Blending anaerobic co-digestates: synergism and economics
N. Navaneethan, P. Topczewski, S. Royer and D. Zitomer

ABSTRACT
Co-digestion is the process in which wastes from various sources are treated together. Therefore, more organic carbon is added to make efficient use of existing digesters. The objectives of this study were to compare potential co-digestates, determine synergistic and antagonistic co-digestion outcomes and estimate economic benefits for preliminary screening. Over 80 wastes were identified from 54 facilities within 160 km of an existing municipal digester. Synergistic, antagonistic and neutral co-digestion outcomes were observed for the various wastes. A simple economic comparison resulted in the greatest potential benefits for four co-digestates: yeast flavorings production waste, meat production dissolved air flotation float, acid whey from cheese production and thin stillage from corn ethanol production. Performance was investigated using bench-scale digesters receiving primary sludge with and without co-digestates. Methane production rates were 105 and 66% higher when co-digestates were present, but were anticipated to increase only 57 and 23% due to the additional chemical oxygen demand. Therefore, significant synergistic outcomes were observed during co-digestion. Co-digestion of the most promising wastes with primary sludge in full scale was estimated to generate enough electricity to power more than 2,500 houses.

Key words | anaerobic digestion, biochemical methane potential, co-digestion, greenhouse gas emissions, renewable energy

INTRODUCTION
Anaerobic biotechnology is often applied to treat waste from one location, such as a municipality or industry. However, co-digestion of a mix of material from multiple locations can also be employed. When multiple co-digestates are properly blended, more organic carbon can be digested at a facility to produce more methane and renewable energy.

Increased use of co-digestion can help reduce greenhouse gas (GHG) emissions. GHG emission from materials such as dairy manure that release methane to the atmosphere can be reduced by collecting and burning the methane. Also, the biogas can replace fossil-fuel-derived electricity that generates CO₂ from sequestered carbon, such as coal. It is estimated that biogas plants in Denmark reduced the country’s total 1996 GHG emissions by 0.3% (Maeng et al. 1999). Biomass carbon, such as that in food, ethanol and bio-diesel production waste, is primarily derived from CO₂ fixed from air; therefore digesting and burning this organic carbon recycles CO₂ back to the atmosphere with little or no net increase.

When blending co-digestates, the possible outcomes can be synergistic, antagonistic or neutral based upon methane production that is greater than, less than or the same as that observed when each material is digested alone (Zitomer et al. 2008). These outcomes have not been studied for a broad range of co-digestates in a systematic manner, and no standard test exists to categorize outcomes. In addition, the meaning of ‘methane production’ is not obvious, and must be carefully defined. Methane production can be quantified in different ways, including a rate (i.e. the maximum, instantaneous specific rate of methane production observed, mL CH₄/g volatile solids (VS)-h) or an ultimate yield (i.e. the amount of biogas produced after a significantly long time, mL CH₄/g chemical oxygen demand (COD)). In general, synergism is especially desirable and may result when nutrient-rich and nutrient-deficient wastes are blended; the nutrient-rich wastes cause higher microbial growth and substrate utilization rates. However, other synergistic mechanisms may
exist. For example, synergism has been observed when fats, oil and grease (FOG) wastes were co-digested with municipal wastewater sludge; however, synergism examples are not fully documented and the exact mechanisms have not yet been determined. Antagonism may result when one or more wastes containing toxic or inhibitory substances are mixed with biodegradable wastes.

Co-digestion using municipal anaerobic digesters is especially promising since many exist and are distributed around the world. Often, excess digestion capacity is available, and equipment is in place to use additional biogas for heat and power. Co-digestates considered by others for addition to municipal sludge include municipal solid waste (Rintala & Jaervinen 1996; Hamzawi et al. 1998; Bjornsson et al. 2000; Einola et al. 2001; Sosnowski et al. 2005), food waste (Di Palma et al. 1999; Edelmann et al. 2000; Lafitte-Trouque & Forster 2000), and restaurant FOG (Alatriste-Mondragon et al. 2006; Bailey 2006). By adding these co-digestates, municipal digesters can become regional renewable energy facilities. However, co-digestion costs, including conveyance and biosolids management, should be compared with benefits to help assess the sustainability of any co-digestion program.

The work described herein was performed to assess anaerobic co-digestion of various wastes with municipal sludge as a sustainable energy technology. Objectives were to (1) identify potential co-digestates, (2) determine synergistic, antagonistic and neutral effects and (3) determine economic benefits. On-going work includes investigating changes in microbial community structure during co-digestion of various materials as well as implementing co-digestion after full-scale testing.

**METHODS**

**Potential co-digestates**

A market survey was performed to identify high-strength wastes produced within a 160-km radius of the Milwaukee Metropolitan Sewerage District South Shore Wastewater Reclamation Facility (Oak Creek, WI, USA). Regional industries were contacted and questioned about potential co-digestate identity, quantity and constituent concentrations. After preliminary screening, the most promising wastes were sampled and characterized by constituent analyses, biochemical methane potential (BMP) and anaerobic toxicity assay (ATA) testing. Finally, selected wastes were co-digested in bench-scale digesters.

**BMP and ATA testing**

The BMP protocol of Owen et al. (1979) was used to screen co-digestates in terms of the volume of methane produced per unit of waste at 35 °C and 1 atm. Test systems contained approximately 65 mg COD of waste and 30 mL of biomass. Seed blanks were also prepared with seed sludge but no waste. BMP was calculated as the total volume of methane produced in test systems less the total volume of methane produced by seed blanks.

ATAs were performed to determine the potential inhibitory or stimulatory effect of each waste on maximum methane production rate from acetate (Owen et al. 1979). For each assay, different doses of waste (<12 g COD/L) were added with calcium acetate (10 g/L) as the main, non-limiting substrate to 50 mL of biomass. The maximum methane production rate was determined by linear regression using the initial portion of a graph of cumulative methane production versus time. For inhibitory wastes, the concentration causing a 50% decrease in methane production rate (IC50 concentration) was determined from a graph of methane production rate versus waste concentration.

For both BMP and ATA tests, seed biomass was from a bench-scale anaerobic digester fed non-fat dry milk. Testing was conducted in 160-mL serum bottles sparged with oxygen-free gas (7:3 v/v N2:CO2) and sealed with solid, black, butyl rubber stoppers. All testing was performed in triplicate at 35 °C and 150 rpm using an incubator shaker (model C25KC, New Brunswick Scientific, Edison, NJ). The biogas volume produced was measured at ambient pressure and 35 °C every day using a 100-mL glass syringe with a wetted glass barrel.

**Bench-scale anaerobic digesters**

Three pairs of bench-scale digesters (Control, Co-Digester 1 and Co-Digester 2) were operated. Control digesters were fed synthetic primary sludge, whereas Co-Digesters 1 and 2 each received co-substrates in addition to synthetic primary sludge. All digesters were 4.5-L vessels containing 2.5 L of active volume initially seeded with biomass from a full-scale anaerobic digester (South Shore Wastewater Reclamation Facility). Digesters were operated with daily feeding at a solids retention time of 15 days and were continuously mixed using magnetic stirrers (150 rpm) in a temperature-controlled room (35 °C). Synthetic primary sludge (total solids (TS) = 2.9% and VS = 2.4%) was a mixture of organic (12% fat, 26% protein 5% fiber) and inorganic solids (Natural Choice Dog Food, NutroProducts, Inc., City of Industry, CA, USA) and anaerobic basal medium. Biogas
was collected in gas sampling bags connected to each digester; the volume produced was measured by forcing the collected biogas through a wet test gas meter.

After Day 55, Co-Digester 1 systems were fed the following five co-digestates (described in Table 1) in addition to synthetic primary sludge: float (3.1 mL/day, 0.52 g COD/day), can crushing waste (2.8 mL/day, 0.22 g COD/day), thin stillage (4.9 mL/day, 0.76 g COD/day), flavorings yeast (1 mL/day, 0.26 g COD/day) and acid whey (3.7 mL/day, 0.54 g COD/day). Co-Digester 2 systems were fed with synthetic primary sludge and flavorings yeast waste (4 mL/day, 1.05 g COD/day) which was shown to have synergistic effects in previous work (Zitomer et al. 2008). Control systems were fed only synthetic primary sludge. Feed concentrations and volumes to bench-scale anaerobic digesters were selected based on current feed conditions for the full-scale digester at South Shore Wastewater Reclamation Facility and the volumes of co-digestates produced.

**Cost-benefit analysis**

A simple cost-benefit analysis was performed for co-digestates. This simple analysis was only meant to be used as an estimate for preliminary comparison of co-digestates, and should not be assumed to represent actual full-scale costs. See Table 2 for example calculations for thin stillage waste. The estimated net worth of each co-digestate was calculated as the sum of the estimated value of methane produced \( (A = 0.21 \text{ United State Dollar (USD)/m}^3 \text{ CH}_4 \text{ at } 35 \text{ C}) \), GHG avoided \( (B = 0.005 \text{ USD/kg CO}_2) \) and treatment fee \( (C_1 = 0.28 \text{ USD/kg BOD}_5 \text{ and } C_2 = 0.28 \text{ USD/kg TS}) \) less the sum of waste conveyance \( (D = 0.16 \text{ USD/m}^3 \text{ km}) \) and solids handling and disposal \( (E = 0.11 \text{ USD/dry TS kg}) \). The CO\(_2\) avoidance was estimated assuming fuel switching from bituminous coal (emission factor \( (F) = 0.0088 \text{ kg CO}_2/\text{MJ}) \). The emission factor for biomethane was assumed to be negligible since the CO\(_2\) emitted was assumed to be originally fixed from the atmosphere. Methane unit cost \( (A) \) was estimated from historical natural gas prices in the USA. The unit GHG emission credit value \( (B) \) was estimated from the average daily closing price of 2003-vintage CO\(_2\) credits on the Chicago Climate Exchange. Unit treatment fees \( (C_1 \text{ and } C_2) \) were estimated based on current municipal waste treatment fees charged by municipalities in and near Milwaukee, Wisconsin. The waste BOD\(_5\) concentration was estimated to be 50% of the measured COD concentration. Waste conveyance unit cost \( (D) \) was estimated from tanker truck contract costs after discussion with regional trucking companies. The conveyance distances are given in Table 1. Solids handling and disposal unit cost \( (E) \) was estimated after discussion with operators of various, nearby wastewater treatment plants. A volatile solids reduction value of 50% was assumed; therefore, solids to be disposed of were assumed to be composed of half of the waste volatile solids and all of the

<table>
<thead>
<tr>
<th>Waste</th>
<th>COD (mg/L)</th>
<th>TS (%)</th>
<th>Description</th>
<th>Distance to digester, km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cookie</td>
<td>12,500</td>
<td>0.6</td>
<td>Industrial bakery</td>
<td>153</td>
</tr>
<tr>
<td>Float</td>
<td>132,800</td>
<td>12.5</td>
<td>Dissolved air flotation</td>
<td>26</td>
</tr>
<tr>
<td>Flavorings yeast</td>
<td>215,600</td>
<td>15.7</td>
<td>Food flavorings production</td>
<td>12</td>
</tr>
<tr>
<td>Thin stillage</td>
<td>137,200</td>
<td>9.1</td>
<td>Corn ethanol production</td>
<td>100</td>
</tr>
<tr>
<td>Acid whey</td>
<td>148,000</td>
<td>12.7</td>
<td>Cheese production</td>
<td>79</td>
</tr>
<tr>
<td>Boiler cleaning waste</td>
<td>32,900</td>
<td>5.7</td>
<td>Coal-fired boiler heat exchanger</td>
<td>48</td>
</tr>
<tr>
<td>Metal cutting waste</td>
<td>75,400</td>
<td>2.3</td>
<td>Machine shop</td>
<td>48</td>
</tr>
<tr>
<td>Can crushing waste</td>
<td>76,431</td>
<td>6.1</td>
<td>Soft drink production, expired</td>
<td>120</td>
</tr>
</tbody>
</table>

**Table 2 | Typical cost-benefit calculation**

<table>
<thead>
<tr>
<th>Description of value per m(^3) of waste</th>
<th>Equation(^a)</th>
<th>Value for thin stillage(^b)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value of methane produced ( (A) )</td>
<td>( a = \text{BMP}^4 \text{COD}^4 A )</td>
<td>10.1</td>
</tr>
<tr>
<td>Value of GHG avoided ( (B) )</td>
<td>( b = \text{BMP}^4 \text{COD}^4 \text{B}^4 \text{F}^4 \text{G} )</td>
<td>0.4</td>
</tr>
<tr>
<td>Treatment fee ( (c) )</td>
<td>( c = (\text{COD}/2 \text{C}1) + (\text{TS}/\text{C}2) )</td>
<td>44.7</td>
</tr>
<tr>
<td>Waste conveyance cost ( (d) )</td>
<td>( d = \text{D}^4 \text{ distance} )</td>
<td>16.0</td>
</tr>
<tr>
<td>Solids handling and disposal cost ( (e) )</td>
<td>( e = (\text{VS}/2 + \text{TS}-\text{VS})^4 \text{E} )</td>
<td>5.5</td>
</tr>
<tr>
<td>Total net worth ( (\text{TNW}) )</td>
<td>( \text{TNW} = a + b + c + d + e )</td>
<td>33.8</td>
</tr>
</tbody>
</table>

\(^a\)Values of constants A through G are described in the ‘Cost-benefit analysis’ section herein.

\(^b\)Thin stillage \( (\text{BMP} = 0.35 \text{ L CH}_4/g \text{ COD}, \text{TS} = 0.09 \text{ kg L}, \text{VS} = 0.08 \text{ kg L}, \text{COD} = 137 \text{ g L, distance} = 100 \text{ km})\).
inert solids. A methane heat content (G) of 35 MJ/m³ CH₄ at 35 °C was employed.

**Analytical methods**

COD, TS, VS, metals and alkalinity concentrations were measured using standard methods (APHA *et al*. 1998). The pH was measured using a glass electrode and meter. Biogas methane content and volatile fatty acid (VFA) concentrations were determined by gas chromatography (Series 7890A GC system, Agilent Technologies, Santa Clara, CA, USA) with a thermal conductivity detector and flame ionization detector, respectively.

**RESULTS AND DISCUSSION**

**Identification of most promising co-digestates**

There were 81 wastes from 54 facilities identified during the market survey. The types of wastes (and percent ages of the total number of wastes) were as follows: food production (76%), corn ethanol production (8%), brewing and malting (7%) and other wastes (9%). Other wastes included algae removed from lakefront areas, zoo animal waste and soap production wastes. Food wastes were from meat products, dairy and cheese production, flavorings production, frozen foods, snack foods, candy, soy products and mustard production. From preliminary screening, eight wastes (see Table 1) were chosen for characterization based upon the significant volume produced, high COD concentration, and/or proximity to the digester.

The BMP results for the eight wastes are presented in Figure 1. Methane was produced from all the co-digestates tested, with average BMP values ranging from 20 to 418 mL CH₄/g COD. High BMP values (≥290 mL CH₄/g COD) were observed for six of the wastes: (1) cookie, (2) float, (3) thin stillage, (4) flavorings yeast, (5) can crushing and (6) acid whey (see Figure 1). Low BMP values (<100 mL CH₄/g COD) were observed for metal cutting and boiler cleaning wastes (Figure 1).

The ATA results for various wastes include synergistic, antagonistic and neutral outcomes based on a comparison of maximum methane production rates when calcium acetate was the main co-digestate (see Figures 2–4). The maximum rates of methane production increased approximately 25% for increasing doses of flavorings yeast and thin stillage, and 14% for can crushing waste (see Figure 2); these three wastes showed synergistic effects. Antagonism was observed for boiler cleaning wastewater (IC₅₀ = 9.5%), metal cutting waste (IC₅₀ = 12%) and cookie waste (IC₅₀ > 50%) as shown in Figure 3. Antagonistic outcomes may have been caused by inhibitory concentrations of copper (68 mg/L) and chromium (6.9 mg/L) in boiler cleaning waste. The inhibitory substances in metal cutting and cookie wastes are unknown. Neutral outcomes were observed for float and acid whey wastes (see Figure 4).

**Cost-benefit analysis**

Cost-benefit analysis results are presented in Figure 5. The economic estimate resulted in high positive values for four co-digestates: (1) flavorings yeast, (2) float, (3) acid whey and

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**Figure 1** | BMP results for eight promising co-digestates. Error bars represent standard deviation of triplicate measurements. The CH₄ volume is reported at 35 °C, 1 atm.

**Figure 2** | Synergistic anaerobic activity outcomes. Average activity increased with increasing waste concentration.
During the co-digestion period (Days 55–100), methane production rates of Co-Digesters 1 and 2 systems increased by 105 and 66% in comparison to the Control systems, respectively. When extra organic carbon is added to co-digesters, the methane production rate is expected to increase. But the extra methane production from the additional co-digestate carbon was theoretically anticipated to be 57 and 23% greater from Co-Digesters 1 and 2, respectively. Therefore, the additional methane resulting from synergism in Co-Digesters 1 and 2 was 48 and 43% of the Control methane production.

TS and VS removal efficiencies in Co-Digesters 1 and 2 increased by 50 and 33%, respectively, in comparison to the Control systems. The biogas methane content was $62 \pm 1\%$ under all three digester conditions. The average effluent values of the following parameters were not statistically different in the three digester systems (average value ± standard deviation): pH ($7.28 \pm 0.05$), alkalinity (6,000 ± 60 mg/L as CaCO$_3$), effluent SCOD (1,040 ± 40 mg/L) and total VFA (0.31 ± 0.05 eq/L).

Bench-scale digester results were used to estimate the energy production and carbon dioxide avoidance from full-scale co-digestion that will be pilot tested within three months (see Table 3). The full-scale Co-Digester 1 scenario involves a feed volume including 1,890 m$^3$/day primary sludge, 38 m$^3$/day float, 12 m$^3$/day flavors yeast, 61 m$^3$/day thin stillage, 45 m$^3$/day acid whey and 36 m$^3$/day can crushing waste. The Co-Digester 2 scenario will involve a feed including 1,890 m$^3$/day primary sludge and 12 m$^3$/day flavors yeast. Co-Digesters 1 and 2 scenarios were estimated to result in a decrease in net CO$_2$ emissions assuming that biogas replaces coal as fuel (see Table 3).

The electricity generated from Co-Digestion 1 and 2 scenarios was estimated to produce enough energy to power 2,500 and 340 houses more than that generated from digesting primary sludge alone. However, actual full-scale energy production and CO$_2$ emissions may vary due to other factors.
Co-digestion outcomes can be categorized as synergistic, antagonistic or neutral based on the rate of acetate plus co-digestate biogas production being greater than, the same as, or less than that observed when the acetate and co-digestate are each digested alone. Promising co-digestates can be identified based on waste characteristics as well as the volume of waste produced and apparent toxicity. A simple net-benefit analysis of promising co-digestates is a tool to select materials for full-scale co-digestion. The co-digestion of five wastes (float, spent yeast, thin stillage, acid whey and soft drink can crushing waste) in addition to primary sludge is potentially feasible at full scale. Co-digestion of these wastes increased biogas production significantly more than the value predicted based upon BMP values alone. Hence, co-digestion is one method to increase renewable energy production via anaerobic digestion.

### REFERENCES


Bailey, R. 2006 City of Riverside, California Grease to Gas to Power. City of Riverside, California.


### Table 3

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Co-Digester 1</th>
<th>Co-Digester 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Primary sludge flow (m³/day)</td>
<td>1,890</td>
<td>1,890</td>
<td>1,890</td>
</tr>
<tr>
<td>Co-digestate flow (m³/day)</td>
<td>0</td>
<td>192</td>
<td>12</td>
</tr>
<tr>
<td>Total methane (ML/day)</td>
<td>15.1</td>
<td>34.1</td>
<td>17.7</td>
</tr>
<tr>
<td>Methane energy (1,000 MJ/day)</td>
<td>530</td>
<td>1,190</td>
<td>620</td>
</tr>
<tr>
<td>Estimated CO₂ emissions avoidance (tonnes/year)</td>
<td>17,000</td>
<td>38,200</td>
<td>19,900</td>
</tr>
<tr>
<td>Average US homes provided electricity (houses)</td>
<td>2,000</td>
<td>4,500</td>
<td>2,340</td>
</tr>
</tbody>
</table>

*Assuming methane heat content of 0.035 MJ/L CH₄ at 35 °C (930 BTU/ft³).

*Assuming switching from bituminous coal and coal emissions factor of 0.088 kg CO₂/MJ (Hong & Slastick 1994).

*Assuming average US household electricity usage of 90 MJ/day (25 kWh/day) and biogas-to-electricity conversion efficiency of 34% (10,000 BTU/kWh) (Speece 1996).

### CONCLUSIONS

Co-digestion outcomes can be categorized as synergistic, antagonistic or neutral based on the rate of acetate plus co-digestate biogas production being greater than, the same as, or less than that observed when the acetate and co-digestate are each digested alone. Promising co-digestates can be identified based on waste characteristics as well as the volume of waste produced and apparent toxicity. A simple net-benefit analysis of promising co-digestates is a tool to select materials for full-scale co-digestion. The co-digestion of five wastes (float, spent yeast, thin stillage, acid whey and soft drink can crushing waste) in addition to primary sludge is potentially feasible at full scale. Co-digestion of these wastes increased biogas production significantly more than the value predicted based upon BMP values alone. Hence, co-digestion is one method to increase renewable energy production via anaerobic digestion.

Figure 6 | Methane production rate of digesters. *Theoretical CH₄ production = CH₄ production from control + theoretical CH₄ production of co-digestates which was calculated using BMP values of co-digestates.


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