: The progress of the temperature, FOS/TAC and pH.

was low, but we can expect a better result by an operating device with a volume of 20–50 m^3. The average heat input of biogas (calculated from biogas net calorific value and batch volume in the reactor) amounted to 0.746 kW_{th} m^{-3}. Assuming a 30% electrical efficiency in eventual biogas cogeneration, the electric power could be 0.22 kW_{el} m^{-3} at least. This value is higher than has been verified, for example, by Besgen [33] at four small agricultural biogas stations with two-stage wet processes (max. 0.13 kW_{el} m^{-3}). By contrast, it is significantly less than that published from pilot studies (0.33–0.42 kW_{el} m^{-3}) by Kayhanian [34] and Kayhanian and Tchobanoglous [35], or by Banks [36] from full-scale high-solids digestion in the DRANCO system (0.5–0.6 kW_{el} m^{-3}).

3.2 High-solids digestate

The average daily production of liquid digestate was approximately 4.8 kg which formed approximately 66 wt% of substrate fed. The samples acquired on the last day contained 13.5 wt% of TS and 82.4 wt% of VS in TS in average. The average parameters of high-solids digestate are shown in the last column in Table 1. Approximately 0.15 wt% was formed of volatile fatty acids. The total carbon content (40.6 wt%$_{TS}$) was almost completely formed by organic carbon. The C:N ratio was very low from the process point of view (7:1) which was caused by low C:N of the inoculum. The optimum C:N ratio is 15–20:1 [37]. More than half of the nitrogen content (5.8 wt%$_{TS}$) was formed of ammonia nitrogen. Nitrate nitrogen content was relatively negligible. The solids were not analyzed completely, but the crude fiber content was 10.6 wt%$_{TS}$, and lipids content was 3.1 wt%$_{TS}$. Simple carbohydrates and starch contents were low. Approximately 1.7 wt% of TS was formed by phosphorus, which was higher than necessary (C:P ratio was only 24:1). Kayhanian and Rich [38] recommend a C:P

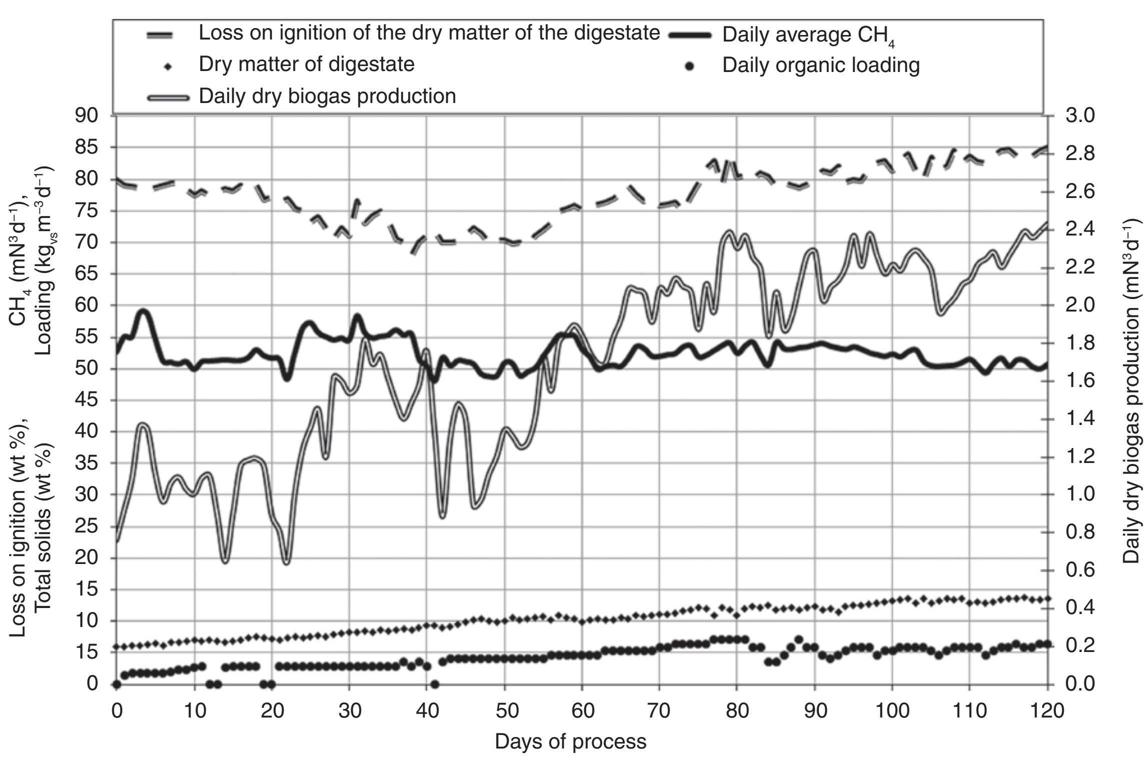

Figure 3: The progress of organic loading and biogas production.

Table 3: Average process parameters.

Parameter	Mark (unit)	Average value
Organic loading rate	OLR (kg_{VS} $m^{-3}d^{-1}$)	4.27
Hydraulic retention time	HRT (days)	85
Daily biogas production (0°C, 101325 Pa)	B_N (m_N^3 d^{-1})	1.71
Specific biogas production (per kilogram of substrate)	B_m (m_N^3 kg^{-1})	0.23
Specific biogas production (per kilogram of volatile solids)	B_{VS} (m_N^3 kg_{VS}^{-1})	0.80
Biogas production intensity (relative to the working volume of the reactor)	B_r (m_N^3 m^{-3} d^{-1})	3.42
Methane content	CH_4 (vol%)	52.5
Specific methane production (per kilogram of substrate)	M_m (m_N^3 kg^{-1})	0.12
Specific methane production (per kilogram of volatile solids)	M_{VS} (m_N^3 kg_{VS}^{-1})	0.42
Methane production intensity (relative to the working volume of the reactor)	M_r (m_N^3 m^{-3} d^{-1})	1.79

ratio in the range 120–150:1. Potassium content was also excessive; the C:K ratio was 12:1. Kayhanian and Rich [38] recommend a C:P ratio in the range 45–100:1. Iron content was at the upper limit (0.65 $wt\%_{TS}$) and the content of nickel, as one of the most important micro-nutrients, was 1.5 × higher than the concentration needed, which is 0.002 $wt\%_{TS}$. Co and Mo were present.

The corn silage digestate met legislative limits for risk elements (Cd, Pb, Hg, As, Cr, Mo, Cu, and Zn) with TS content above 13 $wt\%_{TS}$ according to the Regulation no. 271/2009 Coll., as amended, as a result of the input material. Only Cd, Ni and Zn contents were significantly closer to the limits.

Digestate quality parameters set for land reclamation according to the Regulation no. 341/2008 Coll., Addendum no. 5, table no. 5.3, as amended (maximal humidity 98.0 wt%, minimum total nitrogen as N re-calculated for a dried sample 0.3 wt%, and pH in the range of 6.5–9.0) were also met. On the basis of risk element contents, it was able to classify this digestate into Group 2 and Class I (most valuable class) of digestate for land reclamation (table no. 5.1 – maximum limit of 170 mg kg_{TS}^{-1} for copper and maximal limit of 65 mg kg_{TS}^{-1} for nickel). This means that this digestate could be used outside agricultural or forest lands – on sport and recreational grounds and green lands, as well as in urban areas, apart from outside playing fields, on urban green fields, parks, forest parks, industrial zones, waste dumps, and sludge beds.

The smell was mostly ammonia. After cooling down to 20°C, the pH value increased from 7.8 to 8.2 and the smell dropped down at a level comparable to liquid digestate from well operated agricultural biogas stations.

4 Conclusion

Lab-scale testing verified that the horizontal partially mixed bag-type bioreactor with hot air heating is a suitable device for high-solids anaerobic digestion of the most common agricultural fibrous substrate – corn silage. The average achieved methane production intensity of 1.79 m_N^3 m^{-3} d^{-1} is comparable to some conventional technologies. The bag-type fermenter should be useful for small farmers requesting silage or haylage digestion with minimum liquid manure addition.

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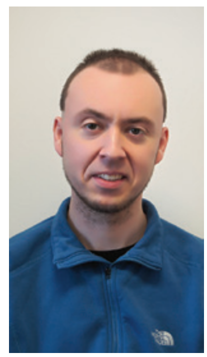
Bionotes



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