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Temperature-phased anaerobic digestion of the hydromechanically separated organic fraction of municipal solid waste with sewage sludge

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ABSTRACT

This paper examines the temperature-phased anaerobic digestion (TPAD) process treating the mixture of municipal sewage sludge with the hydromechanically separated organic fraction of municipal solid waste (HS-OFMSW). The experiments showed that the performance of the TPAD process strongly depends on the conditions applied in the thermophilic stage. The TPAD system operated at a solids retention time (SRT) of 1 and 14 days in the first and second steps, respectively, achieved the overall methane yield of 333 l CH_4 $kgVS^{-1}$ and the volatile solids reduction of 52.1%, whereas the corresponding values reported for a control single-stage mesophilic process were 230 l CH_4 $kgVS^{-1}$ and 37.23%, respectively. However, when an SRT of the thermophilic reactor was extended to 2 days, the methane production in the subsequent mesophilic stage significantly decreased. It was therefore concluded that the prolonged exposure of feedstock to the thermophilic temperatures can lead to greater intensity of protein degradation. Consequently, higher amounts of ammonia are liberated to the liquid phase, which results in the inhibition of methanogenesis in the subsequent mesophilic step. Moreover, ammonia affects the release and distribution of volatile fatty acids, which also influences the performance of the whole TPAD system.

1. Introduction

Municipal solid waste (MSW) creates a great environmental problem in Poland. According to the Central Statistical Office, in 2013, approximately 9.5 million tons of MSW were collected in Poland, of which as much as 63% was deposited in landfill sites, and only 13% was subjected to biological treatment (mainly composting) (Bochenek et al., 2014). However, the organic fraction of municipal solid waste (OFMSW) can form up to 80% of the collected MSW. As the system of MSW selection is still poorly developed in Poland, alternative installations of mechanical sorting are being launched, for instance the hydromechanical sorting plant based on the BTA Process in Puławy. The BTA® Process was developed in Germany in 1984 by the BTA Biotechnische Abfallverwertung GmbH & Co (now BTA Company GmbH) in cooperation with the University of Applied Sciences, Munich. This process comprises of a water pulper to remove heavy materials (glass, stones, bones, etc.) and light fraction (foil, plastics, textiles, wood, fibers, and others), which is followed by a hydrodynamic grit removal system. The residue after these operations is the hydromechanically separated organic fraction of municipal solid wastes, suitable for biogas production. However, due to generally lower organic matter and nutrient contents, the organic fraction of municipal solid waste derived from mechanical sorting gives a lower biogas yield compared to the production of biogas from source sorted OFMSW (Bolzonella et al., 2006; Dong et al., 2010). In the previous research, it was demonstrated that biogas production from hydromechanically separated OFMSW can be significantly enhanced when the wastes are co-digested with municipal sewage sludge which is also regarded as a substrate giving moderate to low biogas yields (Borowski, 2015). The semi-continuous co-digestion process of sewage sludge with HS-OFMSW (mixed in the proportion of 1:1 by weight) operated in mesophilic conditions (35 °C) gave nearly 500 l of biogas per kg VS, compared with around 300 l $kgVS^{-1}$ obtained from HS-OFMSW alone. But when thermophilic conditions were applied, biogas production from the mixture dropped to 276 l $kgVS^{-1}$, which was attributed to the inhibition of methanogenesis by free ammonia and volatile fatty acids. Literature data concerning the performance of the anaerobic thermophilic digestion process are ambiguous. Thermophilic digestion often gives higher volatile solids and COD removal rates, greater biogas yields

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and provides more effective pathogen inactivation, in comparison to mesophilic treatment (Bolzonella et al., 2012; Mao et al., 2015; Provenzano et al., 2013). On the other hand, several studies pointed out numerous disadvantages of the thermophilic process over the mesophilic one including higher sensitivity to operational conditions, decreased stability due to the accumulation of ammonia and volatile fatty acids (especially propionic), poor supernatant quality, lower methane content in biogas and higher net energy input (Bolzonella et al., 2012; Mao et al., 2015; Lv et al., 2010; Song et al., 2004). Temperature-phased anaerobic digestion is a relatively new technology developed at Iowa State University, which combines the advantages of thermophilic and mesophilic processes while avoiding the disadvantages of each one. It consists of a short (1–3 days) thermophilic pre-treatment stage followed by a second mesophilic stage operated with a longer retention time. The thermophilic stage enhances hydrolysis and acidogenesis rates, which are often rate-limiting steps in biomethanation, whereas the mesophilic stage provides stable conditions for syntrophic acetogenesis and methanogenesis due to the greater resistance of mesophilic methanogens to inhibitory or toxic compounds (Lv et al., 2010). As a result, enhanced biodegradation of a feedstock and greater biogas yields can be achieved. Other advantages of the TPAD system include: lower VFA concentrations in effluent from a mesophilic reactor, increased system stability, efficient pathogen inactivation as well as reduced overall reactor volume and operational costs in full scale treatment plants (Aslanzadeh et al., 2014; Kim et al., 2011; Rubio-Loza and Noyola, 2010). It was also reported, that temperature phased anaerobic digestion outperforms both mesophilic, and thermophilic single stage processes as well as that of a two-stage mesophilic system (Ge et al., 2010, 2011b; Schmit and Ellis, 2001).

The TPAD system has been applied mainly for municipal sewage sludge stabilization (Bolzonella et al., 2012; Ge et al., 2011a, 2011b; Kim et al., 2011; Rubio-Loza and Noyola, 2010; Song et al., 2004). However, this technology has also been found to be effective in treating food waste (Aslanzadeh et al., 2014; Chu et al., 2008; Kim et al., 2011), OFMSW (Aslanzadeh et al., 2014; Schmit and Ellis, 2001), olive mill solid residue (Rincon et al., 2009), grass silage (Orozco et al., 2013), swine wastewater (Kim et al., 2012) and cattle manure (Lv et al., 2013; Sung and Santha, 2003). The thermophilic stage of TPAD can be operated at either acidic or neutral pH. The former approach favors hydrolysis and acidogenesis thus inhibiting methanogenesis in the thermophilic step. In the latter approach, the neutral pH of the thermophilic step is intended to achieve a dynamic balance between hydrolysis/acidogenesis and methanogenesis. In this case, methane is produced in both stages, and the mesophilic reactor is used as a polishing stage alleviating the disadvantages of thermophilic digestion, as mentioned above (Lv et al., 2010, 2013; Schmit and Ellis, 2001; Sung and Santha, 2003).

The paper describes the experiments with the semi-continuous TPAD process, treating the mixture of sewage sludge with the hydromechanically separated OFMSW. The specific objectives of the research were: 1) to evaluate the impact of a short thermophilic pretreatment on the subsequent mesophilic digestion, 2) to determine biogas and methane yield from the mixture of sewage sludge and HS-OFMSW treated in a single-stage and two-stage anaerobic digestion processes, 3) to assess the stability of the TPAD system, and discuss the role of ammonia and volatile fatty acids as potential inhibitors of methanogenesis.

2. Materials and methods

2.1. Materials

Municipal sewage sludge used in this study originated from the Wastewater Treatment Plant (WWTP) in Kutno, Poland. Organic fraction of municipal solid wastes was sampled from a hydromechanical sorting plant at the Municipal Service Office in Puławy. Both plants have been further described by Borowski (2015). The main characteristics of the raw sewage sludge as well as municipal solid waste are summarized in Table 1. Municipal solid waste used in the experiments had slightly different characteristics, compared to the substrate applied in the previous study (Borowski, 2015), due most likely to seasonal variations in the composition of waste delivered to the sorting plant. The concentrations of nitrogen and phosphorus, and particularly carbon containing compounds were lower than the figures described in the cited paper. Carbon constituted only around 55% TS, whereas the average contents of volatile solids and COD were 46.7% TS and 496 g $kgTS^{-1}$, respectively.

Sewage sludge delivered to the laboratory had a high TS concentration of 160.4 g kg^{-1}, due to its origin from the plant in Kutno, which subjects this sludge to dewatering prior to lime stabilization. Contrary to HS-OFMSW, the sludge was abundant in organics and nutrients. Volatile solids accounted for around 82% TS and the average COD was 1138 g $kgTS^{-1}$. The contents of nitrogen and phosphorus in the sludge were 4 times higher than the corresponding values determined in municipal waste.

2.2. Experiments

The experiments were carried out in four identical reactors, one used as the first thermophilic stage, and the others as the second mesophilic stage or as a control mesophilic digester. The reactors were cylindrical in shape, made of glass, each having a working volume of 3 L. They were placed in thermostats to provide constant mesophilic (35 ± 1 °C) or thermophilic (55 ± 1 °C) conditions. Each reactor was coupled with a 4 l gas collecting tank to provide strict anaerobic conditions and to measure daily biogas production. The thermophilic reactor was fed with the feedstock twice a day. Part of the effluent of the thermophilic reactor was then used for feeding the mesophilic reactors operated at two different SRT values, which gave two total solids retention times of the system (15 and 10 days). Three experimental runs were performed (Table 2). In the first run, the mesophilic digester was operated as a single-stage process (control run) with an SRT of 15 days and an organic loading rate (OLR) of 2.85 kgVS m^{-3} d^{-1}. In the second experimental run, the TPAD process was established as follows - the thermophilic reactor in the first stage was operated with an SRT of 2 days and a corresponding OLR of 21.35 kgVS m^{-3} d^{-1}. The subsequent SRTs used in the mesophilic second stage were set at 13 and 8 days, which were equivalent to OLRs of 2.35 and 3.82 kgVS m^{-3} d^{-1}, respectively. However, due to the high instability and a stoppage in biogas

Table 1
Characteristics of sewage sludge and hydromechanically separated OFMSW used for the experiments.

Indicator	Unit	Sewage sludge	HS-OFMSW
Total solids	g kg−1	160.40 ± 10.27	37.29 ± 11.76
Volatile solids	g kg−1	132.28 ± 10.63	17.43 ± 6.46
	% TS	82.47 ± 2.23	46.74 ± 2.31
Chemical oxygen demand	gO_2 $kgTS^{-1}$	1137.5 ± 134.9	495.9 ± 138.6
Elemental analysis			
Carbon	% TS	66.30 ± 2.50	55.30 ± 2.05
Nitrogen	% TS	7.25 ± 0.50	1.75 ± 0.23
Phosphorus	% TS	2.55 ± 0.30	0.62 ± 0.11
Hydrogen	% TS	5.35 ± 0.25	4.95 ± 0.50
Sulfur	% TS	0.72 ± 0.08	0.06 ± 0.01
C/N	–	9.16	31.60

± Standard deviation.