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%. Kourpaie 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 activated sludge. 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. 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.
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

| Stages | Feeding rate (g/d) | TS content in feed (g) | FW ratio in feed (%) | Time of operation (d) |
|--------|--------------------|------------------------|---------------------|-----------------------|
| 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 | ISO 10304–1/2 |
| 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                              | DIN 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 (N x 6.25)   | 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.

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    | 1.3x10^4     | 3.2x10^5   |
| coliforms               | cfu/g    | 5.6x10^8     | 3.8x10^8   |
| Fecal coliforms         | cfu/g    | 9.1x10^7     | 3.2x10^5   |

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 anti-epileptic 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.
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

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

| Compound             | Concentration (mg/kg) |
|----------------------|-----------------------|
| Acetaminophen        | 0.0                   |
| Atenolol             | <0.01                 |
| Carbamazepine        | 0.14                  |
| Chlorotetracycline   | <0.003                |
| Ciprofloxacin        | 0.36                  |
| Clarithromycin       | 0.010                 |
| Clindamycin          | <0.01                 |
| Clofibric acid       | <0.01                 |
| Diclofenac           | 0.23                  |
| Caffeine             | <0.01                 |
| Doxycycline          | <0.003                |
| Enrofloxicin         | <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                 |
| Norfloxicin          | <0.01                 |
| Sulfadiazine         | <0.001                |
| Propanolol           | 0.17                  |
| Roxithromycin        | <0.01                 |
| Sulfamethoxazole     | <0.001                |
| Tetracycline         | <0.003                |
| Trimethoprim         | <0.01                 |

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

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

| Stages | CH₄ production rate (L/h) | Cumulative CH₄ volume/stage (L) | Total VSₑₑₚₑₑ/stage (g) | Yield (ml/gVSₐₕₑₑₑ) |
|--------|--------------------------|--------------------------------|-------------------------|----------------------|
| 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                 |

### 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.
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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