April 2012, Volume 3, No.2
International Journal of Chemical and Environmental Engineering

Potential Use of Sludge from Potato Processing Industry WWTP as a Co-substrate in Anaerobic Digestion of Organic Fraction of Municipal Solid Waste

Satoto E. Nayono[a,*], **Josef Winter**[b], **Claudia Gallert**[b]
[a] *Department of Civil Engineering, Yogyakarta State University (UNY), Karangmalang Yogyakarta 55281, Indonesia*
[b] *Institute of Biology for Engineers and Biotechnology of Wastewater, Karlsruhe Institute of Technology, am Fasanengarten, 76131 Karlsruhe, Germany*
[*] *Corresponding Author E-Mail: satoto.nayono@uny.ac.id*

Abstract
This paper presents the results of a preliminary study on the characteristics, methane production potential and solids elimination potential of sludge resulting from aerobic treatment of potato industry wastewater (later be called potato sludge). The results of this study are considered important to examine the suitability of potato sludge as a co-substrate in anaerobic digestion of Organic Fraction of Municipal Solid Waste (OFMSW). From this study, it was revealed that potato sludge has relatively high organic matter content. The volatile solids content of the sludge reached about 22 % of the total weight. It had a maximum methane production of around 0.40 m^3 $CH_4 \cdot kg^{-1}$ VS. More than 80 % of its maximum methane production in batch assays was achieved within the first 4 days of incubation indicating that it was easily degradable. The concentrations of heavy metals in the potato sludge were lower than the inhibitory or toxic concentration limit. More than 70 % of its volatile solids were eliminated during solid elimination tests. Therefore, potato sludge is considered as suitable for anaerobic digestion either as a sole substrate or co-substrate.

Keywords: anaerobic digestion, co-digestion, co-substrate, methane production, volatile solids elimination

1. Introduction

Potato processing industries use a large volume of water during the production processes. The activities in this kind of industry such as washing, peeling, blanching, slicing and shredding during production of potato chips or other potato products cause a huge amount of wastewater. Malladi and Ingham [1] stated that the wastewater generated from potato industries is normally characterized by high organic matter load (carbohydrates, starches, proteins, vitamins, pectines and sugars) and total suspended solids (TSS) resulting in high biochemical oxygen demand (BOD) and chemical oxygen demand (COD). Therefore, this highly polluted wastewater requires a treatment before it is discharged into water bodies.

Due to its high concentration of readily biodegradable compounds, the potato industry wastewater is mostly treated with various combinations of aerobic and anaerobic biological processes [2]. A combination of surface and intermittent vertical flow wetlands, lagoons, ponds and land applications have been also used as treatment methods. Although these biological treatment processes can be applied as the efficient methods to treat the potato industry wastewater, the drawbacks are the long residence periods required, which imply a huge reactor capacity to cope with the volume of the wastewater. Moreover, the microorganisms are extremely sensitive to such factors as pH, temperature and sludge washout [3]. However, since aerobic processes are considered as more effective to treat liquid waste, aerobic techniques such as activated sludge systems are still widely used to treat this type of wastewater.

One disadvantage of the application of aerobic method is the production of excess sludge in relatively huge volume. Sludge management is considered as one of the most difficult and expensive processes in industrial or domestic wastewater treatment engineering. It is estimated that the cost of sludge management comprises approximately 35% of the capital cost and 55% of annual operation and maintenance costs of a wastewater treatment plant [4]. On the other hand, sludge quantities continue to increase, but the options for sludge disposal are limited due to the more strict regulations applied to protect the environment.

Compared to composting, anaerobic digestion of organic solid waste has several advantages, such as better handling of wet waste, the possibility of energy recovery in the form of methane, less area requirement and less emission of bad odor and green house gasses [5, 6]. Furthermore, if the digestate of an anaerobic digester has to be disposed in a landfill, anaerobic digestion of

OFMSW has advantages such as: minimization of masses and volume, inactivation of biological and biochemical processes in order to avoid landfill-gas and odor emissions, reduction of landfill settlements, and immobilization of pollutants in order to reduce leachate contamination [7].

Co-digestion of OFMSW with other types of waste is an interesting alternative to improve biogas production, to obtain a more stable process and to achieve a better handling of waste. However, some possible disadvantages (*e.g.* transport costs of co-substrate, additional pre-treatment facilities and the problems arising from the harmonization of the waste generators) have to be taken into account [8]. The key factor of successful co-digestion is that the balance of macro and micro nutrients can be assured by co-substrate.

A good co-substrate should fulfil several requirements, such as: i) its concentration of organic substances should be comparable with the organic solid waste substrate, so that addition will not significantly affect the hydraulic retention time, ii) it should consist of easily degradable organics with a high biogas production potential, iii) it may not contain any dangerous or poisonous substances, which possibly hinder anaerobic digestion or composting, iv) it should have a content of macro and micro nutrients which have possibility to improve the characteristics of main substrate, v) it must be available in sufficient quantities at a reasonable price, and vi) it should be storable.

Various types of organic solid waste streams such as sewage sludge from centralized wastewater treatment plant, refuse from market activities, animal manure and organic industrial waste have been proposed as co-substrate for anaerobic digestion of OFMSW. Reports on co-digestion of the organic fraction of municipal solid waste with any other waste streams, such as energy crops [9], market residues [10], sewage sludge [11], manure [12], foodwaste [13], press-off leachate from composting facility [14] are existing. Sewage sludge is available in abundant quantity in line with the presence of wastewater treatment plants. Co-digestion with sewage sludge will improve the characteristics of OFMSW including its content of micro and macro nutrients, lead to a better C/N ratio and facilitate the adjustment of moisture content. The optimal mixture of OFMSW and sewage sludge depends on the specific waste characteristics and the system used in the digestion process. For wet anaerobic digestion, the best performance (in term of biogas production and volatile solids-VS reduction) can be achieved when the mixture of OFMSW and sewage sludge is within the range of 80:20 on TS basis or 25:75 on volume basis [11].

Full-scale applications of solid waste co-digestion have been reported by several authors. In Ref. [15] it is reported that in 2001, Denmark had already 22 large-scale centralized biogas plants operated under co-digestion mode and treating mainly manure together with other organic waste such as industrial organic wastes, source sorted household waste, and sewage sludge. Positive results including the increase of energy production and degradation efficiency from a full-scale co-digestion of sewage sludge and OFMSW in the city of Velenje, Slovenia were also reported [16].

Despite the positive results from laboratory experiments and/or full-scale experience, in many European and North American countries, co-digestion of organic solid waste is less applied than it was expected. It is quite common that an organic solid co-substrate is added to manure digesters in small amounts, but often these co-substrates are high-energy yielding industrial sludge and only quite exceptionally, solid waste from households or market waste is added. Among the biogas plants identified, only about 9.7 % of the organic solid waste treated was done by means of co-digestion, mostly with liquid manure. The percentage of installed co-digestion plants has dropped from 23% in the period 1990–1995 to 5% in the period 2006–2010. However, due to the high prices for agricultural crops, many energy crop digestion plants are looking for organic waste feedstock [17]. Therefore, the use of excess sludge resulting from aerobic treatment of potato industry wastewater (later be called potato sludge) as co-substrate in anaerobic digestion of OFMSW can be considered as a potential solution.

2. Materials and Methods

2.1 Potato sludge and inoculums

The excess sludge from the wastewater treatment plant of a potato processing plant was delivered from a local potato chip company which operated its own wastewater treatment plant. The sludge was taken after the sludge thickening drying bed. A scheme of the wastewater treatment plant is depicted in Fig. 1.

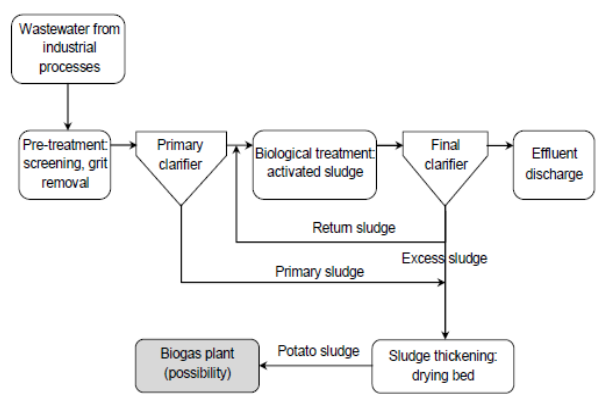

Figure 1. Schematic process overview of potato industry wastewater treatment plant

For batch experiments for biogas (methane) production, the anaerobic sludge inoculums was obtained from the effluent of a full-scale wet anaerobic digestion plant in Durlach treating source-sorted OFMSW from the city of Karlsruhe, Germany. Before using the digester effluent as inoculum for batch assays the anaerobic sludge was sieved to remove coarse materials such as leaves, branches, bones, nutshells, *etc*.

2.2 Experimental set-up and analytical methods

The potential of methane production of potato sludge was investigated in triplicate assays in Schott-bottles of one liter volume. The test was performed by adding 1.79 g wet potato sludge to an anaerobic sludge inoculum making the total volume of each assay 200 mL (corresponding to an additional 0.48 g of COD or 0.40 g of VS). Control assays for methane production from the inoculum alone (no addition of substrates) and from the inoculum plus glucose were run. After displacing the head space air with N_2 in order to have anaerobic conditions, the bottles were placed in an orbital shaker and incubated at 37 °C. The cumulative methane production of the assays was measured 2-3 times a day.

German Standard Methods for Water, Wastewater and Sludge Analysis [18] were employed to determine total solids (TS), VS, ammonia and total Kjeldahl nitrogen (TKN). COD concentration was determined according to Wolf and Nordmann [19] using potassium dichromate in a mixture of sulphuric acid and phosphoric acid to oxidize organic matter. Silver sulphate was used in this solution as a catalyst. After incubating the sample in a thermoblock at 150 °C for 2 hours, the green Cr^{3+} ions concentration was spectrophotometrically measured at 615 nm (Ultrospec II Spectrophotometer - Biochrom Ltd., Cambridge). The result was then converted to the COD value by comparison with a standard curve of potassium hydrogen phthalate (0 – 1250 mg · L^{-1}).

Volatile fatty acids (VFA) concentration was determined using a gas chromatograph (PACKARD model 437A) equipped with a flame ionisation detector (FID) following the method developed by Gallert and Winter [20].

Biogas composition (methane and carbon dioxide) was analysed with a gas chromatograph (PACKARD model 427) equipped with a Micro-WLD-detector and a Carboplot 007 column (with 0.53 mm of inner diameter and 27.5 m of length) packed with Poropack N (80-100 mesh; Sigma, Deisenhofen). The temperature settings used were as follows: column at 110 °C, injector and detector at 250 °C. Nitrogen served as the carrier gas at a flow rate of 25 mL·$min.^{-1}$.

One hundred μL gas samples were withdrawn from gas sampling ports using a Pressure Lok® syringe (Precision Sampling Corp., Baton Rouge, Louisiana) and injected into the gas chromatograph. As a reference, a mixture of 60% methane and 40% carbon dioxide was injected under the same conditions to determine the concentration in the samples.

Heavy metals (Cr, Cu, Mn, Fe, Co, Ni, Cd, Pb and Zn) were analysed by graphite-furnace atomic absorption spectrometry using a Varian Spectra AA 220 FS (Mulgrave, Australia). The spectraAA was equipped with an air-acetylene burner with an air flowrate of 13.5 L·min^{-1} and an acetylene flowrate of 2 L·min^{-1}. For the measurement of soluble heavy metal concentrations, samples were centrifuged two or three times to get a clear supernatant and diluted to a concentration that could be detected by the Spectra AA. Further dilutions were done when concentrations were above the detection limits.

3. Results and discussion

3.1 Characteristics of potato sludge

The important characteristics of potato sludge such as its density, TS, VS, total and soluble COD, TKN, and VFAs are presented in Table 1.

From Table 1, it can be seen that potato sludge has relatively high organic matter content. The volatile solids content of the sludge reached about 22 % of the total weight. The value of total COD was close to the value of TS at approximately 93 %. However, the value soluble COD (measured as COD of the supernatant after centrifugation of sample) only reached 10 % of total COD. During the storage of the potato sludge, there was already a beginning acidification process, indicated by the presence of acetic acid and propionic acid in relatively high concentration.

Table 1. Main characteristics of potato sludge

Parameter	Unit	Value
pH	-	4.35
Density	ton·m^{-3}	1.02
Total solids (TS)	% (w/w)	29.1 ± 0.22
Volatile solids (VS)	% TS	76.8 ± 0.14
Chemical oxygen demand (COD total)	g·g^{-1} TS	0.926
Soluble COD	g·g^{-1} TS	0.092
Total Kjeldahl nitrogen (TKN)	g·g^{-1} TS	0.03
Acetic acid	mg·g^{-1} TS	13.90
Propionic acid	mg·g^{-1} TS	2.84
Butyric acid	mg·g^{-1} TS	n.d.*
Valeric acid	mg·g^{-1} TS	n.d.*

Some important heavy metal concentrations in the potato sludge are presented in Table 2. Many heavy metals are essential for anaerobic digestion since heavy metals affect the activity of enzymes which are required for proper energy metabolism of organisms that drive anaerobic reaction sequences. A proper dosage of heavy metals is required for anaerobic processes. Nickel ions at a concentration of 5 mg·L^{-1} for instance will stimulate methane production by *Methanobacterium thermoautotrophicum* to its optimum production [21].

Table 2. Heavy metals concentration in potato sludge - comparison of inhibitory and toxicity concentrations for anaerobic digestion

Type of heavy metal	Potato sludge (mg·L^{-1})	Inhibitory (mg·L^{-1})[a]	Toxic (mg·L^{-1})[a]
Cadmium	2.97	-	20-600
Chromium	n.d.	100-300	200-500
Cobalt	n.d.	n.a	n.a
Copper	59.36	40-250	170-300
Iron	3748.84	n.a.	n.a.
Lead	8.90	300-340	340
Manganese	20.78	n.a.	n.a.
Nickel	5.94	10-300	30-1,000
Zinc	8.90	150-400	250-600

[a] after Kouzeli-Katsiri and Kartsonas (1986)

Although the presence of heavy metals in organic matter may cause stimulation for anaerobic digestion, many researches also revealed that heavy metals in higher concentration may cause inhibition or even exert toxic effects. The action of heavy metals as nutrients/stimulants or toxicants was affected by many factors, such as the total metal concentration, the environmental conditions (pH and redox potential), the kinetics of precipitation, complexation and adsorption [22]. Moreover, Kouzeli-Katsiri *et al.* [23] noted that the toxicity of a heavy metal for anaerobic digestion depends upon several important factors such as the chemical form in which the metal exists in sludge or in the digester, the acclimation ability of organisms and the possibility of antagonism and synergism among heavy metals.

From Table 2, it can be seen that almost all of the essential metals (except for molybdenum, which was not measured) were available in the potato sludge. With the exception of iron and copper, the heavy metal concentrations were relatively low and far from inhibitory or toxic concentration according to Konzeli-Katsiri and Kartsonas [24].

3.2 Methane production potential

Examination using batch assay tests in duplicate was employed to determine the methane production potential of potato sludge. The tests were performed in 1 L Schott-bottles that were inoculated with anaerobic sludge from the full-scale mesophilic biowaste reactor in Karlsruhe-Durlach. For the comparison, a zero control (only inoculum without additional substrate) and a positive control using glucose as the substrate were also performed.

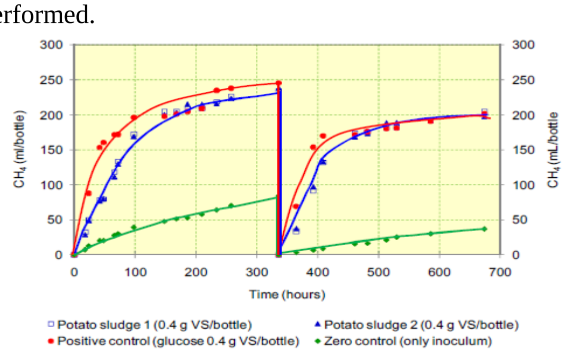

Figure 2. Cumulative methane production during batch assay tests

The batch assay tests were performed in two feeding runs. After the methane production from the first feeding was considered in a plateau phase, the second feeding was started. In both feeding runs, the zero control still produced methane indicating that there was residual methane productivity from sludge components. However, the net methane productions of both feedings were relatively similar. Figure 2 shows that with the same additional amount of VS, potato sludge produced nearly the same amount of methane compared to glucose, although potato sludge needed longer time to obtain maximum methane production..

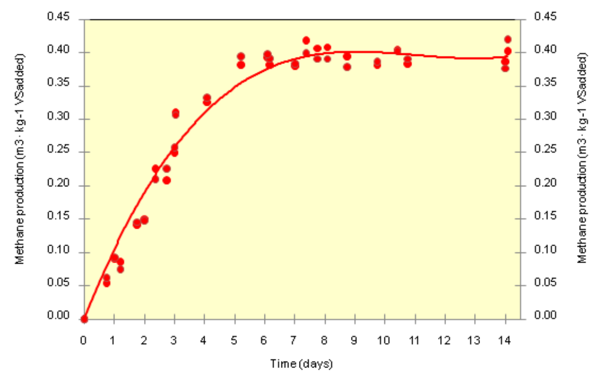

Figure 3. Methane production potential of potato sludge (at 37 °C).

Figure 3 depicts the net methane potential production of potato sludge. The curve represents methane production from potato sludge only and was obtained by subtracting methane production in assays with potato sludge addition and methane production in zero control (only inoculum sludge, without any addition of substrate). The maximum methane production potential appeared to be around 0.40 m^3 $CH_4 \cdot kg^{-1}$ VS_{added} and was achieved in approximately two weeks of incubation. Compared to biowaste suspensions, potato sludge had a higher methane production potential (0.37 m^3 $CH_4 \cdot kg^{-1}$ VS_{added}). From Figure 2 and Figure 3, it can be concluded that potato sludge is a readily biodegradable substrate with a high potential of methane production. To obtain 80% of its maximum methane production potential, potato sludge only required 3.8 days of incubation.

3.3 Solids elimination

Total solids and volatile solids elimination tests were carried out using triplicate batch assays with 1.0 L Schott-bottle. The assays were inoculated with 900 mL of anerobic sludge inoculums from the same source as for the methane production assays and 100 mL of potato sludge were added. Incubation of the assays was in a thermostated orbital shaker at 37 °C. The degraded concentrations of TS and VS and their elimination (in %) are plotted in Figure 4. More than 70% of the maximum elimination was achieved during the first ten days of incubation. After that, the elimination rate was slower. It was considered as not significant after 45 days. From Figure 4, it is shown that potato sludge had relative good solids elimination. More than 70% of its volatile solid was eliminated, giving a TS elimination of around 50%.

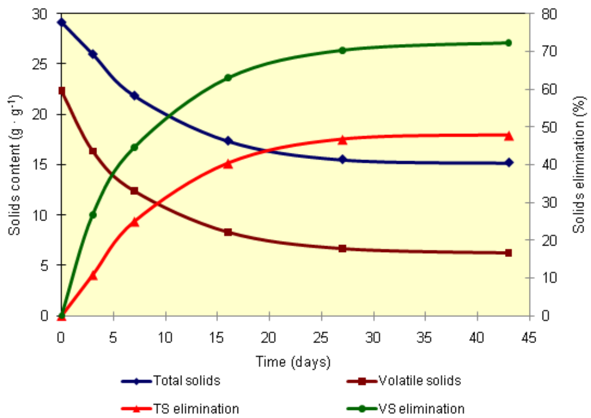

Figure 4. TS and VS degradation potential of potato sludge.

3.4 Volatile fatty acids development and degradation

The concentrations of VFA in the TS and VS elimination assays were also examined daily. The development of VFA concentrations in the assays are presented in Figure 5. From the figure, it can be seen that acetic acid was produced and degraded rapidly. After reaching a maximum concentration of around 570 mg·L^{-1} in two days, acetic acid was rapidly degraded with a maximum degradation rate of 19.6 mg·L^{-1}· h^{-1} and completely degraded after 5 days of incubation. The accumulation of acetic acid was presumably due to the lack of methanogenic bacteria during “start-up” of the assays. The methanogens are generally considered to be more sensitive to environmental conditions such as low pH value or the presence of toxic substances. Moreover, the methane conversion from acetate is also known to be a rate-limiting step in methanogenesis, especially at a temperature of more than 18 °C [25].

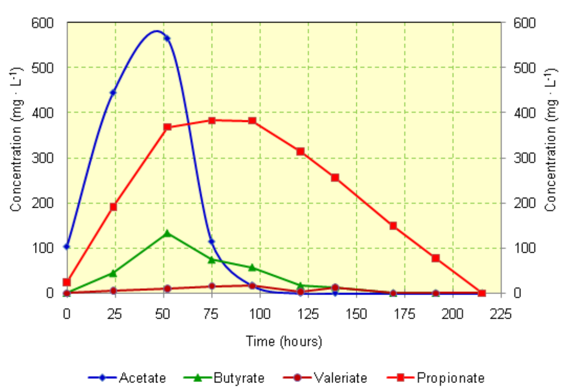

Figure 5. Volatile fatty acids development during solids elimination test.

The production and accumulation of propionic acid was also observed in the assays. The production and degradation rate of propionic acid was slower than that of acetic acid. The concentration of propionic acid reached its maximum value of 380 mg·L^{-1} after three days and was completely degraded after 9 days of incubation with a maximum degradation rate of propionate of 3.2 mg·L^{-1}· h^{-1}. Propionic acid (or other higher fatty acids) accumulated when the rate of hydrolytic and fermentative activity exceeded the rate of acetogenic conversion of fermentation of intermediates to acetate and hydrogen. It is usually produced because methanogenic bacteria cannot consume hydrogen at the rate at which it is produced.

4. Conclusion

Excess sludge from a wastewater treatment plant treating wastewater from the potato industry was examined in order to assess its suitability as a substrate for anaerobic digester. The concentrations of heavy metals in the potato sludge were lower than the inhibitory or toxic concentration limit. Potato sludge was also relatively easy degradable and had a maximum methane production potential of around 0.40 m^3 CH_4·kg^{-1} VS_{added} achieved in approximately two weeks of incubation (more than 80% of its maximum methane production were obtained within the first 4 days of incubation). More than 70% of the volatile solid was eliminated during solid elimination tests. Judged by its relatively high methane production potential, degradability rate and solids removal potential, potato sludge is suitable for anaerobic digestion either as a sole substrate or co-substrate.

Acknowledgment

Parts of this paper have been included in the first author’s dissertation report entitled *Anaerobic Digestion of Organic Solid Waste for Energy Production*. Satoto E. Nayono was a recipient of a PhD-Grant from Bundesministerium fur Bildung und Forschung, Bonn within the IPSWaT programme. We also thank DFG for financial support of the research.

References

[1] Malladi, B. and Ingham, S.C., 1993. Thermophilic aerobic treatment of potato-processing wastewater. *World Journal of Microbiology and Biotechnology*. Vol. 9: 43-49.

[2] Mishra, B.K., Arora, A. and Lata, 2004. Optimization of a biological process for treating potato chips industry wastewater using a mixed culture of *Aspergillus foetidus* and *Aspergillus niger*. *Bioresource Technology*. Vol. 94 (1): 9-12.

[3] Kobya, M., Hiz, H., Senturk, E., Aydiner, C. And Demirbas, E., 2006. Treatment of potato chips manufacturing wastewater by electrocoagulation. *Desalination*. Vol. 190: 201-211.

[4] Knezevic, Z., 1995. Pilot-scale evaluation of anaerobic co-digestion of primary and pretreated waste activated sludge. *Water and Environmental Research*. Vol.67:835–41.

[5] Baldasano, J.M. and Soriano, C., 2000. Emission of greenhouse gases from anaerobic digestion processes: comparison with other municipal solid waste treatments. *Water Science and Technology*. Vol. 41 (3): 275-282.

[6] Hartmann, H. and Ahring , B. K., 2006. Strategies for the anaerobic digestion of the organic fraction of municipal solid

waste: an overview. *Water Science and Technology*. Vol. 53 (8): 7-22.

[7] Fricke, K., Santen, H. and Wallmann, R., 2005. Comparison of selected aerobic and anaerobic procedures for MSW treatment. *Waste Management*. Vol. 25: 799-810.

[8] Mata-Alvarez, J., Macé, S. and Llabrés, P., 2000. Anaerobic digestion of organic solid wastes: an overview of research achievements and perspectives. *Bioresource Technology*. Vol. 74: 3 – 16.

[9] Nordberg, A. and M. Edström, 2005. Co-digestion of energy crops and the source-sorted organic fraction of municipal solid waste. *Water Science and Technology*. Vol. 52 (1-2): 217-222.

[10] Gallert, C., Henning, A. and Winter, J., 2003. Scale-up of anaerobic digestion of the biowaste fraction from domestic wastes. *Water Research*. Vol. 37: 1433-1441.

[11] Hartmann, H., Angelidaki, I. and Ahring, B.K., 2003. Co-digestion of the organic fraction of municipal solid waste with other waste types (in: *Biomethanization of the organic fraction of municipal solid wastes*. Editor: Mata-Alvarez, J.). Amsterdam: IWA publishing company.

[12] Hartmann, H. and Ahring, B. K., 2005. Anaerobic digestion of the organic fraction of municipal solid waste: influence of co-digestion with manure. *Water research*. Vol. 39: 1543-1552.

[13] Nayono, Satoto E., Winter J., and Gallert C., 2009. Foodwaste as a Co-Substrate in a Fed-Batch Anaerobic Biowaste Digester for Constant Biogas Supply. *Water Science and Technology*. Vol. 59 (6): 1169–1178.

[14] Nayono, Satoto E., Winter J., and Gallert C., 2009. Anaerobic Digestion of Pressed Off Leachate from the Organic Fraction of Municipal Solid Waste. *Waste Management*, Vol. 30 (10): 1828-1833.

[15] Angelidaki, I. and Ellegaard, L., 2003. Codigestion of manure and organic wastes in centralized biogas plants. *Applied Biochemistry and Biotechnology*. Vol. 109 (1-3): 95-105.

[16] Zupančič, G.D., Uranjek-Ževart, N. and Roš, M., 2008. Full-scale anaerobic co-digestion of organic waste and municipal sludge. *Biomass and Bioenergy*. Vol. 32: 163-167.

[17] de Baere, L., 2008. The DRANCO process: a dry continuous system for solid organic waste and energy crops. *Proceedings of International Symposium on Anaerobic Dry Fermentation*. Berlin: Feb. 20-22, 2008. Available online at: http://www.ows.be /pub/Dranco-Process_IBBKfeb08.pdf

[18] DEV (*Deutsche Einheitsverfahren*), 1983. Standard Methods for Water, Wastewater and Sludge Analysis. English Translation from: *Deutsche Einheitsverfahren zur Wasser-, Abwasser und Schlammuntersuchung*.Weinheim: Verlag Chemie.

[19] Wolf, P. and Nordmann, W. 1977. A field method for COD analysis in wastewater. English Translation from: *Eine Feldmethode für die Messung des CSB von Abwasser*. *Korespondenz Abwasser*. Vol. 24: 277-279.

[20] Gallert, C. and Winter, J., 1997. Mesophilic and thermophilic anaerobic digestion of source-sorted organic wastes: Effect of ammonia on glucose degradation and methane production. *Applied Microbiology Biotechnology*. Vol.48: 405-410.

[21] Oleszkiewicz, J.A. and Sharma, V.K., 1990. Stimulation and inhibition of anaerobic processes by heavy metals - A review. *Biological Wastes*. Vol. 3: 45-67.

[22] Aquino, S.F., and Stuckey, D. C., 2007. Bioavailability and toxicity of metals nutrients during anaerobic digestion. Journal of *Environmental Engineering.* Vol. 133 (1): 28-35.

[23] Kouzeli-Katsiri, A., Kartsonas, N. and Priftis, A., 1988. Assessment of the toxicity of heavy metals to the anaerobic digestion of sewage sludge. *Environmental Technology*. Vol. 9 (4): 261-270.

[24] Kouzeli-Katsiri, A., and Kartsonas, N., 1986. Inhibitory of anaerobic digestion by heavy metals, in: *Anaerobic digestion of sewage sludge and organic agricultural wastes* (Bruce, A.M., Konzeli-Katsiri, A., and Newman, P.J., Eds.), 104-119. Elsevier Applied Science Publisher, London, UK.

[25] van Haandel, A.C., Monroy, O., Celis, B., Rustrian, E. and Cervantes, F.J., 2005. Principles of process design in industrial wastewater treatment system. In: *Advanced biological treatment processes for industrial wastewaters (Eds.:* Cervantes, F.J., Pavlostathis, S.G. and van Haandel, A.C.). London: IWA Publishing.