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CO-FERMENTATION OF SEWAGE SLUDGE AND WASTE FROM OIL PRODUCTION

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Abstract: The paper presents the results of anaerobic digestion and co-digestion under mesophilic conditions in the OxiTop system and in lab-scale fermentors. The goal of the study was to determine the effect of reaction-based oil waste on biogas production in co-fermentation with sewage sludge (mixture of thickened primary and excess sludge). The average water content in sewage sludge was 97 %, with 70 % of total volatile solids concentration (TVS) in total solids. Weight content of oil waste in the mixture of sewage sludge ranged from 15 to 45 % (w/w) and the increase in TVS to 83.7 % was observed. The primary investigations of gas productivity by manometric method (OxiTop) showed that biogas production increased with increasing content of oil waste in the mixture with sewage sludge. The rate constant of the first-order kinetics for biogas production was determined. To determine the yield parameters of co-fermentation, the experiment was performed in four continuously stirred anaerobic reactors with a working volume of 10 dm^3. Organic loading rate (OLR) changed from 0.9 to 3.1 kg $TVS/m^3 \cdot d$. High correlation between biogas flow rate and OLR was observed. Volumetric biogas production rate and the average methane content in the biogas increased from 0.79 to 1.98 $m^3/m^3 \cdot d$ and from 52.3 to 62.3 %, respectively, as OLR increased. The results obtained in lab-scale fermentors are promising and open the possibilities of the implementation of co-fermentation of sewage sludge and oil waste.

Keywords: co-fermentation, gas production, methane, oil waste, sewage sludge

INTRODUCTION

Anaerobic digestion is often considered as the most promising way to reclaim energy from materials with a high organic matter concentration. Depending on the total solids concentration (TS) of the feed for the anaerobic digestion process it can be classified as a wet process with TS below 10 %, a dry process with TS above 25 % and a semi-dry anaerobic digestion with TS around 16-22 % (Bolzonella *et al.* 2006). Dry fermentation is advantageous because an organic loading rate of 10 kg $VS/m^3 \cdot d$ and higher can be applied, however complete mixing of the medium is problematic and full contact of biomass and substrate is not guaranteed. In the case of wet fermentation full contact of organic substrate with microbial biomass and homogenous conditions are possible. In continuously stirred tank reactors an influent substrate concentration of 3-8 % of total solids is added daily and an equal amount of effluent is withdrawn (Gunaseelan, 1997).

A considerable amount of information has been gathered about the performance of sewage sludge digesters. In fact, more than 36,000 anaerobic digesters are today operating in Europe, treating around 40-59 % of the sludge generated (Mata-Alvarez *et al.* 2000). Both primary and secondary sludge are fed into anaerobic digesters, mainly to obtain a reduction of the organics in sewage sludge and for biogas production. It was estimated that in municipal sewage treatment plants conventional sewage sludge digesters are regularly oversized thus easily providing a free digestion capacity of 30 % or even more (Braun, 2002). Provided that there is an availability of free capacity, the treatment of waste as co-substrate in existing digesters would allow transportation costs due to the wide distribution of sewage treatment plants to be minimized. In most cases the biogas energy can be properly used and the digestate can be recycled or treated safely. The biogas can be treated as the renewably energy source and used in integrated sewage and waste co-digestion plants.

Co-digestion is the simultaneous digestion of a mixture of two or more substrates. Mostly the major amount of a main basic substrate (e.g. manure or sewage sludge) is mixed and digested together with a single, or a variety of additional substrates. The use of co-substrate in most cases improves the biogas yield due to positive synergisms established in the digestion medium, co-fermentation can also help to maintain the required moisture content and C/N ratio. For example, the organic fraction of municipal solid waste (OFMSW), food waste such as fruit and vegetable waste can be co-digested. OFMSW can be used to feed the digesters but the composition of municipal solid waste is affected by various factors, including climate, regional differences as well as changes in technology. Mata-Alvarez, Cecchi (1990) reported on the co-digestion of the organic fraction of municipal solid waste with sewage sludge in existing digesters. Both of these wastes are produced in large quantities and in many places. Using biological activity tests, an optimal mixture for biogas production, was identified as 25 % of OFMSW and 75 % of sewage sludge (Mata-Alvarez *et al.* 2000). In an industrial trial Edelmann *et al.* (1999) co-digested the fruit and vegetable waste (chopped; size 1-2 mm) to achieve a homogenous medium with the primary sludge. Fruit and vegetable waste (FVW) and leaves are characterized by moisture contents higher than 80 % and have a high biodegradability. Operating digesters with FVW is somewhat problematical because the harvest of fruit and crops varies with season. The potential for anaerobic digestion of grasses, woods or weeds have been studied but large-scale fermentation is limited by nitrogen and phosphorus content and seasonality. However, the results of Edelmann *et al.* (1999) showed an improvement in the co-digestion of sludge and FVW in comparison with sewage digestion. Bouallagui *et al.* (2004) studied anaerobic digestion of FVW under different operating conditions using different types of bioreactors. A major limitation of anaerobic digestion of FVW was a rapid acidification of the waste decreasing the pH and resulting in large volatile fatty acids production that stressed and inhibited the activity of methanogenic bacteria.

About 90 % of the full scale plants currently operating in Europe for the anaerobic digestion of sewage sludge, organic fraction of municipal solid wastes or biowastes, relay on continuous one-stage systems (Braun, 2002). One-stage systems are preferred because of their simpler design and lower investment costs, moreover these types of reactors commonly operate on a large scale (sewage sludge digesters at wastewater treatment plants WWTPs). The most common is one-stage mesophilic digestion in a continuously stirred reactor with an influent substrate concentration 3-8 % of total solids. The hydraulic retention time (HRT) in the digester tanks ranges from 2 to 4 weeks, mostly 20 days.

It is expected that oil waste arising from oil production might prove to be a useful substrate in co-fermentation with sewage sludge. Lipids, characterized either as fats or oils and greases, are among the main organic materials found in food wastes and some industrial wastewater, such as those coming from slaughterhouses, dairy industries or fat refineries. High oil production generates many by-products – such as biodiesel. As an alternative fuel, biodiesel can be used in pure form or mixed with petroleum-based diesel (Van Gerpen, 2005) but its production also generates glycerol as the main by-product. There will be an essential need to treat this kind of waste. Lipids consist mainly of triacylglycerides and long-chainfatty acids (LCFA) which, under anaerobic conditions, are finally converted to methane. Co-digestion is an interesting option for improving yields of anaerobic digestion of sewage sludge. Due to increased biogas yields, the co-digestion of bio-wastes (including oil waste) together with municipal sewage sludge in existing municipal sewage digesters can considerably reduce wastewater treatment costs. Biswas *et al.* (2006) observed that the methane concentration of biogas increased with increasing in fat concentration. The volumetric biogas production was expected to increase with the raising content of oil waste as a co-product with sewage sludge. The goal of the study was to determine the impact of the content of oil waste from solvent extraction on biogas production in co-fermentation with sewage sludge.

MATERIALS AND METHODS

As co-substrates mixtures of sewage sludges and oil waste from solvent extraction were used.

Characteristics of raw sewage sludge

The raw sewage sludge used in this work was collected from a wastewater treatment plant located in Olsztyn, a city of approximately 200,000 inhabitants in NE Poland. The wastewater treatment system involves chemical precipitation of phosphorus by PIX (ferric sulphate) that determined the amount of mineral fraction in sewage sludge. A mixture (50:50, v/v) of thickened primary and thickened excess sludge collected from the thickener and pre-fermentor, respectively, was used as co-feed. The average water content was 97 %, containing 70 % of volatile solids (VS) in the total solids. Table 1 presents the average values of micro- and macro-elements in the sewage sludge.

Characteristics of oil waste

Oil waste from solvent extraction was collected from the rape oil plant in Kwidzyn (Poland). It was characterized by strong earthy odour and greasy consistency. Oil waste is susceptible to putrescence with a lightly acid reaction. The calorific value of this waste is 19866 kJ/kg. The total solids of oil waste ranged from 40 to 50 %. Oil waste contains a high concentration of organics, total volatile solids contribute to 95 % of total solids, whereas fatty solids (extracted by petroleum benzene) make up 29.3 % of total solids.

Table 1 shows the main characteristics of the reaction-based vegetable oil waste, involving metals and hexane as a solvent used at oil production.

Table 1. Characteristics of sewage sludge and oil waste

Component	Unit	Oil waste	Sewage sludge
		Value	
Pb	mg/kg TS	<0.1	19.71
Cd	mg/kg TS	<0.05	2.10
Cr	mg/kg TS	<0.3	36.14
Cu	mg/kg TS	1.46	102.8
Ni	mg/kg TS	1.88	14.50
Hg	mg/kg TS	<0.01	0.194
Zn	mg/kg TS	48.0	488.1
Hexane	mg/kg TS	111.1	-
Carbon	%	40.7	-
Hydrogen	%	3.5	-
Oxygen, nitrogen	%	12.9	-
Sulphur	%	0.07	-
Ash	%	2.11	22.03
Total nitrogen	%	-	6.81
Total phosphorus	g/kg TS	-	28.11
Ca	g/kg TS	-	20.4
K	g/kg TS	-	5.10
Mg	g/kg TS	-	4.35

Organization of the experiment

The experiment was arranged in two parts. In the first part, fermentation manometric tests with the determination of biogas production potential were performed. In the second part, to determine the yield parameters of co-fermentation of sewage sludge and waste from oil production, continuously stirred anaerobic reactors were used.

Biogas production potential (GB_{21})

As regards the GB_{21} method, the gas production potential was determined manometrically using the pressure sensitive OxiTop system according to PN-EN ISO 11734:2003. The OxiTop Control system (WTW, Germany) consists of glass vessels with stubs, sensors with pressure meter and heating box. Samples of sewage sludge and mixtures of oil waste and sewage sludge were prepared. The control sample was the one with sewage sludge. The weight content of oil waste in the mixture of sewage sludge changed from 15 to 45 % (w/w). Table 2 shows the organisation of the experiment in OxiTop vessels. A 100 g of sample was placed in the reaction vessels. The duration of the experiment was 21 days at an ambient temperature of 35°C and self-moisture content (the experimental conditions follow those suggested by Heerklange, Stegman, 2005). Each variant of the experiment was carried out in triplicate.

Table 2. Organisation of the experiment in OxiTop system vessels (OT)

Parameter	OT_1	OT_2	OT_3	OT_4
Weight content of oil waste [% (w/w)]	0	15	30	45
Temperature [°C]	35			
Reaction time [d]	21			
Sample mass [g]	100			
Vessel volume [cm^3]	500			

Gas production in OxiTop system vessels proceeded with first-order kinetics. The results allowed the determination of the cumulative biogas production [C_0 – Ndm^3] and the rate constant for biogas production [k – d^{-1}]. Adjustment of the experimental results of the biogas production to the model was analysed using the STATISTICA 7.0 software statistics package (StatSoft, Tulsa OK, USA). The kinetic parameters of biogas production (k, C_0) were determined at the significance level of $p<0.05$. Correlation analyses ($p<0.05$) between volumetric biogas production and organic loading rate (GPR, OLR) were also performed.

Yield parameters in lab-scale fermentors

The experiment was performed in four continuously stirred anaerobic reactors each with a working volume of 10 dm^3. Each fermentor was equipped with a water jacket, an electronic system of temperature correction, pH and redox probes. Upper valves allowed feeding and bottom valves allowed sampling. Piping was made of stainless steel and the biogas produced in each reactor was collected into Tedlar gas bags. It was assayed using a gas analyzer GA2000+ (Geotechnic Instruments).

At the beginning of the experiment each reactor was inoculated with digested sludge from the digestive chamber of the municipal wastewater treatment plant in Olsztyn. After 30 days of adaptation, reactors were fed with the substrates: R1 – 100 % (w/w) of sewage sludge, R2 15 % (w/w) of oil waste and 85 % (w/w) of sewage sludge, R3 – 30 % (w/w) of oil waste and 70 % (w/w) of sewage sludge, R4 – 45 % (w/w) of oil waste and 55 % (w/w) of sewage sludge. Substrates were prepared once for 2 weeks.

Table 3. Operating parameters of co-fermentation process in lab-scale fermentors

Parameter	R_1	R_2	R_3	R_4
Weight content of oil waste [% (w/w)]	0	15	30	45
Temperature [°C]	35			
Reactor volume [dm^3]	12			
Reactor working volume [dm^3]	10			
Flow rate Q [dm^3/d]	0.5			
Hydraulic retention time HRT [d]	20			
Feeding intervals [h]	24			

Portions of the sewage sludge and oil waste were mixed in the appropriate proportions and frozen. To achieve intended HRT the flow rate was adjusted to 0.5 dm^3/d. The fermentors were fed once a day. In our experiment the intended HRT on the level of 20 d responded to HRT in anaerobic digester at WWTP in Olsztyn. Table 3 presents the operating parameters during the experiment.
Calculation and analytical methods

To determine the operating parameters of co-fermentation in lab-scale fermentors the following equations (Mata-Alvarez, Macè, 2004) were used:

- Hydraulic retention time (HRT) [d]:

$$HRT = \frac{V}{Q} \tag{1}$$

where: V = the reactor volume [m^3]; Q = the flow rate [m^3/d].

- Organic loading rate (OLR) [$kg_{substrate}/m^3_{reactor} \cdot d$]:

$$OLR = \frac{Q \cdot S}{V} \tag{2}$$

where: S = substrate concentration [$kg_{substrate}/m^3_{reactor}$] expressed in terms of total volatile solids (TVS) [kg TVS/m^3].

- Gas production rate (GPR) (volumetric biogas production) [$m^3_{biogas}/m^3_{reactor} \cdot d$]:

$$GPR = \frac{Q_{biogas}}{V} \tag{3}$$

where: Q_{biogas} = biogas flow rate [m^3/d].

In the samples of sewage sludge and in the mixtures of oil waste and sewage, sludge total solids were determined as the residue (dry matter) after water evaporation (24 h drying at 105°C to constant weight). Total volatile solids were measured by ignition at 500°C. TS and TVS were determined according to PN-EN 12879:2002 (U).

RESULTS AND DISCUSSION

Table 4 presents the experimental arrangement, in the case of the substrate used in biogas production potential (GB_{21}) method and in the fermentors. Four variants of the substrates were prepared. In the first variant only sewage sludge was used as the feed to the fermentor. In the next three variants the total volatile solids was gradually increased from 77.1 to 83.7 % as a result of increasing the content of oil waste in the mixtures with sewage sludge.

Table 4. Characteristic of co-substrate loaded into measuring vessels (OT) and lab-scale fermentors (R)

Parameter	OT_1/R_1	OT_2/R_2	OT_3/R_3	OT_4/R_4
Oil waste content in the mixture [weight % (w/w)]	0	15	30	45
Moisture content [%]	97.4	96.0	94.3	92.6
TS [%]	2.6	4.0	5.7	7.4
TVS [%]	69.3	77.1	81.2	83.7

Biogas production potential (GB_{21})

In Germany and Austria the method of biogas production for 21 days (GB_{21}) is applied as a standardized test for the assessment of the biogas production rate of various kinds of substrates (Heerklange, Stegman, 2005). The assay allows investigation of the kinetics of anaerobic digestion of sewage sludge and sewage sludge in co-digestion with oil waste. In the present investigations it was presumed that biogas was generated with first-order kinetics:

$$C = C_O \cdot (1 - exp(-k \cdot t)) \qquad (4)$$

where: C = biogas production [Ndm^3]; C_0 = max. biogas production (cumulative biogas production) [Ndm^3]; k = rate constant for biogas production; t = time [d].

Respirometric measurements showed one phase biogas production in case of the fermentation of sewage sludge as a homogenous substrate (Fig. 1a). The rate of biogas production increased with increasing content of oil waste in the mixture with sewage sludge. The experimental data revealed that co-fermentation proceeded in two phases, both described by its own specific first-order equation (Fig. 1b, c, d). The rate constant (k_1) and max. biogas production (C_{01}) of sewage sludge digestion and the phase I of co-digestion were approximately the same ranging from 0.347 to 0.399 d^{-1} and 0.131 to 0.139 Ndm^3, respectively.

In the phase II that took place in the samples with heterogeneous substrate, k_2 and C_{02} increased parallel with increasing oil waste content in the mixture. The highest rate constant of the biogas production (0.349 d^{-1}) and maximal biogas production (0.245 Ndm^3) were observed for the mixture of sewage sludge with 45 % (w/w) of oil waste (Table 3).

Table 5. Kinetic parameters of biogas production (GB_{21} method)

Parameters		OT_1	OT_2	OT_3	OT_4
Determination coefficient (R^2)		0.9957	0.9947	0.9979	0.9979
I phase	Max. biogas production (C_{01}) [Ndm^3]	0.133	0.134	0.139	0.131
	Constant rate (k_1) [d^{-1}]	*0.347*	*0.399*	*0.349*	*0.397*
	Duration time (t_1) [d]	21	9.7	8.4	5.1
II phase	Max. biogas production (C_{02}) [Ndm^3]	-	0.247	0.197	0.245
	Constant rate (k_2) [d^{-1}]	-	*0.144*	*0.282*	*0.349*
	Duration time (t_2) [d]	-	11.3	12.6	15.9

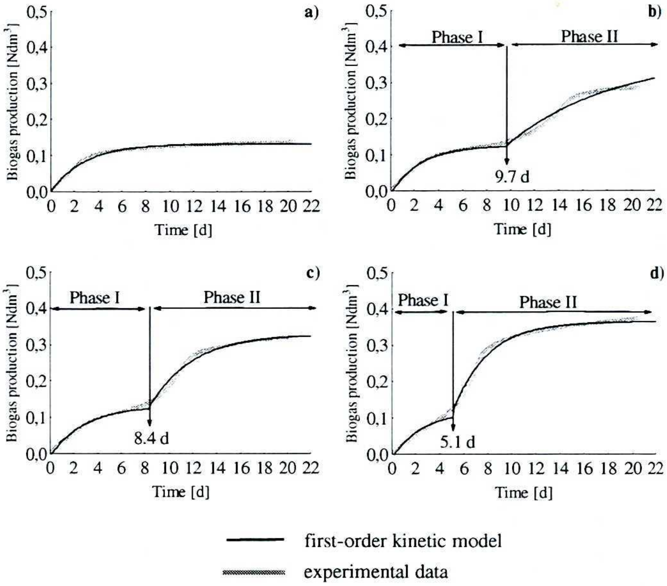


Fig. 1. Biogas production curves during 21 days of fermentation of sewage sludge (a), and co-fermentation of sewage sludge with 15 % (w/w) of oil waste content (b), sewage sludge with 30 % (w/w) of oil waste content (c), sewage sludge with 45 % (w/w) of oil waste content (d); two first-order kinetic lines for the co-fermentation (phase I and phase II) are shown (b, c, d), vertical pointer mark the break point on the border of the phase I and II and the duration time of the phase I reducing from 9.7 d to 5.1 d with increasing oil waste content in the mixture with sewage sludge

Figure 1 depicts cumulative biogas production curves over the 21 days of the experiment. The curve of sewage sludge fermentation increases and follows the first kinetic-model line. The course of co-fermentation confirmed the dependency of gas-formation on the contribution of oil waste in the mixture with sewage sludge. The trend line of co-fermentation consisted of two first-order kinetic models with the break point on the border of the phase I and phase II. The duration of the phase I was reduced from 9.7 d to 5.1 d with increasing oil waste content in the mixture with sewage sludge.

Similar values of the rate constant of the biogas production (k_1) during the anaerobic digestion of sewage sludge and phase I of co-fermentation suggest that biogas was generated only from the volatile fatty acids (VFA) coming from sewage sludge. For the mixtures of oil waste and sewage sludge, phase II started after production of volatile fatty acids from long chain fatty acids.

Figure 1. Biogas production curves during 21 days of fermentation of sewage sludge (a), and co-fermentation of sewage sludge with 15 % (w/w) of oil waste content (b), sewage sludge with 30 % (w/w) of oil waste content (c), sewage sludge with 45 % (w/w) of oil waste content (d); two first-order kinetic lines for the co-fermentation (phase I and phase II) are shown (b, c, d), vertical pointer mark the break point on the border of the phase I and II and the duration time of the phase I reducing from 9.7 d to 5.1 d with increasing oil waste content in the mixture with sewage sludge

Sewage sludge was found to be the best biodegradable component (Mata-Alvarez *et al.* 2000). Probably, the co-substrate (oil waste) used in our experiment did not contain easily accessible VFA to improve biogas production immediately. Fat and fatty components, including long chain fatty acids (LCFA), had to be transformed to volatile fatty acids that were involved in methanogenic reaction.

The lipids energetic potential and their biodegradability indicate that anaerobic digestion is one of the best treatment methods for these wastes. During anaerobic transformation, the lipids are hydrolysed to LCFA and glycerol. LCFA are slowly degraded to VFA (Li *et al.* 2002, Lalman *et al.* 2001). Finally, methane is generated from VFA. Biswas *et al.* (2006) proposed the following reaction schemes:

$$\text{Fat} + CO_2 \xrightarrow{\substack{\text{Biomass}\\ \text{(acidogenic)}}} \text{LCFA} + \text{Biomass} \quad \text{(i)}$$

$$\text{LCFA} + CO_2 \xrightarrow{\substack{\text{Biomass}\\ \text{(methanogenic)}}} CH_4 + \text{VFA} + \text{Biomass} \quad \text{(ii)}$$

$$\text{VFA} \xrightarrow{\substack{\text{Biomass}\\ \text{(methanogenic)}}} CH_4 + CO_2 + \text{Biomass} \quad \text{(iii)}$$

Biswas *et al.* (2006) studied biogas generation kinetics using different substrates. Methane was generated from both VFA and LCFA originated from carbohydrate, protein and fat. The kinetic parameters revealed that VFA methanogenesis was several times faster in comparison with LCFA methanogenesis.

The cumulative biogas production was the lowest for sewage sludge fermentation – 0.137 Ndm^3. The cumulative biogas production after the 21 days of the experiment rose with increasing weight content of oil waste in the mixture with sewage sludge (0.284 Ndm^3 – 15 % (w/w), 0.316 Ndm^3 – 30 % (w/w), 0.374 Ndm^3 – 45 % (w/w) of oil waste content).

In our study, after phase I, in the measuring vessels with co-substrate, biogas production gradually increased. With increasing content of oil waste in the mixture with sewage sludge the duration time of the phase I decreased from 9.7 d to 5.1 d. Probably, in the samples with a higher contribution of oil substrate, VFA production was higher and biogas production increased because of the higher accessibility of the substrate for VFA production. Angelidaki *et al.* (2002) suggest that the presence of dissolved LCFA may inhibit the anaerobic microbial activity, although according to Cavaleiro *et al.* (2001) an adaptation period allows a high LCFA concentration. Different values of inhibition concentration for different LCFA are reported. For oleic acid the inhibition concentration are in the range of 30-300 mg/dm^3, for stearic acid 100-300 mg/dm^3 and 30 mg/dm^3 for linoleic acid. Nevertheless, microorganisms show a high adaptation capability to high loads of LCFA (Lalman *et al.* 2000, Alosta *et al.* 2004).

Yield parameters in lab-scale fermentors

A high production of volatile fatty acids is a limitation to anaerobic digestion in one-step systems because it may stress and inhibit the activity of methanogenic bacteria. Moreover, it may cause a rapid acidification resulting in pH decrease in the reactor (Bouallagui *et al.*, 2004). In our experiments daily measurements did not reveal any rapid changes of pH or redox potential. The pH ranged from 7.12 to 7.86. The lowest value of redox potential was observed in case of sewage sludge fermentation (Table 6). Under these conditions no disturbances were observed. Bouallagui *et al.* (2004) tried to assess the performance of a two-phase anaerobic digestion of a mixture of fruit and vegetable wastes in the anaerobic sequencing batch reactor. The temperature in the reactor was maintained at 35°C. During the primary experiment, when not controlled, the pH dropped rapidly to 4 and the inhibition of hydrolysis was observed. After that, pH was maintained at 6. Several authors suggested that the optimal pH for efficient hydrolysis and acidogenic bacteria activity lies between 5 and 6 (Raynal *et al.* 1998, Rajeshwari *et al.* 2001). Lastella *et al.* (2002) suggested that in a well-balanced system with methanogenic bacteria, pH has to range between 7 and 8.

Table 6. Operating conditions of lab-scale fermentors

Parameter	R_1	R_2	R_3	R_4
Temperature [°C]	36.35 ± 0.4	35.06 ± 0.29	35.37 ± 0.83	35.18 ± 0.35
pH	7.12 ± 0.02	7.83 ± 0.03	7.86 ± 0.06	7.72 ± 0.07
Redox [mV]	- 496.93 ± 2.19	- 480.96 ± 3.39	- 466.29 ± 16.76	- 475.68 ± 11.64

The organic loading rates (OLR) in the reactors were calculated on the basis of the daily additions of the substrate. In the fermentor (R_1), the feed with sewage sludge OLR was 0.9 kg TVS/m^3·d. In the parallel reactors (R_2, R_3, R_4) feeding with the mixture of sewage sludge and oil waste, OLR increased and finally reached 3.1 kg TVS/m^3·d. The gas production rate (GPR, *Materials and methods, formula 3*) was expressed as the so-called space time yield: volume of the gas per volume of the reactor within time, called volumetric gas production as well. GPR in R_1 fed with sewage sludge was the lowest 0.79 Nm^3/m^3·d in comparison with the reactors with co-substrate (0.9, 1.6 and 1.98 Nm^3/m^3·d, respectively). It was observed that when the contribution of oil waste in the mixture with sewage sludge was higher the volumetric gas production increased (Table 7).

Table 7. Operating and yield parameters of the fermentation process

Parameter	R_1	R_2	R_3	R_4
VS [kg TVS/m^3]	18.02	30.84	46.28	61.94
Organic loading rate OLR [kg TVS/m^3·d]	0.90	1.54	2.31	3.09
Biogas flow rate Q_{biogas} [Nm^3/d]	0.008	0.009	0.016	0.020
Gas production rate GPR [Nm^3/m^3·d]	0.79	0.90	1.63	1.98

Lindorfer *et al.* (2007) presented the study on co-digestion of energy crops and manure in a two stage, agricultural biogas plant. In contrast to our results, the authors achieved a slightly higher volume related biogas productivity ranging from 1.5 to 2.91 Nm^3/m^3·d at a higher organic loading rate increasing from 2.11 to 4.25 kg VS/m^3·d. Similar values of volumetric biogas production may indicate that oil wastes are wastes with a high potential of biogas production. It might be supposed that higher values of biogas production with increasing OLR resulted from shorter HRT.

Fernández *et al.* (2005) checked the potential of mesophilic anaerobic digestion for the treatment of animal fat with the organic fraction of municipal solid wastes. To avoid problems with reactor instability and to permit a stable co-digestion process, OLR was fixed at a value of 0.97 kg TVS/m^3·d. The fat content in the influent of the reactor was progressively increased by 4, 7, 14, 21 and 28 % causing an increase in OLR from 0.97 to 1.24 kg TVS/m^3·d. It resulted in the increase in biogas production from 0.43 to 0.68 Nm^3/m^3·d. In our experiment, anaerobic digestion performed at OLR from 0.9 to 3.1 kg TVS/m^3·d and the growing tendency of volumetric biogas production was confirmed. It indicates the necessity of further study under higher OLR.

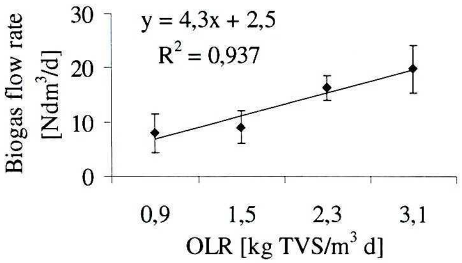
In the present experiment daily measurements of the biogas flow rate using Tedlar gas bags allowed us to determine the volume of the biogas produced during the day. The average values of the biogas flow rate are shown in Figure 2. The results indicate a high correlation between biogas flow rate and organic loading rate. As we expected after our experience with GB_{21} measurements, increasing the oil waste content resulted in an increase in biogas flow rate.

Figure 2. Correlation between biogas flow rate [Ndm^3/d] and organic loading rate [kg TVS/m^3·d] in lab-scale fermentors

Figure 3 shows the percentage concentrations of methane and carbon dioxide in the biogas from lab-scale fermentors. The average methane content of the biogas generated in sewage sludge fermentation was 52.3 %. A slight increase to 54.4 % was visible during the co-fermentation of a mixture of 15 % (w/w) oil waste and sewage sludge. However, the biogas composition after co-fermentation of the mixture of sewage sludge with a higher content of oil waste (R_3 and R_4) revealed a further increase in methane content to 62.3 %.

Figure 3. Biogas composition in the lab-scale fermentors

In the study by Fernández *et al.* (2005) the methane concentration in biogas was in the range from 56 to 65 %, however there was no correlation between OLR and methane content.



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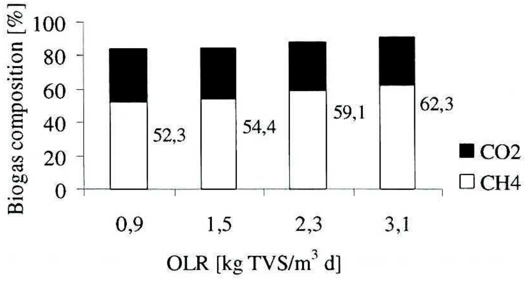

Fig. 3. Biogas composition in the lab-scale fermentors

CONCLUSIONS

Kinetic results show that, during the anaerobic digestion of sewage sludge and phase I of co-fermentation, the rate constant and biogas production were approximately the same ranging from 0.347 to 0.399 d^{-1}. It was suggested that biogas was generated only from the volatile fatty acids (VFA) present in sewage sludge. In parallel, the production of VFA from oil waste took place. The pH ranged from 7 to 8 and it did not cause any disturbance of biogas production resulting from acidification. The higher the dosage of oil substrate the higher was the cumulative biogas production.

The lab-scale experiment in fermentors revealed that oil waste can be successfully used as a co-substrate in operating sewage sludge digesters. The increasing organic loading rate from 0.9 to 3.1 kg TVS/m^3·d caused an increase in volumetric biogas production.

To conclude, at hydraulic retention time (HRT) 20 d there is a possibility of increasing the organic loading rate (OLR) to 3.1 kg TVS/m^3·d by addition of oil waste without limitation of methane concentration in the biogas.

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