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Research Article

Evaluation of Co-Digestion at a Commercial Dairy Anaerobic Digester

Co-digestion of dairy manure with off-farm waste has become a common practice on US farms, however, little data at a commercial-scale is present within the literature. In response, a mesophilic, mixed plug-flow reactor co-digesting 16.36% v/v food processing substrates with dairy manure, was monitored for its performance and substrate effects. Co-digestion, as compared to substrate or manure-only digestion, allowed for more preferred levels of key micronutrients, neutral pH, and additional alkalinity while also producing C/N and C/N/P ratios of 28:1 and 112:4:0.5, respectively. Reduction percentages were 45.36, 55.28, 67.72, and 99.87% for TS, VS, COD, and VFA, respectively, while fecal coliform bacteria as an indicator organism showed a 2 $\log_{10}$ reduction. A manure-only modeled baseline was developed for comparison with the experimental co-digestion data with co-digestion resulting in a 110% increase in biogas production and a tripling of gross receipts with 72% of all receipts being directly due to substrate supplementation. Specific methane productivities for the manure-only and co-digestion scenarios were 0.23 and 0.37 m^3 CH_4/kg VS_{load}, respectively. Addition of substrates tripled project gross revenues and accounted for 72% of all receipts, however, inclusion of substrates led to significant increases in total nitrogen and phosphorous loading to the farm.

Keywords: Anaerobic digestion; Co-digestion; Dairy manure; Economic analysis; Nutrient management

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1 Introduction

The typical US dairy manure management strategy is to collect and store manure using an open-air liquid/slurry lagoon which can lead to concerns in odor, air and water quality, and greenhouse gas (GHG) emissions. Anaerobic digestion (AD) technologies can assist in alleviating these environmental concerns. The AD treatment of dairy manure has been shown at the commercial-scale to lead to odor reduction, waste stabilization, pathogen reduction, and GHG emission reductions [1–4]. Beyond these benefits, the AD process is also of interest to dairy operations because the methane (CH_4) rich biogas can be used to generate electricity and heat [5].

However, several economic studies of commercial dairy digesters in Europe and the US have revealed that electrical sale receipts are often not enough to offset the high capital costs of AD units ($1500/cow for 1500–2500 cow operations; [6]). A Danish study concluded that manure-only digestion resulted in an average biogas yield of 20–30 m^3/metric ton while a production of 30 m^3/metric ton was required to offset capital costs and solidify positive economics [7]. Bishop [8] echoed these results by showing that generation of a positive net present value was highly dependent upon electrical sale price received, often requiring prices above those attainable in certain regions of the US, such as the Pacific Northwest [9].

The most actively applied process for overcoming sole reliance on received electrical prices and providing supplemental revenue is co-digestion of the manure with additional organics brought to the farm gate. Typical organic substrates used for co-digestion purpose are food processing wastes, industrial greases and oils, and organic fraction municipal solids (OFMSW). By practicing co-digestion the producer gains additional revenue through a combination of received tipping fees, additional biogas production, and the resulting increase in received green tags. Co-digestion of manure with various substrates has been actively researched at laboratory and pilot-scale [10–21] with a few studies completed at commercial-scale [7, 22, 23]. These studies conclude that manure with its high alkalinity and availability of macro- and micro-nutrients generates positive synergisms with many received substrates, which allows for significant enhancement of biogas productivity.

Furthermore, digesters utilizing substrates for co-digestion are capable of operating under organic loading rates (OLR) and volatile fatty acid (VFA) concentrations as high as 10 kg VS/m^3/day and 8 g/L, respectively [18]. Depending upon the type, concentration, and flowrate of the substrate used, biogas production can be enhanced by as much as 25–400% [17, 24]. In addition to the benefits, there are several potential drawbacks to the use of substrates for co-digestion.

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Abbreviations: **AD,** anaerobic digestion; **AU,** animal units; **COD,** chemical oxygen demand; **FC,** fecal coliform; **HRT,** hydraulic retention times; **TAN,** total ammonia nitrogen; **TKN,** total Kieldahl nitrogen; **TP,** total phosphorous; **TS,** total solids; **VFA,** volatile fatty acid; **VS,** volatile solids

These drawbacks include inhibitory effects on methanogenic growth given various types of substrates and the loading rates utilized [25], concerns regarding pathogen and heavy metal contamination within the substrates [12], and nutrient over-loading on the farm. USDA APHIS [26] statistics relate that approximately 36% of all dairy CAFOs experience nitrogen overloads while 55% experience phosphorous overloads. By bringing substrates through the farm gate, producers could be making the nutrient overloading problem worse.

Recognizing that there is considerable interest in co-digestion in the US and very limited commercial information exists in regard to this practice, a monitoring and evaluation project was initiated at a Washington State dairy digester practicing co-digestion. Research goals were to:

(1) Evaluate the role co-digestion plays in regard to digester performance by comparing substrate-only, manure-only, and co-digestion data at both laboratory and commercial-scale and
(2) Quantify the role of co-digestion against a manure-only control on project economics and farm nutrient management. Although in the end this is a case specific study limited by the specific substrates and digester technology employed, it is expected that the data and conclusions derived will offer researchers information previously unattainable in regard to data quantity, scale, comparison to manure-only baseline, comparison of commercial-scale performance to laboratory-batch predictions, and application to economics and nutrient balance.

2 Materials and methods

2.1 Digester description

The test AD facility utilized a patented plug-flow digester with biogas-induced axial dispersion and sludge recycling. The digester was designed by GHD Incorporated of Chilton, WI, USA. Design size was set at 2025 animal units (AU) with a wet-equivalent dairy cow equal to 1.35 AU. Scrape manure was piped or trucked to a receiving pit and pumped directly into the mesophilic (37.8°C) digester heated with reclaimed waste heat from a 450/500 kW Caterpillar G398 (Peoria, IL, USA) reciprocating engine and generator set. Coarse fibrous solids were separated from the digester effluent using a US Farm (Tulare, CA, USA) 0.30 cm slope screen with dewatering auger. One half of the separated solids were dried, using excess waste heat, to produce a high quality fiber product, and peat replacement. The other half was used onsite as bedding replacement. The liquid stream from the separator was stored in a lagoon until regional regulations allowed land-application. Co-digestion substrates entered the farm gate via tipping fee contracts ($20–35/ton) and were loaded in regular batches to a collection pit for mixing with the manure. Particular off-farm substrates received as tipping fees and included in the digestion mixture were, with their respective substrate volumetric percentages: egg breakage waste (51.8%), fish breading waste (32.9%), crab meat trimmings (5.72%), and ravioli sauce waste (5.59%). Tab. 1 gives specific operating details.

2.2 Sampling protocol

For a 6-month period and on a weekly basis, polyethylene bottles (250 mL) were used to obtain samples from six different locations around the digester: (1) Manure inlet to collection pit; (2) substrate inlet to collection pit; (3) sampling port directly in front of digester inlet; (4) sampling port at effluent exit point from digester; (5) post-separation liquid inlet to lagoon; and (6) post-separation coarse fibrous solids. Biogas was sampled at a port just proximal to the engine/generator set using Tedlar bags (Smith Air Sample, Hillsborough, NC, USA). Samples were packed in ice, transported to the laboratory overnight, and stored at 4°C for later parameter analysis. Manure and biogas flow measurements were logged using a Siemens Mag 8000 (Spring House, PA, USA) electromagnetic liquid flow meter and an Aaliant Target Mark V (Spartanburg, SC, USA) strain gage gas meter, respectively. Manure, substrate, and influent and effluent characteristics are summarized in Tab. 2, while sampling sites are identified in Fig. 1.

2.3 Analytical methods

All analytical methods for the parameters listed below, including total solids (TS, 2540B) and volatile solids (VS, 2540E) were conducted according to their referenced standard method [27]. Chemical oxygen demand (COD) was analyzed with a Hach 45600 COD Analyzer (Loveland, Colorado, USA; 5220D). Alkalinity, pH, and Ripley ratio values were analyzed using a Mettler Toledo T50A Automatic Titrater (Schwerzenbach, Switzerland; 2320B) [28]. Protein, total Kieldahl nitrogen (TKN), and total ammonia nitrogen (TAN) were analyzed using a Tecator 2300 Kjeltec Analyzer (Eden Prairie, MN, USA; 4500-NorgB; 4500NH_3BC). Total phosphorous (TP) was digested and analyzed using an O-I-Analytical FS3000 Flow Injected Analyzer (College Station, TX, USA; 4500PB; 4500PE). Potassium was analyzed using a Varian Spectra AA220 (Palo Alto, CA, USA; 3111B). VFA including

Table 1. Operating parameters for commercial digester

Parameters	Unit	Mean[a)]
Cows	AU	938 ± 87
Digester volume (liquid)	m^3	3899
Manure flow	m^3/day	102.96 ± 12.13
Percentage substrate	%	16.36 ± 1.60
Total flow	m^3/day	122.02 ± 12.21
Hydraulic retention (HRT)	days	31.95 ± 2.92
Organic loading rate (OLR)	kg VS/m^3/day	2.01 ± 0.19
Temperature	°C	37.8 ± 0.5
Substrate type and %	Egg (55.8), fish bread (32.9), crab (5.72), ravioli (5.59)	
Design	GHD modified plug flow with axial mixing	
Manure handling system	Scrape pit/AD/Screw press/Storage lagoon	
Engine set	Caterpillar G398 coupled to a 450 KW Generator	

a) Data is the average of daily herd and flow recordings with mean standard deviations ($n = 198$) at $\alpha = 0.05$

Table 2. Influent and effluent parameters and percentage reduction performance

Parameters (g/L)	Scrape manure[a)]	Substrate mixture[b)]	Digester influent[c)]	Digester effluent	Mean % reduction[d)]
TS	52.01 ± 12.98	178.11 ± 8.7	76.54 ± 7.00	41.82 ± 4.03	45.36
VS	41.33 ± 10.94	163.41 ± 6.9	64.00 ± 3.93	28.62 ± 3.54	55.28
FS	10.68 ± 2.08	14.7 ± 1.3	12.54 ± 1.69	13.67 ± 3.96	NA
COD	54.52 ± 13.82	222.73 ± 23.5	84.13 ± 15.04	27.16 ± 4.87	67.72
VFA	5.10 ± 1.12	21.82 ± 1.91	7.71 ± 1.76	0.01 ± 0.02	99.87
TKN	2.45 ± 0.22	13.55 ± 1.84	4.12 ± 0.93	3.84 ± 0.53	NA
TAN	1.72 ± 0.19	0.64 ± 0.50	1.87 ± 0.45	2.65 ± 0.76	+41.71
TP	0.39 ± 0.04	1.37 ± 0.21	0.51 ± 0.14	0.44 ± 0.10	NA
K	2.44 ± 0.60	1.34 ± 0.18	2.31 ± 0.35	2.28 ± 0.27	NA
pH	6.94 ± 0.08	5.18 ± 0.23	6.87 ± 0.41	7.88 ± 0.14	+14.37
Alkalinity	9.63 ± 3.22	3.39 ± 0.78	8.96 ± 1.00	14.23 ± 1.80	+58.82
FC (kcfu/g)	356 ± 95	–	339 ± 247	3.42 ± 7.06	98.99

a) Data is the average of ($n = 6$) with mean standard deviations at $\alpha = 0.05$.
b) Data is the average of triplicates with mean standard deviations ($n = 3$) at $\alpha = 0.05$. Individual substrates mixed according to flow percentage and analyzed as mixture.
c) Data is the average of ($n = 24$) with mean standard deviations at $\alpha = 0.05$.
d) NA refers to mean reduction parameters not statistically relevant as determined by general linear model (GLM) ANOVA analysis with Statistical Analysis System program 9.0 (SAS Institute Inc., NC) at $\alpha = 0.05$ with $n = 24$ samples. All reductions were with calculated p-values < 0.0001 except for FS (0.2121), TKN (0.2355), TP (0.0417), and K (0.4567).
Total solids (TS); volatile solids (VS); fixed solids (FS); chemical oxygen demand (COD); volatile fatty acids (VFA); total Kieldahl nitrogen (TKN); total ammonia nitrogen (TAN); total phosphorous (TP); potassium (K); fecal coliform (FC).

acetate, propionate, and butyrate were analyzed using a Dionex DX-500 IC (Sunnyvale, CA, USA) using a method as detailed in Hu and Chen [29]. Fat content was measured using a Soxhlet apparatus (5520D) while carbohydrate content was calculated from subtraction of known protein, fat, moisture, and ash values. Biogas composition, including CH_4, CO_2, and hydrogen sulfide (H_2S) were analyzed using a Varian GC CP-3800 (Palo Alto) using a method as detailed in Wen et al. [30]. Fecal coliform (FC) counts were determined using method 07.01 as described in TMECC [31].

2.4 Manure baseline development

Commercial-scale operation of the digester did not allow for an opportunity to study the co-digestion process directly against a manure-only control. Instead, an indirect manure-only comparison was modeled using laboratory batch manure studies and additional literature data. Regression of VS destruction against time during laboratory batch digestion with an AER-208 Anaerobic Respirometer (Challenge Systems, Springdale AR) using protocols outlined in Frear et al. [32] allowed for development of a simple model capable of determining VS concentrations at various hydraulic retention times (HRT; Fig. 2). At the 32 day HRT for the commercial digester, the model predicted a 40.6% VS reduction performance. This value is in line with an earlier EPA [2] commercial-scale dairy manure-only digestion study which predicted 42.1% VS reduction at an HRT of 32 days and Jewell et al. [33] who predicted 40.6% at 30 days HRT. Hill [34] and Moller et al. [35] have shown that the theoretical methane productivity for dairy cattle fed on high energy roughage and concentrates is generally consistent near 0.57 m^3 CH_4/kg VS destroyed at 38°C and 1 atm. By combining the predicted VS reduction potential with their theoretical methane productivity, values for total biogas production from a manure-only scenario were obtained. Methane production was inferred using a mean methane content of 55.9% for dairy manure digestion as determined by EPA [2]. Biogas and methane production along with other known parameters for the commercial digester and its scrape manure were utilized to generate performance and economic outputs for the manure only scenario.

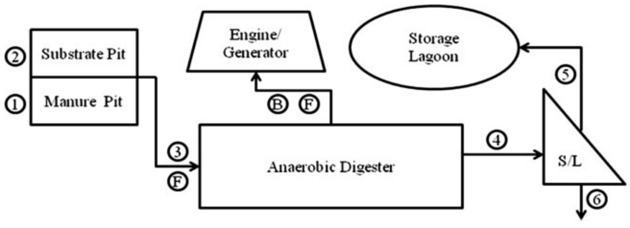

Figure 1. Project sampling sites (biogas (B), flow meter (F), and sampling (1–6)).

2.5 Economic and nutrient comparison between manure-only baseline and co-digestion

An enterprise budget spreadsheet was utilized to compare the two scenarios of co-digestion and manure-only. In order to simplify comparisons and maintain consistency, equal flow rates to the digester were assumed for both scenarios. Co-digestion was assumed

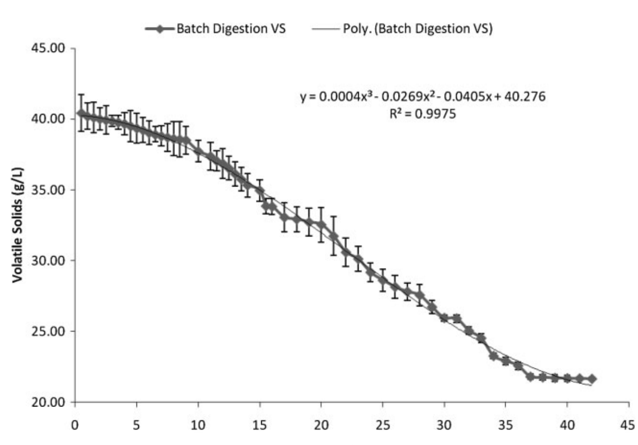

Figure 2. Regression model of VS reduction against HRT.

Table 3. Parameter enhancements via co-digestion

Substrate	C/N ratio	Alkalinity (g $CaCO_3$/L)	pH	Nutrients N:P:K	Micronutrients elements
Scrape manure	11:1	9.63 ± 3.22	6.94 ± 0.08	6:1:6	Fe, Mn, Ni, Co, Mb
Substrate[a)]	56:1	3.39 ± 1.40	5.19 ± 0.96	10:1:1	Se, Ni
Co-digestion	28:1	8.96 ± 1.00	6.87 ± 0.41	8:1:4.5	All

a) Individual substrates mixed according to flow percentage and analyzed as mixture.

to be a result of a mean flow rate of 122.02 m^3/day of mixed material consisting of a mean substrate flow volume percentage of 16.36% and scrape manure from 938 AU. The manure-only scenario was at an equal overall flow rate composed of just scrape manure from an assumed 1098 AU. All electrical and waste heat production outputs were calculated indirectly using available biogas and methane composition data which were then applied to the 450 kW Caterpillar G398 manufacturer flow-rate and engine efficiency specifications; assuming a 90% runtime for the year and a 15 kW parasitic load to the generator. The indirect calculation was necessary as during the course of the study, the original 300 kW engine and generator set (later replaced with the 450 kW model) was undersized causing extensive flaring of the over-production of biogas. Received electrical prices and associated green energy tags were assumed to total $0.05/kWh as per the existing long-term contract with Puget Sound Energy (Seattle, WA, USA). Carbon credits were contracted through Chicago Climate Exchange [36] with a market value of $5.50/metric ton CO_2-eq, minus a 50% commission fee. A Washington state tax credit was available to AD units at a rate of $0.02/kWh. Fiber sales were assumed to be $10/ton for bedding offset and $25/ton for value-added fiber. All other necessary spreadsheet inputs regarding capital expenditures, operating and maintenance costs, tipping fees, and flow rates were obtained directly from the dairy producer.

3 Results and discussion

3.1 Digester stability

Tables 2 and 3 summarizes important physical and chemical wastewater as well as nutrient information for the respective manure, substrate, and co-digestion fractions being studied. As can be seen from Tabs. 2 and 3, development of the specific co-digestion mixture, represented by 16.36% v/v supplementation of an off-farm substrate mixture with scrape dairy manure, led to important changes in the chemical structure of the digester feed. These changes include increased VS, COD, and VFA loadings capable of simultaneously increasing the biodegradable fraction and overall biogas potential of the digester feed (Tab. 2) as well as changes to important AD parameters such as pH, alkalinity, micronutrient availability, and N/P/K, C/N, and C/N/P ratios (Tab. 3). VS, COD, and VFA loadings as compared to a manure-only scenario increased by 54.9, 54.3, and 51.2%, respectively, resulting in an OLR of 2.01 kg VS/m^3/day and VFA loading of 7.71 g/L. While the OLR was relatively low in comparison to levels deemed attainable under stable co-digestion scenarios, it is the VFA loading rate that is at the high end of the range, which might cause possible digester souring [18]. Meanwhile, as compared to manure-only, alkalinity, as a measure of buffer control capability within the digester, remained high at a level of 8.96 g $CaCO_3$/L, pH maintained near neutral, and importantly, C/N and C/N/P ratios of 28:1 and 112:4:0.5, respectively, materialized allowing for ratios very near the idealized 25–32:1 and 115:4:1 ratios for AD [37].

Ripley et al. [28] determined that a ratio of volatile acids over total alkalinity below 0.25 for digester effluent is indicative of a stable digestion process with spikes and troughs deviating from the steady state indicating upset and potential failure. Ripley ratios reported during the study period were 0.15 ± 0.04 (Fig. 3) showing excellent stability and with such a small standard deviation, no notable period of upsets. These constant levels along with the recording of effluent VFA concentrations consistently below detection level and constant effluent pH levels, point to a very strong reactor stability that slightly increased over time.

The stability as indicated by the Ripley Ratio and digester performance are in contrast to studies completed in regard to ammonia, protein, and long chain fatty acid (LCFA) inhibition suggested by other AD and cow rumen researchers. Koster and Lettinga [38] showed that TAN concentrations above 1.7 g/L (at pH 8.0) can be inhibitory to methane-forming bacteria, however, mean influent and effluent TAN levels of 1.87 and 2.65 g/L, respectively, in this study showed no adverse inhibition. Rumen fermentation (idealized plug-flow digester with solids retention and mixing) studies indicate that total fat and protein levels within a dairy cattle dry matter diet should not exceed 7 and 18%, respectively [39]. Determination of dry matter intake for this co-digestion feed consisted of 13 and 34% fat and protein, respectively, with no indication of fermentation inhibition as anticipated by rumen studies. Reasons for the digester stability could include the aforementioned high level of manure alkalinity (above the 2–5 g/L recommended by Metcalf and Eddy [40]), availability of manure macro- and micronutrients [18], and bacterial acclimatization [41, 42].

3.2 Reduction performance and mixing

Table 2 values for fixed solids (FS), TP, and TKN show no statistical difference between digester influent and effluent concentrations. An

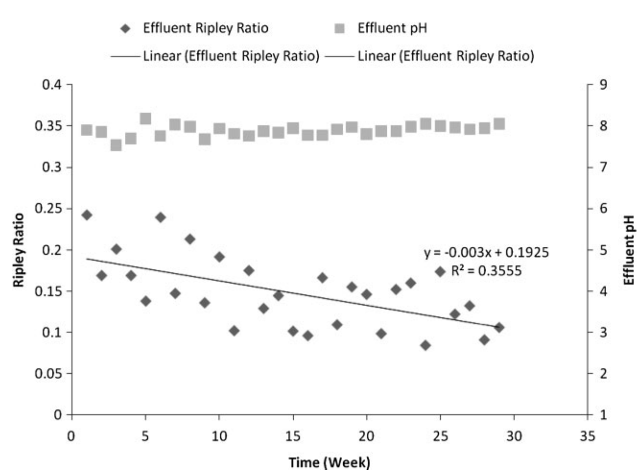

Figure 3. Effluent Ripley ratio and pH of commercial co-digestion reactor.

operational concern of commercial digesters is the potential for solids build-up in the digester due to improper mixing. Although the biological and chemical processes occurring in the digester will cause a certain degree of mineralization of organic N and P, both TP and TKN should stay constant throughout the digestion process. Differences between influent and effluent concentrations could indicate an unwanted organic accumulation, thus TP and TKN values can be indirect indicators for effective mixing and fluid/solids flow. In addition, analysis of FS (TS-VS) can point to accumulation of inert solids such as sand and grit that might develop from farm operations. Data indicates that no accumulation of either FS, TP, or TKN took place, indicating that the axial mixing within the digester was not experiencing stratification and was maintaining plug-flow properties even though the studied TS and flow rates were well below that normally identified for use with traditional plug-flow systems [5]. The apparent ability of GHD modified plug flow technology to maintain axial mixing as compared to more traditional plug-flows may explain the previously noted increased biogas production when compared to similar but traditional non-mixed plug-flow studies [2].

Although commercial digester discussion often centers upon overall biogas production, a key function of the digester is to remediate air and water quality concerns. Previous manure-only digester studies [2, 3, 43] have shown that commercial dairy digesters are capable of TS, VS, COD, and VFA reductions in the range of 25–35, 30–40, 38–42, and 86–88%, respectively. Table 2 lists the reduction results for this co-digestion commercial evaluation, showing reductions higher than the ranges given above for all parameters identified; 45.36, 55.28, 67.72, and 99.87%, respectively. This elevated performance is not surprising given that the substrates being co-digested were extremely high in TS, VS, COD, VFA, and organic fraction (OF = VS/TS). The long HRT may also have contributed to the additional biodegradation and reduction.

Reductions in FC populations during this mesophilic digestion process were nearly 99% or $2\log_{10}$ which is comparative to the $2.3\log_{10}$ reduction noted by US-EPA [2] but considerably lower than the $3.1\log_{10}$ reported by Wright et al. [44]. The lower pathogen reduction estimate for this study might be explained by the significant portion of the digester influent being composed of pre-consumer substrates which contain a low FC count.

3.3 Biogas production

Direct comparison of the manure-only and co-digestion scenarios (Tab. 4) shows the important role that substrates have on overall digester biogas production, productivity, and performance. Specific methane productivities (B_o) for the manure-only and co-digestion scenarios were 0.23 and 0.37 m^3 CH_4/kg VS_{load}, respectively, showing a 60.9% increase in productivity under the co-digestion scenario. Overall gas production more than doubled (110% increase), which was not surprising as the volumetric replacement with substrate led, in regard to mass balance, to a 48.7% increase in VS as compared to manure-alone with the substrate component comprising 43.8% of the total VS with a perceived higher degree of biodegradability. Laboratory batch digestion of the substrate-alone mixture at the same reaction conditions with manure-only digestion confirmed this assumption with results exhibiting a 75.9 ± 3.7% VS reduction (data not shown).

While the co-digestion led to a notable increase in specific methane productivity, only a slight change can be seen between co-digestion and manure-only in regard to the theoretical methane productivity as related to VS destruction (B_u). The Bushwell formula has been used to calculate theoretical B_u values given experimental data for composition of particular wastewaters, including municipal and agricultural wastewaters entering anaerobic digesters [40]:

$$C_nH_aO + \left(n - \frac{a}{4} - \frac{b}{2}\right)H_2O \rightarrow \left(\frac{n}{2} - \frac{a}{8} + \frac{b}{4}\right)CO_2 + \left(\frac{n}{2} + \frac{a}{8} - \frac{b}{4}\right)CH_4 \quad (1)$$

using the following assumptions:

$$VS_{lipid}(C_{57}H_{104}O);\ VS_{protein}(C_5H_7O_2N);\ VS_{carb}(C_6H_{10}O_5);\ \text{and}\ VS_{VFA}(C_2H_4O_2)$$

For co-digestion scenario VS total = 64.0 kg/m^3 with respective VS fractions being 38.92, 32.82, 15.31, and 12.95% for protein, carbohydrate, lipid, and VFA, respectively (data not shown), while for manure-only the VS total = 41.3 kg/m^3 and VS fractions taken from Moller et al. [35].

Calculated theoretical B_u values for manure and co-digestion were 0.57 m^3 CH_4/kg $VS_{Destroyed}$ at 38°C and 1 atm and 0.61 m^3 CH_4/kg $VS_{Destroyed}$ at 38°C and 1 atm, respectively. The slight increase in value is due to nearly 4× and 2× increases in fat and protein percentages, respectively, for co-digestion material. The experimentally derived B_u for this study was 0.66 ± 0.14 m^3 CH_4/kg $VS_{Destroyed}$ at 38°C and 1 atm which is above what theoretical calculations suggest; however, the mean difference is well within the standard deviation. The ratio of B_o/B_u for the two scenarios becomes 0.56 and 0.42 for the co-digestion and manure-only scenarios, respectively, summarizing the degree to which the biodegradability or conversion efficiency of the wastewater was increased (33%). Notably, this 33% increase in biodegradability as defined by B_o/B_u is equivalent to the percent difference in VS reduction for manure and substrate (36%). The co-digestion scenario produced a volumetric performance of 1.19 ± 0.10 m^3 biogas/(m^3/day) which was a 109% improvement over the manure-only modeled scenario of 0.57 m^3 biogas/(m^3/day). It is important to note though that if the commercial digester had not

Table 4. Biogas production and reactor performance

Parameters	Units	Co-digestion	Manure-only[a)]
Total biogas	m^3 biogas/day	4649 ± 377	2216
CH_4 productivity	m^3 CH_4/kg VS_{Added}	0.37 ± 0.05	0.23
CH_4 productivity	m^3 CH_4/kg $VS_{Destroyed}$	0.66 ± 0.14	0.57
Vol. production	m^3 biogas/m^3/day	1.19 ± 0.10	0.57
Biogas comp.	% CH_4	61.37 ± 6.47	55.9

[a)] Simulation of manure-only production using described assumptions, literature data from Hill [34] and US-EPA [2], batch digestion data, and flow rate of 122.02 m^3/day.

been oversized, resulting in such a large HRT, the volumetric performance would most likely have been higher.

3.4 Economic comparison

In order to emphasize the importance of multiple revenue streams as well as to show a side-by-side economic comparison of the two different co-digestion and manure-only scenarios, enterprise budgets were developed for the AD test facility, using assumptions and parameters detailed earlier in Section 2. Figure 4 is a summary of outputs from the enterprise budgets showing the various revenue streams. Yearly revenues for the digester tripled under the co-digestion scenario with 72.3% of all co-digestion scenario receipts being a result of revenue directly attributable to the substrate addition. Clearly, substrate addition has a profound effect on digester economics with tipping fee supplementation being the largest factor. There is some question, though, in regard to the long-term sustainability of tipping fees as organic wastes become more and more sought after as a focus on sustainability and clean technologies increases.

Carbon and renewable energy credits are an important component within the revenue and economic models of a digester project. If all possible avenues for carbon credits are assumed (manure carbon credits from lagoon storage baseline [1], substrate carbon credits from landfill baseline [45], and renewable energy from coal power baseline [36]), the manure-only scenario would mitigate 4050 metric tons of carbon dioxide equivalent (CO_2e) while the co-digestion scenario would mitigate 10 253 metric tons of CO_2e or 2.53 times as much. For perspective, at the carbon trading rates identified, these carbon credits account for 6.9 and 5.4% of total project revenue, respectively; providing insight to the role carbon credits could play in AD development now and in the future.

3.5 Nutrient balance

One concern regarding on-farm co-digestion is the potential for nutrient overload on dairy CAFOs operating under stringent nutrient management plans designed around limited land area. Figure 5 shows significant nutrient load increases to the farm, particularly in regard to TKN, at the given substrates and volumetric flow percentage applied. This is not surprising as the protein content of the manure was 18% while the protein content of the co-digestion substrates were nearly double at 34%. Thus, those 36 and 55% of dairy producers who already overload N and P nutrient on their farms [26] will have to examine whether the economic benefits of co-digestion can offset possible changes in their nutrient management plans unless a nutrient recovery system that integrates with the AD unit is implemented.

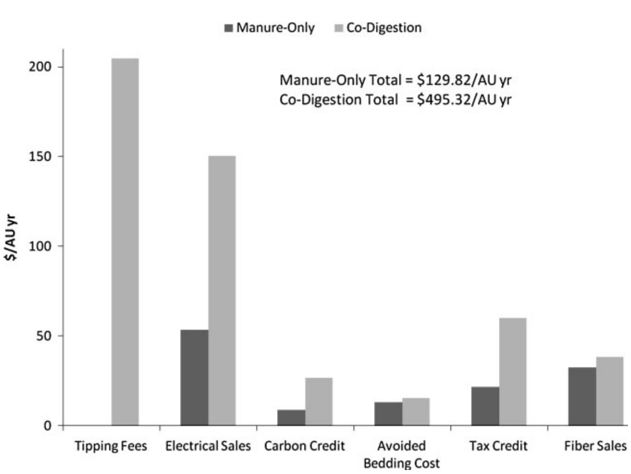

Figure 4. Co-digestion and manure-only revenue scenarios.

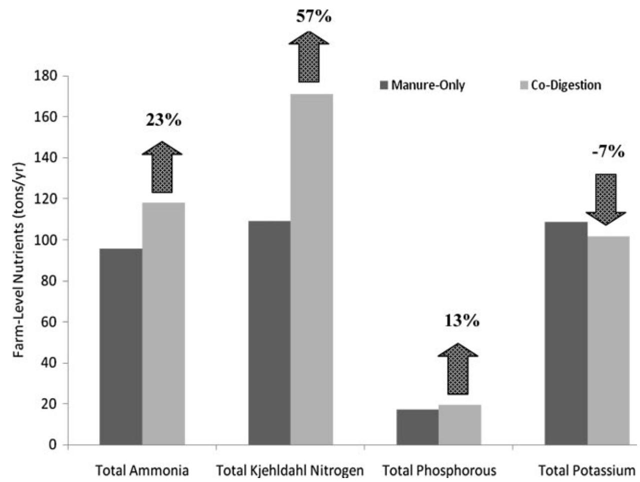

Figure 5. Nutrient farm load under different scenarios.

4 Concluding remarks

The combination of substrate with dairy manure at the volumetric ratio applied allowed for more preferred levels of key micronutrients, neutral pH, and additional alkalinity, while also producing, in the end, C/N and C/N/P ratios of 28:1 and 112:4:0.5, respectively, which are very near idealized ratios of 25–32:1 and 115:4:1 for AD. Based on average Ripley ratios of 0.15, the digester showed excellent stability. Reduction percentages were 45.36, 55.28, 67.72, and 99.87% for TS, VS, COD, and VFA, respectively, while FC bacteria as an indicator organism showed a 2 $\log_{10}$ reduction. Compared to the manure-only baseline, co-digestion resulted in a 110% increase in biogas production and a tripling of gross receipts with 2/3 of all the co-digestion receipts being directly due to the substrate supplementation. Specific methane productivities for the manure-only and co-digestion scenarios were 0.23 and 0.37 m^3 CH_4/kg VS_{load}, respectively. Co-digestion had its concerns as 56.7, 23.4, and 12.6% more TKN, TAN, and TP were loaded to the farm.

With such a positive outcome in performance and economics, the US dairy AD industry will undoubtedly experience a continuing trend toward co-digestion and accordingly on-farm entry of industrial or municipal solid waste. Attention will have to paid, though, to the effect this has on long-term viability of the project and the farm. Substrate availability and tipping-fees will be subject to variability and price, potentially impacting future balance sheets. Entry of solid waste to the farm gate will have immediate and long-term effects to the farm as state regulations and nutrient balance plans will most likely be altered. Future AD research will accordingly need to focus on development of effective and economical technologies for the recovery of nutrients from the effluent so the excess loading can be avoided while also introducing new saleable products from the co-digestion of substrates.

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