Enhancing Methane Yields by Anaerobic Co-digestion of Sludge with Food Residues*

Aburawaa, A. A.¹, Alrousan, D.², Hayek, B.³

¹GIZ Water Portfolio – Jordan, Field Project Officer, Decentralized Integrated Sludge Management (DISM) project, Dept. of Water Management and Environment, Faculty of Natural Resources and Environment, Hashemite University.

²Dept. of Water Management & Environment, Faculty of Natural Resources & Environment, Hashemite University.

³GIZ Water Portfolio – Jordan, Team Leader, Decentralized Integrated Sludge Management (DISM) project.

Corresponding author: aaburawwa@yahoo.com, ayman.aburowaa@giz.de, dheaya@hu.edu.jo; dheaya@gmail.com, bassam.hayek@giz.de, basam.hayek@gmail.com

*This publication has been produced as a result of the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH implemented project “Decentralized Integrated Sludge Management” - DISM activities on behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ). All rights for the content of this paper are reserved for GIZ, the views presented are entirely the responsibility of the authors.

Abstract

Disposal of biodegradable waste (food residues and sewage sludge) has become a stringent waste management and environmental issue. As a result, anaerobic digestion has become one of the best alternative technologies to treat the food wastes and sewage sludge which can be an important source of bioenergy. This study focuses on the evaluation of biogas and methane yields from the co-digestion of different sewage sludge and food wastes mixture ratios. The biogas potential tests using both types of substrates were performed in lab scale and under mesophilic conditions (35°C). It was observed that the optimal mixing ratio of food waste to sewage sludge was 1:2, corresponding to biogas production of 0.184 Nm³/kg VS. The study examines

the possibility of increasing biogas production up to 75% using food waste substrate addition to sewage sludge in anaerobic co-digestion.

Keywords: anaerobic, co-digestion, food residues, sewage sludge, methane, mesophilic conditions.

Introduction

About 50'000 tons of dried solid sludge are generated annually in Jordan as a by product of wastewater treatment in the 31 wastewater treatment plants (WWTP) distributed all over Jordan and treating more than 152MCM per year (MWI, 2015). Around 60% of the total municipal wastewater produced in Jordan is treated in As-Samra WWTP in Zarqa governorate, the plant serves the biggest two cities, Amman and Zarqa, where 71% of the population are living. To accommodate for the increasing demand, As-Samra WWTP is currently undergoing expansion to reach a daily capacity of 367,000 m³. As-Samra WWTP utilizes anaerobic digesters to stabilize sludge, which is then dewatered using belt filter press system. While As-Samra's sludge is utilized as energy sources, only one of the other 30 wastewater treatment facilities has proper utilization of sludge for energy production, which is in Al Shalalah WWTP in the north of Jordan. Thus the quantities of generated sludge in other treatment plants still create a serious environmental problem.

Nowadays, sludge management is an integral part of any modern municipal wastewater treatment plant in order to dispose sludge in a proper environmental way and also economically not to lose sludge valuable nutrients and to make

efficient use of material and energy. Similarly, Jordan suffers from a solid waste crisis, which is looming in Jordan with more than 2 million tons of municipal waste and 18,000 tons of industrial wastes are being generated annually. Alarmingly, less than 5 % of total solid waste is currently recycled in Jordan.

Because of the growing demand on energy and limitation of resource in Jordan, wastewater sludge and solid wastes can be considered as alternative sources for energy production. Nowadays the possibilities for biogas production as an alternative energy source are becoming more important (MOUSDALE, 2008), and from a practical viewpoint determining the capabilities of different organic materials to produce biogas are vital. Anaerobic digestion (AD) and Co-digestion are promising environmental sustainable biotechnologies that can treat the organic fraction of the municipal solid waste and wastewater sludge to produce biogas as a source of energy. Using such biotechnologies would necessarily help in solving the problem of the huge accumulated sewage sludge and food wastes and reduce the greenhouse gases emissions from them. Digestion process will result in enhancing physical and chemical characteristics of sludge and make it more suitable for land applications.

The process of anaerobic digestion consists of three steps: Solubilization,

Acidogenesis, and Methanogenesis (KIM, 2003). In the first hydrolysis step, the complex organic polymers (proteins, carbohydrates, and fats) are degraded into simple sugars, amino acids and fatty acids by the heterogeneous microorganism. As the second step, acidogenic bacteria produce fermentation intermediates, mainly volatile fatty acids (VFAs), and lastly, in the methane step, methane and carbon dioxide with a small amount of hydrogen (H_2) and traces of hydrogen sulphide (H_2S) and ammonia (NH_3) are produced from these intermediates by methanogenic bacterial metabolism (ABATZOGLOU, 2009). In each step, the gas production and decomposition rates of organic waste are influenced by environmental factors such as temperature, pH and hydraulic retention time (HRT) and substrate concentration (CRISTANCHO, 2006; GÜNGÖR-DEMIRCI, 2004; MATA-ALVAREZ, 2002).

Anaerobic digestion is conducted using simple reactor technologies such as Single Batch reactor, continuous stirred tank reactor (CSTR) and Plug flow reactor (PFR), (RITTMANN, 2012). The degradation process is complex and depends on a balanced action of several microbial groups (GUJER, 1983) in the absence of oxygen and renewable energy biogas is generated (CHEN, 2008).

Biogas from the anaerobic degradation of wastewater can be used in micro-turbines or internal combustion engines for generating electricity (CRAWFORD, 2010). The US EPA estimates that over 80% of municipalities that utilize anaerobic digestion flare excess biogas (EPA, 2007). Typical digester gas energy recovery systems can recover 20-40 % of the energy requirement for wastewater treatment

plants that use the activated sludge process (CRAWFORD, 2010).

A substance or compound is biodegradable if it can be source of energy for the metabolism and for the growth of the biomass which performs its degradation; on the contrary, a substance is indicated as poorly or non-biodegradable, if structural (molecular) or external causes (concentration levels, availability of nutrients, etc.) hinder their degradation and thus remains partially or totally undegraded in the environment. It may happen that some intermediates are more recalcitrant or even toxic. The degradation process is complex and depends on a balanced action of several microbial groups (GUJER, 1983) in the absence of oxygen and renewable energy biogas is generated (CHEN, 2008).

Some factors may influence the activity of microorganisms, thus the biodegradation process. From a biochemical point of view, temperature and pH influence the reaction rate of an enzymatic process, in the sense that each enzyme is characterized by an optimal range of temperature and pH. Generally, when the temperature increases, the reactions are accelerated and the growth rate is higher; but if the temperature becomes too high, a process of irreversible denaturation of the cellular components may occur whereas if the temperature becomes too low, both the bacterial growth and substrate utilization eventually cease.

On behalf of the German Federal Ministry for Economic Cooperation and Development (BMZ), GIZ is supporting the Water Authority of Jordan in its efforts to find suitable solutions for the treatment and reuse of sewage sludge. The project

aims to reduce the carbon footprint of the sludge handling process. To this end, it considers the use of sludge primarily as a source of energy, but also as a soil conditioner and a fertilizer. The project also seeks to demonstrate an integrated approach to the treatment and reuse of sludge in combination with other biomass sources (co-digestion). After the energy potential of the sludge has been tapped, any residual sludge undergoes further processing, together with other sources of biomass, to produce a treated organic mix that can be used to improve soil quality. The integrated approach ensures the involvement of all significant stakeholders, from the relevant ministries and municipalities, to the water utilities and farmers. The project also includes close scientific cooperation with Mu'ta University in Karak by building and operating anaerobic co-digestion experiments using a (100 L) STR system and using the same biomass, the University is located close (2.5 km) to the Mu'ta-Mazar demonstration plant in the Governorate of Karak.

Objective

The objective of the current study was to find the maximum mixing ratio of food waste and sludge, and methane production using Laboratory Equipment Modular compact basis plant BTP-2 which is the standard system for substrate testing and gas yield tests.

Material & Methods

The biogas yield experiment in Mu'ta Almazar WWTP was performed to simulate

the real digester. For this purpose, the (Modular compact basis plant BTP-2) device is ideal as shown in Figure 2. The device has one testing unit with reactor volume capacity up to 17 L of degradable material (liquid or pulps). The units can be thermostatically managed from 0 to 60°C, with temperatures of 35-55°C are ideal for the anaerobic tests. The device is equipped with a mixer, stirring the solution at programmed mixing intervals. With continuous monitoring of pH-values, temperature and biogas production. Data collection using data logger technology.

The producing of biogas is analyzed with **OPTIMA 7** biogas analyzer as shown in Figure 3 simultaneous measurements of up to 7 gas components. The biogas measurements include O₂, H₂S, CH₄ and CO₂ (infrared for CO₂/CH₄).

Figure 1 – Biogas Test Plant BTP2.

Figure 2 – OPTIMA Biogas Analyzer.

Seeding Sludge (Inocula)

Seeding sludge (Inocula) was taken from Mu'ta university biogas reactor. Once collected, the seeding sludge was added to biogas BTP-2. Analyses of its volatile and total solids content (VS, TS) were performed at the lab of the WWTP.

Substrate

Sludge and a mixture of food residues and sludge were used as substrate in this study. Food residues were taken from Mu'ta University military wing restaurant, after grinding by an electric blender, the material was stored in a refrigerator at 4°C. The sludge was taken from Mu'ta Almazar WWTP, the physicochemical parameters (pH, TS, VS, T-N) were determined according to standard methods (Standard methods for the examination 2010) in the Royal Scientific Society (RSS) and Eurofins Umwelt

Ost GmbH Hauptniederlassung Jena, berlin – Germany. The physicochemical characteristics of substrate are presented in Table 1.

Table 1 – Physicochemical Characteristics of substrate used in this study.

Parameters	Sludge	Foodwaste
pH	6.75	4.6
Total Solid %	0.61	32.1
Volatile Solid %	59.2	29.8
Electrical Conductivity $\mu\text{S}/\text{cm}$	2400	
Total Nitrogen %	34.1	2.8
$\text{NH}_4\text{-N}$ %	22.4	0.003
$\text{NO}_3\text{-N}$ mg/Kg	281	<10

Productivity, yield, and degree of degradation

Productivity ($P_{(\text{CH}_4)}$), yield ($A_{(\text{CH}_4)}$) and degree of degradation (η_{VS}) are appropriate parameters for describing the performance of a biogas experiment. If gas production is given in relation to digester volume, this is referred to as the productivity. This is defined as the quotient of daily gas production and reactor volume and is consequently an indication of the efficiency. Productivity can be related to both biogas production ($P_{(\text{biogas})}$) and methane production $P_{(\text{CH}_4)}$ and is given in $\text{Nm}^3/(\text{m}^3 \cdot \text{d})$.

$$P_{(\text{CH}_4)} = \frac{V_{(\text{CH}_4)}}{V_R} [\text{Nm}^3 \text{m}^{-3} \text{d}^{-1}] \quad \text{Eq. (1)}$$

Where:

Methane productivity

V_{CH_4} : methane production [Nm^3/d];

V_R : reactor volume [m^3].

Gas production expressed in relation to the input materials is the yield (Lebuhn 2014). The yield can likewise be related to biogas production ($A_{(biogas)}$) or methane production ($A_{(CH_4)}$). This is defined as the quotient of the volume of gas produced and the amount of organic matter added and is given in Nm^3/t VS.

$$A_{CH_4} = \frac{V_{CH_4}}{m_{VS}} \left[Nm^3 t^{-1} VS \right] \quad \text{Eq. (2)}$$

Where:

Methane yield

V_{CH_4} : methane production [Nm^3/d];

m_{VS} : added volatile solids [t/d]).

The yields denote the efficiency of biogas production or methane production from the loaded substrates. They are of little informative value as individual parameters, however, because they do not include the effective loading of the digester. For this reason, the yields should always be looked at in connection with the organic loading rate. The degree of degradation (η_{VS}) provides information about the efficiency with which the substrates are converted. The degree of degradation can be determined on the basis of volatile solids (VS) or chemical oxygen demand (COD). Given the analytical methods most commonly used in practice, it is advisable

to determine the degree of degradation of the volatile solids (LEBUHN, 2014).

$$\eta_{VS} = \frac{VS_{sub} \times m_{FM} - (VS_{vsc} \times m_{vsc})}{VS_{sub} \times m_{FM}} \times 100\% \quad \text{Eq. (3)}$$

Where:

Degree of degradation (η_{VS}) of biomass,

VS_{sub} : volatile solids of added fresh mass [kg/t fm];

m_{FM} : mass of added fresh mass [t];

VS_{vsc} : volatile solid content of digester discharge [kg/t FM];

m_{vsc} : mass of digestate [t])

Experimental Design

The experiment was conducted using 17L reactor of modular compact basis plant BTP-2 as shown in Figure 1. The various mixtures of food residual and sewage sludge were added to each batch experiment. Their initial concentrations were all set, as shown in table 3. Each experiment contained organic waste co-digested with different ratio of sludge, food residual and Inocula. The experiment was started with Inocula 100%, other treatments were made by mixing food residual/sludge by a ratio of (30%, 50%) food residue addition as volatile solid (VS), and the final experiment have been 100% sludge. Everythirty minutes temperature, gas flow rate, total gas volume and pH value and stirring at 100 rpm are carried out by the device, while maintaining temperature at $35 \pm 5^\circ C$.

Table 2 – Batch experiment operating conditions.

Temperature	Batch Experiment No.	Preparation of Substrate			
		Sewage Sludge (% of VS)	Sewage Sludge (g VS add)	Food waste (% of VS)	Food waste (g VS add)
Mesophilic (35°C)	1	100	29.4	0	0
	2	75	29.4	25	10.6
	3	65	29.4	35	15.6

Result and Discussion

Effect of food waste addition on co-digestion performance based on mixing ratio food waste with sludge used in BMP, three batch experiments were operated at 35°C with different mixtures of food waste and sewage sludge using mesophilic seed sludge. As shown in Figure 3, accelerated hydrolysis was observed by the addition of the proper amount of food waste within the same temperature conditions. Mesophilic digestion showed a higher conversion rate in hydrolysis as well as acidogenesis. In mesophilic conditions, the major portion of biogas was sharply increased within the first six days by fast acidogenesis and methanogenesis. In anaerobic digestion of organic materials including large molecules or sterically incompatible molecules or crystalline

molecules, which cannot be easily transported into the bacterial cells, a further step of hydrolysis by exoenzymes should be considered (Borghi 1999).

Figure 4 shows that as the mixing ratios of food waste increased up to 35%, cumulative biogas production also increased. Similar observation was reported by (HEO, 2004) for the digestion of separately collected (SC) food residues and sewage sludge. Therefore, it indicated that the application of co-substrate significantly improved feed characteristics, resulting in higher biogas and methane potential.

Higher ultimate methane yield of food waste can be found in Table 3, which shows reported data from various OFMSW. Also, it was confirmed that co-substrate, food waste, gave higher methane yields than previously reported BMP values (Table 3).

Figure 3 – Daily Biogas Production.

Figure 4 – Cumulative Biogas Production.

Table 3 – Comparisons of biogas production from co-digestion of various food waste and sewage sludge in mesophilic conditions.

Reference	Food Residues	SPG (l/g VS)	Methane CH ₄ %
This study	SS only	0.09	n.r
Food waste Source	26.5 % Food waste, 73.5 % SS	0.112	48
(University Canteen)	34 % Food waste, 66 % SS	0.184	55
(CABBAL et al., 2013)	100 % WAS	0.39	64
Food waste Source	58.5 % Food waste, 41.5 % WAS	0.62	n.r
(Canteen, Supermarket, Household)	25 % Food waste, 75 % WAS	0.45	53.8
(CAVINATO et al., 2013)	100 % WAS	0.15	61.8
Food waste Source	50 % Food waste, 50 % WAS	0.34	60
(Canteen, Supermarket, Household)			
(NIELFA; CANO; FDZ-POLANCO, 2015)	100% biological sludge	0.27	60
Synthetic OFMSW			
(ZUPANČIČ; URANJEK- ŽEVARTB; ROŠA, 2008)	80% Food waste, 20% biological sludge	0.22	n.r
Domestic refuse (swill)			

SS : sewage sludge ; WAS : Waste of Activated Sludge, OFMSW: Organic fraction municipal solid waste

The Biogas yields of all experiments are shown in Table 3. Within the mesophilic digestion condition the biogas yield increased by 19% with the addition of 26.5 % food residues to the total VS. (Cabbai, et al. 2013) reported that within food residues addition by 25% biogas yield increased by 13%, intrinsically. These trends of biogas yields could be explained by higher degrading capability and methanogenic activity as shown in Figure 3. (KIM, 2003) has reported that the important factors for the enhanced performance of co-digestion are the additional organic carbon, nutrient balance and adequate mixing ratio.

Additional carbon source supplied by food residues create preferable environment for the growth and activity of anaerobic microorganism.

Conclusion

The experiment has shown that the codigestion of sewage sludge mixed with food waste had a distinct positive effect on biogas and methane yields by keeping the adequate fraction of food waste. As expected using food waste substrates positively affects biogas and

methane production, with a significant increases biogas yield in the range of 20% to 30%, and an increase in the range of 50 to 60% in removable VS by increase the food waste substrate in the range of 26% to 35%. Biogas cumulative production during co-digestion of food waste with sludge increases notably when increasing the food waste to sewage sludge ratio.

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Acknowledgements

The authors would like to thank GIZ Water Portfolio for allowing using DISM project findings for this publication. Thanks to DISM project colleagues for their technical support and to Mu'ta Almazar WWTP staff and University of Muta for their cooperation.

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