Optimization of anaerobic fermentation of kitchen waste

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Abstract

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Anaerobic fermentation is a suitable method of energetic and material utilisation of waste coming from restaurants and canteens. Laboratory experiments of wet anaerobic fermentation were performed in a continuous reactor and in batch reactors under mesophilic conditions. Effects of hydraulic retention time, organic loading rate, period of feeding and recirculation of digestate were examined in the continuous reactor. Effects of substrate pre-treatment (crushing, heating, freezing) were examined in the batch reactors. Degree of substrate degradation ranged between 83–85% within hydraulic retention time of 2–30 days. Appropriate organic loading rate was found in the range 2–3 kg of volatile solids per m^3/day. Recirculation of digestate (both an inoculum for fresh substrate and replacement of fresh water supply) caused an increase in ammonia concentration and led to immediate inhibition of the process. The results further showed a positive effect of substrate pre-treatment in the initial phase of fermentation. However, degree of degradation did not show a significant increase for the period of 20 days of fermentation.

Keywords: biogas; methane; digestion; waste treatment; biowaste

Material waste is a by-product of almost all human activities and results in stress and pollution for the environment. Total waste production is not directly proportional to the economic development of the country. Modern manufacturing and processing technologies result in lower production of waste while maintaining current productivity and standard of living. Biodegradable waste constitutes approximately one quarter of total waste. This is a sufficiently large subset that deserves our attention.

Landfilling is environmentally inappropriate and it is legally restricted under Act No. 264/2011 Coll., on waste. Agriculture, horticulture, forestry, hunting, fishing, food processing, leather, and textiles are the industries which produce the greatest amount of biodegradable waste. A substantial 20% of total biodegradable waste production comes from municipal waste (according to the Waste Management Information System ISOH). Waste prevention is the primary goal of the waste management. Another is a hierarchy of waste management, where the Czech Republic still has imperfections. In 2002, 70% of municipal waste ended up in landfills, 79% in 2007, 83% in 2009 and hence, the Czech Republic ranks among the worst in the European Union (according to Eurostat, the EU statistics). The aim of the Czech Republic should be substantial reduction in landfilling through the development of energetic and material utilisation of biodegradable waste through lower environmental impact processes. This investigation focuses on the handling and utilization of restaurant, catering facility, and kitchen biodegrad-

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able waste. Great potential is expected for a method of anaerobic fermentation widely used in biogas plants (Bernstad, La Cour Jansen 2011).

Kitchen waste is defined by the Decree No. 381/2001 Coll. of the Ministry of the Environment, which determines Waste catalogue, list of dangerous waste and indices of the waste and state for export, import and transit of the waste and progress at administration agreement to import, export and transit of the waste (Waste catalogue), amended by Decree No. 503/2004 Coll. The kitchen waste from restaurants, canteens, and catering establishments has the potential to spread biological pathogens and infectious diseases (ie. swine flu, foot-and-mouth disease, and diarrhoea). Kitchen waste should be handled in the same way as animal by-products in accordance to the Regulation (EC) No. 1069/2009. According to this regulation, these wastes should be used or disposed of in special facilities such as composting plants, biogas plants or incinerators (this excludes household kitchen waste and vegetable waste which did not come into contact with raw materials of animal origin). Dumping of kitchen waste into sewer networks through garbage disposal units is forbidden without permission, as is the feeding livestock with kitchen waste.

Kitchen waste constitutes a considerable amount of biodegradable waste and it is necessary to process it further in accordance with Act No. 264/2011 Coll. Everyone is obliged to ensure waste recovery prior to its disposal. According to §3 of the Act, the most environmentally friendly method that ensures protection of human health should always be given priority. It also states that material utilisation of waste (composting and anaerobic digestion) has priority over energetic utilisation (incineration). Anaerobic fermentation seems to be the optimal method for treating wet waste such as kitchen waste (Hřebíček et al. 2009).

Energy production from the combustion of biogas produced during anaerobic fermentation is classified as renewable energy according to Directive 2001/77/EC (on the promotion of electricity produced from renewable energy sources). In recent years, interest in the use of anaerobic fermentation has grown and the construction of biogas plants may be subsidized by the EU or the state. The goal of EU energy policy is to increase the proportion of energy production from renewable energy sources. At present, kitchen waste is used as one of the secondary raw materials in the process of wet or dry anaerobic fermentation in biogas plants. Kitchen waste is a suitable substrate for anaerobic fermentation (Zhang et al. 2007). It is also an energy-rich material which should be investigated as the main raw material for the biogas plant. However, due to its high protein and fat content, there have been procedural problems with high concentrations of ammonia and volatile fatty acids (Banks et al. 2010).

If this investigation is able to increase the biogas yield per unit of waste, even small biogas plants would achieve economic profit.

MATERIAL AND METHOD

Description of the continuous reactor. The laboratory experiment was conducted on laboratory equipment consisting of 30-liter double-skinned stainless steel reactor (Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic) which was equipped with a mechanical stirrer with a time switch, a thermostat for heating the substrate (Huber Kältemaschinenbau GmbH, Offenburg, Germany), a computer with sensors (measuring pH and temperature), dosing pump (GRYF HB, spol. s r. o., Havlíčkův Brod, Czech Republic) for pH adjustment, the flowmeter Bronkhorst High-Tech type LOW-ΔP-FLOW (BRONKHORST HIGH-TECH B.V., AK Ruurlo, the Netherlands) connected to a computer and a wet gasholder (Faculty of Mechanical Engineering, Brno University of Technology, Czech Republic). A drain neck and a neck for the sampling were placed in the bottom. Feeding was initially conducted manually once a day thereafter the system was retrofitted by peristaltic dosing pump and 2-liter reservoir for the substrate. Dräger X-am 7000 (Drägerwerk AG & Co. KGaA, Lübeck, Germany) was used for biogas analysis. It simultaneously detected the concentration of CH_4, CO_2, H_2S and O_2. The experiment was monitored with a high resolution camera (TL-SC3171, TP-LINK Technologies Co., Ltd., Shenzhen, China) with night vision. The system was also configured for remote monitoring via the internet and performed hourly data recording.

Interconnection of individual devices is shown in the technological scheme in Fig. 1.

The course of the continuous experiment and sampling. The aim of the experiment was approaching real conditions of the biogas plant, especially in continuous operation. The experiment was conducted in six periods.

Period 1: Adaptation. The reactor was filled with a mixture of raw and digested sludge (from WWTP Brno

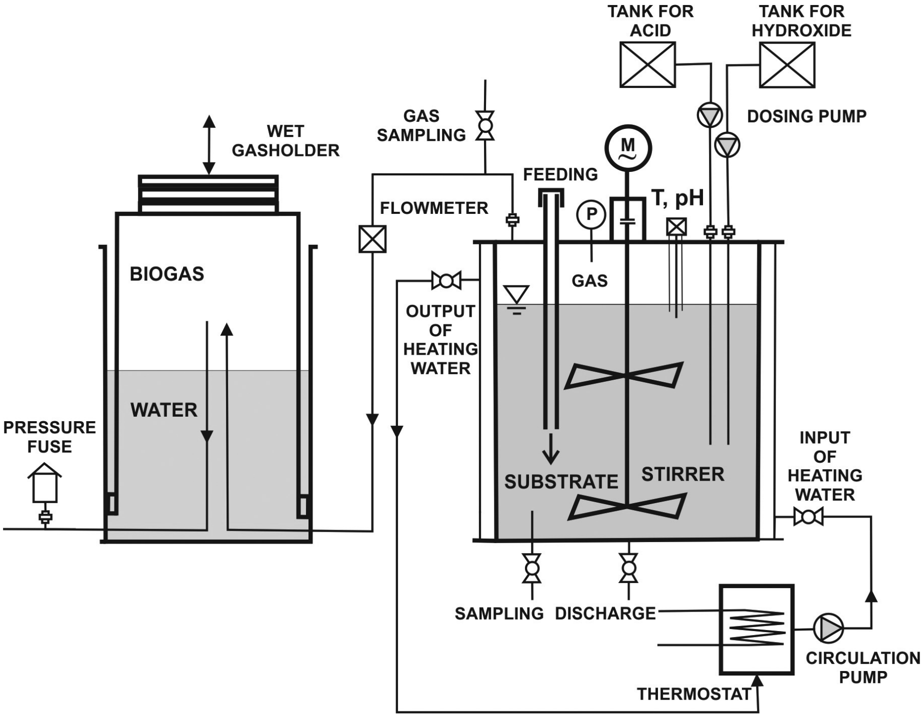

Fig. 1. Technological scheme of the continuous reactor

Modřice, Czech Republic). After stirring the mixture, a sample of 0.2 kg was taken to determine parameters of the substrate – total solids (TS) at 105°C (moisture analyser Kern MLS 50-3; KERN & Sohn GmbH, Balingen, Germany) and volatile solids (VS) at 550°C. The reactor was stirred in intervals (3-minute stirring/5-minute break) and maintained at a temperature of 36°C throughout the experiment. Overpressure in the reactor was maintained at 1.2 kPa. After 5 days, the amount of methane bacteria in the substrate was sufficient according to the 67% methane content in biogas.

Fresh kitchen waste was brought every other day from the university dining service (a varied menu restaurant) and crushed by garbage disposal units (WMstandard370, Anaheim Manufacturing Company, Anaheim, USA). During the crushing the waste was diluted with water to achieve a better fluidity. During 30 days 22 batches were delivered to the reactor, it meant 11.5 kg of substrate. Table 1 shows the average values of main parameters of raw and crushed kitchen waste and discharged digestate after fermentation (before feeding).

Period 2: Effects of hydraulic retention time and organic loading rate. Period 2 had a duration of 97 days. During the first half of the period, the hydraulic retention time was kept at twenty days, and during the second half it was extended to thirty days. The organic loading rate both in the first and in the second half was decreased from 5 to 2.5 kg of VS/day. Although the bacteria responded very quickly to new changes in the process, adaptation to the new conditions and stabilization of the process took weeks. Once a day on workdays, fresh substrate was added and afterwards digestate was discharged and analyzed. Average values of treated fresh kitchen waste were 15–17% of TS, 89–94% VS and pH 3.5–4.5. Average values of digestate were 3–3.5% of TS and 58–72% of VS. Temperature and pH inside the reactor was monitored continuously. Partial gas concentrations of CH_4, CO_2, H_2S and O_2 in the biogas were also measured once a day.

Period 3: Effect of feeding period. Weekend breaks of the feeding caused repeated interruptions in the continuity of the process. Therefore the system was modified. With the help of automatic

Table 1. Average values of main parameters

	Total solids (%)	Volatile solids (%)	Ratio C/N	pH
Raw kitchen waste	25–30	–	–	–
Treated kitchen waste	15–17	89–94	14–24	3.5–4.5
Digestate	3–3.5	58–72		7.2–7.7

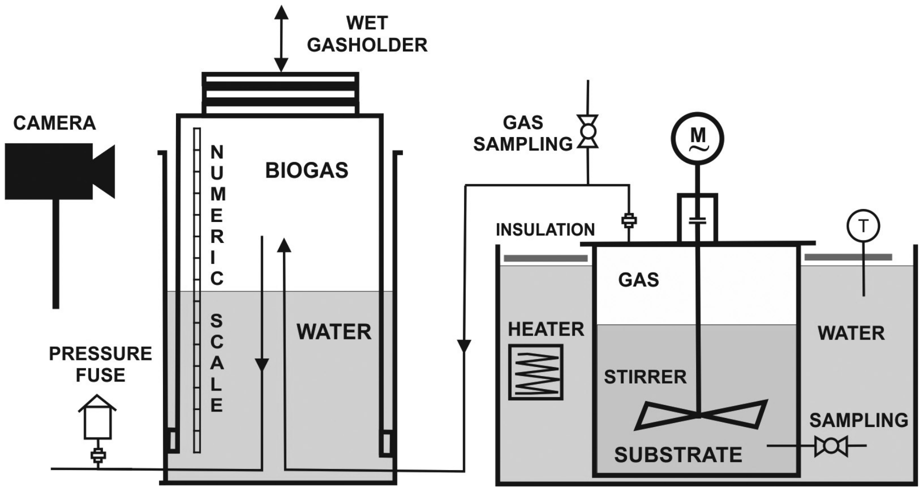

Fig. 2. Technological scheme of the batch reactor

dosing, the system could be fed several times a day while unattended. Together with this innovation monitoring of biogas production began at one hour intervals to find effective process parameters. This period spanned 30 days.

Period 4: Recirculation of digestate. Discharged untreated digestate served to dilute the solid kitchen waste at grinding and to replace supplies of clean water into the reactor. The advantage of digestate should be the presence of suitable bacteria and thus acceleration of the fermentation process in the fresh substrate.

Period 5: Cofermantation with frying oil. The fifth period of the experiment focused on the cofermantation of kitchen waste with used frying oil. Although literature (Li et al. 2011) reported a positive improvement of the process, this was not confirmed. The experiment was terminated after 5 days because there was a marked inhibition methanogenesis even at a low organic loading rate.

Period 6: Changing temperature to thermophilic conditions. In the sixth period the adaptation from mesophilic conditions of 36°C to thermophilic conditions of 50°C took place. The strategy chosen for changing operational process temperature took one-step. According to Boušková et al. (2005), this strategy significantly reduces adaptation time compared to stepwise change. But during this experiment there was more suspended feeding. Mixing of the digester was limited to 5 minutes a day to preserve heat distribution in the reactor. Adaptation took place 30 days after the feeding was restored. However, methanogenesis did not start during next 10 days. For lack of nutrients in the reactor proliferation of thermophilic bacteria probably did not arise. The experiment had to be closed for reconstruction of the laboratory.

Description of the batch reactor. Three plastic electric mixers were used for laboratory experiments with a batch process. Their volume was 500 ml with a net volume of 350 ml. The transparent container had a flat bottom and a removable lid with a stirrer. Holes were drilled into the walls of container and fitted with sampling tubes. Reactors were immersed into the water heated aquarium heaters. Biogas was captured in the wet gasholder, biogas yield was monitored by camera, and Dräger X-am 7000 was used for biogas analysis.

Interconnection of individual devices is shown in the technological scheme in Fig. 2.

The course of the batch experiment and sampling. The aim of the experiment was to determine the effect of the pre-treatment substrate on biogas yield and degree of decomposition of organic dry matter during fermentation. The experiment was performed according to the theory of single-stage wet anaerobic fermentation.

The input materials used were lunch leftovers from public catering which included potatoes, pasta, rice, chicken, chicken livers, chicken skin, potato chips, pieces of cooked peppers, carrots, and tomatoes.

Digested kitchen waste which had already undergone a controlled process of fermentation was the base substrate used to start the process of anaerobic fermentation.

Four different pre-treatments were selected and they were carried out immediately after delivery of fresh substrate to the laboratory. All samples were analyzed for the amount of total solids at 105°C, volatile solids at 550°C, and pH. Afterwards batch reactors were filled with a mixture of fresh pretreated substrate and digested kitchen waste.

Characteristic of pre-treatments:
(a) crushed kitchen waste in a garbage disposal unit,
(b) minced kitchen waste with particle sizes of approximately 15 mm,
(c) pasteurization of kitchen waste – crushing, heating to 70°C and cooking 70 min,
(d) crushed and frozen kitchen waste – for 12 h at −15°C and then melted in a laboratory oven at 40°C for 30 min.

There were three experiments. In the first experiment, input batches were mixed in a 1:1 ratio (digested kitchen waste: pre-treated fresh kitchen waste). The experiment was terminated unsuccessfully after 10 days because there was no onset of methanogenesis. In the second experiment input batches were mixed in a 3:1 ratio and the three pre-treatments, A, B and, C, were compared to each other during 20 days of monitoring. In the third experiment, pre-treatments B, C, and D were compared.

During the experiments, the volume of generated gas was recorded daily. Gas concentrations of CH_4, CO_2, H_2S and O_2 were analyzed on the 2, 4, 6, 8 and 10th day. Between the 10 and 20th day of the experiment there was not enough gas in the gasholders to perform the analysis. After the experiment, the value of total solids, volatile solids, and pH were measured.

RESULTS AND DISCUSSION

Optimization of hydraulic retention time

Kitchen waste coming from leftovers of lunch dishes proved to be suitable as a substrate with good degradability of organic matter for wet anaerobic fermentation. Degree of substrate degradation was in the range of 83–85% with a very small difference in hydraulic retention when 20 or 30 days were compared. Thus this substrate needed less hydraulic retention time than 20 days to decompose and after this time it is already near its maximum degradation during anaerobic fermentation at 36°C, which is also confirmed by Kim et al. (2006). Fig. 3 shows the selected measured data from the third period of the experiment.

Optimization of organic loading rate and feeding period

The organic loading rate is the maximal amount of organic dry matter in the reactor volume per day which can be delivered without overfeeding bacteria and leading to process inhibition.

Discontinuing feeding during weekends became a significant complication while searching for optimal parameters. The overloaded reactor could

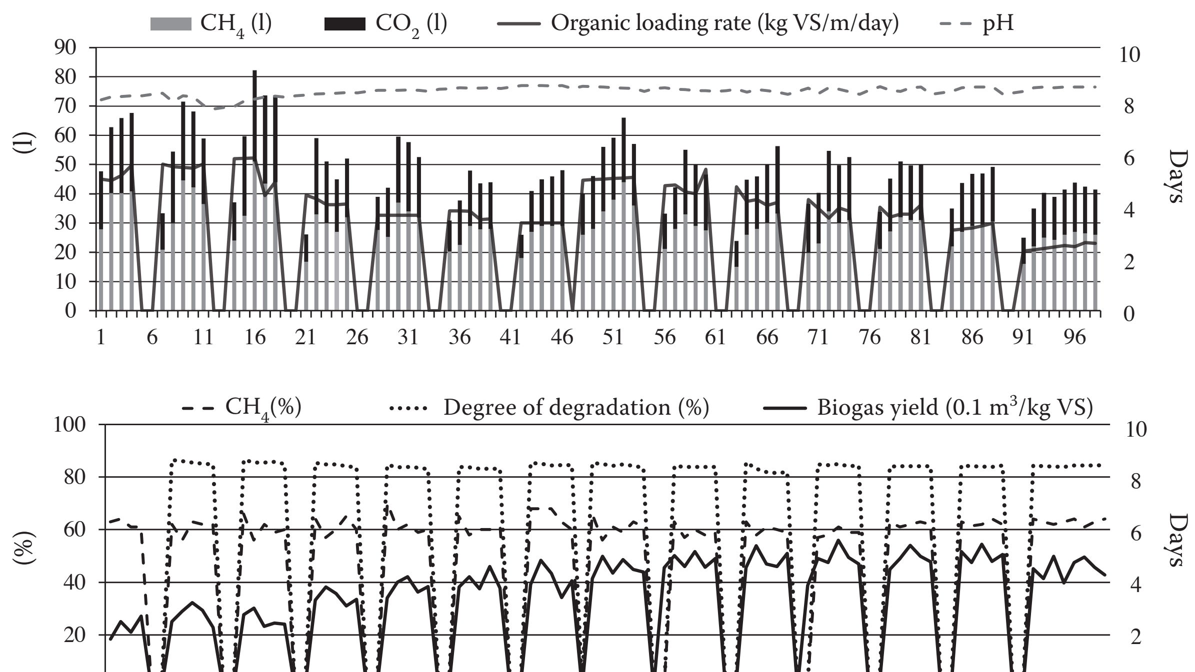

Fig. 3. Measurement record of the third period of the continuous experiment

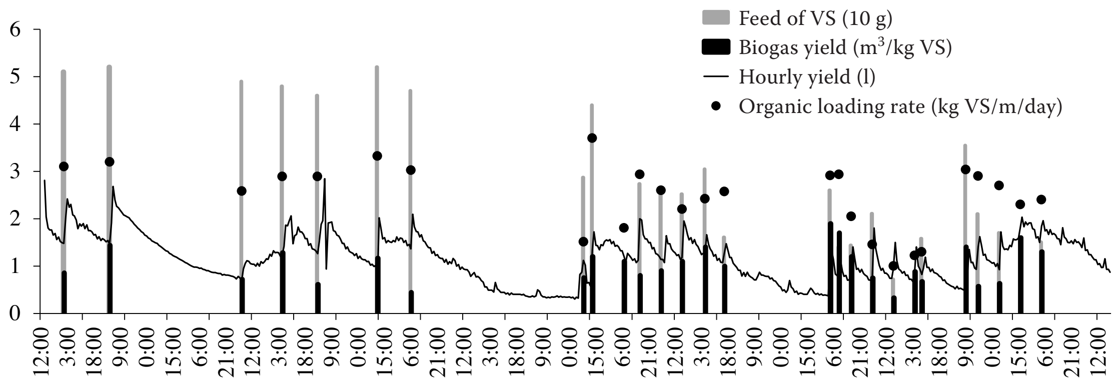

Fig. 4. Measurement record of the fourth period of the continuous experiment

take a rest during two days and afterwards it took up to three days to reach previous gas production. Short term, the process managed an organic loading rate 5 kg VS/m^3/day [VS – volatile solids (only organic matter)], which is referred in the scientific literature as the absolute upper limit. The optimum reached in our experiment was in the range 2–3 kg VS /m^3/day, which is above the average value (normal load at 35°C is between 0.5 to 1.5 kg VS/m^3/day according to Schulz (2004).

Even feedings are recommended to achieve the ideal organic loading race, even at intervals several times a day. Biogas production was monitored at intervals of one hour and the automatic dosing pump was fed at intervals of several hours to achieve an even and high gas production. Measurement record is shown in Fig. 4. Theoretical assumptions were confirmed. Feeding intervals of several hours increase the biogas yield but only with proper organic loading rate.

Effect of digestate recirculation

The advantage of digestate should be the presence of suitable bacteria and thus acceleration of the fermentation process in the fresh substrate. A benefit of recirculating filtered digestate was previously confirmed (Stabnikova et al. 2008a). The recirculation of unfiltered digestate was examined to inoculate fresh substrate and as a replacement of fresh water at entrance grinding in the garbage disposal unit. It led to immediate inhibition of process. The problem is due to nitrogen compounds in excess of ammonia in the digestate. Fresh kitchen waste contains a large share of proteins which are degraded during hydrolysis and it also leads to increasing of concentrations of ammonia and ammonium ions in the digester. This is further confirmed by Shahriari et al. (2012). Liu et al. (2012) focused on limited utilization of digestate recirculation.

Effect of substrate pre-treatment

The increase of biodegradability of the pre-treatment substrate is based on access to substances for enzyme disintegration. Kitchen wastes (KW) are in a particular form and an important step towards its degradation is conversion into more accessible forms – solution. Substrate pre-treatment shortens

Table 2. Parameters of pre-treated samples and results of fermentation in the batch reactor

	Total solids (%)	Volatile solids (%)	pH	Biogas yield (l/kg VS)	Degree of degradation (%)
Crushed Test 2	16.5	91	4.2	549	82.2
Particles 15 mm Test 2	17.8	91	4.1	534	81.8
Pasteurization Test 2	17.3	91	4.4	540	84.2
Particles15 mm Test 3	16.8	91	3.9	497	82.4
Pasteurization Test 3	16.1	90	4.4	510	83.2
Freezing Test 3	15.3	90	4.4	530	85.3
Digestate (inoculum)	3.55	72	7.6		

VS – volatile solids

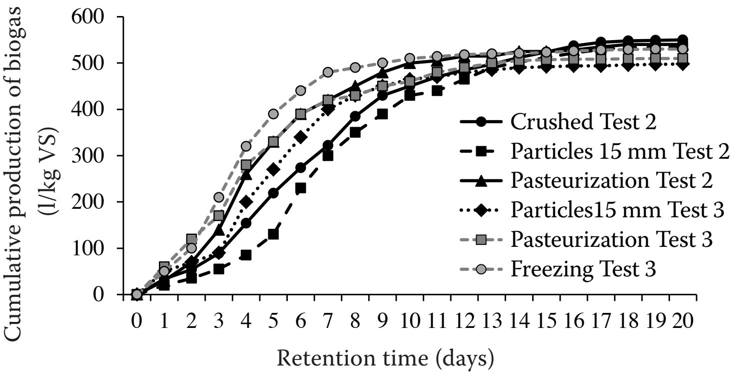

Fig. 5. Cumulative production of biogas in the batch reactors (methane proportion was highest in the tenth day of measurement for all samples in the range 68–71%)
The proportion of undesirable gases H_2S and O_2 did not exceed the value of 0.5% and 0.004%

the first stage of decomposition – hydrolysis. Table 2 shows parameters of pre-treated samples and the subsequent production of biogas and the degree of decomposition after fermentation. Fig. 5 shows the specific biogas production related to the amount of volatile solids in the samples.

The first test with batches in a 1:1 ratio (digested KW (kitchen waste)/pre-treated KW) is not included in the results. The test was terminated after 10 days because there was no onset of methanogenesis. Significantly high organic loading rate caused stimulation of acidogenesis and inhibiton of methanogenesis. The second and third test took place with input batches in a 3:1 ratio.

The results show that different pre-treatments accelerate the initial phase of anaerobic fermentation, but by the 13th day the total biogas yield is very similar. This is similar to the results obtained by Wang et al. (2009). The degree of decomposition of the samples after 20 days of fermentation did not differ much and biogas yield was not dependent on the method of pre-treatment. One of the main reasons is that while storing foods or making meals, the majority of the food was already cooked or frozen. Thus, pre-treatment processes which are similar to those mentioned have a negligible effect and increasing of the biogas yield is not significant if we take the energy expended for disintegration of the substrate into account.

On the contrary, a significant effect can be achieved by pre-treatments which did not cross the life cycle of substrate as heating at 120°C or freezing at –80°C (Stabnikova et al. 2008b; Ma et al. 2010). Qiao et al. (2011) shows a slight reduction in the production of biogas (identically with methane) from kitchen waste by the hydrothermal pre-treatment at 170°C for 1 hour. Other types of biomass such as pig manure, cow manure, mixed vegetables and fruit, or sewage sludge showed an increase of the gas production. The cow manure showed increasing biogas production but decreasing methane production.

In any case, kitchen waste in accordance with Regulation (EC) No. 1069/2009, which establishes health rules regarding animal by-products and derived products not intended for human consumption, has to go through a pasteurization and sterilization unit (70°C for 60 min) and grinding (maximum particle size 12 mm) before entering the digester.

Based on statistical analysis which was carried out to check the independence of the values of single measurements at an α level of 0.02, single pre-treatments of raw substrate did not affect the final result of the biogas yield.

CONCLUSION

The results of this investigation indicate that kitchen waste coming from catering services is a suitable raw material for wet mesophilic anaerobic fermentation. This material is easily biodegradable even without the application of pre-treatments (83–85% degree of degradation after 20 days of fermentation) and the biogas yield after 15 days of fermentation reaches a min. 95% of the total yield. This reduces the need of the reactor size and hydraulic retention time. The organic loading rate can be maintained at higher values of the recommended range 2–3 kg of VS/m^3/day. The biogas yield confirms the reported literature values of 0.25 to 0.55 m^3/kg of VS with methane share of 57–67% (Pastorek et al. 2004; Li et al. 2010). The proportion of methane decreases with shorter hydraulic retention time and higher organic loading rate which was as expected. For the purpose of individual fermentation of kitchen waste, it is recommended to further examine the thermophilic dry anaerobic fermentation technology with one continuous reactor, as a technologically simpler process suitable for less wet waste. Sufficiently long thermophilic process could also substitute the function of the sterilization unit to meet the legislative requirements.

References

Act No. 264/2011 Coll., amending Act No. 185/2001 Coll., on waste and on the amendment of certain other laws, as amended. Effective date from August 31, 2011.

Banks J.Ch., Chesshire M., Heaven S., Arnold R., 2010. Anaerobic digestion of source-segregated domestic food waste: Performance assessment by mass and energy balance. Bioresource Technology, *102*: 612–620.

Bernstad A., La Cour Jansen J., 2011. A life cycle approach to the management of household food waste – A Swedish full-scale case study. Waste Management, *31*: 1879–96.

Boušková A., Dohányos M., Schmidt J.E., Angelidaki I., 2005. Strategies for changing temperature from mesophilic to thermophilic conditions in anaerobic CSTR reactors treating sewage sludge. Water Research, *39*: 1481–1488.

Decree No. 381/2001 Coll. of the Ministry of the Environment, which determines Waste catalogue, list of dangerous waste and indices of the waste and state for export, import and transit of the waste and progress at administration agreement to import, export and transit of the waste (Waste catalogue), amended by Decree No. 503/2004 Coll.

Directive 2001/77/EC, on the promotion of electricity produced from renewable energy sources in the internal electricity market.

Hřebíček J., Friedman B., Hejč M., Horsák Z., Chudárek T., Kalina J., Piliar F., 2009. Integrovaný systém nakládání s odpady na regionální úrovni (Integrated Waste Management System at the Regional Level). Brno, Littera: 202.

Kim J.K., Oh B.R., Chun Y.N., Kim S.W., 2006. Effects of temperature and hydraulic retention time on anaerobic digestion of food waste. Journal of Bioscience and Bioengineering. *102*: 328–332.

Li Ch., Champagne P., Anderson B., 2011. Evaluating and modeling biogas production from municipal fat, oil, and grease and synthetic kitchen waste in anaerobic co-digestions. Bioresource Technology, *102*: 9471–9480.

Li R., Chen S., Li X., 2010. Biogas production from anaerobic co-digestion of food waste with dairy manure in a two-phase digestion system. Applied Biochemistry and Biotechnology, *160*: 643–654.

Liu J., Zhao S., Zhang L., 2012. Study on anaerobic digestion performance of kitchen wastes: Inhibition of ammonia nitrogen and volatile acid on the anaerobic methanogenesis. Advanced Materials Research, *347–353*: 2497–2503.

Ma J., Duong T.H., Smits M., Verstraete W., Carballa M., 2011. Enhanced biomethanation of kitchen waste by different pre-treatments. Bioresource Technology, *102*: 592–599.

Pastorek Z., Kára J., Jevič P., 2004. Biomasa – obnovitelný zdroj energie (Biomass – Renewable Energy Source). Prague, FCC Public: 276.

Qiao W., Yan X., Ye J., Sun Y., Wang W., Zhang Z., 2011. Evaluation of biogas production from different biomass wastes with/without hydrothermal pretreatment. Renewable Energy, *36*: 3313–3318.

Regulation (EC) No. 1069/2009, laying down health rules as regards animal by-products and derived products not intended for human consumption and repealing Regulation (EC) No. 1774/2002 (Animal by-products Regulation).

Schulz H., Eder B., 2004. Biogas Praxis. Staufen, Ökobuch Verlag: 168.

Shahriari H., Warith M., Hamoda M., Kennery K.J., 2012. Effect of leachate recirculation on mesophilic anaerobic digestion of food waste. Waste Management, *32*: 400-403.

Stabnikova O., Liu X.Y, Wang J.Y., 2008a. Anaerobic digestion of food waste in a hybrid anaerobic solid–liquid system with leachate recirculation in an acidogenic reactor. Biochemical Engineering Journal, *41*: 198–201.

Stabnikova O., Liu X.Y, Wang J.Y., 2008b. Digestion of frozen/thawed food waste in the hybrid anaerobic solid–liquid system. Waste Management, *28*: 1654–1659.

Wang H., Wang H., Lu W., Zhao Y., 2009. Digestibility improvement of sorted waste with alkaline hydrothermal pretreatment. Tsinghua Science & Technology, *14*: 378–382.

Zhang R., Hamed M., Hartman K., Wang F., Liu G., Choate Ch., Gamble P., 2007. Characterization of food waste as feedstock for anaerobic digestion. Bioresource Technology, *98*: 929–935.

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