Int. J. Environ. Res., 9(3):805-812, Summer 2015
ISSN: 1735-6865

Intensification of the Biomethanisation Process in Wastewater Treatment plant

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Received 1 Aug. 2014; Revised 31 Dec. 2014; Accepted 1 Jan. 2015

ABSTRACT: In the present study, the increase of organic loading rate (OLR) influences the biomethanisation of sewage sludge. The research was conducted at technical scale in wastewater treatment plant in Tyrowo (near Ostróda, Poland). It has been shown that the increase of OLR, by adding co-substrates, cause the increase of biogas production but not biogas yield coefficient. The substrates used for anaerobic digestion were primary sludge and excess sludge. As co-substrates there were fats, thin stillage and whey. The highest total biogas production of 115977 m^3/month and electricity production of 231.3 MWh were obtained for the highest OLR of 1.88 kg VS/m^3·d. Anaerobic co-digestion of primary and excess sewage sludge with co-substrates at the highest OLR caused an increase of pH to 7.7 and volatile fatty acid concentration to 616 mg/dm^3, but there was no loss to the stability of the process. Regardless of organic loading rate, the concentration of ammonium nitrogen was within the optimal range.

Key words: Anaerobic digestion, Biogas, Co-substrates, WWTP, Sewage sludge

INTRODUCTION

In Poland, the management of sewage sludge during wastewater treatment is problematic because although it has been continuously produced, as of 1 January 2013 it cannot be stored (Bień *et al.*, 2011). According to the Central Statistical Institute (Polish Statistical Institute, 2013), a total of 533.3 thousand tones dry weight of sewage sludge was produced in municipal wastewater treatment plants in Poland in 2012.

Sewage sludge can be stabilized by methane fermentation. The primary benefit of this method is that it produces biogas containing methane that can be converted into electricity or heat. Production of useful energy from biogas can make sewage treatment plants more profitable by providing some of the energy necessary for treatment. The estimated energy consumption of wastewater treatment plants per volume of treated wastewater is 0.45 kWh/m^3 (Krzemień, 2012).

Sewage treatment plants can be made more profitable by increasing the amount of energy produced from methane fermentation. To accomplish this, co-substrates can be added to the sewage sludge. This is relatively cheap and technically simple because it does not require modernization of existing facilities. Food industry wastes can be used as co-substrates, such as fats (Noutsopoulos *et al.*, 2011), whey (Shilton *et al.*, 2013), manure (Borowski and Weatherley, 2013) and thin stillage (Mohana *et al.*, 2009). Adding fats to sewage sludge to increase the total amount of substrate by 20 to 60% can increase biogas production from 18 to 50% (Noutsopoulos *et al.*, 2011). Addition of grease sludge to sewage sludge, up to 60% of the total VS load of the feed, resulted in a 55% increase of biogas yield (Noutsopoulos *et al.*, 2013). The addition of whey as a co-substrate has increased biogas production by 51% (Shilton *et al.*, 2013). In addition, Borowski and Weatherley (2013) found that increasing the amount of substrate by 30% with chicken manure increased biogas production approximately 150%.

Among the substrates, lipid-rich waste is considered to be most attractive due to its high methane

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potential. Co-digestion of fat, oil and grease (up to 64% of VS) and sewage sludge enhanced methane production, with an increase around 137% over digestion with sewage sludge alone (Wan *et al.*, 2011). With the addition of grease trap sludge (10–30% of the total VS added) to the sewage sludge, the methane yield was increased by 9–27% (Davidsson *et al.*, 2008). Other authors reported that the addition of grease waste (23% of VS added), caused an increase of 138% in the methane yield (Silveste *et al.*, 2011).

The process of hydrolysis of fats and oils to glycerol and long chain fatty acids (LCFA) is rapid, resulting in the accumulation of LCFAs in the wastewater (Angelidaki and Ahring, 1992). This process is summarized by Noutsopoulos *et al.* (2013): First, extracellular enzymes called lipases catalyze hydrolysis of triglycerides into free LCFAs and glycerol. Glycerol is degraded intracellularly, mainly to acetate by acidogenic bacteria. LCFAs are transformed to acetate (or propionate), hydrogen and CO_2 via the β-oxidation biochemical pathway. After these degradations, hydrogenotrophic and acetotrophic methanogenesis takes place. High LCFA concentrations can have an inhibitory effect on microorganisms, necessitating a longer time (above 100 days) for the lag phase period in the β-oxidation process (Silva *et al.*, 2014). This is due to the adsorption of LCFAs to microbial surfaces, which limits nutrient transport to the cell (Pereira *et al.*, 2005). Wan *et al.* (2011) reported that the increase of fat, oil and grease content (to 74% of VS) during co-digestion with sewage sludge meant that the digester initially failed but slowly self-recovered. However, the methane yield was only about 50% of a healthy reactor with the same organic loading rate. Luostarinen *et al.* (2009) showed that grease trap sludge additions of 55% and 71% of feed VS resulted in increased VS in digested material and decreased methane production, indicating overloading and LCFA inhibition.

The complexity of anaerobic digestion and the possibility of its inhibition means selecting appropriate substrates is vital for the process. Proper proportions of substrates in the mixture ensure a carbon to nitrogen ratio that allows for the development of micro-organisms, prevents process inhibition and optimizes methane production. For anaerobic digestion, the optimal C/N ratio is generally assumed to range from 20 to 70 (Burton and Turner, 2003) but some authors indicate that ratios from 12 to 16 allow successful digestion (Mshandete *et al.*, 2004). Factors that inhibit anaerobic digestion include the temperature, the pH, the concentration of ammonia nitrogen or volatile fatty acids, or the presence of compounds toxic to microorganisms.

The addition of co-substrates to sewage sludge increases the organic loading rate (OLR) (Shilton *et al.*, 2013). An inappropriate ratio of substrates in the feedstock and a high OLR can inhibit the process. When the rates of hydrolysis and acidogenesis are higher than that of methanogenesis, volatile fatty acids accumulate in the reactor and the pH decreases. If pH drops below 6.5, this inhibits methanogens, lowering methane production (Nagao *et al.*, 2012). Knowledge is relatively poor about the effect of co-substrates on industrial-scale anaerobic digestion of sewage sludge from a municipal sewage treatment. The present work examines this subject in relation to biogas production in wastewater treatment plants (WWTP).

MATERIALS & METHODS

The study was conducted on an industrial scale in the WWTP in Tyrowo (province of Warmia and Mazury, Poland). The average flow rate was 6000 m^3/d from a population of 94 000. Primary sludge, excess sludge and co-substrates were used for anaerobic digestion (Fig.1). The process was carried out in mesospheric conditions at 36-38°C.

The anaerobic chamber was made of reinforced concrete surrounded by a 10 cm layer of semi-hard mineral wool, which was covered with corrugated metal. The chamber had an inner diameter of 20 m and a capacity of 5000 m^3. Sludge was circulated in the chamber by a stirrer-assisted circulating pump. The precipitate was heated by moving sludge from the bottom of the chamber with the circulation pump and adding it to the heat exchangers. After heating, the digestate was mixed with raw sludge and returned to the anaerobic chamber.

The outflow of digested sludge matches the input of mixed sludge. The biogas generated during sludge digestion is desulfurised in two desulfurers. The purified biogas then goes to the power generator.

The boiler room is equipped with two De Dietrich boilers with a capacity of 505 kW each, one of which can be fueled with natural gas (NG 50) in the absence of biogas. The generator set with heat recovery consists of two cogenerators (Man gas company) with a total thermal power of 638 kWp and 438 kW of electrical power.

The substrates for biogas production were mixture of thickened preliminary and excess sludge from the WWTP in Tyrowo (Poland). Fats from the food industry, thin stillage and whey were used as co-substrates. The characteristic of substrates are shown in Table 1.

During the first 3 months of operation (series 1), thickened primary and excess sludge and fats were used as substrate; during the second 3 months, (series 2) thickened primary and excess sludge, fats, thin stillage and whey were used (Fig. 2). In each series, the proportions of co-substrates changed very little from month to month, whereas the total amount of substrate varied.

In series I, the hydraulic retention time was 65 days; in series II, it decreased to 36 days because more co-substrates were added. The duration of each series was 90 days. The OLR was different every 30 days because of changes in the total amount of substrate added.

RESULTS & DISCUSSION

In series I, the organic loading rate (OLR) ranged from 0.58 to 0.66 kg VS/$m^3\cdot$d; in series II, the range of OLR was 1.56 - 1.88 kg VS /$m^3\cdot$d. The increase of OLR was caused by addition of thin stillage, whey and fats.

Fig. 3 shows the daily production of biogas and total biogas production during the experiment.
The biogas production rate (r_B) was calculated with the following equation:

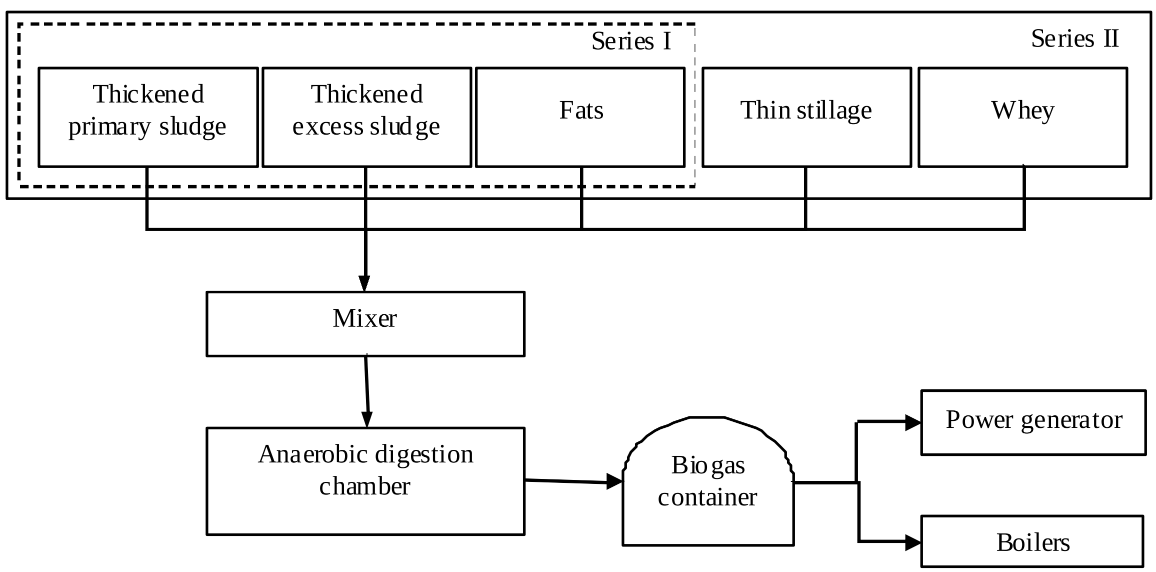

Fig. 1. Schematic of biogas production in the wastewater treatment plant in Tyrowo (Poland)

Table 1. Characteristics of the substrates

Characteristics	Unit	Fats	Whey	Thin stillage	Preliminary sludge	Excess sludge
Total solids	%	11.4	6.65	8.6	4.8	4.8
Volatile solids	%	81.4	91.7	95.5	80.6	77.2
pH	–	5.9	3.9	4.1	6.0	6.3
COD	mg/dm^3	13500	50000	59100	16300	
VFAs	mg/dm^3	4018	na	na	4120	
Sulfate	mg/dm^3	250	89	80	na	
Total nitrogen	mg/dm^3	1212	1268	645	2590	
Ammonium	mg/dm^3	na	98	na	252	
Total phosphorus	mg/dm^3	4.35	688	865	1135	

na – not analyzed

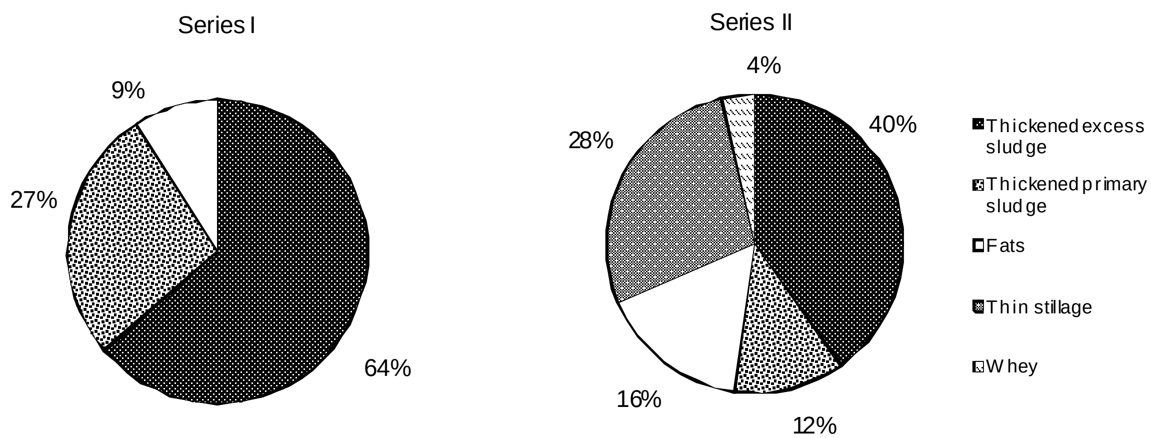

Fig. 2. The percentage of substrates added to the reactor in the first 3 months (series 1) and the second 3 months (series 2)

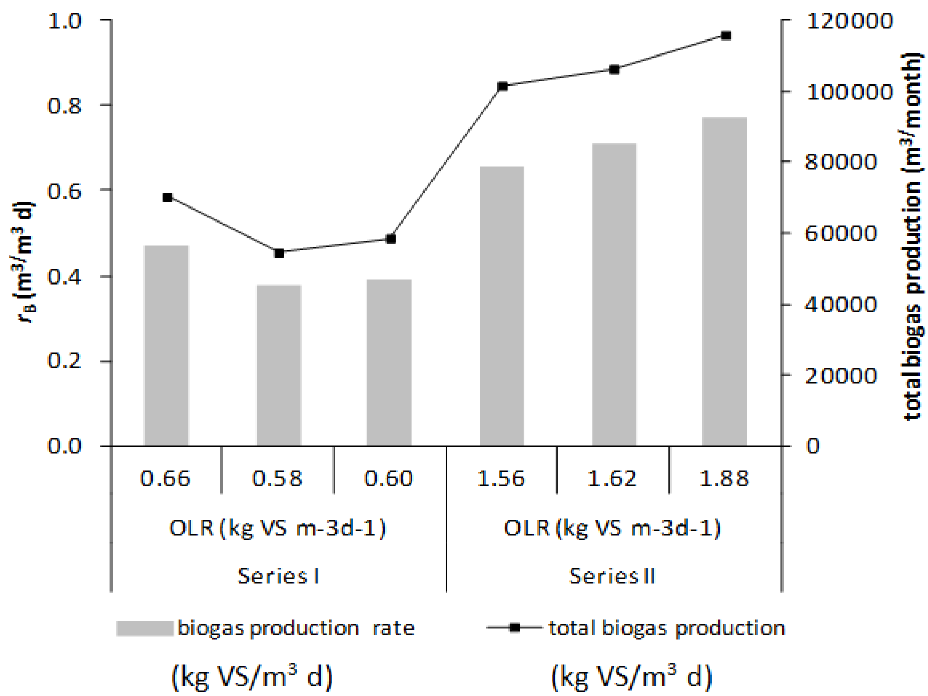

Fig. 3. The biogas production rate and total biogas production per month

$$r_B = \frac{v_B}{V} \quad (1)$$

where v_B is the volume of biogas produced per day (m^3/d), and V the volume of the chamber (m^3).

Addition of thin stillage and whey increased biogas production. In series I, the highest biogas production rate (0.41 $m^3/m^3 \cdot d$) was obtained at OLR 0.66 kg VS/$m^3 \cdot$d. The methane content in biogas averaged 65.2%. In series II, the addition of thin stillage, whey and fats increased biogas production about 58% (0.71 $m^3/m^3 \cdot d$). The methane content remained almost the same – 66.2%.Total biogas production was the highest (115977 m^3/month) at the highest OLR of 1.88 kg VS/$m^3 \cdot$d. Neczaj *et al.* (2012) reported that the addition of 10% of feed VS from grease trap waste increased the biogas production by 16%, compared to the period when reactor was feed only with sewage sludge at OLR between 2.44 and 2.87 kg VS/$m^3 \cdot$d.

The biogas yield coefficient (Y_B) was calculated with the following equation:

$$Y_B = \frac{v_B}{VS_{added}} \quad (2)$$

where v_B is the volume of biogas produced per day (m^3/d), and *VS* the volatile solids added to the chamber (kg VS/d).

Addition of thin stillage and whey caused the decrease of biogas yield coefficient. The highest biogas yield coefficient (0.71 m^3/kg VS) was in series I at OLR 0.66 kg VS/m^3·d. In series II, the biogas yield coefficient decreased to and average of 0.42 m^3/kg VS (Fig. 4). Comino *et al.* (2012) showed that co-digestion of a 50% cattle slurry and cheese whey mixture produced 0.62 m^3/kg VS. Approximately 55% of the biogas was methane, while maximum removal efficiencies for COD and BOD were 82% and 90%, respectively.

In the present study, the volatile solids reduction was from 43.7% (OLR 0.58 kg VS/m^3·d) to 75.8% (OLR 1.62 kg VS/m^3·d), which was caused by addition of thin stillage and whey (Table 2). Davidsson *et al.* (2008) reported that the addition of 10% of grease trap sludge to sewage sludge digesters was seen to increase volatile solids from 45% to 54% at OLR 2.5 kg VS/m^3·d. Similar results were obtained by Neczaj *et al.* (2012), where at a 90:10 ratio of sewage sludge to grease trap sludge, volatile solids reduction was 55.14% (OLR 2.44-2.87 kg VS/m^3·d).

The biogas obtained in the Tyrowo wastewater treatment plant is converted into heat and energy in quantities sufficient to cover all the plant's needs, even in winter conditions (if the temperature does not drop below minus 15°C). Table 3 shows the amount of electricity generated.

The amount of electricity generated was higher in series II than in series I. In series II, the average electricity generated was 218.5 MWh. This met all the demands of the WWTP. 79.5% of the energy generated was used for the WWTP, and the rest was sold. In series I, 2.5 times less energy was obtained than in series II, which covered only 50% of the needs of the WWTP.

Changes in the substrate concentration in the feedstock influenced biogas production. The proper pH allows for stable anaerobic conversion of organic matter into biogas, and this value should range from 6.8 to 7.4 (Ledakowicz *et al.*, 2010). Without these results, acidogenesis can dominate methanogenesis, increasing the ratio of volatile fatty acids to alkalinity, which leads to a decrease in pH. In this study, pH was in the optimal range, except at an OLR of 1.88 kg VS/m^3·d, but this did not negatively affect the process and biogas production did not decrease (Table 3).

In a properly functioning anaerobic reactor the concentration of volatile fatty acids should range from 100 to 500 mg/dm^3, with alkalinity no less than 500 mg $CaCO_3$/dm^3. Increasing the concentration of

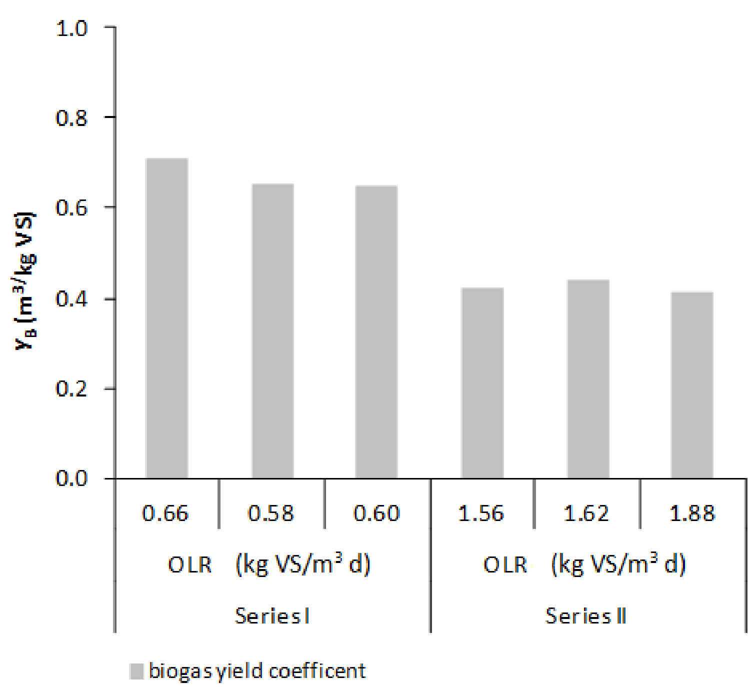

Fig. 4. The biogas yield coefficient in series 1 and 2

Table 2. Characteristics of the digestate

Characteristics	Unit	Series I			Series II		
		OLR (kg VS/m^{3}·d)			OLR (kg VS/m^{3}·d)		
		0.66	**0.58**	**0.60**	**1.56**	**1.62**	**1.88**
Total solids	%	2.3	3.4	2.3	2.4	2.1	3.1
TS removed	%	54.6	32.8	54.6	66.9	71.0	59.8
Volatile solids	%	67.2	66.2	64.5	64.7	67.2	63.1
VS removed	%	61.4	43.7	63.0	73.3	75.8	69.0
pH	–	7.4	7.4	7.4	7.5	7.3	7.7
COD	mg/dm^3	1395	1495	1624	3640	2510	5120
COD removed	%	91.3	85.0	89.9	87.2	89.2	81.8
VFAs	mg/dm^3	271	220	210	368	299	616
Alkalinity	mg/dm^3	5350	6485	5875	7250	5550	8330
VFAs/Alkalinity	–	0.05	0.03	0.04	0.05	0.05	0.07
Organic nitrogen	mg/dm^3	1986	2005	1965	2331	2510	2820
Ammonium	mg/dm^3	1670	1877	1745	2012	2190	2128
Total phosphorus	mg/dm^3	825	948	844	988	765	1075

Table 3. The amount of electricity generated during the 1 month phases of the experiment

Series	OLR (kg VS/m^{3}·d)	Energy production (MWh)	Energy used (MWh)
I	0.66	64.7	184.4
	0.58	106.8	169.9
	0.60	93.9	174.7
II	1.56	202.2	168.1
	1.62	222.0	176.6
	1.88	231.3	176.8

volatile fatty acids lowers pH and is toxic to methanogens (Magrel, 2002). In the months studied, VFA concentration averaged 234 mg/dm^3 at an OLR of 0.66 kg VS/m^{3}·d, although addition of co-substrates increased this measure. At an OLR of 1.88 kg VS/m^{3}·d, VFA concentration was highest, at 616 mg/dm^3, which is slightly above optimal. However, process stability was not lost, and the VFA to alkalinity ratio was 0.07, which did not exceed the limit of 0.4 (Borja *et al.*, 2004). At the highest OLR, the concentration of dissolved organic substances measured as COD was 2.5 times the average concentration.

Another measure that informs about the stability of methane fermentation is the concentration of ammonium (N-NH_4). A concentration of ammonium above 4.0 g/dm^3 inhibits the process (Angelidaki and Ahring, 1994). However, a concentration of ammonium less than 0.50 g/dm^3 also reduces the activity of the methanogens (Procházka *et al.*, 2012). In series I, the ammonium concentration was average 1764 mg/dm^3 and in series II increased to average 2110 mg/dm^3, which was in the optimal range, and the concentration of organic nitrogen averaged 1985 mg/dm^3 and 2554 mg/dm^3 in series I and II, respectively. The highest values were obtained at the highest OLR, where the concentrations of organic nitrogen and ammonium were 2820 mg/dm^3 and 2128 mg/dm^3, respectively.

CONCLUSIONS

This study demonstrated, on a technical scale, the influence of thin stillage and whey on anaerobic digestion of sewage sludge in a mixture of fats. The addition of co-substrates increased the organic loading rate (OLR), biogas production and the amount of energy produced, but it caused the decrease of the biogas yield coefficient. At the highest OLR (1.88 kg VS/m^3·d), both the monthly total production of biogas (115 977 m^3) and electricity production (231.3 MWh) were highest. This shows that adding the proper amounts of these co-substrates intensifies biogas production from sewage sludge with fats.

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