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Anaerobic Co-Digestion of Domestic Sewage Sludge with Food Waste: Incorporating Food Waste as a Co-Substrate Under Semi-Continuous Operation

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ABSTRACT

Anaerobic co-digestion of domestic sewage sludge with food waste as a substrate for biogas production and as a mean for waste management was conducted. The food waste was incorporated into the bioreactor as a co-substrate semi-continuously via replacement mode and addition mode of operations in ratios up to 50%. The methane gas yield under the replacement mode of operation ranged from 295 to 1358 ml/gVS$_{added}$ and from 192 to 462 ml/gVS$_{added}$ for the replacement mode of operation and the addition mode of operation, respectively. The results indicate that the methane gas yield increases along with the percentage share of food waste in the feed. Anaerobic co-digestion under semi-continuous operation enabled handling large organic loadings compared to batch co-digestion processes.

Keywords: biogas, co-digestion, sludge, food waste, semi-continuous operation, methane

INTRODUCTION

The production of biogas from organic wastes through anaerobic digestion processes has been used in wastewater treatment plants for on-site co-generation of electrical energy and heat (Zitomer et al. 2008). This method can dramatically lower the wastewater treatment facility operating costs while also stabilizing the sludge generated. It is also possible to achieve substantial reductions in the greenhouse gas emissions (Li et al. 2011). The energy content of the gas can also differ depending on the type of substrate being used.

Anaerobic digestion with the addition of co-substrates (co-digestion) can be used to boost the biogas production and aid in municipal organic waste management. Co-digestion has long been regarded as a low-cost, commercially versatile method of reducing process limitations and increasing methane yields (Alatriste-Mondragón et al. 2006).

Recently, many research works have been carried out to study the effect of co-digestion using several types of organic wastes on the amount and methane content of the produced biogas. Prabhu et al. (2016) investigated the anaerobic co-digestion of food waste (FW) and sewage sludge. They concluded that mixing FW with sewage sludge in the ratio of 1:2 increased the biogas production up to 823 ml/gVS (21 days). Gelegenis et al. (2007) studied the anaerobic co-digestion of diluted poultry manure and whey in the ratio of (V/V=65:35). Their results indicated a 40% increase in methane production in comparison to the anaerobic digestion of pure poultry manure. The anaerobic co-digestion of sewage sludge with mixed fruit waste and cheese whey resulted in an increase in methane production in comparison to the anaerobic digestion of sewage sludge alone (Hallaji et al. 2019). Dai et al. (2016) developed a new strategy that enabled simultaneous increase of biogas production up to 310 ml/gVS and methane content in the produced gas up to 74% from the anaerobic co-digestion of sewage sludge and perennial ryegrass. Maragkaki et al. (2018) improved biogas generation from sewage sludge by co-digesting with a dried mixture of Food waste, Cheese whey and Olive mill wastewater (FCO). The obtained results showed that addition of 5% FCO raised the biogas production by nearly 170%, with methane content of 69.5%. Koupaie et al. (2014) investigated the anaerobic co-digestion of sewage sludge with two juice-based beverage industrial wastes, screen cake and thickened waste activated sludge. The results of their investigations showed that the maximum ultimate cumulative methane yield can reach 890.90 mL/gVS$_{removed}$. Moreover, the cost-benefit analysis results showed that the capital, operating and total costs could be decreased by 21.5%, 29.8% and 27.6%, respectively using a co-digester, rather than two separate digesters. Fitamo et al. (2016) proved that the co-digestion of sewage sludge with food waste, grass clippings and green waste in different mixing ratios increased the methane yield up to 48%.

Only a few studies have looked at full-scale implementations of this principle. As an efficient and cost-effective solution, anaerobic co-digestion with the addition of low-cost municipal organic wastes could also be considered. As a result, municipally available organic wastes such as Fats, Oils, and Grease (FOG) and Kitchen Waste (KW), which can be obtained near the wastewater treatment facility, may be used as co-substrates. A study conducted by Cockrell (2008) revealed a 50% increase in the production of biogas using FOG as a co-substrate in a full-scale digester. Kabouris et al. (2008) studied FOG as a co-substrate and found that it increased the methane production significantly. Food wastes, which are also major components of KW, were evaluated by Li et al. (2002), Gunaseelan (2004), Carucci et al. (2005), Gomez et al. (2006), and Labatut et al. (2011), and found to be effective in increasing the methane yield output.

The objective of this study was to assess the methane production potential via the co-digestion of sewage sludge with different percentage of food waste under semi-continuous operation. Incorporating food waste as a co-substrate was conducted under two mode of operations, namely: replacement mode and addition mode of operation. The work was carried out as part of the research work for the Decentralized Integrated Sludge Management (DISM) project, implemented by Deutsche Gesellschaft fuer Internationale Zusammenarbeit (GIZ) and the Water Authority of Jordan.

EXPERIMENTAL

Description of experimental setup

The anaerobic bio-reactor was designed to be operated under semi-continuous mode. Figure 1 shows a schematic drawing of the apparatus employed in this study.

The system comprised mainly of two digesters (100 liters each) and a feeding vessel. The temperature of the two digesters was maintained constant at 37°C using internal coil-heat exchanger controlled with PID-controller. The hot water was continuously circulated via centrifugal pumps. The produced gas passed through three successive gas purification bottles prior to a gas flow meter and burner. The first purification bottle was used empty. The second purification bottle contained water. The third purification bottle contained caustic soda solution (2M). Mixing inside each digester was accomplished via motor-driven mixer placed at the bottom of the reactor. The time of mixing was controlled to maintain soft-one-minute mixing per hour (50 rpm) to assure good homogeneity inside the digester. Accessories such as relieve valves, check valves and sensors were fitted to the system to facilitate sampling and operation of the system and ensure safety. The methane percentage in the biogas produced was tested every three days. For each analysis, 50 ml gas sample was collected and subjected to the volumetric gas analysis by using the liquid displacement method.

The prototype was tested for 10 days period using Glucose solution (5% concentration), the purpose was to detect any leakage, to test the effectiveness of the heating system as well as configure the temperature control system and the gas-meter reliability.

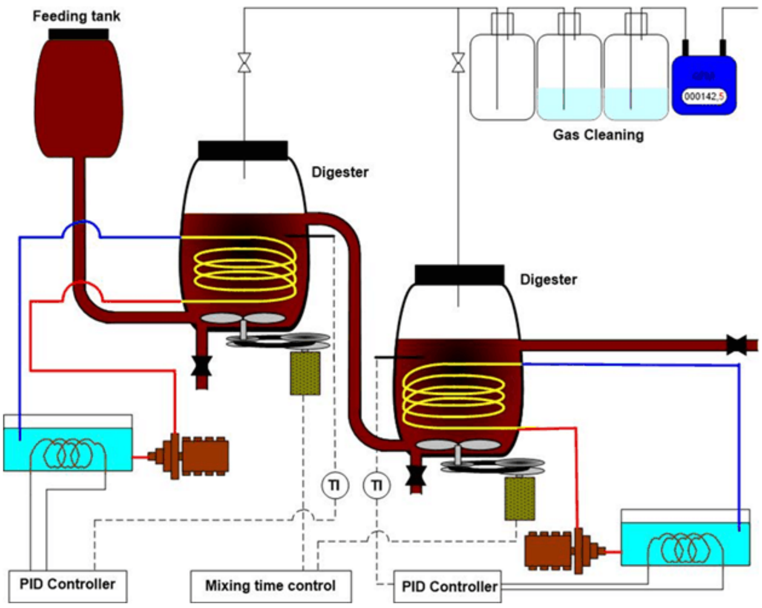

Figure 1. Experimental setup

Operation of the setup

The sewage sludge samples were collected from Mutah-Mazar Waste Water Treatment Plant (WWTP) directly from the secondary thickener (thickened secondary sludge). The sludge was stored in a dark plastic container for immediate use and characterization.

Food waste was collected from both the civil and military wings restaurants of the Mutah University campus. The collected food waste was mixed and homogenized. The representative food waste samples were obtained by multi-quartering standard procedure. The final representative food waste sample was minced then stored in a refrigerator (at 4°C) for subsequent use and characterization. The inoculums used for starting up the digesters were obtained from anaerobic digesters at Al-Shalalah WWTP. The inoculums were directly applied after testing.

Two operating modes were tested for conducting the co-digestion process. In the first mode of operation (replacement process), the two digesters are operated at once. The working volume of each digester was 50 L. Initially, each digester was fed with 50 L inoculum brought from the Al-Shalalah WWTP and left for one week in the two digesters prior to feeding. Incorporating feed into the two digesters was carried out by feeding a mixture comprising constant total solid content (115.5 g). Feeding was carried out every day by manual injection of the prescribed feed mixture into each digester. Table 1 shows the program of feeding followed in this mode of operation.

In the second mode of operation (addition process), the two digesters were operated sequentially. The total solid content was increased by gradually adding FW to a constant sludge amount. A prescribed amount was daily fed to the feeding chamber. This daily addition

Table 1. Operating conditions for the replacement mode of operation (calculations are based on TS of 4.62% and 31.58% for sludge and FW respectively)

Stages	Feeding rate (g/d)		TS content in feed (g)	FW ratio in feed (%)	Time of operation (d)
	Sludge	FW			
Stage 1	Batch of 50 L inoculum to each digester and left resided for one week				
Stage 2	2500	0	115.5	0	26
Stage 3	2250	37	115.5	10	12
Stage 4	2000	73	115.5	20	20
Stage 5	1750	110	115.5	30	20
Stage 6	1500	146	115.5	40	23
Stage 7	1250	183	115.5	50	25
Stage 8	Collection of Treated Organic Matter (TOM)				

to the first digester would cause an overflow of the same amount to the second digester. Finally, the second digester would also generate an overflow as TOM. Table 2 shows the program of feeding followed under this mode of operation.

Analytical procedure

The sewage sludge and food waste samples were subjected to characterization following standard analytical methods and procedure. Table-3 shows the parameters characterized along with the standard method applied. The analyses were performed at the laboratories of EUROFINS UMWELT GmbH in Berlin – Germany through the DISM, GIZ.

RESULTS AND DISCUSSION

Sewage sludge and food waste characterization

Table 4 shows the physiochemical properties of sewage sludge and food waste.

The carbon-to-nitrogen ratio (C/N) for sewage sludge was calculated based on the total carbon and total nitrogen contents in sludge as 5.4, while the C/N ratio for food waste was calculated as 14.0. The C/N ratio for the food waste employed in this study is in agreement with those reported in literature. For example, the C/N ratio for food waste collected in the city of San Francisco, California was reported to be 14.8 (Zhang et al. 2007). The C/N ratio for the

Table 2. Operating conditions for the addition mode of operation

Stages	Feeding rate (g/d)	TS content in feed (g)	FW ratio in feed (%)	Time of operation (d)
Stage 1	Batch of 50 L of totally digested matter to each digester			
Stage 2	5074	234	10	22
Stage 3	5148	258	18	21
Stage 4	5222	281	25	20
Stage 5	5296	304	31	20
Stage 6	5370	328	36	21
Stage 7	5444	351	40	4
Stage 8	Collection of TOM from the second digester			

Table 3. Standard methods followed for sewage sludge and food waste characterization

Parameter	Sewage sludge	Food waste
Total solid	EN 14346	EN 12880
Total volatile solid	DIN EN 12879	DIN EN 12879
Lipophilic substances	LAGA KW/04	LAGA KW/04
Salt content	gemäß Methodenbuch der BGK e.V	
Chloride	ISO 10304–1/2	ISO 10304–1/2
Ammonium nitrogen	DIN 38406-E5–2	DIN 38406-E5–2
Nitrate nitrogen	Calculation	Calculation
Total nitrogen	EN 13342	EN 13342
Total organic carbon	DIN EN 13137	DIN EN 13137
Phosphorous	ISO 11885	ISO 11885
Calcium	ISO 11885	NA
Potassium	ISO 11885	NA
Magnesium	ISO 11885	NA
Salmonella	Book of Methods BandesgütegemeinschaftKompost e. V.2006, Kap IV, C1	
Escherichia Coli	DIN 38411	DIN 10183–3
Coliforms	DI 38411	DIN 1083–3
Fecal coliforms	DIN 10183–3	DIN 10183–3
Total fats	NA	ASU L 06.00–6
Total protein (Nx6,25)	NA	ASU L 06.00–7
Energy value	NA	EU 1169/2011
Pharmaceuticals	DIN CEN/DM 16178	NA

Table 4. Physiochemical properties of sewage sludge and food waste

Parameter	Unit	Sewage sludge	Food waste
pH	-	6.6	4.6
Density	g/L OS	990	1000
Total solid	% OS	4.62	31.58
Total volatile solid	% DM	78.7	88.0
Lipophilic substances	% OS	4	0.16
Salt content	mg/100 g OS	145	14.18
Chloride	mg/L eluate	320	1700
Ammonium nitrogen	% OS	0.015	0.014
Nitrate nitrogen	% OS	< 0.001	< 0.001
Total nitrogen	% OS	0.29	0.9
Total organic carbon	% DM	34	40.7
Phosphorous	% OS	0.116	0.119
Calcium	% OS	0.128	NA
Potassium	% OS	0.044	NA
Magnesium	% OS	0.0344	NA
Total fats	g/100g	NA	6.2
Total protein (Nx6,25)	g/100g	NA	5.6
Carbohydrates	g/100g	NA	19.3
Energy value	kJ/100g	NA	653
OS: Original Substance DM: Dry matter			

food waste collected in a dining hall in Korea was reported to be 14.7 (Han and Shin 2004). Another study for food waste in Korea reported the C/N ratio of 18.3 (Shin et al. 2004). Therefore, incorporating food waste as a co-substrate with sewage sludge in the digestion process will significantly improve the feed characteristics for biogas production.

The measured concentrations of P, Ca, Mg and K for the feed indicate good nutrition content that will increase the growth rate and activity of microorganisms. This was reflected in the digestion efficiency and the final digested matter content. Jiries et al. (2017) reported a significant increase in NPK in the soils irrigated with untreated wastewater. Moreover, El-Hasan et al. (2019) has proven that application of treated bio-solids shows considerable enhancement of the macro and micro nutrients in favor of plantation.

Table 5 shows the results of the microbiological analysis for both sewage sludge and food waste.

The results show the presence of *Escherichia coli* and coliforms in both sewage sludge and food waste. *Salmonella* was not detected in either sewage sludge or food waste.

Table-6 shows the concentration of some selected pharmaceuticals in the domestic sewage sludge employed in this study.

The results shown in Table 6 indicate the presence of high concentrations of some ingredients of pharmaceuticals in the sewage sludge. The antieliptic and anticonvulsant carbamazepine concentration is 0.14 mg/kg which is several order of magnitude higher than that reported for the sludge samples collected from Quebec Urban Community wastewater treatment plant in Canada (Mohapatra et al. 2012).

The fluoroquinolone antibiotic ciprofloxacin is present at high level in the sewage sludge. The results indicate ciprofloxacin is 0.36 mg/kg. Lillenberg et al. (2010) reported ciprofloxacin concentrations of 0.111 and 0.426 mg/kg in Tartu and Tallinn cities in Estonia respectively.

Table 5. Microbiological analysis of sludge and food waste

Parameter	Unit	Sewage sludge	Food waste
Salmonella	in 50 g	Not detected	Not detected
Escherichia coli	cfu/g	1.3x104	3.2x105
coliforms	cfu/g	$5.6x10^5$	$3.8x10^5$
Fecal coliforms	cfu/g	$9.1x10^3$	$3.2x10^5$

Table 6. Concentration of some selected pharmaceuticals in domestic sewage sludge

Compound	Concentration (mg/kg)
Acetaminophen	0.0
Atenolol	<0.01
Carbamazepine	0.14
Chlortetracycline	<0.003
Ciprofloxacin	0.36
Clarithromycin	0.010
Clindamycin	<0.01
Clofibrinic acid	<0.01
Diclofenac	0.23
Caffein	<0.01
Doxycycline	<0.003
Enrofloxacin	<0.001
Ibuprofen	<0.01
17-beta-Estradiol	<0.01
Estriol	<0.01
Estron	<0.01
17-alpha-Ethinylestradiol	<0.01
Lincomycin	<0.01
Ketoprofen	<0.01
Oxytetracycline	<0.003
Metoprolol	0.020
Naproxen	<0.01
Salicylic acid	<0.01
Norfloxacin	<0.01
Sulfadiazine	<0.001
Propanolol	0.17
Roxithromycin	<0.01
Sulfamethoxazole	<0.001
Tetracycline	<0.003
Trimethoprim	<0.01

The macrolide antibiotic clarithromycin is also present at high level in sewage sludge. The results indicate that the concentration of clarithromycin is 0.01 mg/kg.

The anti-inflammatory painkiller diclofenac is present at high level in the sewage sludge. The results indicate diclofenac is 0.23 mg/kg. Jones et al. (2014) reported 0.07 mg/kg as a median concentration of diclofenac in the sewage sludge from 28 wastewater treatment plants in the UK.

Profile of methane gas production: Replacement mode of operation

Figure 2 shows the production rate of methane gas as a function of time under replacement mode of operation. Figure 3 shows the cumulative methane gas volume as a function of time.

When feeding the two digesters with only inoculums (digested sludge), low production rate of methane gas could be achieved. This can be attributed to the limited availability of volatile organic matter in the feed. Similarly, upon introducing the sludge from the Mutah-Mazar WWTP to the two digesters (stage 2), methane gas increased slightly at an average rate of 1.2 L/h.

It should be mentioned that feeding between stages was stopped for two days to let the bacteria starve for substrates. This mode of feeding caused sharp drop in the methane gas production between the feeding stages. At higher doses of food waste in the feed, the hourly methane gas production rate was fluctuating with time. Table 7 reports the average methane gas production rate and yield for the different stages of feeding.

Co-feeding food waste with sludge while maintaining the same total solid content at 115.5 g in the feed increased the methane gas production rate. Increasing the contribution of food waste from 0 to 50% (based on the total solid content in the feed) increased the average methane rate production from 1.1 to 5.4 L/h respectively. The presence of food waste with sludge has promoted higher methane production rates since the food waste provides additional source of volatile matter for methane biosynthesis. The gradual increase in

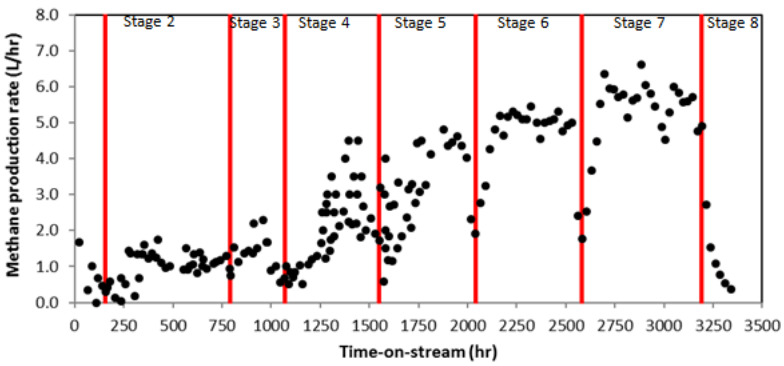

Figure 2. Methane gas production rate as a function of time under replacement mode of operation

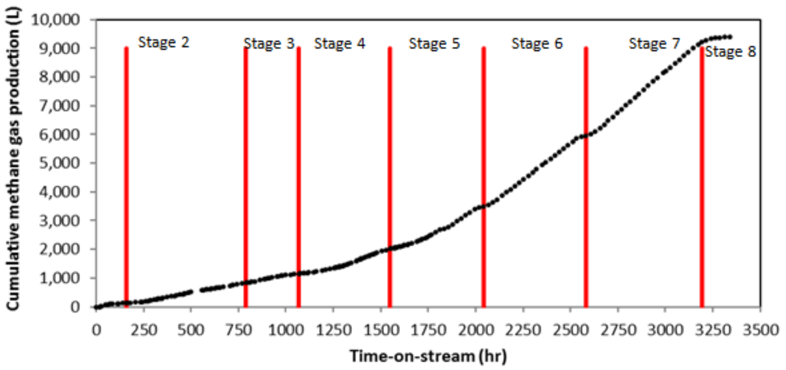

Figure 3. Cumulative methane gas volume as a function of time under replacement mode of operation

Table 7. The average methane gas production rate under replacement mode of operation

Stages	CH_4 production rate (L/h)	Cumulative CH_4 volume/ stage (L)	Total VS_{added}/stage (g)	Yield (ml/gVS_{added})
Stage 2	1.1	697	2363	295
Stage 3	1.2	328	1104	297
Stage 4	1.8	864	1861	464
Stage 5	3.0	1472	1882	782
Stage 6	4.6	2465	2189	1126
Stage 7	5.4	3268	2407	1358

the percentage of food waste in feed has enabled the bacteria to adapt the new conditions, thereby increasing the production rate of methane gas.

The methane gas yield under the replacement mode of operation ranged from 295 to 1358 ml/gVS_{added}. The results indicate that the methane gas yield increases along with the percentage share of food waste in the feed. Feeding with high percentage of food waste will provide more readily biodegraded carbonaceous organic matter, thereby increasing the amount of biogas produced based on the amount of volatile matter present in the feed.

The methane gas yields obtained in this study are in agreement with those reported in literature for similar systems. Xie et al. (2017) reported the methane gas yield of 799 ml/gVS_{added} for the co-digestion of primary sludge with food waste. The researchers reported 159 and 652 mL/gVS_{added} for the mono-digestion of primary sludge and food waste, respectively.

Operating the reactor under semi-continuous mode has promoted higher methane gas yields compared to batch co-digestion processes. For the same feed conditions and mixing ratios in batch system experiments, Aljbour et al. (2021) reported the methane gas yields in the range of 299 to 459 mL/gVS_{added}.

Profile of methane gas production: Addition mode of operation

Figure 4 shows the production rate of methane gas as a function of time under addition mode of operation. Figure 5 shows the accumulative methane gas volume as a function of time.

Table 8 reports the average methane gas production rate and yield for the different stages of feeding under addition mode of operation.

The methane gas production rate was smoothly increasing with time in the first stages under the addition mode of operation. Under high feed loading (stages 6 and 7), the rate of methane gas production fluctuated.

The amount of gas produced increased along with both TS and subsequently the TVS content of the feed. However, the methane gas yield under addition mode of operation is lower than in the process under replacement mode of operation. For example, at 10% food waste (based on TS present in the feed), the methane gas yields were 192 and 297 ml/gVS_{added} for addition and replacement modes of operation respectively. This might be attributed to the increased amount of total solid present in the reactor that caused substrate overdosing with respect to the available reactor volume and mass of microorganisms.

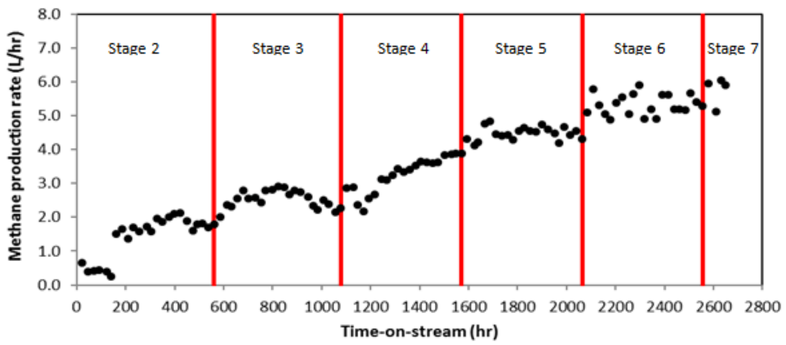

Figure 4. Methane gas production rate as a function of time under addition mode of operation

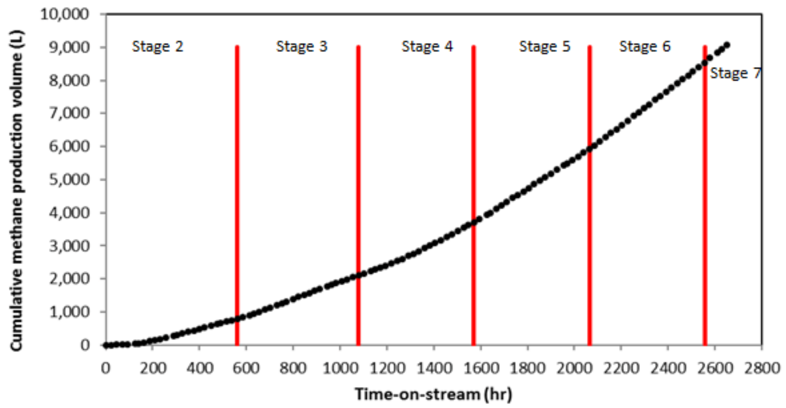

Figure 5. Cumulative methane gas volume as a function of time under addition mode of operation

Table 8. The average methane gas production rate and yield under addition mode of operation

Stages	CH_4 production rate (L/h)	Cumulative CH_4 volume/stage (L)	Total VS_{added}/stage (g)	Yield (ml/gVS_{added})
Stage 2	1.5	788	4099	192
Stage 3	2.6	1311	4355	301
Stage 4	3.4	1612	4554	354
Stage 5	4.6	2211	4960	446
Stage 6	5.2	2615	5651	463
Stage 7	5.6	535	1157	462

CONCLUSIONS

The anaerobic co-digestion of domestic sewage sludge with food waste was successfully conducted for biogas production. Incorporating food waste as a co-substrate was carried out under semi-continuous operation.

Increasing the food waste share in the feed increased the methane gas production rate and yield (in comparison to the anaerobic digestion of pure sewage sludge). Incorporating food waste under replacement mode of operation promoted higher biogas production rates and yields compared to the addition mode of operation.

Anaerobic co-digestion under semi-continuous operation enables handling large organic loadings compared to batch co-digestion processes. It is recommended to feed the food wastes continuously without interruption to maintain the bacterial activity and thus the digestion process at an adequate level.

Disclaimer

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REFERENCES

1. Alatriste-Mondragón, F., Samar, P., Cox, H.H., Ahring, B.K., Iranpour, R. 2006. Anaerobic codigestion of municipal, farm, and industrial organic wastes: a survey of recent literature. Water Environment Research, 78, 607–36.
2. Aljbour, S.H., El-Hasan, T., Al-Hamiedeh, H., Hayek, B., Abu-Samhadaneh, K. 2021. Anaerobic co-digestion of domestic sewage sludge and food waste for biogas production: A decentralized integrated management of sludge in Jordan. Journal of Chemical Technology and Metallurgy.
3. Carucci, G., Carrasco, F., Trifoni, K., Majone, M., Beccari, M. 2005. Anaerobic digestion of food industry wastes: effect of codigestion on methane yield. Journal of Environmental Engineering, 131, 1037–45.
4. Cockrell, P. 2008. Greasing digester-gas production. Water environment technology, 20, 70–73.
5. Dai, X., Li, X., Zhang, D., Chen, Y., Dai, L. 2016. Simultaneous enhancement of methane production and methane content in biogas from waste activated sludge and perennial ryegrass anaerobic co-digestion: The effects of pH and C/N ratio. Bioresource technology, 216, 323–30.
6. El-Hasan, T., Hamaidah, H., Aljbour, S., Bani Hani, N., Ismail, F., Shakhatreh, Y., Al Majali, D. (2019) 'The results of implementation of treated wastewater and Bio-soilds generated from WWTP on the plantation of fodder at marginal areas at Al-Karak, south Jordan. In: Al., A.E. (Ed.) Water Perspectives in emerging countries: water in agricultural practices. Cuviller Verlag, Gottingen.
7. Fitamo, T., Boldrin, A., Boe, K., Angelidaki, I., Scheutz, C. 2016. Co-digestion of food and garden waste with mixed sludge from wastewater treatment in continuously stirred tank reactors. Bioresource technology, 206, 245–54.
8. Gelegenis, J., Georgakakis, D., Angelidaki, I., Mavris, V. 2007. Optimization of biogas production by co-digesting whey with diluted poultry manure. Renewable energy, 32, 2147–60.
9. Gomez, X., Cuetos, M.J., Cara, J., Moran, A., Garcia, A.I. 2006. Anaerobic co-digestion of primary sludge and the fruit and vegetable fraction of the municipal solid wastes: Conditions for mixing and evaluation of the organic loading rate. Renewable energy, 31, 2017–24.
10. Gunaseelan, V.N. 2004. Biochemical methane potential of fruits and vegetable solid waste feedstocks. Biomass and bioenergy, 26, 389–99.
11. Hallaji, S.M., Kuroshkarim, M., Moussavi, S.P. 2019. Enhancing methane production using anaerobic co-digestion of waste activated sludge with combined fruit waste and cheese whey. BMC biotechnology, 19, 19.
12. Han, S.-K., Shin, H.-S. 2004. Biohydrogen production by anaerobic fermentation of food waste. International journal of hydrogen energy, 29, 569–77.
13. Jiries, A., Al-Nasir, F., El-Hasan, T. 2017. Pasture land in a desert area at Al-Karak province/Jordan. Solutions to Water Challenges in MENA Region: Proceedings of the Regional Workshop, April 25–30, 2017 Cairo, Egypt. Cuvillier Verlag.
14. Jones, V., Gardner, M., Ellor, B. 2014. Concentrations of trace substances in sewage sludge from 28 wastewater treatment works in the UK. Chemosphere, 111, 478–84.
15. Kabouris, J.C., Tezel, U., Pavlostathis, S.G., Engelmann, M., Todd, A.C., Gillette, R.A. 2008. The anaerobic biodegradability of municipal sludge and fat, oil, and grease at mesophilic conditions. Water Environment Research, 80, 212–21.
16. Koupaie, E.H., Leiva, M.B., Eskicioglu, C., Dutil, C. 2014. Mesophilic batch anaerobic co-digestion of fruit-juice industrial waste and municipal waste sludge: Process and cost-benefit analysis. Bioresource Technology, 152, 66–73.
17. Labatut, R.A., Angenent, L.T., Scott, N.R. 2011. Biochemical methane potential and biodegradability of complex organic substrates. Bioresource technology, 102, 2255–64.
18. Li, C., Champagne, P. and Anderson, B.C. 2011. Evaluating and modeling biogas production from municipal fat, oil, and grease and synthetic kitchen waste in anaerobic co-digestions. Bioresource technology, 102(20), pp.9471–9480.
19. Li, Y.Y., Sasaki, H., Yamashita, K., Seki, K., Kamigochi, I. 2002. High-rate methane fermentation of lipid-rich food wastes by a high-solids co-digestion process. Water Science and Technology, 45, 143–50.
20. Lillenberg, M., Yurchenko, S., Kipper, K., Herodes, K., Pihl, V., Lõhmus, R., Ivask, M., Kuu, A., Kutti, S., Litvin, S.V. 2010. Presence of fluoroquinolones

and sulfonamides in urban sewage sludge and their degradation as a result of composting. International Journal of Environmental Science Technology, 7, 307–12.

21. Maragkaki, A., Vasileiadis, I., Fountoulakis, M., Kyriakou, A., Lasaridi, K., Manios, T. 2018. Improving biogas production from anaerobic co-digestion of sewage sludge with a thermal dried mixture of food waste, cheese whey and olive mill wastewater. Waste management, 71, 644–51.
22. Mohapatra, D.P., Brar, S.K., Tyagi, R.D., Picard, P., Surampalli, R.Y. 2012. Carbamazepine in municipal wastewater and wastewater sludge: ultrafast quantification by laser diode thermal desorption-atmospheric pressure chemical ionization coupled with tandem mass spectrometry. Talanta, 99, 247–55.
23. Prabhu, M.S., Mutnuri, S. 2016. Anaerobic co-digestion of sewage sludge and food waste. Waste management research, 34, 307–15.
24. Shin, H.-S., Youn, J.-H., Kim, S.-H. 2004. Hydrogen production from food waste in anaerobic mesophilic and thermophilic acidogenesis. International Journal of Hydrogen Energy, 29, 1355–63.
25. Xie, S., Wickham, R., Nghiem, L.D. 2017. Synergistic effect from anaerobic co-digestion of sewage sludge and organic wastes. International Biodeterioration Biodegradation, 116, 191–97.
26. Zhang, R., El-Mashad, H.M., Hartman, K., Wang, F., Liu, G., Choate, C., Gamble, P. 2007. Characterization of food waste as feedstock for anaerobic digestion. Bioresource technology, 98, 929–35.
27. Zitomer, D.H., Adhikari, P., Heisel, C., Dineen, D. 2008. Municipal anaerobic digesters for codigestion, energy recovery, and greenhouse gas reductions. Water Environment Research, 80, 229–37.