Journal of Environmental Management 128 (2013) 233–242

Contents lists available at SciVerse ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Impact of co-digestion on existing salt and nutrient mass balances for a full-scale dairy energy project

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ARTICLE INFO

Article history:
Received 6 February 2013
Received in revised form
21 April 2013
Accepted 27 April 2013
Available online 7 June 2013

Keywords:
Dairy manure
Anaerobic digestion
Co-digestion
Salinity
Nutrients

ABSTRACT

Anaerobic digestion of manure and other agricultural waste streams with subsequent energy production can result in more sustainable dairy operations; however, importation of digester feedstocks onto dairy farms alters previously established carbon, nutrient, and salinity mass balances. Salt and nutrient mass balance must be maintained to avoid groundwater contamination and salination. To better understand salt and nutrient contributions of imported methane-producing substrates, a mass balance for a full-scale dairy biomass energy project was developed for solids, carbon, nitrogen, sulfur, phosphorus, chloride, and potassium. Digester feedstocks, consisting of thickened manure flush-water slurry, screened manure solids, sudan grass silage, and feed-waste, were tracked separately in the mass balance. The error in mass balance closure for most elements was less than 5%. Manure contributed 69.2% of influent dry matter while contributing 77.7% of nitrogen, 90.9% of sulfur, and 73.4% of phosphorus. Sudan grass silage contributed high quantities of chloride and potassium, 33.3% and 43.4%, respectively, relative to the dry matter contribution of 22.3%. Five potential off-site co-digestates (egg waste, grape pomace, milk waste, pasta waste, whey wastewater) were evaluated for anaerobic digestion based on salt and nutrient content in addition to bio-methane potential. Egg waste and wine grape pomace appeared the most promising co-digestates due to their high methane potentials relative to bulk volume. Increasing power production from the current rate of 369 kW to the design value of 710 kW would require co-digestion with either 26800 L d^{-1} egg waste or 60900 kg d^{-1} grape pomace. However, importation of egg waste would more than double nitrogen loading, resulting in an increase of 172% above the baseline while co-digestion with grape pomace would increase potassium by 279%. Careful selection of imported co-digestates and management of digester effluent is required to manage salt and nutrient mass loadings and reduce groundwater impacts.

1. Introduction

The benefits of anaerobic digestion with concurrent energy production at dairy farms and other livestock facilities are well-documented (Camarillo et al., 2012; Massé et al., 2011). Although there is extensive experience with such projects worldwide, dairy biomass energy is still an emerging practice in the U.S. (US EPA, 2011). One issue limiting advancement of biomass energy is concern over alterations to farm-level salt and nutrient mass balances (Anders, 2007). Dairies are required to have nutrient management plans to avoid contamination of groundwater. Although nitrogen has traditionally been the major concern, salts are also becoming an issue. Co-digestion of agricultural products with dairy manure necessitates importation of materials containing unknown

Abbreviations: BOD, Biochemical oxygen demand; C, Total carbon; cBOD, Carbonaceous BOD; CH_4, Methane; CO_2, Carbon dioxide; Cl, Chloride ion; COD, Chemical oxygen demand; DM, Dry matter mass; DOC, Dissolved organic carbon; FS, Fixed solids; HRT, Hydraulic retention time; H_2S, Hydrogen sulfide; K, Potassium ion; N, Total nitrogen (elemental analyzer); NDIR, Nondispersive infrared sensor; NO_3–N, Nitrate-nitrogen; O_2, Oxygen gas; ON, Organic nitrogen; P, Phosphorus; S, Total sulfur; SpC, Specific conductance; sCOD, Soluble COD; TAN, Total ammonia nitrogen; TDS, Total dissolved solids; TN, Total nitrogen (Timberline); TS, Total solids; VS, Volatile solids; w.w., wet weight.

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http://dx.doi.org/10.1016/j.jenvman.2013.04.060

Nomenclature

f_{CH_4}	Fraction of biogas CH_4, $m^3\ m^{-3}$
f_{CO_2}	Fraction of biogas CO_2, $m^3\ m^{-3}$
f_{H_2S}	Fraction of biogas H_2S, $m^3\ m^{-3}$
f_{N_2}	Fraction of biogas N_2, $m^3\ m^{-3}$
f_{O_2}	Fraction of biogas O_2, $m^3\ m^{-3}$
f_{sf}	TS content of feed-waste, $kg\ kg^{-1}$
f_{sg}	TS content of sudan grass silage, $kg\ kg^{-1}$
f_{ss}	TS content of manure solids, $kg\ kg^{-1}$
f_{wf}	Water content of feed-waste, $kg\ kg^{-1}$
f_{wg}	Water content of sudan grass silage, $kg\ kg^{-1}$
f_{ws}	Water content of manure solids, $kg\ kg^{-1}$
m_{gc}	Mass of biogas condensate, $kg\ d^{-1}$
m_{gd}	Mass of dry biogas, $kg\ d^{-1}$
$m_{TS,f}$	Mass of TS in feed-waste, $kg\ d^{-1}$
$m_{TS,g}$	Mass of TS in sudan grass silage, $kg\ d^{-1}$
$m_{TS,e}$	Mass of TS in effluent solids, $kg\ d^{-1}$
$m_{TS,s}$	Mass of TS in manure solids, $kg\ d^{-1}$
$m_{TS,tm}$	Mass of TS in thickened slurry, $kg\ d^{-1}$
m_{wf}	Wet mass of feed-waste, $kg\ d^{-1}$
m_{wg}	Wet mass of sudan grass silage, $kg\ d^{-1}$
m_{wps}	Wet mass of screwpress solids, $kg\ d^{-1}$
m_{ws}	Wet mass of manure solids, $kg\ d^{-1}$
m_{wtm}	Wet mass of thickened slurry, $kg\ d^{-1}$
M_{CH_4}	Molecular weight of CH_4, $kg\ mol^{-1}$
M_{CO_2}	Molecular weight of CO_2, $kg\ mol^{-1}$
M_{O_2}	Molecular weight of O_2, $kg\ mol^{-1}$
M_{H_2S}	Molecular weight of H_2S, $kg\ mol^{-1}$
M_{N_2}	Molecular weight of N_2, $kg\ mol^{-1}$
p	Gas pressure, kPa
Q_{gd}	Dry biogas flow, $m^3\ d^{-1}$
Q_e	Total effluent flow, $m^3\ d^{-1}$
Q_i	Total influent flow, $m^3\ d^{-1}$
Q_{tm}	Thickened influent slurry flow, $m^3\ d^{-1}$
Q_p	Screwpress effluent flow, $m^3\ d^{-1}$
R	Gas constant, $8.314 \times 10^{-3}\ m^3\ kPa\ mol^{-1}\ K^{-1}$
S_{sl}	Specific gravity of effluent, unitless
T	Temperature, K
ρ_{sf}	Dry density of feed-waste, $kg\ m^{-3}$
ρ_{sg}	Dry density of sudan grass silage, $kg\ m^{-3}$
ρ_{ss}	Dry density of manure solids, $kg\ m^{-3}$
ρ_w	Density of water, $kg\ m^{-3}$

quantities of nutrients and salts onto dairy farms (Frear et al., 2011). The regional impact of such a shift in resources necessitates an evaluation of salt and nutrient loadings at dairy farms with anaerobic digestion systems and an assessment of the potential impact of co-digestion.

Contamination of groundwater with nutrients (e.g. nitrates) and salts occurs in areas that are intensively farmed and the repercussions are severe (Bouwman et al., 2009; Rhoades, 1997). Impacted groundwater is less valuable for irrigation since salinity adversely impacts plant growth (Grattan and Grieve, 1999). Groundwater containing high nitrate and salt concentrations is also less desirable as a drinking water source. Increased groundwater salinity has direct economic consequences in arid and semi-arid regions that rely on groundwater for irrigation (Medellin-Azuara et al., 2008). Dairies contribute to regional salt and nutrient loadings, mostly as a result of their manure management practices (Almasri and Kaluarachchi, 2004; Chang et al., 2005; Harter et al., 2002; van der Schans et al., 2009). Harter et al. (2002) identified animal holding areas, manure storage lagoons, and forage fields irrigated with liquid manure as potential sources of groundwater contamination at dairies.

Salt and nutrient management is currently practiced at dairy farms using a mass balance approach (Chang et al., 2005; Harter et al., 2002; van der Schans et al., 2009). Nitrogen mass inputs onto the farm such as animal feed, chemical fertilizers, and imported water have been quantified and compared with farm exports including milk, meat, and manure compost in order to quantify air emissions and contributions to groundwater (van der Schans et al., 2009). The results indicate that for fields irrigated with effluent from manure storage lagoons, an estimated 45% of the applied nitrogen will leach to the underlying groundwater (van der Schans et al., 2009). To protect surface and groundwater quality, dairy managers are required to control groundwater contamination by limiting manure application rates, using groundcover crops that fix nutrients, and other practices as part of their nutrient management plans (e.g. CRWQCB, 2007). In California, nutrient management plans are intended to reduce contamination of surface and groundwaters with "ammonia, nitrates, phosphorus, chloride, boron, salts, pathogens, and organic matter" (CRWQCB, 2007). Environmental regulators are requiring that mass balances be performed prior to import of co-digestates onto dairy farms (CRWQCB, 2010). These mass balances can be used to identify appropriate digester feedstocks, optimal feed rates, and management strategies for digestates that may require treatment or export to prevent accumulation of nutrients and salts on dairy farms (Hjorth et al., 2010; Yu et al., 2010).

Previous mass balance calculations for full-scale agricultural anaerobic digesters have been completed for solids, organics, nitrogen, phosphorus, and potassium; however, data on salts and sulfur were not collected (Möller et al., 2010; Pognani et al., 2012; Schievano et al., 2011). Other researchers have compared digester inputs with digester effluent without completing a formal mass balance (Alburquerque et al., 2012; Frear et al., 2011; Möller and Müller, 2012; Möller and Stinner, 2010; Pognani et al., 2009; Tambone et al., 2010). In previous studies the elemental contributions of individual digester feedstocks were not always tracked separately. Sulfur has not been intensively studied although it is important as a result of its role in biological systems and its presence in biogas (Möller and Müller, 2012). In the USA there are air standards for sulfur, with more stringent standards being enforced in California. To address difficulties in monitoring multiple salts and nutrients in digester studies, it was desired to determine if easily measurable constituents such as solids and conductance could be used in lieu of testing for individual elements. Characterization of salts and nutrients in anaerobic digestion systems is important for understanding chemical transformations and identifying potentially inhibitory conditions (Appels et al., 2008).

In this study, we characterized salt and nutrient loadings at a full-scale dairy biogas energy facility where co-digestion was being considered. The study objectives were to: (1) establish the mass balance of solids, carbon, nutrients, and salts for multiple process flows at the full-scale anaerobic digestion facility, (2) determine if solids and specific conductance were predictive of nutrients and salts, (3) characterize the salt and nutrient content as well as the methane generating capacity of potential co-digestates, and (4) calculate the effect of salt and nutrient mass balances if off-site feedstocks were imported to achieve power plant capacity.

2. Materials and methods

2.1. Site description

A detailed description of the project site was previously published (Camarillo et al., 2012). Briefly, two upright, above-ground, complete-mix anaerobic digesters with a working capacity of 6400 m^3 (Biogas Energy Inc., Kensington, CA) and a 710 kW internal combustion reciprocating engine with a generator (Guascor, St. Rose, LA) were used to produce energy at a dairy farm in central California (Fig. 1). A lane flush manure collection system was used where wash water was screened in slope screens (0.3 cm) and settled prior to re-use for lane flushing. Approximately 4500 $m^3\ d^{-1}$ of flush wastewater was circulated with 757 $m^3\ d^{-1}$ added from dairy operations. The design digester temperature was 38 °C and the design hydraulic retention time (HRT) was 24–30 days. Digester feedstocks consisted of screened and thickened manure influent slurry, manure solids from the slope screens, whey wastewater, animal feed-waste, and sudan grass silage. Solid and liquid feedstocks were added to the digesters separately. Solid feedstocks were added collectively to a metered hopper according to the following w w^{-1} percentages: sudan grass (50%), manure solids (46%), and feed-waste (4%). Whey wastewater was added directly to the flush wash water (<15 $m^3\ d^{-1}$). Digester effluent solids were separated using a screwpress and then used onsite for cattle bedding. The screwpress effluent, along with excess lane flush water, was stabilized in a storage lagoon (>120 days HRT) prior to use for onsite irrigation. A biological hydrogen sulfide (H_2S) removal system was located in the anaerobic digesters: netting was suspended in the headspace to support a biological community of sulfur oxidizing bacteria and ambient air was injected to support biological sulfur oxidation.

2.2. Continuous data collection

Continuously monitored parameters were recorded every minute by a centralized computer system. Thickened influent slurry flow and total solids (TS) were measured using a Seametrics Magmeter (Kent, WA, USA) and a Hach SOLITAX sc meter with Hach-Lang SC100 controller (Loveland, CO, USA), respectively. Biogas flow was measured using an Endress + Hauser Prowirl vortex flow meter (Greenwood, IN, USA). The mass of solids added to the digesters was measured using a PTM AV20/5 metered scale (Visano, Italy). Biogas methane (CH_4), O_2, and H_2S were measured using a Gasmess-Systeme Gmbh ExTox ET-4D2/IMC-4D sensor (Unna, Germany). All biogas measurements were made on dry biogas downstream of condensate collection.

2.3. Grab sample collection

Samples were collected between July 2009 and February 2012 as part of this study. The samples were placed on ice immediately after collection and transported to the laboratory for analyses. Biogas was measured for CH_4, CO_2, O_2, and H_2S during site visits using a handheld GasData GFM 416 Biogas Analyzer (Whitley, UK). Measurements of pH and specific conductance (SpC) were made in the field. Total dissolved solids (TDS) of slurry samples were determined by multiplying SpC values by 0.67 (Gupta, 2011). Potential co-digestates were identified by the dairy managers from agricultural producers in California; selection was based on proximity and prevalence of agricultural products (CDFA, 2011). Samples of the five co-digestates (egg waste, grape pomace, milk waste, pasta waste, whey wastewater) were obtained directly from the waste producers and then transported to our laboratory for analysis.

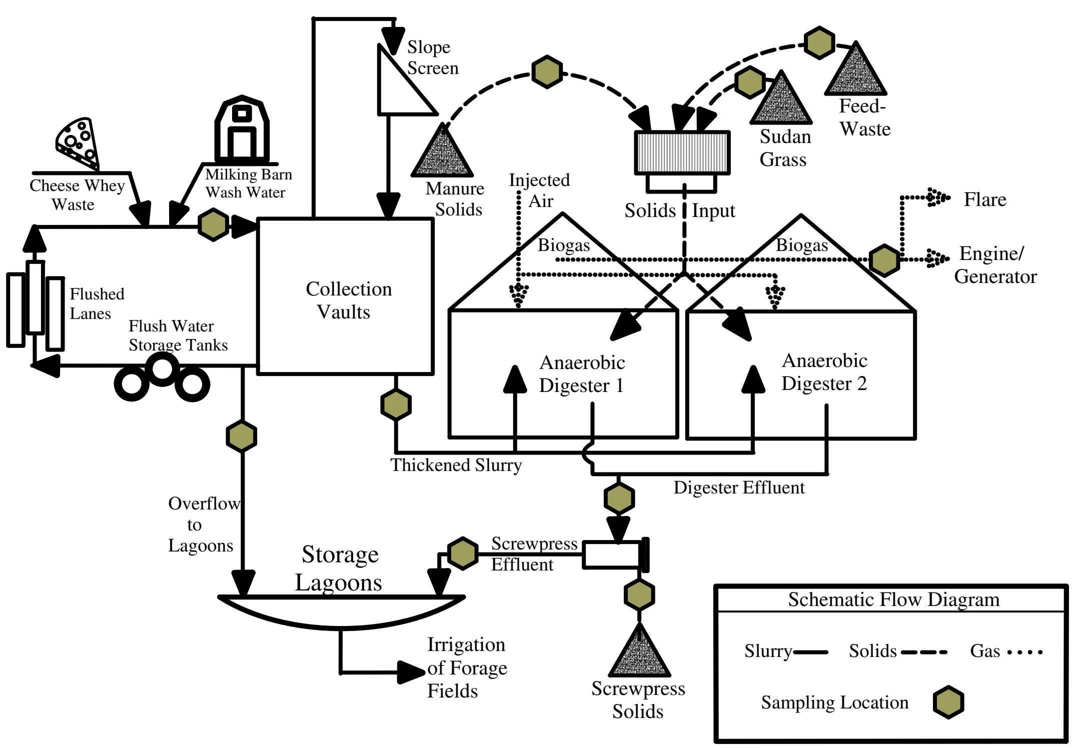

Fig. 1. Schematic of the dairy energy system consisting of two complete-mix anaerobic digesters (total volume of 6400 m^3) and a 710 kW internal combustion engine. Digester feedstocks were screened and thickened lane flush water, animal feed-waste, sudan grass silage, manure solids from the slope screens, and whey wastewater. Digester effluent liquid and solid streams were separated using a screwpress. The screwpress effluent, along with excess lane flush water, was stabilized in a storage lagoon with an HRT longer than 120 days.

2.4. Analytical methods

The pH and specific conductance (SpC) were measured using a YSI pH10 m (Yellow Springs, OH, USA) and a Multi-Parameter pH/SpCond PCSTestr 35 probe (Oakton Vernon Hills, IL, USA). Alkalinity was measured by titration to an endpoint of 4.5 by SM 2300 (APHA, 2005). Total solids (TS), volatile solids (VS), and fixed solids (FS) were analyzed by SM 2540 B and E (APHA, 2005). Total carbon, nitrogen, and sulfur (C, N, S) were analyzed on a Thermo Scientific Flash2000 Organic Elemental Analyzer (Waltham, MA, USA) following drying at 105 °C and processing using a VWR Hard Tissue Homogenizer (West Chester, PA, USA). Total phosphorus (P) was determined for slurry samples by persulfate digestion using a Tuttnauer Brinkman autoclave (Westbury, NY, USA) and colorimetric determination by the ascorbic acid method, SM 4500-P B, E (APHA, 2005). Total phosphorus was determined for solid samples by adding 5 mg of dried sample to 25 mL of ultrapure Millipore water (Billerica, MA, USA), digesting according to SM 4500-P B 5, and measuring colorimetrically by the ascorbic acid method, SM 4500-P-E (APHA, 2005). Total phosphorus HACH PhosVer3 reagents (Loveland, CO, USA) were used along with a Perkin–Elmer Lambda35 spectrophotometer (Shelton, CT, USA).

Chloride (Cl) was measured by US EPA Method 9212 using a Thermo Scientific electrode (Beverly, MA, USA). Twenty-five mL of ionic strength adjustor, consisting of 1 M nitric acid and 15 g L^{-1} sodium bromate, was added to 25 mL samples. Potassium (K) was measured by SM 3500 C (APHA, 2005) using an Oakton Instruments electrode (Williston, VT, USA). One mL of ionic strength adjustor (5 M NaCl) was added to 50 mL liquid samples. Approximately 0.1–0.3 g dry solids were analyzed for potassium and chloride by first grinding the solids prior to mixing with 50 mL ultrapure water. The TDS of solid substrates were determined by suspending dry solids in ultrapure water, measuring SpC, and applying a TDS SpC^{-1} ratio of 0.67. Multiple dilutions of solids and water were analyzed with reproducible results.

Chemical oxygen demand (COD) was measured by Hach Method 8000 (Loveland, CO). Dissolved organic carbon (DOC) was analyzed on a Teledyne-Tekmar Apollo 9000 (Mason, OH, USA) by high temperature combustion according to SM 5310 B (APHA, 2005) and quantified using a nondispersive infrared sensor (NDIR) detector. Samples for DOC and soluble COD (sCOD) were first filtered using Whatman GF/F (0.7 μm) filters (Maidstone, UK). Unfiltered samples were analyzed for 5-day biochemical oxygen demand (BOD) by SM 5210 B (APHA, 2005). Dissolved oxygen measurements were made using a YSI 5000 DO meter (Yellow Springs, OH). Carbonaceous BOD (cBOD) was determined by adding 0.16 mg of nitrification inhibitor (N-serve, Hach, Loveland, Colorado) to a duplicate sample set.

Total ammonia nitrogen (TAN), nitrate nitrogen (NO_3–N), and total nitrogen (TN) were quantified using the Timberline Instruments TL-2800 Ammonia Analyzer (Boulder, CO). TAN was determined using unfiltered samples while NO_3–N was performed on filtered samples. Samples for TN were first treated by persulfate digestion and autoclaved for 30 min in a Tuttnauer Brinkman autoclave (Westbury, NY, USA). Organic nitrogen (ON) was calculated by subtracting NO_3–N and TAN from TN.

Methane potentials for egg waste and grape pomace co-digestates were determined using batch tests. Sample bottles (250 mL) were prepared with various masses of singular co-digestates diluted with ultrapure water to 10 mL, 50 mL of single-source carbon media (Stringfellow and Alvarez-Cohen, 1999), and 50 mL of inoculum from a bench-scale anaerobic reactor that was originally inoculated with contents from a dairy digester. Grape pomace was dried and ground prior to use. Sample bottles were maintained at 38.9 °C in a Thermo Scientific Shkr Max Q 6000 incubator with the mixing speed set at 125 rpm. Biogas production was measured using Digi-key MPX5100GP-ND pressure transducers (Thief River Falls, MN, USA) and biogas methane was determined on a Shimadzu GC-8A gas chromatograph (Kyoto, Japan).

2.5. Data analysis

Total influent flow (Q_i) was determined by summing volumetric contributions of thickened influent slurry and solid feedstocks (Eqn. (1)) using the following dry densities: 1293 kg m^{-3} for feedwaste (ρ_{sf}), 1421 kg m^{-3} for sudan grass silage (ρ_{sg}), and 1576 kg m^{-3} for manure solids (ρ_{ss}) (Bohnhoff and Converse, 1987; Lee and Chung, 1985; McNulty and Kennedy, 1982). Whey wastewater was not included in mass balances; the flow was minimal (<15 m^3 d^{-1}) and only a fraction was fed into the digesters. Effluent flow (Q_e) was determined by subtracting the biogas mass from the total mass of digester inputs (Eqn. (2)). Dry biogas mass (m_{gd}) was determined by summing gas constituents using the ideal gas law (Eqn. (3)). Effluent flow (Q_p) and solids mass rate (m_{wps}) from the screwpress separator were calculated using a mass balance on the total wet mass (Eqn. (4)). The mass balance for the dry matter (DM) for the anaerobic digestion system is shown in Eqn. (5); similar calculations were completed for VS, FS, C, N, S, P, Cl, and K. Gas volumes were adjusted to represent volumes at 0 °C and 100 kPa, standard conditions per the International Union of Pure and Applied Chemistry (IUPAC).

$$Q_i = Q_{tm} + m_{wf}\left[f_{sf}\rho_{sf}^{-1} + f_{wf}\rho_w^{-1}\right] + m_{wg}\left[f_{sg}\rho_{sg}^{-1} + f_{wg}\rho_w^{-1}\right] + m_{ws}\left[f_{ss}\rho_{ss}^{-1} + f_{ws}\rho_w^{-1}\right] \quad (1)$$

$$Q_e = \left(m_{wtm} + m_{wf} + m_{wg} + m_{ws} - m_{gc}\right)(S_{sl}\rho_w)^{-1} \quad (2)$$

$$m_{gd} = Q_{gd}pR^{-1}T^{-1}\left(f_{CH_4}M_{CH_4} + f_{CO_2}M_{CO_2} + f_{O_2}M_{O_2} + f_{H_2S}M_{H_2S} + f_{N_2}M_{N_2}\right) \quad (3)$$

$$m_{wps} = (Q_e - Q_p)S_{sl}\rho_w \quad (4)$$

$$m_{TS,tm} + m_{TS,g} + m_{TS,f} + m_{TS,s} = m_{gd} + m_{TS,e} \quad (5)$$

Mean values are reported ± standard deviation where sufficient data were collected. Statistical analyses were performed using JMP software (Cary, NC). Data comparisons were made using Wilcoxon/Kruskel–Wallis non-parametric tests with chi approximation and ANOVA with Tukey–Kramer HSD for means comparison.

3. Results and discussion

3.1. Mass balance for a full-scale dairy energy project

A mass balance was completed for the anaerobic digestion system with an error of less than 5% for most constituents (Table 1). The high degree of accuracy can be attributed to the large number of grab samples, extensive data sets collected using online sensors, and consistent feed practices throughout project. Manure waste streams, consisting of thickened slurry and screened manure solids, were the dominant digester inputs, comprising 69.2% of influent DM and 84.8% of influent FS (Fig. 2). In the mass balance the 15.7% retention of FS was likely the result of sand and mineral solid accumulation in the digesters, which was verified by dairy managers when the digesters were taken out of service for

Table 1
Mass balance for solids, nutrients, and salts in the anaerobic digesters.

Site name	Flow, loading	Units	DM[a] (kg d^{-1})	VS[b] (kg d^{-1})	FS (kg d^{-1})	C (kg d^{-1})	N (kg d^{-1})	S (kg d^{-1})	P (kg d^{-1})	Cl (kg d^{-1})	K (kg d^{-1})	TDS (kg d^{-1})
Thickened slurry	108 ± 60	m^3 d^{-1}	8544	5595	2949	2615	197.3	57.9	36.9	38.8	75.1	408.7
Feed-waste	2290 ± 3180	kg d^{-1}	868	780	88	351	13.8	1.3	3.0	3.0	15.0	36.4
Sudan grass silage	13,300 ± 6700	kg d^{-1}	3711	3184	527	1526	57.0	5.4	14.0	23.3	78.5	178.6
Manure solids	16,600 ± 6300	kg d^{-1}	2987	2504	479	1255	46.5	8.3	10.0	4.8	12.4	50.8
Injected air[c]	466 ± 71	m^3 d^{-1}	545	–	–	–	417	–	–	–	–	–
Total input			16,655	12,063	4043	5747	731.6	72.9	63.9	69.9	181.0	674.5
Dry biogas[c]	7480 ± 2340	kg d^{-1}	7480	–	–	2945	248.0	2.5	–	–	–	–
Digester effluent	133 ± 62	m^3 d^{-1}	9390	5980	3410	2836	248.4	66.9	61.9	70.6	178.2	650.9
Screwpress effluent	121	m^3 d^{-1}	5076	3164	1913	1515	150.2	58.5	38.1	66.8	156.1	675.6
Screwpress solids	12,200	kg d^{-1}	2846	2284	561	1125	61.2	13.7	15.8	4.7	16.4	46.9
Total output			16,870	5980	3410	5781	496.4	69.4	61.9	70.6	178.2	650.9
Percent difference [(output−input) input^{-1}]			4.7%	−50.4%	−15.7%	0.6%	−57.8%	−4.8%	−3.1%	1.0%	−1.5%	3.5%

[a] Dry matter (DM), volatile solids (VS), fixed solids (FS), carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K), total dissolved solids (TDS).
[b] Online sensor data for TS was used for TS and VS mass balances, based on VS TS^{-1} = 0.65 observed for grab samples.
[c] Data not reported were not measured and assumed negligible.

maintenance. The 633 kg d^{-1} retention of FS suggests the two 25 m diameter tanks are filling with sand at the rate of 0.15 m yr^{-1} based on a bulk density of 1.6 g cm^{-3} for sand. The 50.4% reduction in VS observed reflects a high degree of conversion of organic matter during digestion, resulting in a 50.9% transfer of C from liquid to gaseous forms.

The error in the N balance was higher than for other constituents. The 57.8% error in closure in the N balance is likely a function of uncertainty in measurements of air injected into the digester headspace for biological sulfur oxidation. Real-time monitoring of air injection was not conducted and calculations were based on observations made during site visits when gauge readings were taken. Excluding the injected input air and the biogas in the N mass balance, there was a 21.0% reduction in N, equivalent to 66.2 kg d^{-1}.

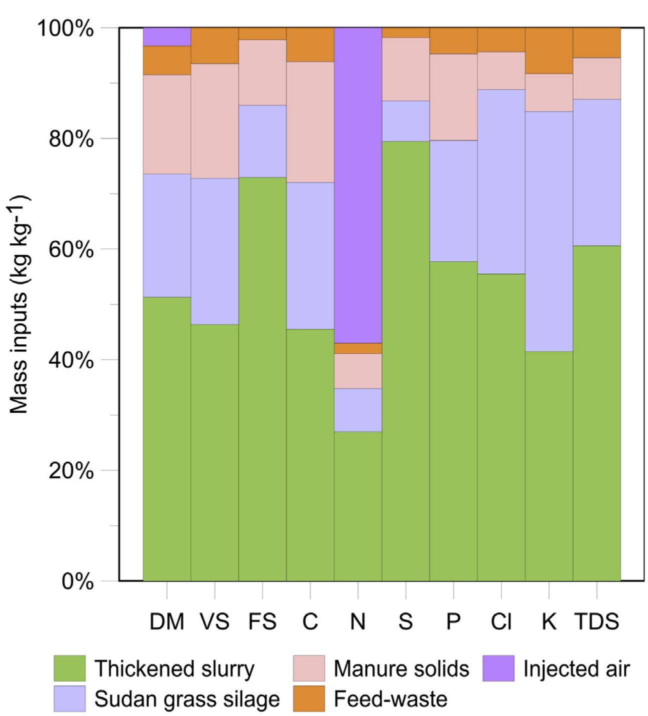

Fig. 2. Elemental contributions (kg kg^{-1}) of the digester inputs expressed as a percentage of the total influent mass loading. Abbreviations: dry matter (DM), volatile solids (VS), fixed solids (FS), carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K), and total dissolved solids (TDS).

In a previous study examining mass balance for three full-scale reactors, the reduction in N resulting from anaerobic digestion was less than 10% (Schievano et al., 2011). In another study of a full-scale anaerobic digestion and composting facility, N decreased by 13.1% (Pognani et al., 2012). Partial volatilization of N in the digesters occurs although the quantity and chemical transformation pathways are not clear. Quantifying the degree of N volatilization in the digesters is important since these facilities may be replacing or augmenting manure storage lagoons where approximately 35% volatilization occurs (van der Schans et al., 2009). Obtaining a better understanding of N volatilization and mineralization in anaerobic digesters is important for predicting N emissions from dairy farms and N pollution to underlying aquifers.

The mass balance for S indicates that 79.4% of the influent S originated with the thickened influent slurry (Table 1). The combined manure inputs contributed 90.9% of influent sulfur, but represented only 69.2% of the influent DM. Sulfur contributions of 7.4% and 1.8% from the sudan grass silage and feed-waste, respectively, were low relative to their respective DM contributions of 22.3% and 5.2%. Only 3.6% of the total S was transferred from the digester feedstocks to the biogas, while 96.4% of effluent S was present in the digester effluent. The minimal amount of S volatilization may be attributed to the biological sulfur removal system located in the headspace of the digesters, which converts gaseous and corrosive H_2S into elemental S. Sulfur crystals have been observed in the headspace of the digesters, verifying the functionality of this treatment method. Following solids separation of the digester effluent, 81.0% of the S remained in liquid form, although the separated solids were significantly enriched with S relative to solid digester feedstocks ($p < 0.05$). As noted by Möller and Müller (2012), few data are available for the fate of sulfur in anaerobic digestion systems. Digester S content may be a concern due to air quality regulations and protection of the engine from corrosion. However, these concerns could be mitigated by a well-functioning S removal system. The S content of 449 mg kg^{-1} w.w. observed here for the digester effluent was slightly higher than the 200–400 mg kg^{-1} w.w. range reported in a review by Möller and Müller (2012) although digester sulfur content is variable depending on digester feedstocks. Additionally, the biological S removal system used in the biogas headspace is likely increasing S in the digester liquid.

The digester effluent had significantly higher concentrations of P, Cl, and K compared with the thickened influent slurry ($p < 0.05$), while N, C, and S concentrations were not significantly different (Table 2). Introduction of co-digestates with the manure resulted in increased digester Cl and K. Sudan grass silage contributed only

Table 2
Characterization of solids, nutrients, and salts in dairy digester samples.[a]

Samples	TS[b] (g kg^{-1} w.w.)	VS (g kg^{-1} w.w.)	FS (g kg^{-1} w.w.)	C (g kg^{-1} w.w.)	N (g kg^{-1} w.w.)	S (mg kg^{-1} w.w.)	P (mg kg^{-1} w.w.)	Cl (mg kg^{-1} w.w.)	K (mg kg^{-1} w.w.)	TDS (g kg^{-1} w.w.)
Lane flush water	14.9 ± 5.5	10.0 ± 4.0	4.89 ± 1.52	4.43 ± 2.53	0.46 ± 0.17	225 ± 132	134 ± 50	356 ± 97	705 ± 156	3.99 ± 0.57
Overflow to lagoon	13.0 ± 4.1	8.37 ± 2.77	4.66 ± 1.41	3.32 ± 1.24	0.41 ± 0.12	194 ± 105	127 ± 44	369 ± 75	697 ± 186	4.19 ± 0.56
Thickened slurry	67.5 ± 21.2	44.2 ± 12.8	23.3 ± 9.0	24.1 ± 5.8	1.80 ± 0.31	536 ± 250	334 ± 126	351 ± 77	697 ± 161	3.70 ± 0.81
Feed-waste	379 ± 161	341 ± 149	38.3 ± 13.1	150 ± 63	5.45 ± 2.28	605 ± 301	1150 ± 519	1260 ± 650	5940 ± 2740	14.0 ± 6.4
Sudan grass silage	279 ± 71	239 ± 59	39.6 ± 24.6	118 ± 32	4.22 ± 1.15	376 ± 211	1410 ± 1160	1550 ± 1060	6130 ± 3430	14.0 ± 5.4
Manure solids	180 ± 33	151 ± 24	28.8 ± 25.0	75.2 ± 13.1	2.81 ± 0.59	489 ± 223	702 ± 196	309 ± 116	744 ± 238	3.11 ± 0.49
Digester 1	74.0 ± 12.9	50.1 ± 9.3	23.8 ± 4.9	20.6 ± 5.3	1.81 ± 0.35	547 ± 249	446 ± 91	565 ± 134	1323 ± 335	4.89 ± 0.67
Digester 2	71.3 ± 13.3	49.9 ± 9.1	21.4 ± 4.5	19.7 ± 2.4	1.68 ± 0.06	498 ± 223	417 ± 79	540 ± 120	1246 ± 301	5.25 ± 0.81
Digester effluent	69.4 ± 18.1	44.2 ± 10.8	25.2 ± 11.3	19.3 ± 6.3	1.65 ± 0.42	449 ± 294	458 ± 85	521 ± 122	1320 ± 380	4.81 ± 0.49
Screwpress effluent	41.3 ± 8.3	25.7 ± 6.0	15.5 ± 3.2	11.3 ± 2.6	1.13 ± 0.28	439 ± 104	310 ± 96	542 ± 112	1270 ± 420	5.49 ± 0.72
Screwpress solids	233 ± 39	187 ± 33	46.0 ± 10.1	92.1 ± 16.0	5.07 ± 1.14	1164 ± 612	1390 ± 296	396 ± 99	1400 ± 420	3.95 ± 0.87

[a] Specific gravity observed was 1.02 for thickened slurry and digester effluent and 1.00 for lane flush and overflow.
[b] Total solids (TS), volatile solids (VS), fixed solids (FS), carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K), total dissolved solids (TDS), wet weight (w.w.).

22.3% of influent DM, but a higher proportion of the Cl and K loadings, 33.3% and 43.4%, respectively. Although only representing a small proportion of the digester influent, the feed-waste had an elevated K concentration of 8.3% while its DM contribution was only 5.2%. The digester effluent was enriched with P relative to the thickened influent slurry since P was retained while DM was converted to gaseous products. The digester N content of 2.65% DM was low relative to previous studies where 3.1–14% DM was typical, while the digester C content of 30.2% DM was also below the expected range of 36–45% DM and the C:N ratio of 11.4 was above the previously observed range of 3–8.5 (Möller and Müller, 2012). These differences may be related to the degree of conversion of feedstocks (based on feedstock kinetics and digester HRT) and the types of feedstocks that were added. In the previous study most of the data sets summarized originated from digesters that were primarily fed energy crops and crop residues, while manure was the primary input in this study. The digestate P content of 0.70% DM and K content of 1.94% DM observed here were within the ranges of 0.6–1.7% and 1.9–4.3%, respectively, reported by Möller and Müller (2012).

Following digester effluent solids separation, the screwpress solids contained 35.9% of effluent DM, while containing 41.9% of VS and 42.6% of C (Fig. 3). Screwpress solid and effluent mass rates were determined using a mass balance separate from the anaerobic digester (Table 1). The error of closure was 15% or less for all elements except FS where there was a 27% difference between calculated screwpress input and outputs. Solids separation resulted in a significant reduction of C, N, P, Cl, and K in the effluent ($p < 0.05$) although the screwpress effluent still contained high concentrations of Cl, K, and TDS. Following separation, 93.4% of the effluent Cl and 90.5% of the effluent K were present in the screwpress effluent. Solids separation was more efficient than what was reported by Bauer et al. (2009); based on their regression analysis, a digestate with a DM content of 6.9% would be expected to contain approximately 19% of DM in the screwpress solids while 35.9% of effluent DM was present in the screwpress solids in this study. Lower content of DM, C, P, and K in the separated solids was observed compared with what was reported by Bauer et al. (2009). In the study of Möller et al. (2010), approximately 49% of effluent DM was present in the separated solids although energy crops and agricultural residues were used exclusively in that study. Möller et al. (2010) observed separation of 22.5% of the FM into the screwpress solids while 9% was observed here. Möller et al. (2010) also found that N and K were preferentially located in the screwpress effluent while P tended to be associated with the screwpress solids. These results demonstrate the importance of collecting anaerobic digestion data that reflect various feedstocks.

Anaerobic digestion resulted in transformation of many water quality constituents (Table 3). Compared with the thickened influent slurry, digester effluent had significantly higher alkalinity, SC, and TAN while most indicators of organic material (DOC, sCOD, BOD, and cBOD) were significantly reduced ($p < 0.05$). The decrease in alkalinity was likely caused by production of volatile fatty acids due to anaerobic metabolic activity. The increase in TAN from 295 ± 81 mg L^{-1} to 576 ± 47 mg L^{-1} was also likely caused by microbial degradation of proteins in the digesters. The 48.3% increase in SpC from the thickened influent slurry to the digester effluent was due to salinity contributions of the solid digester feedstocks. The C/N ratio for the thickened influent slurry was 13.3 ± 1.7, which was not significantly different ($p > 0.05$) than that of the digester effluent, 11.5 ± 1.5. The stability in the C/N ratio likely

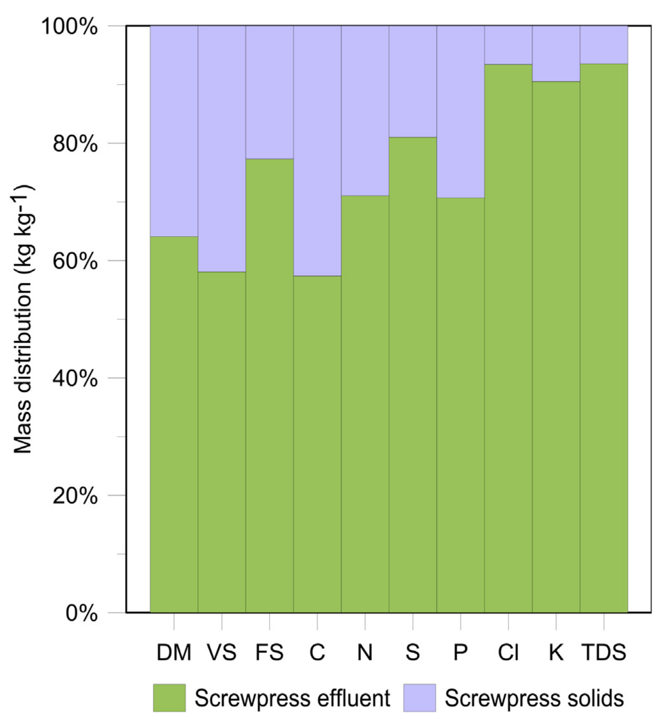

Fig. 3. Digester effluent constituents (kg kg^{-1}) in solid and slurry streams following solids separation with the screwpress separator. Elements in the separated solid and liquid streams expressed as a percentage of the total effluent mass loadings. Abbreviations: dry matter (DM), volatile solids (VS), fixed solids (FS), total carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K), and total dissolved solids (TDS).

Table 3
Water quality data for dairy digester slurry samples.

Slurry samples	pH	Alkalinity ($g L^{-1}$ as $CaCO_3$)	SpC[a] ($mS cm^{-1}$)	DOC ($mg L^{-1}$)	COD ($g L^{-1}$)	sCOD ($g L^{-1}$)	BOD ($g L^{-1}$)	cBOD ($g L^{-1}$)	TAN ($mg L^{-1}$)	ON ($mg L^{-1}$)	TN ($mg L^{-1}$)
Lane flush water	7.99 ± 0.25	3.07 ± 0.78	5.96 ± 0.85	952 ± 281	14.7 ± 6.2	4.51 ± 0.65	2.30 ± 0.82	1.89 ± 0.74	295 ± 101	472 ± 315	740 ± 339
Overflow to lagoon	7.75 ± 0.32	3.01 ± 0.56	6.25 ± 0.84	981 ± 205	12.6 ± 5.06	4.51 ± 0.95	2.34 ± 0.61	2.07 ± 0.61	309 ± 84	374 ± 190	641 ± 207
Thickened slurry	7.36 ± 0.28	4.55 ± 0.82	5.63 ± 1.24	1055 ± 265	54.8 ± 15.8	8.14 ± 0.69	4.35 ± 0.71	3.39 ± 0.47	295 ± 81	736 ± 195	1000 ± 172
Digester 1	7.26 ± 0.12	6.72 ± 0.91	7.44 ± 1.03	527 ± 114	61.4 ± 15.8	4.97 ± 1.11	1.65 ± 0.78	0.89 ± 0.46	513 ± 112	974 ± 429	1459 ± 433
Digester 2	7.25 ± 0.12	6.34 ± 1.04	7.99 ± 1.24	518 ± 109	57.1 ± 18.4	7.20 ± 2.57	1.51 ± 0.68	0.92 ± 0.43	499 ± 111	805 ± 390	1265 ± 415
Digester effluent	7.30 ± 0.11	6.65 ± 0.99	7.32 ± 0.75	593 ± 31	52.5 ± 15.9	4.65 ± 1.85	1.75 ± 0.22	1.02 ± 0.15	576 ± 47	na[b]	1204 ± 225
Screwpress effluent	7.29 ± 0.11	6.05 ± 0.87	8.35 ± 1.10	552 ± 114	34.7 ± 11.8	3.98 ± 1.58	1.29 ± 0.55	0.78 ± 0.67	467 ± 116	803 ± 464	1259 ± 434

[a] Specific conductance (SpC), dissolved organic carbon (DOC), chemical oxygen demand (COD), soluble COD (sCOD), biochemical oxygen demand (BOD), carbonaceous BOD (cBOD), total ammonia nitrogen (TAN), organic nitrogen (ON), total nitrogen (TN).
[b] na = data not available.

reflects the C loss due to microbial conversions balanced by C inputs from the solid feedstocks. The digestate TAN content of 47.8% TN and pH of 7.3 are within the ranges of 44–81% and 7.3–9.0, respectively, as reported by Möller and Müller (2012), demonstrating agreement with previous studies.

Gas and fluid flows were measured continuously as part of the mass balance study. The influent digester flow (Q_i) was 141 ± 62 m^3 d^{-1}, resulting in an average HRT of 48.3 days and the total volumetric reduction of feedstocks resulting from anaerobic digestion was 6%. Online TS measurement for thickened influent slurry was 83.6 ± 21.9 g kg^{-1} w.w., which was statistically similar to the grab sample result of 67.5 ± 21.2 g kg^{-1} w.w. ($n = 22$). Biogas production was 5800 ± 1790 m^3 d^{-1} and the biogas constituents were 50.5 ± 3.7% CH_4, 0.81 ± 0.75% O_2, and 293 ± 250 ppm H_2S. Spot measurements on biogas CO_2 ($n = 21$) indicated a concentration of 45.3 ± 3.3%. The unaccounted portion of the biogas (3.4%) was attributed to nitrogen gas (N_2), as ammonia and other biogas constituents are generally present in small concentrations (Rasi et al., 2007; Strik et al., 2006, 2005). Biogas condensate mass was calculated by adjusting the biogas volume to the digester temperature of 38.7 ± 1.4 °C and the headspace gage pressure of 0.3 kPa. A water vapor density of 0.05 kg m^{-3} was used based on the Mollier Diagram and assuming saturated gas. Accordingly, the biogas condensate flow rate was 0.34 m^3 d^{-1}. Due to the minimal flow rate, mass contributions of C, N, and S in the condensate were not included in the mass balance (Eqn. (2)).

3.2. *Use of solids and conductance measurements to predict nutrients and salts*

Regression analyses were performed to determine if TS, VS, and/or SpC were predictive of carbon, nutrients, and salts (Table 4). In slurry samples, TS and VS were predictive of C and N (R^2 values of 0.93–0.95). Less consistent relationships were observed between solids in slurry samples and S and P (R^2 values of 0.43–0.75). In solid samples TS and VS were predictive of C (R^2 values of 0.95 and 0.90, respectively); however, relationships with N, S, and P were much weaker (R^2 of 0.52 and lower). Regression analyses were performed for the individual types of solid substrates (data not shown) and most relationships between solids and individual elements were not improved ($R^2 < 0.80$). Weak relationships were observed between SpC and Cl ($R^2 = 0.19$), and between SpC and K ($R^2 = 0.33$), suggesting that there are other important elements contributing to sample salinity. For example, ionic sulfur species (e.g. HS^-, SO_4^{2-}), ammonium, and organic acids may be contributing to anaerobic digester salinity. These results suggest that multiple elements should be measured to characterize the salt content of anaerobic digesters.

3.3. *Assessment of potential co-digestates*

Previous studies have shown that importation of off-site co-digestates is required to achieve design capacity for electrical generation at this facility (Camarillo et al., 2012). Potential co-digestates were characterized to evaluate their suitability for anaerobic digestion (Table 5). Available products included milk and whey wastewaters, egg waste, pasta waste, and grape pomace from the wine industry. The analytical data show the variable composition of feedstocks. In particular, egg waste contained the highest concentrations of N, S, and Cl relative to the other feedstocks tested, while grape pomace had the highest P and K contents. Grape pomace, consisting of the pressings left over from wine making, was identified as a high density waste product containing 49.4% TS. Egg waste contained 21.8% TS, making it a high density product as well.

When the methane potential was considered in addition to the elemental compositions of feedstocks, the advantage and disadvantages of various feedstocks became apparent (Table 6). Compared with the elemental contributions from other feedstocks relative to their methane production, grape pomace had the highest N, S, and K contributions, while whey wastewater had the highest Cl contribution and milk wastewater had the highest P contribution. Whey wastewater had the lowest elemental contributions of N

Table 4
Regression analyses ($y = mx + b$) demonstrating use of solids (TS and VS) and conductance (SpC) to predict occurrence of C, N, S, P, Cl, and K.[a,b]

y	*x*	Sample type	R^2	*m*	*b*	*n*
C	TS	Slurry	0.93	0.393	0.293	39
N	TS	Slurry	0.94	0.225	0.021	39
S	TS	Slurry	0.43	0.144	0.0054	39
P	TS	Slurry	0.75	0.085	0.0048	98
C	VS	Slurry	0.95	0.102	0.462	39
N	VS	Slurry	0.95	0.210	0.034	39
S	VS	Slurry	0.43	0.142	0.0084	39
P	VS	Slurry	0.74	0.092	0.0070	98
Cl	SpC	Slurry	0.19	0.164	0.0438	99
K	SpC	Slurry	0.33	−0.152	0.168	99
C	TS	Solids	0.95	3.417	0.389	51
N	TS	Solids	0.52	1.218	0.0118	51
S	TS	Solids	0.00	0.636	0.00013	51
P	TS	Solids	0.42	0.043	0.0039	19
C	VS	Solids	0.90	13.14	0.414	51
N	VS	Solids	0.46	1.620	0.0121	51
S	VS	Solids	0.00	0.684	0.0001	51
P	VS	Solids	0.24	0.424	0.0030	19

[a] Total solids (TS), volatile solids (VS), carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K).
[b] Units of SpC are mS cm^{-1} and other units are g kg^{-1} w.w., n = number of samples.

Table 5
Characterization of potential co-digestates.

Samples	SpC[a] (mS cm^{-1})	COD (g L^{-1})	sCOD (g L^{-1})	TS (g kg^{-1} w.w.)	VS (g kg^{-1} w.w.)	FS (g kg^{-1} w.w.)	C (g kg^{-1} w.w.)	N (g kg^{-1} w.w.)	S (mg kg^{-1} w.w.)	P (mg kg^{-1} w.w.)	Cl (mg kg^{-1} w.w.)	K (mg kg^{-1} w.w.)
Egg waste	6.88	392	288	218	208	9.79	131	18.3	1651	1468	3195	1189
Grape pomace	na[b]	na	na	494	463	31.5	209	10.4	944	1529	204	8287
Milk waste	4.54	74.4	10.0	53.3	40.0	13.3	25.9	3.17	211	608	153	na
Pasta waste	2.24	101	8.13	50.2	46.8	3.38	28.3	1.57	107	134	206	na
Whey wastewater	5.79	175	na	63.9	58.5	5.37	28.0	1.45	117	495	2213	1813

[a] Specific conductance (SpC), chemical oxygen demand (COD), soluble COD (sCOD), wet weight (w.w.), total solids (TS), volatile solids (VS), fixed solids (FS), carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K).
[b] na = data not available. SpC was determined for suspensions of dried and ground grape pomace such that the TDS was 30.3 mg TDS g^{-1} TS.

and S, while pasta waste had the lowest P contribution. The methane contents of milk wastewater, pasta waste, and whey wastewater were low relative to other feedstocks (Table 6), indicating that large quantities would be needed for its use in anaerobic digestion. The results indicate that the optimal choice of co-digestate depends on the elements of concern. If transport of off-site wastes is also considered, egg waste and grape pomace become appealing feedstocks because less material would need to be transported due to the higher methane potentials. If the TDS is considered relative to the methane potential, the egg waste had the lowest salt content relative to methane potential. Based on high methane potential per bulk volume, egg waste and grape pomace appear to be good candidates for co-digestion.

3.4. Co-digestation of imported feedstocks and the impact on salt and nutrient balances

The project described herein was described previously in an economic analysis based on the first 15 months of operation (Camarillo et al., 2012). In that study, it was determined that operating the system closer to the power plant capacity was critical for enhancing economic sustainability and that co-digestion was the most feasible approach for accomplishing this goal. Here, the power plant was producing 369 kW, which was lower than the capacity of 710 kW, due to insufficient loading of the anaerobic digesters resulting in low biogas production. Based on the observed 3.08 kWh m^{-3} CH_4 and conservatively assuming an additional 5% is needed due to system inefficiencies such as flared biogas maintenance events, an additional 2790 m^3 CH_4 d^{-1} is needed to reach power plant capacity. To reach design power production capacity, various quantities of co-digestates would be necessary (Table 7). The egg waste and grape pomace would only reduce the HRT from 48.3 d to 40.6 d and 35.5 d, respectively. However, use of milk or pasta waste as co-digestates would reduce the HRT to values below the design range of 24–30 d and use of whey waste as a co-digestate would reduce the HRT to 27 d. Co-digestion with egg waste would result in an egg waste concentration of 36 g TS L^{-1} in the influent, based on a specific gravity of 1.035 for eggs reported by Kirk et al. (2008). Co-digestion with grape pomace would result in 157 g TS L^{-1} of grape pomace in the influent, based on a dry density of 1500 kg m^{-3}, a value used for wood cellular material (Shmulsky and Jones, 2011).

In addition to increasing biogas CH_4 by 92%, importing digester feedstocks would increase salt and nutrient mass loadings to the dairy farm (Table 7). The percent increases for C, N, S, P, Cl, K, and TDS range from 18% to 353%. Co-digestion of egg waste would result in larger increases in Cl, while co-digestion of grape pomace would result in larger increases in all other tested elements. In particular, the TDS would only increase 19% over the current baseline due to co-digestion with egg waste while the TDS would increase 135% as a result of co-digestion with grape pomace. In another study of a full-scale anaerobic digester, co-digestates increased biogas production by 110% while increasing TKN by 57% and increasing P by 13% (Frear et al., 2011). In that study a combination of egg, fish bread, crab, and ravioli wastes were co-digestated; the volumetric contribution of co-digestates was 16% (Frear et al., 2011). The proposed volumetric contributions here are 16% and 27% for egg waste and grape pomace, respectively. The N increases of 161–201% and P increases of 64–146% for egg waste and grape pomace estimated here are higher than the values reported by Frear et al. (2011), which suggests that it is important to collect data on individual feedstocks to clarify elemental inputs.

The optimal selection of feedstocks relies on a farm-specific mass balance and evaluation of underlying groundwater conditions. The selection of egg waste may be preferable here, due to the lower salt content although a higher contribution of Cl will result. The farm-level salt and nutrient increases could potentially present a challenge for managing mass balances. The increase in N loading may be especially problematic in an anaerobic digestion system with co-digestion, as compared with an open storage lagoon where significant volatilization of N occurs (van der Schans et al., 2009). One solution would be to export digester solids that have value as a fertilizer. This solution would result in significant export of N, S, and P although most of the Cl and K would remain in the screwpress

Table 6
Contributions of salts and nutrients relative to methane potential of readily available co-digestates in Central California.

Sample[a]	Methane potential (L CH_4 L^{-1} slurry or kg solid substrate)[b]	Reference for methane potential	Elemental contributions relative to bio-methane production (g m^{-3} CH_4)						
			C[c]	N	S	P	Cl	K	TDS
Egg waste	104.2	This study	1301	182	16.4	14.6	31.7	11.8	45.8
Grape pomace	45.8	This study	4563	227	20.6	33.4	4.5	180.9	326
Milk waste	16.5	Wu et al., 2011	1585	194	12.9	37.2	9.4	na[d]	186
Pasta waste	15.6	Labatut et al., 2011	1832	102	6.9	8.7	13.3	na	97.2
Whey waste	25.3	Labatut et al., 2011	1118	58	4.7	19.8	88.3	72.4	155

[a] Specific gravity for egg waste = 1.035. Specific gravity for milk, pasta, and whey wastes = 1.01.
[b] Methane volumes reported pertain to those for standard conditions (0 °C, 100 kPa).
[c] Carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K), total dissolved solids (TDS).
[d] na = data not available.

Table 7
Impact of co-digestion on existing salt and nutrient mass influent loadings.[a]

Potential co-digestate	Quantity needed to reach capacity	Increase in existing mass loadings (kg d^{-1}, % increase above baseline in parentheses)						
		C[b]	N	S	P	Cl	K	TDS
Egg waste[c]	26.8 m^3 d^{-1}	3630 (63%)	507 (161%)	46 (63%)	41 (64%)	89 (127%)	33 (18%)	128 (19%)
Grape pomace	60,917 kg d^{-1}	12,732 (222%)	634 (201%)	58 (79%)	93 (146%)	12 (18%)	505 (279%)	911 (135%)
Milk waste	169 m^3 d^{-1}	4423 (77%)	541 (172%)	36 (49%)	104 (162%)	26 (37%)	na[d]	519 (77%)
Pasta waste	179 m^3 d^{-1}	5112 (89%)	284 (90%)	19 (27%)	24 (38%)	37 (53%)	na	271 (40%)
Whey waste	110 m^3 d^{-1}	3119 (54%)	162 (51%)	13 (18%)	55 (86%)	246 (353%)	202 (112%)	432 (64%)

[a] Based on co-digesting sufficient imported feedstocks to increase power production from 369 kW to 710 kW.
[b] Carbon (C), nitrogen (N), sulfur (S), phosphorus (P), chloride (Cl), potassium (K), total dissolved solids (TDS).
[c] Specific gravity of egg waste = 1.035. Specific gravity for milk, pasta, and whey wastes = 1.01.
[d] na = data not available.

effluent. Concentration of effluent and disposal of the saline concentrate may be necessary to minimize accumulation of salts on dairy farms that import co-digestate feedstocks.

4. Conclusions

A mass balance for a full-scale dairy anaerobic digester system was successfully completed for solids, nutrients, and salts with digester inputs accounted for separately. Manure digester inputs significantly increased N, S, and P while sudan grass silage contributed significantly to Cl and K inputs. Digester effluent solids were concentrated with N, P, and S while most of the effluent Cl and K were present in the digester liquid. Solids measurements could be used as surrogate measurements for nutrients in slurries, but conductance was not correlated with Cl or K concentrations, suggesting that other ions contributed significantly to salinity.

Evaluation of five potential co-digestates revealed varying elemental contributions relative to their methane potentials. Co-digestion with imported feedstocks to achieve full capacity of the power plant would necessitate import of products containing salts and nutrients, increasing farm-level salt and nutrient mass loadings. The results suggest extensive analytical evaluations are necessary prior to implementation of co-digestion programs on dairy farms and that the selection of digester feedstocks will be dictated by salt and nutrient content in addition to methane potentials.

Acknowledgments

Funding was received from the US Department of Energy National Energy Technology Laboratory, Assistance Agreement DE-EE0001895 and from the California Energy Commission, Contract Number #PIR-10-053. Laboratory and field assistance was received from Matthew Ebia, Michael Jue, Cameron Ross, and Ashley Stubblefield.

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