© IWA Publishing 2016
413
Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

Overcoming barriers to codigestion

D. L. Parry* and L. Fillmore

1100 112th Avenue NE, Suite 500, Bellevue, WA 98004-5118, USA

* Corresponding author. E-mail: David.Parry@ch2m.com

Abstract

Codigestion of organic waste with municipal wastewater sludge is growing rapidly. It has many benefits, including diversion of organic waste from landfills, increased renewable energy from biogas production, and potential for revenue from tipping fees. However, there are still barriers to greater widespread application of codigestion. Economics, need for collaboration between utilities, impacts on wastewater application, unsupportive regulations and risks to core wastewater treatment business are obstacles that slow wider adoption of codigestion throughout the world. The research presented analyzes the economic impacts of codigestion, predicts the additional biogas production, and determines the allowable organic loading rate and fats oils and grease (FOG) addition for stable digestion operation. The economic impacts were analyzed on a life cycle cost basis and presented in terms of required tipping fees for different organic wastes, electric rates and residuals handling costs. Standard biochemical methane potential tests were conducted to estimate biogas production from various organic wastes. The specific energy loading rate (SELR) was used to express the allowable organic loading rate. Results from the economic analysis showed that codigestion using existing digesters at a municipal water reclamation facility is more economical than building new digesters. Codigestion was more economical at facilities with high electricity costs and low cost of residuals. Tipping fees for receiving organic waste would be required to offset the net cost of codigestion for wastes other than FOG. There was a net positive economic benefit of receiving FOG without a tipping fee. The upper limit of FOG for stable digestion was found to be 60 percent of the feed by chemical oxygen demand (COD). Stable digestion can be achieved with an SELR of less than 0.25 kgCOD/day/kgVS. The SELR accounts for the strength or energy content of the organic feed measured in COD. It was observed and accounted for by the SELR that anaerobic digesters loaded at higher solids concentrations (resulting in greater inventory of microorganisms in the digesters) can be fed at higher loading rates. Insights into the economics of codigestion and allowable organic loading rates for high strength organic wastes help to overcome some of the barriers to widespread application of codigestion.

Key words: anaerobic digestion, biochemical methane potential (BMP), biogas, codigestion, energy, fats oils and grease (FOG), specific energy loading rate (SELR)

INTRODUCTION

Throughout the world, wastewater and organic waste are increasingly being viewed as resources where water, energy, biosolids, and nutrients can be reclaimed. The practice of codigesting organic waste with wastewater sludge is growing rapidly and is an example of an integrated solution. Codigestion can involve the wastewater, solid waste, and energy utilities along with the regulatory agencies for water quality, air emissions, and land application. Codigestion is growing rapidly because of numerous benefits such as diversion of organic waste from landfills and conversion of it to biogas: a renewable energy source (Parry 2013c). Still there are barriers to the widespread implementation of organic waste digestion, such as a need for collaboration among utilities, marginal economics, unsupportive regulations and a perceived risk to the core business of wastewater treatment. For example, the renewable energy generator may or may not need all the power produced and the value to sell it can be significantly less than the avoided

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

cost of buying it. The economics are marginally profitable. And even though digestion of organic waste is environmentally friendly, environmental regulations are not always supportive, introducing barriers from air, water and solid waste permitting requirements and discouraging codigestion. Finally, in the case of municipal water reclamation facilities, managers are often resistant to receiving trucked in organic waste because it can be viewed as a risk to their core business of wastewater treatment.

Collaboration is needed between the waste generators and the waste managers to help address these barriers. Research and additional communication can help overcome managers' fears and improve the economic viability of codigestion facilities. Research is needed to find answers on organic loading rates, digester stability and biogas production that leads to improved economic viability and operator confidence in codigestion. Areas of focus include stability of digestion systems receiving a variety of organic wastes, and developing more sophisticated organic loading rates to enable more aggressive loading while maintaining stability. In turn, higher organic loading rates enable more capacity out of existing digesters and saves costs by installing smaller new digesters for a specified capacity – improving the economic viability of standalone organic waste digestion and codigestion facilities.

A standalone organic waste digestion facility (i.e., not located at a water reclamation facility) has many needs, both in terms of assets and operations and maintenance staff. Waste receiving, pre-digestion solids processing, digesters, post-digestion solids processing, biosolids management, biogas treatment and utilization, and wastewater treatment of sidestreams are all needed and require operation and maintenance (O&M) by trained personnel. Codigestion of organic waste with domestic sludge at municipal water reclamation facilities can have much more favorable economics than standalone facilities.

Many water reclamation facilities have available capacity in existing anaerobic digesters that could accommodate organic waste. They also may have biogas treatment and utilization systems like biogas-fueled combined heat and power (CHP) systems. These water reclamation facilities also have wastewater treatment, solids processing, and biosolids systems complete with O&M staff. Even with all these favorable conditions for economic viability, most water reclamation facilities would require a tipping fee to cover their costs to receive organic wastes.

Fortunately, facilities that employ anaerobic digestion to process organic waste are increasing in number because of progressive leaders who are able to overcome the barriers (Vandenburgh *et al.* 2007; Greer 2011). These leaders collaborate across divisions between solid waste, wastewater and energy for mutually beneficial and integrated solutions that recover energy, water, biosolids, and nutrients from waste. They find ways to meet the economic challenge or to overcome the aversion to diversion of organic waste to water reclamation facilities. Organic waste and energy management are incorporated into their core business, and they manage risk and deal with environmental regulations.

One of the key drivers for a codigestion facility is economics. Revenue streams need to be greater than the costs of handling the additional organic wastes by enough margin to recover the capital investment and operating costs. Revenue can be derived from tipping fees for receiving organic waste, biogas production and residual biosolids. The biogas can be used to fuel a boiler or CHP system, sold to a nearby industry, purified to biomethane and sold as renewable natural gas or compressed and used to fuel compressed natural gas vehicles (Craig 2010). The biosolids can be sold as a soil amendment or as a fuel substitute depending on the local market and solids quality (e.g., Class A or B, dewatered cake or dried pellets, compost, etc.).

Costs include construction and operation of a receiving facility, anaerobic digestion, biosolids management (e.g., dewatering, drying), sidestream treatment, biogas treatment and use. There also are costs for processing the organics to remove contaminants, such as cardboard, plastics, metals and produce a digestible pulp.

The economics of a codigestion facility are strongly dependent on the waste characteristics, cost of digestion and cost of biosolids solids processing after digestion. Organic waste such as food waste can

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

be digested separately or with municipal wastewater solids. It has a high volatile solids to total solids percent (VS/TS) of over 80 percent, and digests well with a high VS reduction of over 80 percent. Fats, oils, and grease (FOG) digests well and is essentially all volatile and all converted to biogas. Cow manure, by comparison, has a VS/TS of around 80 percent, but has a low VS reduction of under 40 percent. These different waste characteristics have a strong influence on the economics with respect to costs of biosolids processing after digestion and the amount of biogas produced.

Barriers to codigestion can be overcome with strong leaders to drive codigestion implementation through collaboration with waste management, energy, and wastewater entities. Barriers will also be overcome with improved economics from tipping fee revenue, supportive regulations that encourage codigestion, and greater understanding of maintaining stable digestion operation while practicing codigestion. The feasibility of handling other community wastes by codigestion in water reclamation facility anaerobic digesters has been shown for food wastes (Tsang *et al.* 2007; Gray (Gabb) 2008), fat oils and grease waste (Stoll & Gupta 1997; Li *et al.* 2002; Gelegenis *et al.* 2007) and food processing and rendering wastes (Muller *et al.* 2009; Gough *et al.* 2012). At water reclamation facilities, the domestic sludge represents a majority of the material process and previous research has focused on codigestion with food, FOG, and a variety of other wastes (Li *et al.* 2002; Heo *et al.* 2003; Kim *et al.* 2003; Zitomer & Adhikari 2005; Alatriste-Mondragon *et al.* 2006; Bailey 2007; Chung *et al.* 2007; Kabouris *et al.* 2007, 2009; Rizk *et al.* 2007; Tsang *et al.* 2007; Vandenberg *et al.* 2007; Luostarinen *et al.* 2009; Muller *et al.* 2009). Codigestion has been shown to be an economically feasible food waste management approach (Parry 2012a, 2012b, 2013a). However, there are still several important and frequently asked questions regarding codigestion of organic wastes. These questions include, but are not limited to the following:

- What are the economic impacts of codigestion on the operation of a water reclamation facility?
- How much additional biogas will be produced from adding different organic wastes?
- What is the allowable organic loading rate for stable digestion?
- What fraction of the digester loading can be from food waste or FOG?

Answering these questions will help to overcome some barriers to codigestion. Research conducted by CDM Smith and funded by Water Environment Research Foundation (WERF) and Environmental Sustainability Transfer Certification Program (ESTCP) answered these questions and are presented below.

METHODS

Economic analysis

An economic analysis was conducted to gain insights on codigestion and evaluate tipping fee requirements for water reclamation facilities (Parry 2012a, 2012b, 2012c). Assuming that preliminary processing of the organic waste is covered by others, the required tipping fee that a water reclamation facility would need to cover its cost for handling an organic waste was calculated for different costs for electricity and residual biosolids. The costs for an organic waste receiving facility and sidestream treatment were assumed and kept constant. Digestion costs were assumed and a sensitivity analysis was performed by either assuming existing digesters were used (at no cost) or less digester volume was required because of a higher organic loading rate resulting in a low digester cost.

Biogas production

The additional biogas production from codigesting food waste and grease trap waste with municipal sludge was measured. Fifteen food waste samples from breakfast, lunch and dinner were collected

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

Figure 1 | On-line respirometer and digester bottles.

from the U.S. Air Force Academy dining hall (Mitchell Hall) in Colorado Springs, Colorado for five consecutive days (Parry 2013d). In addition, a sample of grease trap waste was also collected from an oil/grease separator tank at the facility. Samples were stored at 4 °C following collection (Evans 2012).

Biochemical methane potential (BMP) tests were used to assess the anaerobic digestibility and methane production potential of the food waste and grease trap waste samples (Owen *et al.* 1979). In these tests, individual food waste or grease trap waste samples were added at a concentration of 3 g COD/ L to anaerobic digester sludge (King County, Renton, Washington, South Wastewater Treatment Plant (WWTP); solids retention time (SRT) at 24 days), then incubated in sealed, anaerobic serum bottles at 37 °C (99 °F) for 38 days. Nutrients were not added as described in the original BMP method (Owen *et al.* 1979). Biogas production was monitored regularly over the course of the experiment using the wet-syringe volume test method.

Digesters were constructed from 2-L media bottles with a three-port head plate (Amador 2012). One of the ports was used for digester feeding and sampling. A second port was connected to a tedlar bag that served as a 'gas ballast' during liquid addition and withdrawal for the purpose of maintaining anaerobic conditions. The third port was connected to an on-line respirometer. Biogas accumulation, production rate, and concentration were measured using a Columbus Instruments Respirometer System (Columbus, Ohio).

Photographs of the system are included in Figure 1.

Organic loading rate

Conventional methods for monitoring the organic loading rate include hydraulic retention time (HRT) and VS loading rate don't account for the strength of the sludge fed to the digesters nor the characteristics of the digesters for digesting the feed sludge (Parry 2013b). Conventional methods are adequate for monitoring organic loading rates at municipal digesters without codigestion where the strength and concentration of the feed sludge are within a narrow range. The characteristics of organic waste that can be fed to a digester for codigestion vary in concentration and strength and impact the concentration and characteristics of the microorganisms in the digester. A digester with a higher concentration of microorganisms would have a greater capacity to digest organics than one with a lower concentration. A specific energy loading rate (SELR) was evaluated as an improved parameter for monitoring organic loading rates and characterizing digester capacity and stability. The SELR is a measure of energy loading relative to the amount of microorganisms in the digester. Using chemical oxygen demand (COD) as a proxy for energy and VS as a proxy for microorganisms, the SELR is the ratio of the organic loading

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

Figure 2 | Pilot scale digester.

rate to the active microorganisms in the digester and the units are kgCOD/day/(kgVS in digester). Direct measurements of biomass indicators, such as adenosine triphosphate (Velten *et al.* 2007), may be done and should be more accurate, but VS is used for this initial analysis. Tests were conducted in lab-scale 2-liter digesters at the CDM Smith laboratory in Bellevue, WA (Parry 2012a, 2012b, 2012c).

FOG limit

Of particular interest to codigestion facility operators is finding the limit of FOG addition that will still result in stable digester operation. The limits of organic loading rates for digestion of FOG with municipal wastewater sludge are presented based on research using pilot digesters. Two pilot scale digesters (Figure 2), each with an operating volume of 1,200 liters, were fed sludge from the Gold Bar WWTP, in Edmonton, Alberta, Canada (Parry 2012a, 2012b, 2012c).

One of the digesters was operated as a control digester and was fed only sludge and the second digester was the test digester. Equal sludge loadings were maintained to both the control and test digesters. Each digester was fed a total of 60 L/day for a 20-day HRT. From BMP tests a 20 day HRT was found to provide adequate time for digestion of FOG. The test digester was fed sludge and FOG with increasing increments of FOG resulting in COD loadings of 130, 160, 190, 270, 300% of the COD loading of the sludge alone. The incremental increased loading to the test digester corresponded to the amount of FOG representing from 20 to 60% of the feed. Data collected during the study included COD, biogas production and quality, total and VS, volatile fatty acids, pH, alkalinity, Total Kjeldahl Nitrogen and ammonia.

RESULTS AND DISCUSSION

Below are the results and discussion of the economic analysis, biogas production tests, organic loading rate evaluation, and FOG limit stress tests.

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

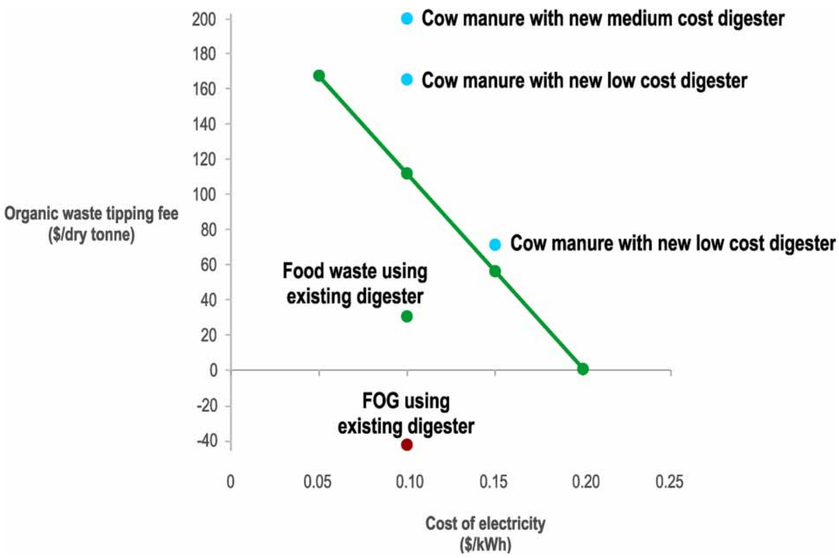

Figure 3 | Organic waste tipping fee required based on electricity cost.

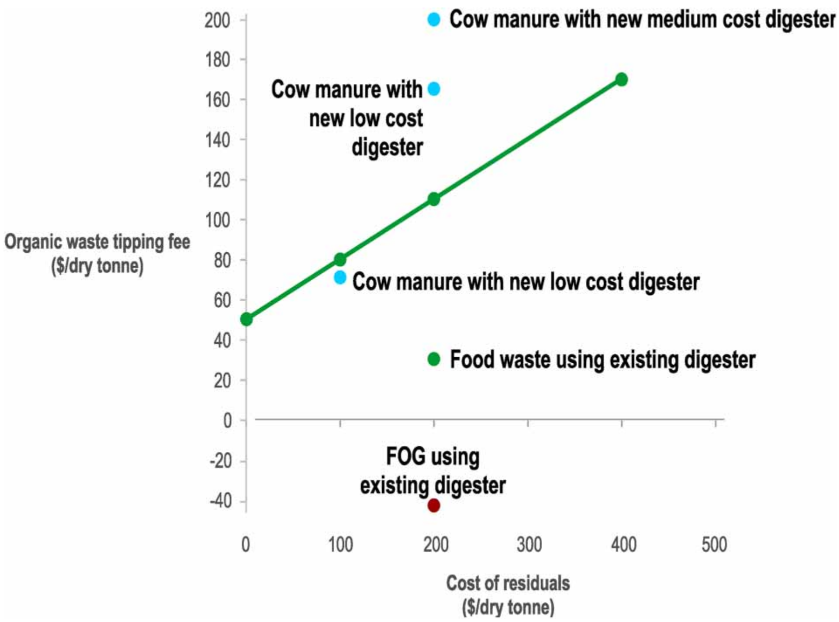

Figure 4 | Organic waste tipping fee required based on residuals cost.

Economic analysis

Results of the economic analysis (Parry 2013a) are shown in the accompanying Figures in terms of the required organic waste tipping fee given different electricity (see Figure 3) and residual biosolids (Figure 4) costs. The economics of an individual organic digestion facility will vary because of site specific conditions. In Figure 3, the tipping fees for food waste vary from $0 to $170/dry tonne for electricity costs of $0.05 to 0.20/kWh. These fees are based on medium cost digesters ($2.6/L with 2.4 g/d/L loading) and medium cost for biosolids residuals ($200/dry tonne). Tipping fee requirements for food waste assuming no cost for an existing digester is shown to illustrate the impact of digestion cost. The fees for cow manure are higher because of the lower VS reduction resulting in less biogas and more residuals. Cow manure is included in this analysis to show the higher costs for receiving an organic waste. The tipping fees for cow manure with a new low cost digester are

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

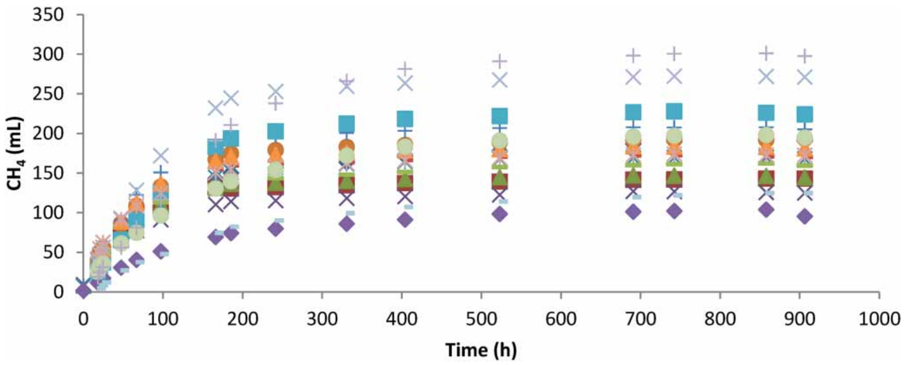

Figure 5 | Biogas production as methane for different food waste and grease trap waste (FOG) samples during BMP tests based on subtracting average methane production by the digester seed sludge-only controls.

shown for both electricity costs at 0.10 and 0.15 $/kWh for comparison. The tipping fee for FOG is negative indicating that the economic benefits of receiving FOG are greater than the costs. FOG is a much more desirable organic waste for codigestion than cow manure.

As shown in Figure 4, the tipping fees for food waste vary from $50 to $170/dry tonne for biosolids residuals costs of $0 to $400/dry tonne. These fees are based on medium electricity costs of $0.10/kWh. The fee for codigestion of food waste using existing digesters is significantly lower than having to build a new digester and demonstrates the benefit of codigestion using existing assets at a water reclamation facility. The tipping fees for cow manure with new low cost digesters are shown for both 100 and 200 $/dry tonne residuals cost. Again, the fee for FOG digestion is shown to be negative indicating an economic benefit.

The economic analysis demonstrates the strong dependence on organic waste characteristics, electricity costs and biosolids residuals costs. The most economic organic waste to energy facility would receive organic waste with high VS and VS reduction, have high electricity rates to get the most value out of the biogas (assuming CHP), and have low residuals management costs.

Biogas production

The biogas production from food waste collected at the Air Force Academy was measured (Evans 2012). The biogas production (methane accumulation trends for BMP tests with individual food waste samples and the grease trap waste sample are shown in Figure 5. Gas production is presented as volume of methane produced over time. These values are corrected for the average methane production by the inoculum alone in bottles without food or grease trap waste. The majority of methane generation was observed in the first 10 days but some generation continued for another 10 to 20 days. The average net methane yield for the food wastes was 390 $\pm$ 90 mL CH_4 per g of food waste COD fed, with values ranging from 190 to 570 mL/g COD. The theoretical value, based on assuming that 5% of the COD used ends up in cell mass, is 380 mL/g COD. The observed methane production from the grease trap waste sample was much higher, at 700 mL/g COD-fed. Some of the variation in the specific methane production is from applying the same average inoculum correction to all bottles. Some of the variation may also be attributable to different biodegradability of individual samples and/or enhancement of inoculum sludge digestion.

A substantial amount of the VS in food waste was converted to biogas (Amador 2012). The average food waste VS/TS ratio was 85% and the VS conversion was 82% resulting in 70% of the TS being converted to biogas. The biogas contained 65% methane and the specific biogas production rate was 844 L biogas/kg of VS converted.

The pilot digesters were fed 100 percent food waste without any municipal sludge. Nutrient deficiencies were observed for nickel, cobalt, and possibly molybdenum (Evans 2012). Nutrient

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

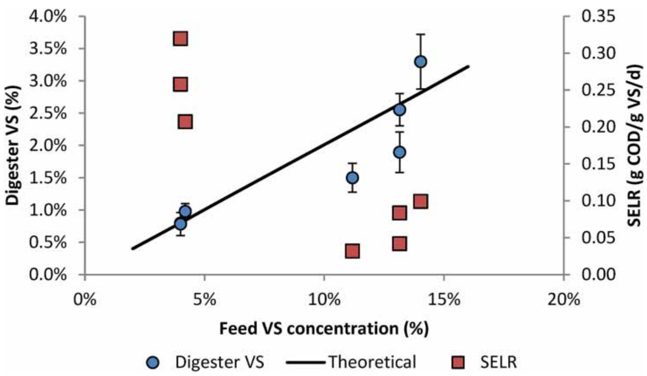

Figure 6 | Effect of food waste/FOG VS concentration in the digester feed on digester stability.

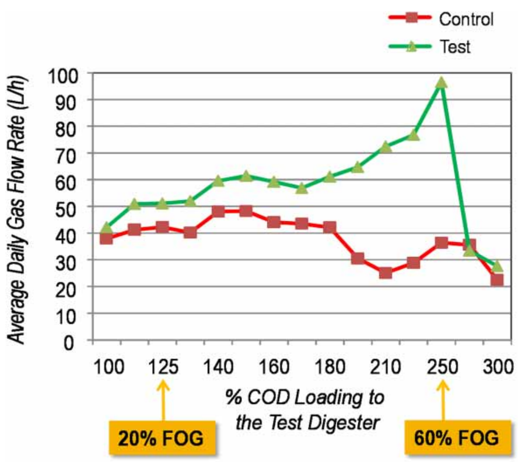

Figure 7 | Biogas production from FOG addition.

deficiency has been observed previously during food waste digestion (Hawkes *et al.* 1992). After the trace nutrient limitations were identified, these three nutrients were added to the feed and stable digestion was observed.

Organic loading rate

The effect of food waste and FOG VS concentrations on percent VS concentration in the digester and organic loading rate was measured and is shown in Figure 6 (Evans 2012). The SELR was calculated for these digesters and was greater in the unstable region (less than 5% VS feed) than in the stable region (greater than 10% VS feed). These data indicate the while the volumetric energy loading rates were similar (2.2 gCOD/d/L compared to 0.5 to 3.3 gCOD/d/L), different digester VS concentrations (i.e., active biomass concentrations) determined whether the digesters were stable – lower digester VS (e.g., 5%) led to too high a SELR. The low feed VS concentration and its commensurate low alkalinity also contributed to digester failure. SELRs of under 0.25 kgCOD/d/kgVS were stable, but reactors became less stable at higher loading rates.

FOG limit

The results of increasing the amount of FOG fed to the control digester compared to the test digester is shown in Figure 7. The average daily gas flow rate was observed to increase proportional to the increased COD up until an overload condition. The test digester was stressed up to 250% COD

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

loading of the test digester or 60 percent of the COD loading as FOG. At this point, the gas flow rate dramatically dropped off indicating a digester overload condition. Before the FOG limit was reached, the gas flow rate in the test digester was more than double that of the control digester demonstrating the potential for significant gas production from codigestion of FOG. The test digester appeared to be stable at 200% COD loading compared to the control digester or 50% of the COD feed to the digester as FOG. The organic loading rate in terms of SELR was also measured and stable digestion for the test digester was realized with SELRs less than 0.25 kgCOD/d/kgVS. The SELR of the control digester averaged 0.15 kgCOD/d/kgVS (Parry 2012a, 2012b, 2012c).

The limit for FOG addition as a percent of the COD fed to the digester would be expected to vary with different sludges and digestion processes. The limit presented here was for FOG added to municipal sludge and fed to a mesophilic digester.

CONCLUSIONS

Codigestion is economical when an adequate tipping fee is collected. Higher offset electrical costs and lower costs for handling residuals after digestion improve the economics. BMP tests demonstrated that substantial additional biogas can be produced with codigestion of food waste. Anaerobic digesters loaded at higher solids concentrations resulting in greater inventory of microorganisms can be fed higher loading rates. An SELR of less than 0.25 kg COD/day/kg VS inventory in the digester will support stable digestion. The upper limit for stable digestion operation appears to be less than 60% of the feed by COD as FOG. Some of the barriers to widespread application of codigestion can be overcome with increased knowledge about biogas production and digester stability with codigestion.

ACKNOWLEDGEMENTS

The authors acknowledge the Water Environment Research Foundation (WERF) and Environmental Security Technology Certification Program (ESTCP) for their financial support of projects referenced in this paper. The authors recognize H. David Stensel at the University of Washington and Ian Buchanan at the University of Alberta for their contributions and those of their graduate students. Malik Shahid and Hassan Katalambula at the Edmonton Waste Management Centre of Excellence (EWMCE) and Bob Bucher at King County, WA worked on the codigestion pilot facility. There are several CDM Smith staff that deserve recognition, because this paper covers several projects, including Patrick Evans, Janelle Amador, Diane Nelsen, Cale McPherson, Cameron Clark, and Scott Vandenburgh.

REFERENCES

Alatriste-Mondragon, 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 Environ. Res.* **78** (6), 607–636.

Amador, J. 2012 Anaerobic Digestion and energy recovery from food waste. In: *Proceedings of the 2012 WEF Residuals and Biosolids Conference*.

Bailey, R. S. 2007 An aerobic digestion of restaurant grease wastewater to improve methane gas production and electrical power generation potential. In: *WEFTEC*, San Diego, CA, pp. 6793–6805.

Chung, G., York, R. & Rank, S. 2007 Making cogeneration pencil out: an aerobic co-digestion of grease trap waste. In: *WEFTEC*, San Diego, CA, pp. 4506–4512.

Craig, D. 2010 Optimization of biogas production and use. In: *Proceedings of the 2010 WEF Residuals and Biosolids Conference*.

Evans, P. J. 2012 Factors controlling stable anaerobic digestion of food waste and FOG. In: *Proceedings of the 2012 WEFTEC*.

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest

Water Practice & Technology Vol 11 No 2
doi: 10.2166/wpt.2016.039

Gelegenis, J., Georgakakis, D., Angelidaki, I., Christopoulou, N. & Goumenaki, M. 2007 Optimization of biogas production from olive-oil mill wastewater, by codigesting with diluted poultry-manure. *Applied Energy* **84**, 646–663.
Gough, H. L., Nelsen, D. A., Muller, C. & Ferguson, J. F. 2012 Enhanced methane generation during theromophilic co-digestion of confectionary waste and grease-trap fats and oils with municipal wastewater sludge. Water Environment Research (in press).
Gray (Gabb), D. M. D. 2008 Anaerobic digestion of food waste. Final Report prepared for U.S. EPA. http://www.epa.gov/region9/organics/ad/EBMUDFinalReport.pdf.
Greer, D. 2011 Codigestion and Cogeneration in Des Moines, BioCycle February Issue
Hawkes, F. R., Rozzi, A., Black, K., Guwy, A. & Hawkes, D. L. 1992 The stability of anaerobic digesters operating on a food-processing wastewater. *Water Sci. Technol.* **25** (7), 73–82.
Heo, N. H., Park, S. C., Lee, J. S., Kang, H. & Park, D. H. 2003 Single-stage anaerobic codigestion for mixture wastes of simulated Korean food waste and waste activated sludge. *Appl. Biochem. Biotechnol.* **105–108**, 567–579.
Kabouris, J. C., Pavlostathis, S. G., Tezel, U., Engelmann, M., Todd, A. C. & Gillette, R. A. 2007 Anaerobic biodegradation of sludge and FOG. In: *WEF/AWWA Joint Residuals and Biosolids Management Conference*, Denver, CO, pp. 407–426.
Kabouris, J. C., Tezel, U., Pavlostathis, S. G., Engelmann, M., Dulaney, J., Gillette, R. A. & Todd, A. C. 2009 Methane recovery from the anaerobic codigestion of municipal sludge and FOG. *Bioresour. Technol.* **100** (15), 3701–3705.
Kim, H.-W., Han, S.-K. & Shin, H.-S. 2003 The optimisation of food waste addition as a co-substrate in anaerobic digestion of sewage sludge. *Waste Manage. Res.* **21**, 515–526.
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 Sci. Technol.* **45** (12), 143–150.
Luostarinen, S., Luste, S. & Sillanpaa, M. 2009 Increased biogas production at wastewater treatment plants through co-digestion of sewage sludge with grease trap sludge from a meat processing plant. *Bioresour. Technol.* **100** (1), 79–85.
Muller, C. D., Gough, H. L., Nelsen, D., Ferguson, J., Stensel, H. D. & Randolph, P. 2009 Investigating the process constraints of the addition of co-digestion substrates to temperature phased anaerobic digestion. In: *WEFTEC Proceedings*, Orlando, FL, 4810–4825.
Owen, W. F., Stuckey, D. C., Healey, J. B., Young, L. Y. & McCarty, P. L. 1979 Bioassay for monitoring biochemical methane potential and anaerobic toxicity. *Water Res.* **13**, 485–492.
Parry, D. L. 2012a Sustainable Food Waste Evaluation (WERF OWSO5R07e). Water Environment Research Foundation.
Parry, D. L. 2012b Co-Digestion of Organic Waste Products with Wastewater Solids (WERF OWSO5R07) Water Environment Research Foundation
Parry, D. L. 2012c Wastewater and organic waste to bioenergy. *Water Pract. Technol.* **7** (4).
Parry, D. L. 2013a Improving Economics of Codigestion (Part I), BioCycle, April issue.
Parry, D. L. 2013b Codigestion Research Builds Facility Operator Confidence (Part II), BioCycle, May issue.
Parry, D. L. 2013c Analyzing Food Waste Management Methods (Part III), BioCycle, June issue.
Parry, D. L. 2013d Food to Fuel Demonstration at US Air Force Academy (Part IV), BioCycle, July issue.
Rizk, M. C., Bergamasco, R. & Tavares, C. R. G. 2007 Anaerobic co-digestion of fruit and vegetable waste and sewage sludge. *Int. J. Chem. React. Eng.* **5**, A29.
Stoll, U. & Gupta, H. 1997 Management strategies for oil and grease residues. *Waste Manage. Res.* **15** (1), 23–32.
Tsang, R. K., Balzer, B., Baumler, R. J. & Frederics, D. 2007 Fueling biogas production at the Nansemond treatment plant with fat oil and grease through advanced anaerobic digestion. In: *WEF/AWWA Joint Residuals and Biosolids Management Conference*, Denver, CO, pp. 537–553.
Vandenburgh, S. R., Parry, D. L. & Stafford, D. 2007 Expansion of co-digestion at Lethbridge Alberta. In: *WEF/AWWA Joint Residuals and Biosolids Management Conference*, Denver, CO, pp. 349–356.
Velten, S., Hammes, F., Boller, M. & Egli, T. 2007 Rapid and direct estimation of active biomass on granular activated carbon through adenosine tri-phosphate (ATP) determination. *Water Res.* **41** (9), 1973–1983.
Zitomer, D. & Adhikari, P. 2005 Extra methane production from municipal anaerobic digesters. *Biocycle* **46** (9), 64–66.

Downloaded from https://iwaponline.com/wpt/article-pdf/11/2/413/381976/wpt0110413.pdf
by guest