Phase II Bioenergy Production from MSW by High Solids Anaerobic Digestion

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AD	Anaerobic Digestion
ANOVA	Analysis of Variance
B	Biosolids
BMP	Biochemical Methane formation Potential assay
BS	Baking Soda
BSOC	Brandon Support Operations Complex
CaCO ₃	Calcium Carbonate
CH ₄	Methane
CHP	Combined Heat and Power
DI	Deionized water
FW	Food Waste
FWEA	Florida Water Environment Association
GHG	Greenhouse Gas
HS-AD	High Solids Anaerobic Digestion
LS	Limestone
L-AD	Liquid Anaerobic Digestion
LCA	Life Cycle Assessment
LCC	Life Cycle Cost
LCCA	Life Cycle Cost Analysis
LCI	Life Cycle Inventory
MSW	Municipal Solid Waste
NH4 ⁺	Ammonium
NH ₄ HCO ₃	Ammonium Bicarbonate
NaHCO ₃	Sodium Bicarbonate (Baking Soda)
OFMSW	Organic Fraction of Municipal Solid Waste
O&M	Operations and Maintenance
OS	Oyster Shells
sCOD	Soluble Chemical Oxygen Demand
S/I	Substrate to Inoculum
SS-AD	Solid-State Anaerobic Digestion
S/S	Substrate to Substrate
PV	Present Value
Т	Temperature
TAG	Technical Advisory Group
TRACI	Tool for Reduction and Assessment of Chemicals and
	Other Environmental Impacts
TS	Total Solids
VFA	Volatile Fatty Acids
VS	Volatile Solids
WTE	Waste to Energy
WWTP	Wastewater Treatment Plant
YW	Yard waste
ZWE	Zero Waste Energy

LIST OF ACRONYMS AND ABBREVIATIONS

FINAL REPORT

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EXCUTIVE SUMMARY

High Solids Anaerobic Digestion (HS-AD) is a promising alternative for managing the organic fraction of municipal solid waste (OFMSW), including yard waste and food waste. Compared with liquid anaerobic digestion (L-AD), HS-AD has lower energy requirements for heating, lower material handling requirements, reactor volumes and leachate production rates and higher biogas methane (CH₄) content. In addition, the digestate from HS-AD can be utilized as a fertilizer (compost) or pelletized fuel because of its low moisture content. However, there has been limited research on HS-AD of OFMSW with biosolids (also known as sewage sludge). Biosolids management is increasingly expensive in Florida due to the relatively limited L-AD capacity for biosolids, stringent recent regulations on land application of biosolids and the high cost of biosolids disposal in landfills. Assessment of the environmental and economic sustainability of HS-AD of OFMSW is limited. Thus, the overall goal of this project was to improve the environmental and economic sustainability of HS-AD of OFMSW and biosolids in Florida. Specific objectives were to: 1) investigate the performance of HS-AD of OFMSW and biosolids under varying operating conditions, 2) apply life cycle assessment (LCA) to assess whether HS-AD is environmentally beneficial, and 3) compare the HS-AD with other waste management options (e.g., landfilling, Waste to Energy (WTE), composting) using life cycle cost analysis (LCCA) to ensure economic sustainability.

<u>Objective 1</u>: The performance of HS-AD under varying operating conditions was investigated using biochemical CH₄ formation potential (BMP) assays. The following conditions were evaluated: 1) addition of biosolids to OFMSW, 2) alkalinity source addition (limestone, oyster shells, sodium bicarbonate), 3) food waste, yard waste and biosolids substrate ratios, 4) substrate to inoculum ratios (S/I), and 5) temperature. Both biosolids and alkalinity source addition enhanced CH₄ yields by enhancing pH buffering capacity. Limestone and oyster shells provided equivalent buffering capacity; however, oyster shells are a low-cost waste product. A 2:1 ratio of oyster shells and sodium bicarbonate provided both slow and fast release sources of alkalinity. Higher initial CH₄ yields were observed with a waste mixture similar to the waste availability in Hillsborough County than with equal fractions of food waste, yard waste and biosolids. Enhanced CH₄ production was also observed at the lowest S/I ratio tested (1.2 based on volatile solids [VS]). Results for HS-AD at varying temperatures were inconclusive, due to high ammonium and volatile fatty acids (VFA) concentrations under thermophilic conditions (>3,600 mg NH₄⁺-N/L and >7,600 mg/L of VFA). These tests are currently being repeated with an acclimated inoculum. Results from Objective 1 showed that hydrolysis of food waste results in the significant VFA and ammonia production, which can inhibit methanogenesis. However, this inhibition can be avoided by: 1) co-digestion of food waste with yard waste and biosolids, 2) adding crushed oyster shells and sodium bicarbonate to the mixture as slow and fast release alkalinity sources, and 3) recirculating sufficient digestate to provide an acclimated inoculum and low S/I.

<u>Objective 2</u>: LCA was used to evaluate environmental impacts and benefits of HS-AD using Hillsborough County's organic waste production rates as a case study. Four impact categories were evaluated: global warming potential, acidification, eutrophication and ecotoxicity. Overall, HS-AD was found to be environmentally beneficial due to recovery of energy and nutrients as electricity, heat, and compost from OFMSW and biosolids. Waste collection and transportation (over a 20-year span) contributed to some negative environmental impacts, particularly eutrophication and ecotoxicity, while negative environmental impacts from construction of HS-AD facilities were negligible. Results from Objective 2 showed that HS-AD of OFMSW and biosolids can provide significant environmental benefits to Florida municipalities by recovering energy and nutrients from waste.

<u>Objective 3</u>: LCCA was used to evaluate economic sustainability of HS-AD in comparison with landfilling, WTE and composting. When land acquisition costs were not included in the analysis, the most economical option was composting, due to its low capital and operations and maintenance (O&M) costs. However, the Life Cycle Cost (LCC) of HS-AD was only slightly higher than composting. The greatest economic benefit of both composting and HS-AD was due to the savings on tipping costs by diversion of OFMSW. When land acquisition costs were considered, the most economical option was HS-AD because it requires less land area than composting and produces energy and compost. Results from Objective 3 showed that HS-AD of OFMSW and biosolids can be a cost-effective waste management option for Florida municipalities by reducing tipping costs and recovering energy and compost. However, HS-AD may not be cost competitive with composting if land acquisition costs are very low.

<u>Conclusions</u>: In Florida, OFMSW is mainly managed by landfilling and WTE facilities. Diversion of OFMSW from landfills can reduce fugitive greenhouse gas (GHG) emissions and improve leachate quality. Diversion of OFMSW from WTE can result in improved energy efficiency and reduced air emissions. The following conclusions can be drawn from this project:

- Addition of biosolids during HS-AD of OFMSW increases CH₄ yields by reducing pH inhibition of methanogenesis. Co-digestion of biosolids with OFMSW in HS-AD also avoids onsite L-AD of biosolids. Advantages of this approach include recovery of energy and nutrients from biosolids while avoiding the production of liquid side-streams which negatively impact mainstream wastewater treatment processes.
- Addition of alkalinity sources, such as limestone and crushed oyster shells, during HS-AD of OFMSW increases CH₄ yields by reducing pH inhibition of methanogenesis. Crushed oyster shells are a low-cost alternative to limestone as a pH buffer. A mix of crushed oyster shells and sodium bicarbonate provided both slow and fast acting alkalinity sources.

- A low S/I ratio (≤ 1.2 on a VS basis) improved HS-AD stability by reducing methanogenesis inhibition due to VFA accumulation. In practice, a low S/I ratio is achieved by mixing acclimated digestate with fresh food waste, yard waste and biosolids.
- The substrate ratio based available amounts of OFMSW available in Hillsborough County improved HS-AD stability compared to equal substrate ratios by reducing inhibition associated with VFA and ammonia production during the start-up period.
- HS-AD can provide environmental benefits of reduced global warming potential, acidification, eutrophication and ecotoxicity by recovering energy and nutrients from the waste.
- Both composting and HS-AD can be economically beneficial options for managing OFMSW and biosolids for Hillsborough County, FL. When land acquisition costs are considered, HS-AD is the lowest cost alternative.
- HS-AD of OFMSW and biosolids is an attractive waste management approach for Florida municipalities that can be integrated with existing waste management infrastructure. Benefits to the waste management industry include: reduced tipping fees, improved landfill leachate quality, improved energy efficiency at WTE facilities, reduced GHG and other air emissions and greater energy and nutrient recovery.

INTRODUCTION AND OBJECTIVES

Bioenergy recovery from municipal solid waste (MSW) is commonly practiced in the US by collecting and utilizing landfill gas for heat, vehicle fuel or conversion to electricity using internal combustion engines or turbines. The most common strategy in the US for enhancing landfill gas production is through recirculation of leachate through the entire waste stream. Many landfills in Europe; however, separate the organic fraction of MSW (OFMSW) for energy recovery through anaerobic digestion (AD). This promotes faster OFMSW degradation, a higher biogas quality based on methane (CH₄) composition, lower fugitive greenhouse gas (GHG) emissions and production of a nutrient rich compost (also called digestate) that can be used as a fertilizer. Depending on the Total Solids (TS) concentration of the substrate, AD can be applied under wet ($\leq 10\%$ TS) or high solids ($\geq 15\%$ TS) conditions. Advantages of HS-AD (also known as solid-state AD [SS-AD] or dry fermentation) over L-AD include lower parasitic energy losses, reduced water use and leachate production and recovery of nutrients as a compost product (Hinds et al., 2017).

The overall goal of this project was to improve the environmental and economic sustainability of HS-AD of OFMSW in Florida. Specific objectives for Phase II were to:

- 1. Investigate the performance of HS-AD of OFMSW with varying alkalinity sources (oyster shells, limestone, sodium bicarbonate), substrate ratios (yard waste [YW], food waste [FW], and biosolids), substrate to inoculum (S/I) ratios and temperatures (35 and 55 °C).
- 2. Apply life cycle assessment (LCA) to assess whether HS-AD is environmentally beneficial.
- 3. Compare HS-AD with other waste management options (e.g., landfilling, WTE, composting) using life cycle cost analysis (LCCA) to ensure economic sustainability.

OBJECTIVE 1: INVESTIGATE HS-AD PERFORMANCE WITH VARYING CONDITIONS

FW and YW make up approximately 25% of the overall MSW stream in the US. HS-AD is a potential waste management option for OFMSW, which is able to recover energy and nutrients. A number of studies have investigated the performance of HS-AD of FW and YW under varying conditions, including TS content, S/I ratios, substrate to substrate (S/S) ratios (FW and YW), and reactor design (Brown and Li, 2013; Chen et al., 2014; Li et al., 2018). Incorporation of biosolids as a co-substrate with FW and YW in HS-AD has the potential to improve substrate characteristics and increase bioenergy production. In addition, biosolids management is increasingly expensive due to relatively limited L-AD capacity for biosolids in the US, stringent recent regulations on land application of biosolids and the high cost and bans on biosolids disposal in landfills (Forbes, 2011). However, there is limited research on HS-AD of FW, YW, and biosolids. Thus, the objective of this task was to investigate the performance of HS-AD of FW, YW, and biosolids with varying operating conditions (e.g. alkalinity source addition, S/S ratios, S/I ratios and operating temperatures) using BMP assays.

Materials: Dewatered sludge cake from mesophilic L-AD of sewage sludge was obtained from the Northeast Water Reclamation Facility (Clearwater, FL) and was used as inoculum for BMP sets 1 through 3, while a laboratory acclimated inoculum was used for BMP sets 4 and 5. The acclimated inoculum was digestate from mesophilic (35°C) BMP reactors operated with FW, YW, and biosolids (> 90 days). Alkalinity sources tested were crushed oyster shells (OS),

limestone (LS) and sodium bicarbonate (NaHCO₃; shown as BS [baking soda] in figures). FW was prepared based on the average FW composition in European countries (MTT Agrifood Research Finland, 2010) and North America (Rajagopal et al., 2017), including fruits/vegetables 72.8%, meat 8.8%, dairy products 5.5%, bread and bakery 6.6%, pasta/rice 6.4 % by wet weight fraction (Dixon, 2018). The FW was chopped into small sizes and then shredded to < 3mm using a food processor (Hamilton Beach, model 70725A). FW was stored at 2-4 °C for < 2 days until use. YW composition was based on information from the city of Tampa's YW facility (grass clippings 25%, oak leaves 25%, pine needles 25%, and wood debris 25% by wet weight fraction) (Dixon, 2018). YW was processed by cutting with scissors and sieving using a 3x3-mm mesh to improve homogeneity (Hinds et al., 2016). YW was stored at room temperature prior to the experiment. Dewatered biosolids were obtained from Hillsborough County's Falkenburg Road Advanced Wastewater Treatment Plant (WWTP) (Tampa, FL). Biosolids were stored at room temperature for < 7 days. Note that the mixing ratio of FW/YW/biosolids=23:62:15 used in digestion sets 3, 4 and 5 (Table 1) reflect the composition of available OFMSW in Hillsborough County, FL (discussed below).

Experimental BMP setup: Five sets of BMP assays were carried out, as shown in Table 1. BMPs were set up in 250 mL glass serum bottles with septum seals and metal crimp caps. Substrate and inoculum were mixed by hand to provide homogeneous conditions. Blank reactors containing only the inoculum were used to correct for CH_4 produced from the inoculum. Deionized water (DI) was added to the reactors as needed to adjust the initial TS content of the mixture to 15-20% (Table 1). BMPs were incubated in a thermostatically controlled room.

BMP	Т	Alkalinity	S/S ratio	S/I	TS	Purpose
set	(°C)			ratio	(%)	
1	35	OS, LS	FW:YW:B=33:33:33	2.7	15	Alkalinity source: OS or LS
2	35	OS	FW:YW=50:50	2.7	20	With and without biosolids addition
			FW:YW:B=33:33:33			
3	35	OS/BS	FW:YW:B=33:33:33	1	20	S/S ratios (equal ratios based on
			FW:YW:B=23:62:15			available amounts in Hillsborough
						Co. MSW)
4	35	OS/BS	FW:YW:B=23:62:15	1.2,	15	S/I ratios
				2.5,		
				3.8		
5	35,	OS/BS	FW:YW:B=23:62:15	1	20	Temperature
	55					

Table	1. BMP	setup.

* T=Temperature, S/S ratio=Substrate to Substrate ratio on a total solids basis, S/I ratio=Substrate to Inoculum ratio on a volatile solids basis, TS= Total Solids, OS=crushed Oyster Shells, LS=crushed Limestone, BS=Baking Soda, FW=Food Waste, YW=Yard Waste, and B=Biosolids

<u>Analytical Methods</u>: TS and VS were measured according to Standard Methods (Method 2540, APHA, 2012). Leachate samples were prepared for chemical analysis by diluting a 15 g digestate sample with 30 mL of deionized water. The diluted sample was centrifuged at 7000 rpm for 10 minutes. The supernatant was then filtered through 0.45 μ m filter paper for analysis of pH, ammonium (NH4⁺-N), VFA, alkalinity and soluble chemical oxygen demand (sCOD). Values obtained from the chemical analysis (except pH) were adjusted to account for dilution using the following equation:

$$C_A = \frac{C_m \times (M_{DI} + M_S \times (1 - TS_S))}{M_S \times (1 - TS_S)}$$

where C_A is the actual concentration (mg/L), C_m is the measured concentration of the diluted sample (mg/L), M_{DI} is the mass of DI water used for the dilution (30 g), M_S is mass of sample used (15 g), and TS_S is total solids content of the samples (g/g).

pH was measured using a calibrated pH meter (Thermo Fisher Scientific Inc., Waltham, MA). Alkalinity concentrations were determined using the titrimetric method (Standard Methods, 2320B). NH4⁺-N was measured using a diffusion conductivity method (Timberline Method Ammonia-001, USEPA ATP No. N08-0004). VFA concentrations as acetic acid were measured by the esterification method using Hach TNT plus 872 test kits. sCOD was measured according to Standard Methods (5200B) using Orbeco-Hellige mid-range (0–1500 mg/L) COD kits.

Biogas was measured using a 50 mL frictionless syringe with a metal luer lock tip (5157; Cadence Science, Inc.) equipped with a 25-gauge needle (305125; BD PrecisionGlide). The gas volume was converted to standard temperature and pressure conditions (STP, 0 °C and 1 atm). Biogas quality (CH₄ content) was determined by dissolving the carbon dioxide portion of a 20 mL biogas sample into an alkaline barrier solution (3 N NaOH) and measuring the resulting liquid displacement (Hinds et al., 2016). The CH₄ yield was calculated by subtracting the CH₄ produced by the blank (or inoculum) from the total cumulative CH₄ production from the BMP and then dividing that number by the substrate grams g VS from the BMP. Statistical significance was determined by analysis of variance (ANOVA, $\alpha = 0.05$) using the Microsoft Excel with p_{critical} = 0.05.

HS-AD with varying alkalinity sources: A comparison of CH₄ yields for HS-AD of FW, YW, and biosolids with no alkalinity source, LS and OS is shown in Figure 1. CH₄ yields were significantly higher when an alkalinity source was added. According to Chen et al. (2015), addition of an alkalinity source improves AD process stability by enhancing pH-buffering capacity and alleviating methanogenesis inhibition due to acidification by VFA produced from fermentation of easily biodegradable FW during the start-up period. Comparing the two different alkalinity sources, OS and LS resulted in similar (p>0.05) CH₄ yields and chemical analysis results (Figure 1, Table 2). This is likely because both alkalinity sources are composed of calcium carbonate (CaCO₃) and had a similar buffering capacity in the digester. OS are a lowcost waste product of the oyster industry (Hamester et al. 2012). Note that a side experiment was performed (data provided in Appendix A) that showed that addition of OS and BS at a 2:1 ratio provided both long term (OS) and short term (BS) alkalinity sources that improved CH₄ yields during HS-AD of YW, FW and biosolids. This mixture was therefore used in subsequent studies (Table 1).



Figure 1. Cumulative CH₄ yields for FW+YW+biosolids w/crushed oyster shells and limestone (Symbol indicates ▲: Limestone, ○: Oyster shells, and ■: No alkalinity source).

Mixture	VFA (mg CH3COOH/L)		pН		Alkalinity (mg CaCO ₃ ,	/L)
	Day 0	Day 44	Day 0 Day 44		Day 0	Day 44
FW+YW+B	110 (±2.8)	<110	7.3 (±0.06)	<7.3	660 (±85)	<660
FW+YW+B w/ OS	180 (±1.4)	110 (±4.9)	7.2 (±0.03)	8.4 (±0.01)	870 (±330)	2,400 (±18)
L FW+YW+B w/ LS	160 (±71)	110 (±1.4)	7.4 (±0.01)	8.4 (±0.01)	580 (±88)	2,200 (±1)

Table 2. Leachate characteristics for HS-AD with and without alkalinity source addition.

*B: Biosolids, OS: Oyster Shells, and LS: Limestone

Addition of biosolids in HS-AD of FW and YW: The performance of HS-AD of FW and YW with and without biosolids addition was investigated. A comparison of CH₄ yields for two digestion sets (i.e. FW+YW and FW+YW+biosolids) is shown in Figure 2. During the start-up period, a low pH was observed for both digester sets (Table 3) because the buffering capacity for the initial condition (3 g/L OS) was not enough to maintain a neutral pH. Additional OS (1.5 g) was added to the digesters on day 15, resulting in improvement of CH₄ content of the biogas and alkalinity concentrations. The results show that CH₄ yields for the digestion set with FW+YW+biosolids were higher than the digestion set with FW+YW. In HS-AD of FW and YW, a low biogas CH₄ content was found for 56 days. This may have been caused by imbalanced conditions that affect the anaerobic microbial community (Brown & Li, 2013). Also, the imbalances resulted in accumulation of VFA and a dramatic drop in pH. In particular, the VFA

concentration of FW+YW (17,914 mg/L) was above the inhibitory concentration for methanogenesis (10,000 mg VFA/L), resulting in inhibition of methanogenic activity and low CH₄ production (Khanal, 2011). HS-AD of FW, YW and biosolids had a higher ammonium (NH₄⁺) concentration than HS-AD with FW+YW due to the higher nitrogen content of the biosolids. However, NH₄⁺ concentrations for both digesters were below the toxic range (1,700 mg N/L) (Gerardi, 2003). Biosolids addition increased the alkalinity concentration because biosolids has high buffering capacity due to NH₄⁺ (Dai et al, 2016). During the start-up period, it was observed that the digesters with FW+YW+biosolids had less pH decrease than the digesters with FW+YW. NH₄⁺ from biosolids degradation could combine with carbon dioxide to produce ammonium bicarbonate (NH₄HCO₃), which is able to buffer acids and remediate the dramatic pH drop (Li et al., 2017). This increment of alkalinity concentration may contribute to the increased CH₄ production by providing better environmental conditions for methanogens.



Figure 2. Cumulative CH₄ yields for FW and YW with and without biosolids (B).

	FW+YW	100100 101			FW+YW+biosolids			
Item	Day 0	Day 14	Day 28	Day 56	Day 0	Day 14	Day 28	Day 56
рН	6.99	5.13	5.37	5.36	6.95	5.69	7.88	8.59
VFA (mg CH3COOH/L)	1,722 (±359)	<i>,</i>	· ·	22,067 (±109)	·	15,612 (±787)	<i>,</i>	4,427 (±2,428)
Alkalinity (mg CaCO₃/L)	550 (±6)	933 (±59)	·	6,230 (±240)		485 (±109)	6,318 (±702)	9,302 (±2,000)
NH4 ⁺ (mg N/L)	407 (±4)	1,323 (±40)	1,736 (±36)	1,875 (±56)		·	· ·	2,624 (±59)

Table 3. Leachate characteristics for HS-AD of FW+YW and FW+YW+biosolids.

VS reduction (VSR) for digestion sets with FW+YW and FW+YW+biosolids are shown in Figure 3. Over 28 days, VSRs for FW+YW and FW+YW+biosolids were 13% and 21%, respectively. Biosolids addition to the FW+YW increased VSR by 1.6 times over 28 days. After 56 days, HS-AD of FW+YW and FW+YW+biosolids achieved approximately 17% and 33% VSR, respectively. The experimental results indicate that biosolids can improve the performance for HS-AD with FW+YW in terms of CH4 yield and VSR.



Figure 3. VSR for HS-AD of FW+YW and FW+YW+biosolids (B).

HS-AD with varying S/S ratios: BMPs were carried out with varying S/S (FW, YW, and biosolids) ratios. An analysis of Hillsborough County's waste production data (Figure 4) showed that a FW:YW: biosolids ratio of 23:62:15 by TS would maximize the use of organic waste resources for the county. In this analysis, it was assumed that: 1) all of the biosolids generated from the county's wastewater treatment facilities would be diverted to HS-AD, 2) FW collected from commercial and industrial facilities (e.g., restaurants, grocery stores, warehouses, schools) would be diverted to HS-AD, and 3) the portion of YW not utilized for mulch would be diverted to HS-AD. In other words, current practices of YW mulch production and residential FW management would not change. The 23:62:15 FW;YW:biosolids ratio was compared with a 1:1:1 ratio based on TS. To avoid a rapid pH drop during the start-up period, a mixture of OS and BS was added to provide slow (OS) and fast release (BS) alkalinity sources.



Figure 4. Production and management flow diagram of FW, GW, and biosolids in 2015 (Hillsborough County, FL).

Figure 5 shows the cumulative CH₄ yields for HS-AD with two different S/S ratios. Both digesters had low CH₄ yields during the start-up period (the first 10 days). Low pH (<7.0) and high VFA/alkalinity ratio (>0.4) were observed on day 6 (Table 4). pH and VFA/alkalinity ratios are common stress indicators for stability of AD systems, and pH 6.6-7.8 and the ratio of < 0.4 typically are considered as optimal for AD (Li et al., 2018; Lay et al., 1997). During the start-up period, a rapid hydrolysis of FW led to increased acidogen activity, which resulted in VFA accumulation and low pH. Because of the low pH and high VFA/alkalinity ratio during this period, methanogen activity was inhibited, which caused the reduction of CH₄ production and CH₄ content in the biogas. A similar phenomenon during the start-up period was also reported by Hinder et al. (2016) and Li et al. (2018).



Figure 5. Cumulative CH₄ yields for HS-AD with different substrate ratios.

	FW	+YW+bios	olids (33:3	3:33)	FW+YW+biosolids (23:62:15)			2:15)
Item	Day 0	Day 6	Day 28	Day 56	Day 0	Day 6	Day 28	Day 56
	8.20	6.86	8.51	8.59	8.14	7.78	8.51	8.41
pH	(±0.11)	(±0.12)	(±0.04)	(±0.06)	(±0.01)	(±0.08)	(±0.02)	(±0.05)
VFA	1,303	16,511	5,292	1,118	1,511	12,598	3,626	949
(mg CH ₃ COOH/L)	(±8)	(±1,625)	(±522)	(±300)	(±135)	(±1,408)	(±525)	(±275)
Alkalinity	6,657	7,698	11,400	11,318	8,853	7,409	11,336	9,866
(mg CaCO ₃ /L)	(±40)	(±503)	(±964)	(±2,716)	(±455)	(±1,153)	(±316)	(±2,271)
$\mathrm{NH_{4}^{+}}$	1,629	2,193	2,261	2,139	1,395	1,654	2,030	1,747
(mg N/L)	(±67)	(±198)	(±220)	(±426)	(±106)	(±296)	(±77)	(±383)
VFA/Alkalinity	0.20	2.14	0.46	0.10	0.14	0.09	0.28	0.38

Table 4. Leachate characteristics for HS-AD with different substrate ratios.

After 10 days, CH₄ yields from both digestion sets significantly increased. The digestion set with FW+YW+biosolids (23:62:15) had a higher CH₄ yield than the set with FW+YW+biosolids (33:33:33) for the first 36 days because the FW+YW+biosolids (33:33:33) had a severe pH variability and VFA accumulation, which negatively affected methanogen activity. The increased YW portion in the substrate (while reducing FW and biosolids) improved the digester stability during the start-up period, which reduced the time required for self-recovery. Thus, HS-AD of FW+YW+biosolids (23:62:15) had a higher cumulative CH₄ yield (117 mL CH₄/g VS) compared to HS-AD of FW+YW+biosolids (33:33:33) (100 mL CH₄/g VS) for the first 30 days. In Table 4, the digestion sets with FW+YW+biosolids (23:62:15), which is due to greater amounts of FW and biosolids in the substrate. Reduction of FW and biosolids (while increasing YW) in HS-AD could improve the digestion stability by reducing the risks of inhibition associated with high VFA and NH₄⁺ concentrations.

After 36 days; however the CH₄ yield from the digester with FW+YW+biosolids (33:33:33) exceeded that of the digester with FW+YW+biosolids (23:62:15). The cumulative CH₄ yields for HS-AD of FW+YW+biosolids (33:33:33) and FW+YW+biosolids (23:62:15) were approximately 168 and 137 mL CH₄/g VS for 56 days, respectively. Since HS-AD of FW+YW+biosolids (33:33:33) had a greater biodegradable portion in the substrate than HS-AD of FW+YW+biosolids (23:62:15), HS-AD of FW+YW+biosolids (33:33:33) had higher cumulative CH₄ yield than HS-AD of FW+YW+biosolids (23:62:15) for 56 days.

Figure 6 shows the VSR for the HS-AD of FW+YW+biosolids (33:33:33) and FW+YW+biosolids (23:62:15). The digestion sets with FW+YW+biosolids (33:33:33) had higher VSR compared to the digestion sets with FW+YW+biosolids (23:62:15) during the first 28 days because the digestion sets with FW+YW+biosolids (23:62:15) had greater amounts of YW in the substrate. YW typically contains lignin, which is a complex organic substance that is difficult to degrade by anaerobic bacteria. After 56 days, the digester with FW+YW+biosolids

(23:62:15) reached 27% VSR, which is comparable with the VSR for the digester with FW+YW+biosolids (33:33:33; 30% VSR).



Figure 6. VSR for HS-AD with different substrate ratios.

HS-AD with varying S/I ratios: A preliminary BMP test was used to evaluate the effect of S/I ratio on CH₄ yield during HS-AD in order to identify the correct range of values to use in these experiments. The results of the preliminary study are provided in Appendix A. Figure 7 shows the cumulative CH₄ yield for BMPs operated at varying S/I ratios. After 21 days, the S/I ratio of 1.2 produced an average cumulative CH₄ yield of 72.7 mL/g total VS, which was the greatest among the experimental sets for that period. Furthermore, the BMPs with S/I ratios of 1.2 continued to have the greatest CH₄ yield until the conclusion of the experiment (day 48). At day 48, the VFA concentration in the digestion sets with an S/I ratio of 3.8 was the highest (>13,850 mg/L), which exceeded the inhibition range for methanogenesis >10,000 mg/L (Khanal, 2011). The digestion set with an S/I ratio of 1.2 had the lowest NH4⁺ concentration among others (<1,520 mg N/L). At the end of the experiment, the digestion set with an S/I ratio of 1.2 produced an average CH₄ yield of 126 mL/g total VS. In contrast, the S/I ratios of 2.5 and 3.8 produced average CH₄ yields of 46.7 and 6.75 mL/g total VS, respectively, which indicated the significant inhibition of the methanogens due to acidification. Therefore, the HS-AD with a S/I ratio of 1.2 provided the best condition for the HS-AD of FW+YW+biosolids by reducing the risk of inhibition due to acidification and high NH₄⁺ concentrations.



Figure 7. Cumulative CH4 yields for HS-AD with varying S/I ratios.

HS-AD with varying operating temperatures: BMPs were operated at 35°C (mesophilic) and 55°C (thermophilic). CH₄ yields for HS-AD under different operating temperatures are shown in Figure 8. Digestion sets operated at mesophilic temperature had higher CH₄ yields than for thermophilic conditions. This was not expected based on prior published data (Zhang et al., 2014; Kim et al., 2006). Typically, higher temperature enhances the hydrolysis rate of the substrate, which results in a greater CH₄ production than under mesophilic conditions. It is likely this result was due to the higher NH₄⁺ and VFA concentrations (>3,600 mg NH₄⁺-N/L and >7,600 mg/L of VFA, respectively) in the inoculum for the thermophilic HS-AD, which consequently cased the reduction of cumulative CH₄ yields. Thus, the results are inconclusive, and HS-AD experiments under mesophilic and thermophilic operating temperatures are being repeated.



Figure 8. Cumulative CH₄ yield for HS-AD with different operating temperature conditions (Mesophilic: 35°C; Thermophilic: 55°C).

OBJECTIVE 2: APPLY LCA TO ASSESS WHETHER HS-AD IS ENVIRONMENTALLY BENEFICIAL

To perform environmental LCA of HS-AD, a life cycle inventory (LCI) analysis was carried out. Since there are no HS-AD systems in Hillsborough County, FL, the LCI was constructed based on a hypothetical system. The system configuration was based on batch single-stage technologies from two companies: BioFerm's Dry Fermentation technology and Zero Waste Energy's (ZWE) SMARTFERM technology. Both technologies consist of concrete-based digesters with steel gastight doors, a percolation tank, biogas storage system, biofilter, and combined heat and power (CHP) units. The main differences between the two technologies are installed locations of percolate tanks and gas storage systems as well as operational temperature. ZWE uses belowground percolate tanks and a double-membrane roof mounted bladders (ZWE,2015), while BioFerm employs ground-level percolate tanks and a flexible gas storage systems (BioFerm, n.d.). Also, ZWE operates under thermophilic conditions while BioFerm operates under mesophilic conditions.

The main data sources reviewed included company websites and product descriptions, case studies of current plants, and bench scale batch studies (BASF, 2014; BING, 2006; CWMI, 1990; EEA Mass, n.d.; Engineering Toolbox a, b & c, n.d.; Goodfellow, n.d.; IFR& FCS, n.d.; Ma et al., 2011; Petric & Selimbašic, 2008; Scano et al., 2014; Sliusar & Armisheva, 2013; Smith & Krüger Inc., 2009; US EPA, 1994 & 2016; Zhang et al., 2009). The materials and assumptions for each component of HS-AD are summarized in Appendix B. To conduct the LCI for the HS-AD, an Excel-based LCI tool was developed (See Appendix B: the tool is available by request from Dr. Qiong Zhang [qiongzhang@usf.edu]). In the tool, input data includes system specifications (e.g., digester dimensions, annual capacity, percent capacity, retention time, percolate tank dimensions, pipe dimensions) and operational information related to waste composition and CH4 yield, such as TS, VS and average heat capacity. Based on the LCI data

obtained from the tool, a preliminary LCA for HS-AD with FW+YW+biosolids (33:33:33) under mesophilic condition was conducted. Results are shown in Appendix C.

In this study, the system boundary was cradle-to-gate (waste collection, transportation, operation), and the functional unit was 1 L CH₄ produced. The impact categories included global warming potential, ecotoxicity, acidification and eutrophication. Available amounts of FW, YW, and biosolids for the HS-AD (total capacity: 81,280 ton/yr) were estimated based on Hillsborough County's FW, YW, and biosolids production in 2015 (shown in Objective 1). Using the TRACI 2 (v. 3.03) method in the SimaPro software professional version, life cycle environmental impacts and benefits were estimated.

Figure 9 (a) shows the percent contributions from the environmental impacts, considering the construction phase only. Digester construction accounted for more than 50% of the total environmental impact because the digester construction was the one that required the largest amount of materials. Construction of the biofilter represented about 30% of the environmental impacts in the acidification category, the CHP unit accounted for 20% of the impact on eutrophication, and construction of the percolate tank accounted for modest (approximately 10% impacts). These results caused environmental impacts (as opposed to benefits) in the all categories.

Figure 9 (b) shows the environmental impacts for the operational phase of HS-AD. The CHP operation and digester heating were two main units that affected the overall impacts for the HS-AD operation, followed by percolate tank operation. The others had negligible impacts, including leachate circulation, exhaust gas blower, biogas collection and air blower operation. As expected, the CHP operation unit provides environmental benefits by producing energy, in the form of heat and electricity. Digester heating resulted in the largest environmental impacts because the unit required a large amount of heat (e.g., 95% of total energy used).

Figure 9 (c) shows the percent contributions of all process considering all phases (i.e., transportation, collection, construction, and operation) on the impact categories. Overall, HS-AD operation was the only process that resulted in environmental benefits because of energy and digestate production. Among all the phases, collection and transportation (over a 20-year span) were the major contributors in all four environmental impact categories, and they were particularly significant in eutrophication and ecotoxicity categories, while the contribution from the construction phase was almost negligible. As a result, HS-AD of FW, YW, and biosolids could provide environmental benefits by recovering energy and nutrients from waste.





Figure 9. Contribution of construction phase only (a), operation phase only (b), and all phases (c) on the impact categories of global warming, acidification, eutrophication, and ecotoxicity (Note that a negative environmental impact is an environmental benefit).

OBJECTIVE 3: COMPARE HS-AD WITH OTHER WASTE MANAGEMENT OPTIONS USING LCCA TO ENSURE ECONOMIC SUSTAINABILITY

LCCA for HS-AD with other waste management options (e.g., landfilling, WTE and composting [windrow]) was conducted using the present value (PV) method. The LCCA was based on fullscale scenarios in Hillsborough County, FL with total capacity 81,280 ton/yr over a 20-year life span. The LCC included infrastructure, O&M, collection, and transportation, and revenue included beneficial products of electricity, heat and digestate. LCC factors for the waste management options were estimated based on data from existing facilities and literature (see Appendix D).

Collection and transportation costs were estimated based on the travel distance of refuse and trailer trucks in Hillsborough County. In practice, Hillsborough County has four transfer stations, one WTE facility, one composting facility, and one landfill. Waste collection and transfer distances were based on existing facilities and estimated using the ArcGIS software. The estimated distances used for this analysis were 211±6 miles for waste collection, 28±19 miles from transfer stations to WTE, and 58±23 miles from transfer stations to landfilling and composting facilities. Since there is no HS-AD system in Hillsborough County, it was assumed that the distance from transfer stations to HS-AD was the same as the WTE, which was 28±19 miles. The other cost factors (e.g., fuel economy, truck capacity, etc.) and detailed assumptions for collection and transportation are described in Appendix D.

Without considering land acquisition, LCCs for each option are shown in Table 5. The results show that WTE had the highest initial and O&M cost, followed by HS-AD, and landfilling. Composting had the lowest initial and O&M costs because it was based on a windrow system, which is a low-cost technology (Wei et al., 2001). Revenues from WTE, HS-AD, and composting options were from beneficial product sales (e.g., electricity, heat and compost).

Although the WTE had the greatest revenue, the high initial and O&M costs led the system to be economically infeasible. Both HS-AD and composting were economically feasible; the annual revenues greatly exceeded the sum of the initial, O&M, collection, and transportation costs. The tipping cost saving was the largest contributor in LCCs for the HS-AD and composting systems. Without considering land costs, the most economical option was windrow composting.

Items	Unit (\$)						
Items	Landfilling	WTE	HS-AD	Composting			
Initial cost	19,350,000	131,476,500	28,121,200	7,096,700			
O&M cost	16,118,900	37,610,900	18,589,600	8,989,000			
Collection cost	13,308,600	13,308,600	13,308,600	13,308,600			
Transportation cost	1,869,800	902,700	902,700	1,869,800			
Tipping cost saving	0	-62,928,000	-62,928,000	-62,928,000			
Electricity sale	0	-86,124,900	-25,893,500	0			
Heat sale	0	0	-2,736,400	0			
Compost (or digestate) sale	0	0	-9,778,800	-10,531,000			
LCC	50,647,300	34,245,800	-40,414,600	-42,194,900			
LCC/wet waste handled for 20 years (\$/ton)	31	21	-25	-26			

Table 5. LCC for different waste management options.

Waste management options have different land requirements, which can affect the LCC. For example, composting and landfilling require larger land areas compared with HS-AD and WTE (Wei et al., 2001). Thus, an uncertainty analysis was conducted by varying land acquisition costs using Monte Carlo simulation with 1000 iterations (Figure 10). By comparing mean values, the most economical option was HS-AD, followed by composting. This is because the HS-AD requires relatively smaller land area when compared to composting. Since composting and landfilling systems require larger land area, the LCC variation was larger compared to the other options due to the uncertainty of land acquisition costs.



Figure 10. Uncertainty analysis results for LCC considering land acquisition (Red bar indicates mean value of LCC).

CONCLUSIONS

HS-AD is a promising alternative to manage FW, YW and biosolids in Florida. Diversion of OFMSW from landfills can reduce fugitive GHG emissions and improve leachate quality. Diversion of OFMSW from WTE can result in improved energy efficiency and reduced air emissions. The overall goal of this project was to improve the environmental and economic sustainability of HS-AD of OFMSW and biosolids in Florida. Research was carried out through bench scale bioreactor studies, life cycle and economic analysis. Specific objectives were to: 1) investigate the performance of HS-AD of OFMSW and biosolids under varying operating conditions, 2) apply LCA to assess whether HS-AD is environmentally beneficial, and 3) compare HS-AD with other waste management options (e.g., landfilling, WTE, composting) using LCCA to ensure economic sustainability.

The following are the major findings of this project:

- Addition of biosolids during HS-AD of OFMSW increases CH₄ yields by reducing pH inhibition of methanogenesis. Co-digestion of biosolids with OFMSW in HS-AD also avoids onsite L-AD of biosolids. Advantages of this approach include recovery of energy and nutrients from biosolids while avoiding the production of liquid side-streams which negatively impact mainstream wastewater treatment processes.
- Addition of alkalinity sources, such as LS and OS, during HS-AD of OFMSW increases CH₄ yields by reducing pH inhibition of methanogenesis. Crushed OS is a low-cost alternative to LS as a pH buffer. A mix of OS and NaHCO₃ provided both slow and fast acting sources of alkalinity.

- A low S/I ratio (≤ 1.2 on a VS basis) improved HS-AD stability by reducing methanogenesis inhibition due to VFA accumulation. In practice, low S/I is achieved by mixing digestate with fresh FW, YW and biosolids.
- The S/S ratio based available amounts of OFMSW available in Hillsborough County improved HS-AD stability compared to equal substrate ratios by reducing inhibition associated with VFA and ammonia production during the start-up period.
- HS-AD can provide environmental benefits of reduced global warming potential, acidification, eutrophication and ecotoxicity by recovering energy and nutrients from the waste.
- Both composting and HS-AD can be economically beneficial options for managing OFMSW and biosolids for Hillsborough County, FL. When land acquisition costs are considered, HS-AD is the lowest cost alternative.
- HS-AD of OFMSW and biosolids is an attractive waste management approach for Florida municipalities that can be integrated with existing waste management infrastructure. Benefits to the waste management industry include: reduced tipping fees, improved landfill leachate quality, improved energy efficiency at WTE facilities, reduced GHG and other air emissions and greater energy and nutrient recovery.

DISSEMINATION AND OUTREACH

A complete list of publications is provided in the metrics section below. Research was disseminated through reports to the Hinkley Center, MS theses, oral and poster presentations at conferences, one book chapter and one peer reviewed journal article. Two peer reviewed journal articles are currently in preparation. Two TAG meetings were held on March 28th, 2017 at USF and on May 15th, 2018 at Hillsborough County's Brandon Support Operations Complex (BSOC). Outreach activities included displays and presentations at USF's Engineering Expo (anaerobic digesters were created out of soda bottles), Van Buren Middle School Great American Teach-In, the USF student chapter of the Florida Water Environment Association (FWEA), and presentations and projects in classes taught by Drs. Ergas and Zhang. Students and faculty working on this project have also been engaged in USF's Food Waste Initiative. The Food Waste Initiative is working toward reducing food waste at USF, distributing waste needy students and bioenergy recovery via AD. Several small scale digesters have been installed at USF and the students have submitted a proposal to the USF Student Green Energy Fund to expand this work.

METRICS

	-	-	-	
Last name, first name	Rank	Department	Professor	Institution
Dixon, Phillip	MS Student	Civil/ Environmental Engineering	Ergas	USF
Lee, Eunyoung	Postdoctoral Researcher	Civil/ Environmental Engineering	Zhang	USF
Wang, Meng	Postdoctoral Researcher	Civil/ Environmental Engineering	Ergas	USF

1. List of graduate student and postdoctoral researchers funded by this Hinkley Center project:

2. List of undergraduate researchers working on this Hinkley Center project:

Last name, first name	Rank	Department	Professor	Institution
Bittencourt, Paula	BS student	Mechanical Engineering	Ergas	USF
Jimenez, Eduardo	BS Student	Civil & Environmental Engineering	Ergas/Zhang	USF
Casimir, Lensey	Casimir, Lensey BS Student Civil & Environmental Engineering		Ergas	USF
Stolte Bezerra Lisboa Oliveira, Deborah	BS Student Biomedical		Zhang	USF
Stolte Bezerra Lisboa Oliveira, Luiza	lte Bezerra Lisboa BS Student Biomedical		Zhang	USF
Waris, Aleem BS Student Chemical & Biomedical		Chemical & Biomedical Engineering	Ergas	USF

3. List of research publications resulting from this Hinkley Center project.

Peer reviewed journal article:

• Hinds, G.R., Mussoline, W., Casimir, L., Dick, G., Yeh, D.H., Ergas, S.J. (2016) Enhanced methane production from yard waste in high-solids anaerobic digestion through inoculation with pulp and paper mill anaerobic sludge, *Environmental Engineering Science*, 33(11): 907-917.

Bool Chapter:

• Hinds, G.R., Lens, P., Zhang, Q., Ergas, S.J. (2017) Microbial biomethane production from municipal solid waste using high-solids anaerobic digestion, In *Microbial Fuels*:

Technologies and Applications, Serge Hiligsmann (Ed), Taylor & Francis, Oxford, UK.

Master's Theses:

- Dixon, P. (2018) Impact of Substrate to Inoculum Ratio on Methane Production in High Solids Anaerobic Digestion (HS-AD) of Food Waste, Yard Waste, and Biosolids, MS Thesis, Department of Civil & Environmental Engineering, University of South Florida.
- Hinds, G.R. (2015) *High-Solids Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste: State of the Art, Outlook in Florida, and Enhancing Methane Yields from Lignocellulosic Wastes,* MS Thesis, Department of Civil & Environmental Engineering, University of South Florida.
- 4. List of research presentations resulting from this Hinkley Center project.

Oral Presentations:

- Ergas, S.J., Hinds, G.R., Anferova, N., Bartáček, J., Yeh, D. (2016) Bioenergy recovery and leachate management through high solids anaerobic digestion of the organic fraction of municipal solid waste, *Proc. World Environmental & Water Resources Congress*; May 22-26, 2016; West Palm Beach, Florida.
- Dixon, P., Bittencourt, P., Lee, E., Wang, M., Jimenez, E., Zhang, Q., Ergas, S.J. (2017) Effects of biosolids addition and alkalinity sources on high-solids anaerobic co-digestion (HS-AD) of food waste and green waste, *WEF Residuals and Biosolids Conference*, April 8-11, Seattle, WA.
- Dixon, P., Bittencourt, P., Anferova, N., Jenicek, P., Bartacek, J., Wang, M., Ergas, S.J. (2016) Effects of biosolids addition, microaeration, and alkalinity sources on High-Solids Anaerobic Co-digestion (HS-AD) of food waste and green waste, *Waste-to-Bioenergy: Applications to Urban Areas, 1st International ABWET Conference*, Jan. 19-20, Paris, France.
- Lee, E., Bittencourt, P., Casimir L., Jimenez, E., Wang M., Zhang, Q., and Ergas, S. (2018) High solids anaerobic co-digestion of food and yard waste with biosolids for biogas production, *Global Waste Management Symposium*, Palm Spring, CA, USA, Feb 11-14, 2018.

Poster Presentations:

- Dixon, P., Waris, A., Lacoff, P., Lee, E., Wang, M., Zhang, Q., Mihelcic, J., and Ergas, S. (2018) Energy from biosolids and municipal solid waste: effect of organic loading rate on methane yield, *Florida Water Resource Conference* (FWRC), Daytona Beach, FL, April, 2018.
- Oliveira, L.S.B.L., Oliveira, D.S.B.L., Lee, E., Jimenez, E., Ergas, S.J., Zhang, Q. (2018) Life cycle assessment for high solids anaerobic digestion of food waste, yard waste, and biosolids, *Thirty-Third International Conference on Solid Waste Technology & Management*, Annapolis, MD, March 11-14, 2018.
- Lee, E., Bittencourt, P., Jimenez, E., Casimir, L., Wang, M., Dixon, P., Zhang, Q., and Ergas, S. (2017) High-solids anaerobic co-digestion of food waste and yard waste with biosolids for sustainable bioenergy production, 2017 International Summit on Energy Water Food Nexus,

Orlando, FL, October, 2017.

- Dixon, P., Lee, E., Bittencourt, P., Jimenez, E., Casimir, L., Wang, M., Zhang, Q., Ergas, S.J. (2017) Effects of biosolids addition and alkalinity sources on high-solids anaerobic co-digestion of food waste and green waste, *Renewable Energy Systems & Sustainability Conference*, Lakeland, FL, July 31-August 1, 2017.
- Dixon, P., Lee, E., Bittencourt, P., Jimenez, E., Casimir, L., Wang, M., Zhang, Q., Ergas, S.J. (2017) Effects of biosolids addition and alkalinity sources on high-solids anaerobic codigestion of food waste and green waste, *SWANA FL 2017 Summer Conference & Hinkley Center Colloquium*, Fort Myers, FL, July 23-25, 2017.
- Bittencourt, P. Jimenez, E., Dixon, P., Wang, M., Ergas, S.J. (2017) Effects of alkalinity and temperature on high-solids anaerobic co-digestion, *USF Undergraduate Research Colloquium*, Tampa, FL, April 6, 2017 (*won the Undergraduate Excellence in Research Awards).
- 5. List of who has referenced or cited your publications from this project?

According to Web of Science, Hines et al., 2015 has the following citations:

- Ekelboom, M., do Carmo Precci Lopes, A., Mudadu Silva, C. de Ávila Rodrigues, F., José Vinha Zanuncio, A., Zanuncio, J.C. (2018) A multi-criteria decision analysis of management alternatives for anaerobically digested kraft pulp mill sludge, *PLOS One*, <u>https://doi.org/10.1371/journal.pone.0188732</u>
- Ergas, S.J., Kinyua, M.N., van der Steen, P., Butler, C.S., Lens, P.N.L., Chandran, K., Mihelcic, J.R. (2016) Innovative Global Solutions for Bioenergy Production, Environmental Engineering Science, 33(11): 841-842.
 - 6. How have the research results from this Hinkley Center project been leveraged to secure additional research funding?
- Eunyoung Lee, Phillip Dixon and Meng Wang were partially supported by an NSF Partnership in International Research and Education (PIRE) grant.
- Phillip Dixon was partially supported as a Teaching Assistant by the USF College of Engineering.
- Paula Bittencourt and Eduardo Jimenez were partially supported (40%) by funds from the USF College of Engineering Research Experience for Undergraduates (REU) program.
- A proposal was submitted to the US-Israel Binational Agricultural Research and Development (BARD) fund on the topic of, "Production of High Value Products from Agricultural Residues via High Solids Anaerobic Digestion, Pyrolysis and Thermo-Catalytic Conversion."
- A proposal was submitted to USF's Student Green Energy Fund by Whitney Fung, Li Zhu, Phillip Dixon, & Gviana Goldberg on the topic of Food Waste Recovery. Drs. Ergas and Zhang were faculty advisors to the student team.
- 7. What new collaborations were initiated based on this Hinkley Center project?

We have initiated collaborations with the following researchers:

- John Kuhn, Department of Chemical & Biomedical Engineering, USF
- Babu Joseph, Department of Chemical & Biomedical Engineering, USF
- Oz M. Gazit, Faculty of Chemical Engineering, Technion Israel Institute of Technology
- Ellen R. Graber, Faculty of Soil, Water & Environmental Sciences, ARO-Volcani Center, Israel.
- Tim Roberge, T2C-Energy, Inc.
- 8. How have the results from this Hinkley Center funded project been used (not will be used) by FDEP or other stakeholders? (1 paragraph maximum).

Bioenergy recovery from OFMSW projects are in planning stages in Hernando and Hillsborough County.

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APPENDIX A. PRELIMINARY EXPERIMENTS

Bench-scale experiment with different S/I ratios and alkalinity sources (fast and slow

<u>release</u>): HS-AD reactor studies with FW+YW+biosolids (FW: YW: biosolids=33:33:33 on a TS basis) at varying S/I ratios and with different alkalinity sources (fast and slow release) were carried out. In this study, crushed OS and sodium bicarbonate (Baking soda: NaHCO₃) were used as slow and fast release rate alkalinity sources, respectively. Two different S/I ratios (1.0 and 1.9 based on VS) and three alkalinity options (no alkalinity addition, OS addition, OS+NaHCO₃ addition[2:1 based on dry weight]) were applied for the HS-AD of FW+YW+biosolids (Figure A.1).



Figure A.1. Applied different S/I ratios and alkalinity options for digesters (OS = oyster shell; BS = baking soda [NaHCO₃])

Figure A.2 shows cumulative CH₄ production and CH₄ content in biogas for HS-AD with different S/I ratios and alkalinity options. All digestion sets with S/I ratio=1 gradually produced CH₄ over 80 days. Among sets with S/I ratio=1, the mixture of OS and NaHCO₃ resulted in the highest CH₄ production rate, followed by OS only. However, the sets with S/I ratio=1.9 without BS had low CH₄ production over the entire period. This may have been due to inhibition of methanogenic activity by acidification. Comparing the sets with S/I ratio=1.9 and 1, reduction of S/I ratio improved CH₄ production as well as CH₄ content in the biogas. CH₄ production of the digester set with S/I ratio 1.9 with the mixture of OS and BS gradually increased after 20 days and this set had a similar CH₄ production trend as the digester with S/I ratio=1 without adding the alkalinity source. The results indicate that NaHCO₃ addition can help overcome the pH drop at the beginning stage of digestion.



Figure A.2. Cumulative CH₄ production (a) and CH₄ content in biogas (b) for HS-AD with different S/I ratios and alkalinity options.

APPENDIX B. LIFE CYCLE INVENTORY AND EXCEL-BASED TOOL

To calculate the materials and energy requirements of HS-AD, an Excel-based Life Cycle Inventory (LCI) tool was developed based on inputs including waste compositions, digester dimensions, percent occupation (based on stackable height), annual capacity, retention time, temperature specifications (operation temperature, ambient temperature, soil temperature). Fixed parameters in the tool (Table B.1) include the density and heat capacity of waste materials and thermal conductivity of the digester components (concrete, steel, polyurethane foam). Through literature review, materials for each components of HS-AD were identified, shown in Table B.2.

Physical property	Value	Reference(s)	Note
Density of food waste (kg/m ³)	447	EPA, 2016	Averaged values from several sources;
Density of yard waste (kg/m ³)	311	CWMI, 1990	Average density of shredded yard waste;
Density of Biosolid (kg/m ³)	400	Smith & Krüger Inc., 2009	Density of dried biosolids
Density of concrete (kg/m ³)	2400	Engineering Toolbox a, n.d.	
Density of galvanized steel (kg/m ³)	7830	Repairing Engineering, 2016; AGA, 2017	Density of steel; Galvanization did not change properties of steel
Density of solid polyurethane foam (kg/m ³)	100	BASF, 2014; BING, 2006	
Specific heat capacity of food waste (kJ/kg*°C)	1.65	EEA Mass, n.d; IFR& FCS, n.d.; Petric & Selimbašic, 2008; Scano et al., 2014; Sliusar & Armisheva, 2013	Averaged values from different studies; 75% moisture content
Specific heat capacity of yard waste (kJ/kg*°C)	1.36	EEA Mass, n.d.; EPA , 1994; Sliusar &	50% moisture content

Table B.1. Physical properties of waste materials and components of the digester.

		Armisheva, 2013	
Specific heat capacity of biosolids (kJ/kg*°C)	0.9	Zhang et al., 2009	Used heat capacity of dry wastewater treatment sludge.
Thermal conductivity of concrete (W/m*°C)	1.52	Engineering Toolbox b, n.d	Thermal conductivity of dense concrete
Thermal conductivity of steel (W/m*°C)	24.3	Engineering Toolbox c, n.d	-
Thermal conductivity of solid polyurethane foam (W/m*°C)	0.025	BASF, 2014; BING, 2006	-

Component	Material	Reference
Loading/preparation area	Masonry/concrete structure	Persson et al., 1979; ZWE, 2015
Digester (s)	Masonry/concrete structure	BioFerm, n.d.;Persson et al., 1979; ZWE, 2015
	Steel structure	ZWE, 2015
Heating System	Steel wires	Persson et al., 1979
	Water/steam Heat Exchanger	SusCon, n.d.
	Electrical Systems	BioFerm, n.d.; ZWE, 2015
Mixing/Agitation System	Mechanical System (Pump or Impellers)	ERC, 2012
	Gas Bubbling	
Percolate Tank	Steel	BioFerm, n.d.
Piping System	Percolate Recirculation System	OCW MIT, 2004; System

	(PVC or HDPE)	group, 2012;
	Biogas Collection System (PVC or galvanized steel)	Energypedia, 2015; Walsh et al., 1988
	Aeration System (PVC or thermoplastic materials; metal - black iron, stainless steel, copper, or aluminum)	EDI, 2011; EXAIR Corporation, 2016
	Exhaust Gas System (PVC, CPVC, Polypropylene, or stainless steel)	DuraVent Inc., n.d.
Pumping System	Percolate Recirculation Pump (peristaltic pump)	Degueurce et al., 2016; Rico et al., 2015
	Compressors (for aeration, exhaust air, and biogas collection systems) (stainless steel Liquid Ring Compressor).	Claro Inc., 2009; Sterling SIHI Inc., 2017.
Biogas Storage System	Flexible storage bag	BioFerm, n.d.
	Roof-mounted double-membrane bladder	ZWE, 2015
Sludge Removal	Sludge Auger	Persson et al., 1979
Mechanism	Mechanical removal using front loader.	BioFerm, n.d.; Koenig, 2011; ZWE, 2015
Drainage Grates	Galvanized steel, cast iron, brass, or PVC.	NDS Inc., 2017
Biofilter	Bulk Media Filters (closed chamber containing single or multiple layers of biofilter media, typically soil, compost, peat, wood chips, or a mixture of these).	Anit & Artuz, n.d.; N.E.M Business Solutions, 2002
Compressed-air Storage Vessel	Fiberglass, Carbon fiber, Kevlar/Aramid fiber	Amalga Composites Inc., n.d.

Gas-tight door	Galvanized steel sheets, solid	BG Doors International Inc.,	
	polyurethane filling.	2014; Heiden Systems, 2016.	

Since the LCA was based on a hypothetical system, several assumptions were made to estimate material and energy requirements for HS-AD. Assumptions regarding the design of the HS-AD plant were the following: only concrete digesters were considered, because steel digesters are not ideal for large-scale digestion system (ZWE, 2015). The ratio of steel to concrete for the concrete structure was assumed to be 110 kg of steel/ m^3 of concrete (ProActive Inc., n.d.). It was assumed that no insulating material would be used. Assumptions for the masonry of the concrete digesters were that the footing and walls would be 20 cm thick, and the ceiling of 10 cm thick. For the footing, it was assumed that the soil had a high load bearing capacity (load-bearing value in the range of 3,500 - 4,000 psi) (Beall, 2001), and thus direct foundation on the subsoil was considered (Beall, 2001). Percolate recirculation was assumed to occur every two hours, totaling 12 times a day and at a ratio of 0.75 L of percolate/kg of waste (Rico et al., 2015). Short and frequent recirculation periods were chosen because such practice was found to improve the stability and speed of the digestion for a batch digester operating under thermophilic conditions (Rico et al., 2015).

It was assumed that the heating of HS-AD is accomplished through the CHP unit. For the determination of the heat requirements, the following assumptions were made: the average annual temperature was assumed to be that of the city of Tampa, which is 73.4 °F, and the maximum and minimum values were 81.7 °F and 65.1 °F, respectively (FCC, 2010). The average soil temperature at a depth of 2 inches was calculated to be 72.6 °F (data from Sellers Lake municipality, the closest city to Tampa with data available), by averaging the values over October 2016 to July 2017 (NWCC, 2017). It was also assumed that the interior temperature of the digesters would be 20 °C (68 °F). The total heating requirement (Ereq.) to run the digesters was calculated as the summation of the heat necessary to heat the waste material to the operating temperature (E_{heat}) and the heat losses (E_{loss}) (Eq. B.1). The energy required to heat the waste material was calculated by using Eq. B.2. The heat loss can be separated into the heat lost by the digesters and the heat lost by the percolate tank, and the heat losses were calculated based on Eq. B.3 (Salter & Banks, 2008). The heat lost to the surroundings could be calculated based on the thermal conductivities (Eq. B.4) of the materials in the digester's walls and doors, the area of heat loss, and the length of heat travel through the materials (Salter & Banks, 2008). For the gastight door that is composed of two sheets of steel with a polyurethane filling in between, it was assumed that the heat transferred across all three layers of material would be the same.

$$E_{req.} = E_{Heat} + E_{loss} \tag{Eq. B.1}$$

$$E_{heat} = \left[(C_{FW} \times x_{FW}) + (C_{YW} \times x_{YW}) + (C_B \times x_B) \right] \times \left(T_{digest} - T_{idle} \right)$$
(Eq. B.2)

$$E_{loss} = U \times A \times (T_{out} - T_{digest})$$
(Eq. B.3)

$$U = \frac{1}{\sum_{i=1}^{n} \frac{l_i}{k_i}}$$
(Eq. B.4)

Where, E_{heat} is the energy requirement to heat the waste material in kJ/kg; C_{FW} is the specific heat capacity of food waste in kJ/(kg K); CYW is the specific heat capacity of yard waste in kJ/(kg K); C_B is the specific heat capacity of biosolids in kJ/(kg K); x_{FW} is the mass fraction of food waste in kg FW/kg total; x_{YW} is the mass fraction of yard waste in kg GW/kg total; x_B is the mass fraction of biosolids in kg B/kg total; T_{digest} is the operational temperature of the digester in °C; T_{idle} is the digester temperature when it is not operating in °C; U is the coefficient of heat transfer in W/(m² K); A is the area through which the heat transfer occurs in m²; T_{out} is the temperature on the outside of the digester in ${}^{\circ}C$; l_i is the thickness of the surface through which heat transfers in m; k_i is the conductivity of each layer of the surface in W/(m K); and n is the number of layers arranged in series. The term Tout varied according to the surface through which heat was being lost. For instance, Tout would be the soil's surface when considering the floor, the ambient temperature when considering the external walls, and the building's interior temperature when considering the internal walls. For simplicity, it was considered that all reactors would be operating at the same time, so there would be no heat transfer between the walls separating adjacent digesters. In reality, digesters are usually operated in parallel with different start up times, so that the production of biogas is constant (Degueurce et al., 2016).

Having established the required CHP unit, the inventory from Ecoinvent, version 3.01, was used to calculate the material requirements for building the CHP unit, per functional unit (1 L of CH4 produced). This database considered a CHP unit with annual capacity of 1,000 kW (Ecoinvent, 2013). The CH₄ yield data was obtained from results of the objective 1. It was assumed that the HS-AD plant has a constant flow-rate of CH₄ to the CHP unit (295 m³/hr) and a lower heating value for CH₄ of 33,943 kJ/m³ (Engineering Toolbox, n.d.). The conversion to electrical energy efficiency was assumed as 35%, and that of heat efficiency as 45% (Li et al., 2017).

The inventory for CHP operation was taken from the electricity and heat produced. For the purposes of inputting data into SimaPro, it was considered that all heat and electricity inputs (for operating digesters, pumps, leachate tank, etc.) would come from the grid, while all heat and electricity outputs (produced from the process) were considered avoided products in the form of electricity from the grid.

Collection data considered residential door-to-door collection of FW and YW using single unit refuse trucks (full capacity: 10 ton), fueled by diesel (EIA, 2017), and a daily average distance traveled by each truck of 211±6 miles/day/vehicle (based on the GIS map in Hillsborough County). To assess the impact of the collection process, the freight carried, measured as distance traveled times mass (tkm), was computed. Transportation data were estimated based on the travel distance of trailer trucks (full capacity: 20 ton) in Hillsborough County. Since there is no HS-AD system in Hillsborough County, it was assumed that the distance from transfer stations to HS-AD was the same as the WTE, which was 28±19 miles. An additional assumption, for simplicity, was that the trucks traveled the whole distance carrying their maximum capacity (when in reality the freight carried by the trucks continually increases per distance traveled, until the maximum capacity is reached).

Figure B.1 shows an example of the input interface in the tool for the BioFerm's HS-AD system. Similar inputs are used to calculate the amount of steel, polyurethane foam, and the energy requirements. The outputs from the tool include: number of digesters required, mass of concrete needed (kg) per mass of waste digested (kg), mass of steel needed (kg) per mass of waste, and energy requirement per mass of waste. The mass of polyurethane foam was also calculated, but it was negligible. It is important to notice that the input of concrete and steel is a one-time event, related to the construction of the digesters, while the energy requirement is recurring. A sample output table from the tool is shown in Figure B.2.

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	<u>HO AD I</u>																				
	A. System's F	roperties	B. Materi	al Requir	ements				C Energ	y Require	ments										
	1. Digesters		1. Digest	ers Con	rete Req.				1. Digest	ters Energ	y Req.										
	2. Waste		2. Digest						2. Digest	ters Heat	Loss Req										
	Digestate				Doors Ste					late Tank											
_	4. Material Pro						d Foam Re	<u>eq.</u>		late Recir											
	 Temperatu 	e Specification								Aeration a			ion Blowe	r Power I	Req.						
							Plastic (FC	GRP) Red													
!					styrene Re				7. Exhau	st Gas Bl	ower Pow	er Req.									
3					Steel Rec				D. OUD.	1. 11											
1 5					Concrete				D. CHP	Unit				Lanada							
_					k Steel Fir				1.000	Jnit Materi	al Deg			Legend:							
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3			18. Biofilt	ter CaOl	12 Req.				2. Trans	portation											
4					n PVC Pip																
5			20. Bioga	as Storag	e System	HDPE F	Req.														
5																					
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9																					
-	Introductio	n HS_AD_1	C&T	(+)																	
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В	с	D	E F	G	н	I	J	К	L	М	N	
A. System Properties												
A. System Tropences	1. Digesters				2. Waste					5 Ter	nperature Specil	ications
Length (m)	Width (m)	Height (m)		Food Waste	Yard Waste	Biosolids		Ave, Density (kg/m3)		Ambient Temp. (deg C		
	30	7 5	Density (kg/m3)	447		400		406.4		23		2.6
Tot. Internal Vol. (m3)	% Occupation	Stackable Vol. (m3)	% Dry Comp. (wt%)	33.3	33.3	33.3		Tot. Moist. Content (9	6)			
		75 787.5	Moist. content (%)	74	18	84		73.5				
Annual Capacity	Retention time	Annual Operation	Wet Mass									
(MTPY)	(days)	Cycles	(MTPY)	20,592				% VS in dry waste				
	583	28 13	% Wet Comp.	34.0	10.8	55.2		85				
Digesters' Temperature (deg C)			Heat Cap. (kJ/kgK)	3.55	2.71	3.36						
(deg C)	38		неат Сар. (кылкук)	3.00	2.11	3.30						
	3. Digestate			4. Material Prop	erties							
TS (kg/kg WW)	VS (kg/kg WW)	Moist. Content (%)				Other (specify on side)	Density (kg/m3)				
		13 82	Concrete	2.400			PVC	1420				
Ratio of leachate prod. To												
initial water (kg/kg)			Steel	7,850	24.3	1						
0	129		Polyurethane foam	100		j						
			FGRP	1744								
			Polystyrene foam	32		1						
			HDPE	950								
B. Material Requiremen	15											
	1. Digesters Concrete R	lea.		2. Digesters Steel Reg.								
Concrete Density	Number of	1	Ratio of steel to		Ratio of steel to							
(kg/m3)	Digesters	Wall thickness (m)	concrete (kg/m3)	Mass of steel (kg)	Wet Waste (w/w)							
	400	15 0.2	1	10 173,600	0.0029	9						
Footing thickness (m)	Ceiling thickness (m)	Vol. footing (m3)										
		0.1 657.856		Gastight Steel Doors Steel Rei								
Vol. longer walls (m3)	Vol. shorter walls (m3) 33.2 10	Vol. ceiling (m3) 8.2 328.928	Thickness (m)		Density of steel (kg/m3 7.850							
4 Tot. vol. concrete (m3)	Ratio of concrete to W		0.0 Ratio of steel to Wet Wa		7,850	-						
	578	et vvaste (ww) 0.0625	Ratio or steel to wet wa	(w/w) 6.80E-05								
	310	0.0023		0.002-03								
4. Gas	tight Doors Polyurethane	Solid Foam	5.1	Digesters Polyurethane Foam R	eq.							
	Volume of	Density of Poly.	Thickness in Walls		Ratio Polyurethane							
Thickness (m)	Polyurethane (m3)	(kg/m3)	and Ceilings (m)	Polyurethane (m3)	to wet waste (w/w)							
		42 100	0.	08 335.9	0.00055	0						
Ratio of Polyurethane to V												
	6.93E	-05										
	6. Digesters FGRP Re	-		7.Digesters Polystyrene Reg.								
Thickness of FGRP	Volume of FGRP	ч .	Thickness in	Volume of	Density of Poly-							
Thickness of FGRP	Volume of FGRP	Density of ECOD (Irolm2)	Thickness in Easting (m)		Density of Poly-							

Figure B.1. Excel based LCI tool: entry interface worksheet (a) Input interface worksheet (b) (Note: The cells in light orange are the input cells).

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	Summary Table H				_					
	Materi	als			-					
Concrete	0.0005 1		0.000042	4.0114						
Digesters Percolate Tank	0.0625 kg/kg 6.43E-04 kg/kg		0.002943 H 3.03E-05 H							
Steel	0.43L-04 Kg/Kg 1	vet waste	3.03L-03 P	(g/L CI H						
Digesters	2.87E-03 kg/kg	vet waste	0.000135 k	ra/L CH4						
Gastight door	6.80E-05 kg/kg		3.2E-06 k							
Percolate Tank	5.75E-04 kg/kg		2.71E-05 k							
Aeration Steel Piping	4.92E-05 kg/kg		2.32E-06 H							
Biogas Steel Piping	6.74E-06 kg/kg	vet waste	3.17E-07 k	g/L CH4						
Exhaust gas Steel Piping	1.42E-04 kg/kg	vet waste	6.67E-06	cg/L CH4						
Polyurethane										
Gastight door	6.93E-05 kg/kg		3.26E-06 H							
Digesters insulation	0.00055 kg/kg 1		2.61E-05 k							
Percolate Tank insulation Fiber Glass Reinforced Plastic	2.82E-05 kg/kg (vet waste	1.33E-06 k	(g/L CH4						
Digesters	(FGRP) 0.0012 kg/kg y	und unmedie	5.69E-05 k	all CH4	_					
Polystyrene	0.0012 kg/kg1	ver waste	5.652-05 /	(g/L CH4						
Digesters	8.73E-05 kg/kg	vet waste	4.11E-06 k	ra/L CH4						
Polyvinyl Chloride (PVC)	0.152-05 kg/kg/	Tet Waste	4.112.001	Gre one						
Percolate recirculation piping	2.72E-06 kg/kg	vet waste	1.28E-07 k	a/L CH4						
Water system piping	3.03E-07 kg/kg		1.43E-08 k							
High Density Polyethylene										
Biofilter	2.00E-03 kg/kg		9.42E-05 H							
Biogas Storage system	1.17E-04 kg/kg	vet waste	5.52E-06	(g/L CH4						
Peat										
Biofilter	2.67E-03 kg/kg	vet waste	0.000126	(g/L CH4						
Ca(OH)2 Biofilter	1.80E-06 kg/kg		8.49E-08 k	4.0114						
Biofilter	1.80E-06 Kg/Kg V	vet waste	2.07E-08 k							
	CaO		6.43E-08 k							
Water	040		0.402 001	lgr E Oriv						
Water biofilter irrigation	13.88 kg/kg	vet waste	0.653526	a/LCH4						
	Ener			•						
Input										
Digesters' Heating	50.41 kJ/kg v	vet waste	0.000659 1	Wh/L CH4						
Digesters' Heat loss	93.80 kJ/kg v	vet waste	0.001227							
Digesters total	144.22 kJ/kg v		0.001886							
Percolate tank heat loss	2.56 kJ/kg v		3.35E-05 k							
Percolate recirculation pumping	0.006 kJ/kg v		7.77E-08 k							
Aeration Blower Biogas Collection Blower	0.78 kJ/kg v 2.67 kJ/kg v		1.02E-05 k 3.49E-05 k							
Exhaust gas Blower	0.398 kJ/kg v			Wh/L CH4						
Output	0.550 KJ/Kg V	ver waste	0.2L-00 P	CONTRACT OF INF						
CHP Heat	260.3 kJ/kg v	vet waste	0.003403	Wh/LCH4						
CHP Electricity	253.0 kJ/kg		0.003309 F							
Introduction HS AD 1	C&T (+)				E 🔳					

Figure B.2. Sample output for the Excel-based LCI tool (Note: This output is for BioFerm's dry digester specified by the inputs in Figure B.1).

APPENDIX C. LIFE CYCLE ASSESSMENT DATA

By using the Excel-based LCI tool, LCI was assessed. The LCA for the HS-AD with FW, YW, and biosolids was based on the mesophilic operation mode and annual capacity of 60,583 MTPY with FW, YW, and biosolids (33:33:33 based on TS). The system boundary was cradle-to-gate (waste collection, transportation, processing (considered as operation)) and the functional unit was 1 L CH₄ produced. The impact categories included global warming potential, ecotoxicity, acidification and eutrophication. Based on the LCI, the impacts based on the categories were calculated through the SimaPro using the TRACI 2 v3.03 method. Figure C.1 shows the percent contribution of each process (transportation, collection, construction of HS-AD, and processing of HS-AD) on the impact categories considered. Overall, processing/operation energy is the only process that resulted in negative contributions to the impact categories, that is, it resulted in a reduction of the environmental setbacks associated with each impact category. Of the other three processes, collection and transportation (over a 20-year span) are the major contributors in all four categories, in which the contribution from construction is almost negligible.

Figure C.2 shows the percent contribution of each unit (CHP operation, pumping, blowers, digesters operation, etc.) for each of the four impact categories considered for the HS-AD operation. CHP operation and digester operation are the two main units for the HS-AD process, followed by percolate tank operation. All other units have very small impacts in the four categories considered. As expected, the CHP operation unit has a negative contribution in all categories, meaning it reduces the environmental impacts of these categories. Coupling a CHP unit to the HS-AD process is beneficial, and was expected to reduce environmental impacts, since it utilizes the CH4 produced by the HS-AD process to produce energy, as both heat and electricity.

Similarly, Figure C.3 presents the percent contribution of each unit for the construction process. CHP construction and digester construction accounts for more than 90% of the impact for all categories. These two units are the ones that require the largest amount of materials, and so it was expected that they would be the units with most impact. Of the other units, construction of the biofilter represents about 5% of the impacts in the acidification category; construction of the percolate tank accounts for modest, positive impacts in the global warming and acidification categories, and negative impact in the eutrophication category.



Figure C.1. Contribution of each process for the impact categories of global warming, acidification, eutrophication, and ecotoxicity.



Figure C. 2. Unit contribution for each impact category for the operation of HS-AD.



Figure C. 3. Unit contribution for each impact category for the construction process.

APPENDIX D. LIFE CYCLE COST ANALYSIS

The life cycle cost (LCC) was computed as follows:

$$LCC = C_I + (C_{O\&M} \times UPV^*) + (C_{C\&T} \times UPV) - (C_{R,t} \times UPV) - (C_{R,h} \times UPV) - (C_{R,d\&C} \times UPV) - (C_{R,e} \times UPV^*)$$
(Eq. D.1)

where C_I is the initial cost, $C_{O\&M}$ is the O&M cost, $C_{C\&T}$ is the C&T cost, $C_{R,t}$ is the revenues from tipping fee saving, $C_{R,h}$ is the revenues from heat sales, $C_{R,d\&c}$ is the revenues from digestate or compost, and $C_{R,e}$ is the revenue from electricity sale. The UPV is a uniform present value factor, and UPV* is a non-uniform present value factor. The discount or interest rate and the escalation rate used to calculate UPV and UPV* were assumed to be 1.9% (the average rate for 10 years) and 0.65%, respectively (EERC, 2017; USIR, 2017).

The HS-AD system was assumed to have the same configuration as a BIOFerm Dry Fermentation system, which is a mesophilic, batch, and single-stage technology (BIOFerm, n.d.). The system is comprised of garage style fermenters, a percolation tank, a biogas storage tank, a biofilter, and a CHP unit. It was assumed that the operating conditions for the HS-AD system were the same as the experimental conditions with a 28-day retention time (See Objective 1). The initial cost was estimated based on the data obtained from current installations of BIOFerm and existing literature (BIOFerm, n.d.; ILSR, 2010). Figure D.1 shows the capital costs as a function of the operating capacity for existing BIOFerm systems in the US. The HS-AD capital cost was estimated based on a regression model shown in Figure D.1. The O&M cost was assumed to be 3% of the initial cost, which is based on Rofoff & Clarker (2014). The electricity and heat productions were estimated by using the equations below (Wang et al., 2016):

$$H_{HS-AD} = Y_{CH4} \xi \eta_{Heat} \tag{Eq.D.2}$$

$$E_{HS-AD} = Y_{CH4} \xi \eta_{Electricity} \tag{Eq.D.3}$$

where H_{HS-AD} is the heat production from the CHP (kWh/d), E_{HS-AD} is the electricity production from the CHP (kWh/d), Y_{CH4} is the CH₄ yield (m³/gVS), ξ is the low heating value of CH₄ for HS-AD (kWh/m³), η_{Heat} is the heat energy conversion efficiency of CHP, and $\eta_{Electricity}$ is the electricity energy conversion efficiency of CHP. For digestate, it was assumed that the digestate quality is the same as the compost quality. The cost of the oyster shells was assumed to be zero because they were considered as wastes from local processing industries. Since, small amounts of oyster shells were used in the HS-AD, transportation costs of this material were not considered in this analysis.



Figure D.1. Capital Costs for the BIOFerm Systems in the US (Circle: Capital Costs Obtained from Literature; Dashed Line: A Regression Model Curve).

Input	Value	Reference
Life cycle cost analysis period (yr)	20	This study
Discount or interest rate (%)	1.89	USIR (2017)
Escalation rate (%)	0.65	EERC (2017)
Electricity price (\$/kWh)	0.104	EIA (2017)
Heat rate (\$/kWh)	0.009	Moriarty (2013)
Digestate price (\$/ton)	11.2	Schwarzenegger (2010)
Tipping fee, non-processable solid waste (\$/ton)	31	
Tipping fee, processable solid waste (\$/ton)	58	Hillsborough County (2016)
High Solids Anaerobic Digestion		
Voletile Solid reduction (%)	24	This study
Low heating value of CH ₄ for HS-AD (KWh/m ³)	9.94	Passos & Ferrer (2015)
Combined Heat and Power Efficiency: Heat (%)	49.5	
Combined Heat and Power Efficiency: Electricity (%)	37.7	BIOFerm, n.d.
WTE: Waste to Energy (incineration)		
O&M cost factor for WTE (\$/ton)	28	Funk et al. (2013); SWANA (2012)

Table D.1. Input parameters for LCCA.

Percentage of reject after mechanical treatment for WTE (%)	89	Fernández-González et al. (2017)
Lower heating value of waste for WTE (MJ/ton)	8000	Habib et al. (2013)
Composting (Windrow)		
Compost production ratio (g compost/g wet mass waste)	0.66	Komilis & Ham (2000)
Compost price (\$/ton)	29	Shiralipour & Epstein (2005)

For other different waste manage options including landfill, composting, and WTE, the LCCAs were estimated based on literature data. It was assumed that the landfill in this analysis was a 57-acre Class I landfill. The initial and O&M costs were estimated based on Table D.2. The tipping costs in Hillsborough County can be classified by two: a processable solid waste and non-processable solid waste. The processable solid waste is that solid waste which is capable of being processed through the Resource Recovery facility, while the non-processable solid waste is that solid waste which is not capable of being processed through the Resource Recovery Facility.

Item		Unit	Value	Reference			
	Clear and Grub	\$/acre	3,000				
	Site Survey	\$/acre	8,000				
	Excavation	\$/acre	330,000				
	Perimeter Berm	\$/acre	16,000				
Capital	Clay Liner	\$/acre	162,000	Duffy, 2015;			
cost	Geomembrane	\$/acre	35,000	US EPA, 2014			
	Geocomposite	\$/acre	44,000				
	Granular Soil	\$/acre	64,000				
	Leachate System	\$/acre	12,000				
	QA/QC	\$/acre	100,000				
	Operations (equipment, staff, facilities and general maintenance)	\$/ton	2.76	Duffy, 2015;			
O&M cost	Leachate Collection and Treatment (assumes sewer connection and discharge	\$/ton	0.06	US EPA, 2014			

Table D.2. Capital and O&M costs for landfill.

cost of \$0.02/gal.)			
Environmental Sampling and Monitoring (groundwater, surface water, air gas, leachate)	\$/ton	0.17	
Engineering Services (consulting firms and in-house staff)	\$/ton	0.33	

The composting system was assumed to be a windrow composting system due to its feasibility (Beattie, 2014). Assumptions made for composting are: 1) initial cost includes paving, grading, fencing, building, leachate system, engineering cost, tub grinder, windrow turner, legal cost, screens, and front-end loader (van Haaren, 2009); and 2) the compost is produced from 65.5% of the wet mass waste (Komilis & Ham, 2000). The initial cost for the composting was calculated based on Table D.3, while the O&M cost for the composting were estimated a regression-based model (Figure D.2), which was based on the O&M costs for existing windrow composting systems (City of Palo Alto Public Works Department, 2008).

Item	Value (\$/ton)	Reference
Paving	27.5	
Grading	2.1	
Fence	0.6	
Building	13.8	
Leachate system	2.8	
Engineering cost	13.8	
Tub grinder	6.9	van Haaren, 2009
Windrow turner	5.5	
Legal cost	4.1	
Screens	5.5	
Front end loader	5.0	
Total cost	87.3	

Table D. 3. Capital cost for composting system.



Figure D.2. The O&M cost factor (\$/ton) as a function of the composting capacity (ton/yr).

The WTE technology typically burns municipal solid waste (MSW) in an environmentally safe combustion system to generate electricity. Direct combustion is the most common technology for the WTE system (Funk et al., 2013). In this system, the MSW is directly burned to generate heat. This heat energy is converted to electrical energy. The initial cost for the WTE was estimated by using a regression model provided in UC Davis California Renewable Energy Center (2016). The O&M cost for the WTE plant in FL was \$28/ton, which was obtained from Funk et al. (2013) and SWANA (2012). The electricity produced (E_{WTE} , kWh) from the WTE was calculated according to Eq. D.4 (Fernández-González et al., 2017):

$$E_{WtE} = 0.28 \left(\frac{kWh}{MJ}\right) \times W \times R_f \times LHV_{WtE} \times n \tag{Eq.D.4}$$

where W is the waste treated at the facility, R_f is the percentage of reject after mechanical treatment (%), LHV_{WTE} is the lower heating value of waste for WTE (MJ/t), and *n* is the yield of the WTE plants.

Collection costs were calculated based on the following assumptions: a diesel refuse truck is 10 tons haul load, the collection is performed for 260 days per year (5 days per week, 8 hours per day), the diesel price is \$2.4 per gallon of diesel (EIA, 2017), and the fuel economy is 3 miles per gallon of diesel (Laughlin & Burnham, 2014).

Transportation costs are related with the distance from the transfer station to final processing facilities such as landfill, composting system, WTE, and HS-AD (the cases of FW and YW) and from the Wastewater Treatment Facility to the facilities (the case of biosolids). A load of the trailer was assumed to be 20 tons. The calculation for the collection and transportation costs are as follows;

$$C_C = \frac{(M_{FW} + M_{YW}) \times D_C \times P}{L_C \times F}$$
(Eq. D.5)

$$C_T = \frac{(M_{FW} + M_{YW} + M_B) \times D_T \times P}{L_T \times F}$$
(Eq. D.6)

 C_C and C_T are collection and transportation costs (\$/year), respectively. M_{FW} , M_{YW} , M_B are total mass of produced FW, YW, and B per year (ton/year), respectively. L_C and L_T are truck haul loads for collection (10 tons/ haul) and transportation (20 tons/ haul), respectively. D_C and D_T is an average travel distance per haul for collection and transportation. F and P are the fuel economy of a truck (3 miles/gal) and diesel price (\$/gal).

The land requirements for the selected waste management options (e.g., landfilling, WTE, composting, and HS-AD) were estimated based on literature and information from existing facilities through interniew (BIOFerm, n.d; City of Palo Alto Public Works Department, 2008; Roy F. Weston, Inc., 1993; van Haaren, 2009). The costs for land in Hillsborough County were estimated from real estate website (LandWatch, n.d.). The average land cost was \$1,327 per m² (\pm \$1,205 per m²). This cost was applied to calculate the land acquisition for the selected waste management options. Table D. 4 shows the results for land acquisition costs of each waste management option (about 81,280 tons of waste processed). The highest land acquisition cost was the composting system due to the longer retention time of the composting system (106 days). Also, this system used the windrow technology, which requires larger land areas than invessel technology. As expected, the second highest land acquisition cost was the landfill facility.

Waste management options	Area requirement (m ²)	
HS-AD facility	3,500	
Composting facility	43,100	
Waste to Energy facility	4,000	
Landfill facility	72,800	

Table D.4. Land acquisition cost for the selected waste managment options