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

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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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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, 8.314×10^{-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.