Bioenergy Production from MSW by Solid-State Anaerobic Digestion

FINAL REPORT
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ABBREVIATIONS, ACRONYMS, AND UNITS OF MEASUREMENT

AD	Anaerobic Digestion
AEESP	Association of Environmental Engineering and Science Professors
BMP	Biochemical Methane Potential
C/N	Carbon to Nitrogen Ratio
CHP	Combined Heat and Power (Cogeneration)
CNG	Compressed Natural Gas
COD	Chemical Oxygen Demand
EU	European Union
FOG	Fats, Oils, and Greases
GHG	Greenhouse Gas
HRT	Hydraulic Retention Time
HS-AD	High-Solids Anaerobic Digestion
IWA	International Water Association
L-AD	Liquid Anaerobic Digestion
LCA	Lifecycle Assessment
MS-OFMSW	Mechanically-Separated Organic Fraction of Municipal Solid Waste
MSW	Municipal Solid Waste
NSF	National Science Foundation
OFMSW	Organic Fraction of Municipal Solid Waste
OLR	Organic Loading Rate
O&M	Operations and Maintenance
P&P Sludge	Pulp and Paper Mill Anaerobic Sludge
PFRP	Process to Further Reduce Pathogens
RECs	Renewable Energy Credits
REU	Research Experience for Undergraduates
RET	Research Experience for Teachers
SGEF	Student Green Energy Fund
S/I	Substrate to Inoculum Ratio
SRB	Sulfate Reducing Bacteria
SRT	Solids Retention Time
SS-OFMSW	Source-Separated Organic Fraction of Municipal Solid Waste
TAN	Total Ammonia Nitrogen
TIER	Tampa Interdisciplinary Environmental Research
TPY	Tons Per Year
TS	Total Solids
UCF	University of Central Florida
UF	University of Florida
US	United States
USF	University of South Florida
VFA	Volatile Fatty Acids
VOC	Volatile Organic Compounds
VS	Volatile Solids
WEFTEC	Water Environment Federation's Technical Exhibition and Conference
WTE	Waste-to-Energy
WW-AD	Wastewater Anaerobic Digestion Sludge

FINAL REPORT (Year 1)

August 18, 2014 – February 1, 2016

PROJECT TITLE: Bioenergy Production from MSW by Solid-State Anaerobic Digestion

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KEY WORDS: Bioaugmentation, Bioenergy, Biogas, Biorecycling, Biosolids, Co-digestion, Compost, Digestate, Food Waste, High-Solids Anaerobic Digestion, Organic Fraction of Municipal Solid Waste, Pulp and Paper Sludge, Resource Recovery, Waste Management, Yard Waste

ABSTRACT

High-Solids Anaerobic Digestion (HS-AD; aka Solid-State AD) is frequently used to process and produce bioenergy from the organic fraction of municipal solid waste (OFMSW), including yard waste, food waste and industrial organics. Compared with landfills or bioreactor landfills, HS-AD promotes faster OFMSW degradation, higher biogas methane content, reduced greenhouse gas (GHG) emissions and recovery of nutrients as compost. OFMSW diversion also saves landfill space and improves leachate quality at landfills. HS-AD of OFMSW has been rapidly increasing over the last decade in Europe and the US; however, no HS-AD facilities currently exist in Florida. The overall goals of this project were to evaluate the potential for HS-AD in Florida and improve methane production during HS-AD of the OFMSW. Specific objectives were to: 1) evaluate the most appropriate technologies for implementing HS-AD of OFMSW in Florida, 2) carry out fundamental research improve the biodegradability of lignocellulosic waste through co-digestion with pulp and paper mill waste anaerobic sludge (P&P), and 3) identify potential sites, collaborators and funding sources for a HS-AD demonstration in Florida.

State-of-the-Art of HS-AD: Current trends in Europe and the US suggest that single-stage HS-AD technologies are most appropriate for implementation in Florida due to their low cost, simplicity and reliability. The suitability of advanced HS-AD technologies, such as continuous and multi-stage systems, will depend on industry and legislative developments. Key factors affecting HS-AD economics include the quality, quantity, and proximity of OFMSW, markets for compost, energy, and renewable energy credits, and public-private partnerships. Source-separation of OFMSW is a critical factor affecting the economics of HS-AD, as it improves energy recovery and compost quality. However, more research is needed on the sustainability of source separation of putrescible waste in warm climates, such as Florida.

Enhancing Bioenergy Production: The potential to enhance methane production from yard waste via inoculation with P&P sludge, which contains microbial populations that are acclimated to a lignin-rich waste stream, was investigated. Side-by-side bench-scale HS-AD experiments were carried out under mesophilic conditions with yard waste inoculated with P&P sludge (bioaugmentation) and domestic wastewater anaerobic digester sludge. A 73% enhancement in methane yield was observed using the bioaugmentation strategy. Trends in volatile fatty acid concentrations suggested that increased methane production was due to acceleration of hydrolysis in the bioaugmented digesters. Additional experiments showed that enhancement could be sustained through digestate recirculation.

Potential for HS-AD Implementation in Florida: A detailed review of MSW management trends in Florida was conducted, with a focus on recent trends in OFMSW generation and management and relevant legislation. This information was used to identify locations where HS-AD may be promising based on potential for bioenergy production, GHG emissions reductions and nutrient recovery. Based on these criteria, the following counties were identified: Miami-Dade, Broward, Palm Beach, Hillsborough, Orange, Pinellas, Duval, Lee and Alachua. However, more research is needed to understand the compatibility of HS-AD with existing MSW infrastructure, particularly WTE. Florida universities may represent an opportunity for HS-AD demonstrations, as they generate large quantities of OFMSW, offer partnership and funding opportunities, and are a hub for education of future MSW professionals. Legislative incentives, as seen in Europe and California, would help foster implementation of HS-AD in Florida.

METRICS:

1. Graduate and postdoctoral researchers funded by this Hinkley Center project:

Name	Rank	Department	Professor	Institution
Hinds, Gregory	Master of Science	Civil & Environmental Engineering	Sarina Ergas	University of South Florida
Dick, George	Master of Science	Civil & Environmental Engineering	Daniel Yeh	University of South Florida
Wang, Meng	Postdoctoral Researcher	Civil & Environmental Engineering	Sarina Ergas	University of South Florida
Anferova, Natalia	Visiting PhD student	Water Technology & Environmental Eng.	Jan Bartáček	Prague Univ. Chemistry & Technology
Dixon, Phillip	PhD	Civil & Environmental Engineering	Sarina Ergas	University of South Florida

2. Undergraduate researchers working on this Hinkley Center project:

Name	Rank	Department	Professor	Institution
Ariane Rosario[a]	Third Year	Civil and Environmental Engineering	Sarina Ergas	University of South Florida
Lensey Casimir[b]	Fourth Year	Civil and Environmental Engineering	Sarina Ergas	University of South Florida

a. Fall 2014 Semester
b. Spring and Summer 2015 Semesters

3. Research publications resulting from this Hinkley Center project:

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, *Proceedings World Environmental & Water Resources Congress*; May 22-26, 2016; West Palm Beach, Florida.

Hinds, G.R., Mussoline, W., Dick, G., Yeh, D.H., Ergas, S.J. (2016) Enhanced methane production in solid-state anaerobic digestion through bioaugmentation, *Proceedings Global Waste Management Symposium Conference;* Jan. 31-Feb. 3, 2016; Indian Wells, California.

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 Theses Department of Civil & Environmental Engineering, University of South Florida; http://scholarcommons.usf.edu/etd/5883.

Hinds, G.R., Dick, G., Yeh, D.H., Ergas, S.J. (2015) Enhanced methane production from yard waste in solid-state anaerobic digestion, *International Water Association (IWA) Specialist Group on Anaerobic Digestion Newsletter*, June 2015.

Hinds, G.R., Dick, G., Yeh, D.H., Ergas, S.J. (2015) Resource recovery from organic solid waste through solid-state anaerobic digestion, *Talking Trash*, Spring, 2015.

Hinds, G.R., Casimir, L., Dawley, M., Yeh, D.H., Ergas, S.J. (2015) Solid-State Anaerobic Digestion: An environmentally and economically favorable approach to OFMSW management? *Talking Trash*, Summer, 2015.

Hinds, G.R., Mussoline, W., Dick, G., Yeh, D.H., Ergas, S.J. (2016) Enhanced methane production from yard waste in high-solids anaerobic digestion through bioaugmentation with pulp and paper mill anaerobic sludge, *Environmental Engineering Science* (abstract accepted for special issue on Innovative Global Solutions for Bioenergy Production, full manuscript to be submitted for peer review March 15, 2016)

Hinds, G.R., Lens, P., Zhang, Q., Ergas, S.J. (2016) 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 (proposal accepted and first draft of chapter submitted to editor).

4. Presentations resulting from this Hinkley Center project:

Hinds, Gregory. “Bioenergy Production from Municipal Solid Waste through Solid-State Anaerobic Digestion.” University of South Florida, College of Engineering Research Day. Tampa, Florida. 19 Nov. 2014.

Hinds, Gregory. “Bioenergy Production from Municipal Solid Waste through Solid-State Anaerobic Digestion.” University of Central Florida, AEESP Lecture Poster Session Cohosted by University of South Florida, University of Central Florida, and University of Florida. Orlando, Florida. 27 Feb. 2015.

Hinds, Gregory. “Enhanced Methane Production from Lignocellulosic Waste in Solid-State Anaerobic Digestion through Bioaugmentation.” University of South Florida, Graduate Student Research Symposium. Tampa, Florida. 10 Mar. 2015.

Rosario, Ariane. “Enhanced Methane Production from Lignocellulosic Waste in Solid-State Anaerobic Digestion through Bioaugmentation.” University of South Florida, Undergraduate Research and Arts Colloquium. Tampa, Florida. 9 Apr. 2015.

Casimir, Lensey. “Solid-State Anaerobic Digestion for the Recovery of Energy and Nutrients from Organic Solid Waste.” University of South Florida, NSF Research Experience for Undergraduates Research Symposium. Tampa, Florida. 29 Jul. 2015.

Dawley, Matthew. “Methane Production by Solid-State Anaerobic Co-digestion of the Organic Fraction of Municipal Solid Waste.” University of South Florida, NSF Research Experience for Teachers Research Symposium. Tampa, Florida. 29 Jul. 2015.

Casimir, Lensey and Anferova, Natalia. “Enhanced Methane Yield from Yard Waste in High-Solids Anaerobic Digestion through Bioaugmentation with Pulp and Paper Mill Anaerobic Sludge.” Hinkley Center Colloquium. Tallahassee, Florida. 23 Sep. 2015.

Hinds, Gregory. “Bioenergy Production from Municipal Solid Waste through High-Solids Anaerobic Digestion: State of the Art and Outlook in Florida.” Hinkley Center Colloquium. Tallahassee, Florida. 23 Sep. 2015.

Casimir, Lensey. “Solid-State Anaerobic Digestion for the Recovery of Energy and Nutrients from Organic Solid Waste.” AEESP Lecture Poster Session Cohosted by University of South Florida, University of Central Florida, and University of Florida. Tampa, Florida. 13 Nov. 2015.

Hinds, Gregory. "Bioenergy Production from Municipal Solid Waste through High-Solids Anaerobic Digestion: State of the Art and Outlook in Florida." AEESP Lecture Poster Session Cohosted by University of South Florida, University of Central Florida, and University of Florida. Tampa, Florida. 13 Nov. 2015.

Hinds, Gregory. "Enhanced Methane Production in Solid-State Anaerobic Digestion through Bioaugmentation." Global Waste Management Symposium (GWMS), Indian Wells, CA. 1 Feb. 2016.

NOTE: Ariane Rosario won the award for Best Poster Presentation at the 2015 USF Undergraduate Research and Arts Colloquium, Lensey Casimir won 2nd Place at the NFS Research Experience for Undergraduates (REU) 2015 USF Research Symposium with his poster presentation, and Matthew Dawley won 2nd Place at the NFS Research Experience for Teachers (RET) 2015 USF Research Symposium with his poster presentation. Greg Hinds won 1st Place for Best Student Presentation at the 2016 GWMS in Indian Wells, CA.

5. Those who have referenced or cited your publications from this project:

To the best knowledge of the authors, the work resulting from this Hinkley Center project has yet to be cited as of January, 2016.

6. The research results from this Hinkley Center project been leveraged to secure additional research funding as follows:

Greg Hinds was partially supported by an NSF funded S-STEM Scholarship during the 2014-2015 academic year.

Greg Hinds was partially supported by a USF Foundation Stessel Fellowship in fall 2015. The fellowship gives priority to graduate students in Environmental Engineering with GPA > 3.5 working in the MSW management field.

Ariane Rosario was partially supported (40%) by funds from the College of Engineering REU program.

Lensey Casimir was fully supported (100%) by funds from the NSF Tampa Interdisciplinary Environmental Research (TIER) REU program.

A science teacher from Plant City High School, Matthew Dawley, was an intern on this project during the summer. Mr. Dawley was funded through an NSF RET program.

An interdisciplinary team of students prepared and submitted a proposal to the USF Student Green Energy Fund (SGEF) to conduct a feasibility study on implementing SS-AD on the USF campus to improve the sustainability of organic waste management at the university. This proposal was not selected for funding.

Proposals were submitted to the Environmental Research and Education Foundation (EREF) on this topic in 2014 and 2015, which were not selected for funding. A pre-proposal was submitted to EREF in collaboration with Hinkley Center Researchers John Kuhn and Babu Joseph and is currently under review.

A team of eight graduate and undergraduate students conducted a design feasibility study for a 5,000 ton per year SS-AD facility on the USF campus for processing OFMSW generated on campus as a Green Engineering class project. The study included a preliminary design, preliminary cost analysis, and life cycle assessment comparing the environmental impacts of onsite OFMSW management via SS-AD compared to the current OFMSW practice at USF – transport and incineration of the waste – and showed that substantial environmental benefits could be incurred through SS-AD implementation.

Natalia Anferova, a doctoral student from Prague University of Chemistry and Technology, Czech Republic, was funded by the EU as part of the Marie Curie International Research Staff Exchange Scheme Biological Waste to Energy Technologies (BioWET) grant (July, 2015-January, 2016). She conducted bench- and pilot-scale experiments exploring the potential to improve biogas quality by integrating microaeration techniques into SS-AD of yard waste, food waste, and biosolids. Results of this work will be incorporated into her dissertation.

7. The following new collaborations were initiated based on this Hinkley Center project:

A team of interdisciplinary students prepared and submitted a proposal to the USF SGEF in the fall, another team of eight students from multiple fields of engineering conducted a design feasibility study for onsite SS-AD at USF.

Bruce Clark, Chris Bolyard, Ramin Yazdani, and Coby Skye joined the TAG and collaborations with them have provided valuable insight into various aspects of the project.

Collaboration and regular communication between the research team and other industrial professionals (Chris Axton, Zero Waste Energy; Norma McDonald, Organic Waste Systems; Whitney Beedle, BioFerm Energy Systems) has significantly increased.

Facility visits to California in May, 2015 by Greg Hinds and in January 2015 by Sarina Ergas and meeting with Ramin Yazdani and other facility staff.

Facility visit to Attero HS-AD facility in Venlo, the Netherlands by Sarina Ergas in September, 2015, and meetings with Adrie Veeken and facility staff.

Collaboration with USF Civil & Environmental Engineering faculty, Qiong Zhang and Yu Zhang on life cycle assessment and transportation aspects of HS-AD or OFMSW.

Collaboration between Marie Steinwachs, the Technical Manager for Waste Diversion at the University of Florida Physical Plant Division, and the research team has been initiated for the development of onsite organic waste management plans involving SS-AD at both UF and USF.

Collaboration with Hinkley Center Researchers John Kuhn and Babu Joseph on the production of liquid hydrocarbon fuels from biogas produced during HS-AD of OFMSW.

Collaboration with Jan Bartáček of Prague University of Chemistry and Technology on enhancing biomethane production from HS-AD of OFMSW using microaeration was initiated, including the student exchange described above.

Discussions with Hillsborough County Public Utilities Department staff about the potential for locating a HS-AD pilot facility at their Northwest Advanced Wastewater Treatment Facility.

8. The results from this Hinkley Center funded project been used by FDEP or other stakeholders in the following ways:

To the best knowledge of the authors, the work resulting from this Hinkley Center project has yet to be used by the FDEP or other stakeholders as of January, 2016.

EXECUTIVE SUMMARY

August 18, 2014 – February 1, 2016

PROJECT TITLE: Bioenergy Production from MSW by Solid-State Anaerobic Digestion

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Introduction

Anaerobic Digestion (AD) can be used to stabilize organic waste while recovering energy in the form of biogas (a mixture of methane and carbon dioxide). Liquid AD is commonly used for treatment of industrial, agricultural and municipal wastewaters, biosolids and sludges. However, high-solids AD (HS-AD aka Solid-State AD; characterized by a total solids [TS] content > 15%) is frequently used to process the organic fraction of municipal solid waste (OFMSW), including yard waste, food waste and industrial organics. Compared with landfills or bioreactor landfills, HS-AD promotes faster OFMSW degradation, higher biogas quality based on methane content, reduced greenhouse gas (GHG) emissions and recovery of nutrients as compost. By diverting OFMSW from landfills, HS-AD also saves landfill space, reduces leachate generation and improves leachate quality. The implementation of HS-AD of OFMSW has been rapidly increasing over the last decade in both Europe and the US; however, no HS-AD facilities currently exist in Florida.

Objectives

The overall goals of this project were to evaluate the potential for HS-AD in Florida and to improve the rate of methane production during HS-AD of the OFMSW. Specific objectives were to: 1) evaluate the most appropriate technologies for implementing HS-AD of OFMSW in Florida, 2) carry out fundamental research at bench- and pilot-scales to improve the biodegradability of lignocellulosic waste through co-digestion with pulp and paper mill waste anaerobic sludge (P&P sludge), and 3) identify potential sites, collaborators, and funding sources for a large scale HS-AD demonstration project in Florida

Objective 1: State-of-the-Art of HS-AD

Trends in AD technology selection in Europe were identified and a detailed chronological database of HS-AD projects in the US was developed. Trends in AD development in the EU indicate that: 1) HS-AD systems are economically and environmentally advantageous over liquid AD (L-AD) systems for processing OFMSW, 2) thermophilic systems are more economical than mesophilic systems, although mesophilic systems have historically been more common, 3) single-stage systems are more common and the technology is more accepted relative to multi-stage systems, although multi-stage systems are increasing in prevalence due to the improvements in process efficiency when well-designed and operated, and 4) continuous systems are more common in general than batch systems, although batch systems are often selected for processing lignocellulosic wastes.

In the US, eight full-scale HS-AD facilities are currently operating, with a total capacity of 189,600 TPY (see map Fig. 2.3). Another 19 or more HS-AD projects are in the planning, permitting, or construction phases. In general, there has been a preference for simple technologies over more sophisticated systems. Single-stage, batch-type thermophilic digesters, such as the SmartFerm and BioFerm systems, constitute more than half of the systems operating in the US today. These systems are capable of processing source separated OFMSW (SS-OFMSW), mechanically separated OFMSW (MS-OFMSW), or comingled MSW. The digestate is free of pathogens and is considered compost by the EPA's *Process to Further Reduce Pathogens* (PFRP) program, but requires post-processing (e.g. trammel screening) to remove contaminants. As the most proven form of HS-AD in the US, these systems are considered the most suitable for HS-AD in the state of Florida. Other more advanced HS-AD technologies such as continuous and multi-stage systems may become increasingly suitable, depending on industry and legislative developments.

Key factors affecting the economics of HS-AD include the quality, quantity, and proximity of available feedstock, markets for compost, energy, and renewable energy credits (RECs), and the development of public-private partnerships. Source-separation of OFMSW is a critical factor affecting the economics of HS-AD, as it improves energy recovery and compost quality. However, more research is needed on the sustainability of source separation of putrescible waste in warm climates, such as Florida. In general, HS-AD technologies cannot compete with the low cost of landfilling. In San Jose California, we also observed HS-AD being used at a landfill site for preprocessing comingled MSW before disposal. This practice has the potential to improve energy recovery efficiency, saves landfill space, reduces greenhouse gas emissions, and reduces leachate generation at landfill sites.

Objective 2: Enhancing Bioenergy Production

Two sets of experiments were carried out to contribute to the improvement of biomethane production in HS-AD. The goal of Experiment 1 was to investigate the potential to enhance methane production from yard waste via inoculation with P&P sludge as an alternative to wastewater anaerobic sludge (a conventional inoculum). Yard waste constitutes a significant fraction of OFMSW; however, the biodegradability of yard waste in HS-AD is low. Chemical, mechanical and thermal pretreatments have been shown to enhance biodegradability but each incurs additional economic and environmental costs. P&P sludge was identified as a promising alternative inoculum for HS-AD of yard waste because it contains microorganisms that are acclimated to metabolizing lignocellulosic materials. In bench-scale studies, methane production from yard waste inoculated with P&P sludge reached 100.2 ± 2.4 L CH_4/kg VS over 106 days of digestion. This yield was 73% greater than that achieved through inoculation with wastewater anaerobic sludge (58.1 ± 1.2 L CH_4/kg VS), a comparable enhancement to that achieved through chemical or thermal pretreatment. Trends in the evolution of volatile fatty acid (VFA) concentrations suggested that hydrolysis was accelerated in the bioaugmented digesters. Additional experiments showed that the enhancement could be sustained through recirculating digestate from the initial digesters, resulting in a 68.5% enhancement of methane yield. Although the observed improvements were comparable to other pretreatment methods, the bioaugmentation strategy used in this study could be a low cost and less resource intensive alternative to pretreatment and, thereby improve the overall sustainability of HS-AD processes.

The goal of Experiment 2 was to investigate potential co-digestion strategies for improving the overall efficiency of HS-AD. Yard waste was co-digested with food waste and municipal wastewater biosolids in different combinations and ratios, and methane yields were measured. Wastewater biosolids are a readily available substrate in many regions of the US facing increased regulation and cost of biosolids disposal, including Florida. However, limited information is available on their co-digestion with OFMSW in HS-AD systems. Oyster shells were identified as a waste product that could be used as an alkalinity source and incorporated into the experiment. The addition of food waste and biosolids led to increases in specific methane yields, but reduced system stability due to high organic loading. The addition of oyster shells was shown to be an effective measure for improving the buffering capacity of HS-AD against overloading and acidification. The oyster shells consist primarily of calcium carbonate and show slow diffusion properties, which promote long term stability of HS-AD systems during high-rate digestion and digestion of putrescible substrates such as food waste.

A pilot-scale HS-AD system was constructed, which was used as a demonstration system and for preliminary pilot-scale experiments exploring the effects of scale on HS-AD.

Objective 3: Potential for HS-AD Implementation in Florida

In Florida, there is a lack of organics recycling infrastructure. Based on the analysis carried out in this project, the statewide recycling rate could be increased by as much as 13% through HS-AD implementation. An estimated 7,000 and 3,500 TPY of bioavailable nitrogen and phosphorus could be recovered, respectively. Approximately 500 MW of energy could be generated from this waste stream, which translates to either 175 MW of electricity (approximately 660,000 metric tons of CO_2 equivalents per year) and 325 MW of heat, or to nearly 80 million diesel gallon equivalents of compressed natural gas. Based on potential for bioenergy production, GHG emissions reductions and nutrient recovery, Miami-Dade, Broward, Palm Beach, Hillsborough, Orange, Pinellas, Duval, Lee and Alachua counties were identified as promising for HS-AD implementation. However, more research is needed to understand the compatibility of HS-AD with existing MSW infrastructure, particularly WTE. The low costs of energy and landfilling in Florida, lack of legislation incentivizing organics recycling, concerns with collection and storage of putrescible waste in warm climates, lack of markets for compost and RECs make the economics and acceptability of HS-AD challenging. Currently, HS-AD implementation would only be economically feasible under specific circumstances where significant quantities of high-quality substrate are available and partnerships can be formed for the provision of substrate and sale of energy and compost (i.e. as seen with the Reedy Creek Improvement District Harvest Energy L-AD project).

It is recommended that demonstration projects at universities and/or existing composting and landfill sites be pursued through the development of public-private partnerships. Furthermore, it is recommended that Florida policy makers promote the transition from the current disposal-based waste management paradigm toward a recovery-based paradigm. Examples of such policies include bans on landfilling recyclables (including yard waste), source-separation mandates, pay-as-you-throw policies, and extended producer responsibility policies.

Conclusions

HS-AD recovers energy from OFMSW and can be paired with composting to enable recovery of nutrients. In the process, GHG emissions that would result from uncontrolled or partially controlled degradation of OFMSW in landfills are avoided. GHG emissions are also offset by the substitution of fossil-fuel derived energy with biomethane, which can be used for heating, electricity generation, and/or vehicle fuel. Diversion of OFMSW from landfills to HS-AD facilities also reduces eutrophication impacts or additional energy and chemicals needed for removing nutrients from leachate at wastewater treatment facilities. The recovery and use of nutrients as fertilizer also reduces the impacts of inorganic fertilizer production (Haber-Bosch process) and depletion of mineral P reservoirs.

Trends in HS-AD development in Europe and the US reveal that the optimization of HS-AD technologies are necessary for accelerating the transition to HS-AD of OFMSW. This research contributed to this effort by carrying out fundamental experiments on methane yield enhancement through bioaugmentation of lignocellulosic waste with waste sludge from anaerobic digestion of pulp and paper mill waste. This bioaugmentation strategy resulted in a significant enhancement in methane yields, which was comparable to enhancements reported in various pretreatment studies. The minimal impact of this strategy with respect to overall operational costs and environmental impacts makes it an attractive alternative to pretreatment.

HS-AD of OFMSW is particularly promising for Florida due to the availability of OFMSW, warm climate and high energy demands in urban areas. However, the legislative incentives that are necessary for improving the cost-competitiveness of HS-AD technologies are generally lacking. Therefore, it is recommended that efforts be initiated to increase recycling of waste organics, especially by large industrial, institutional, and commercial generators (e.g. food packaging plants, agricultural operations, schools, hospitals, grocery stores). HS-AD demonstration projects may be most feasible under certain specific circumstances (e.g. at a landfill with landfill-gas-to-energy, at a large composting site, or at a university with nearby supermarkets, restaurants, hospitals, and schools). For such a project to come to fruition, public-private partnerships and collaborative planning efforts are needed.

1.0 INTRODUCTION

Anaerobic digestion (AD) is the decomposition of organic matter by microorganisms under oxygen-free conditions. As the anaerobic microorganisms consume the organic material, they emit biogas – a gas mixture composed of methane (CH_4) and carbon dioxide (CO_2), at ratios ranging from 1:1 to 3:1, and trace amounts of hydrogen (H_2), hydrogen sulfide (H_2S), nitrogen gas (N_2), and water vapor (Chum et al., 2011). AD is widely used for stabilizing and recovering energy from high-strength industrial, agricultural and municipal wastewaters and organic sludges (Khanal, 2008). Thus, large-scale AD is most often applied as a low solids technology referred to as liquid AD (L-AD) (generally less than 15% total solids [TS]). It was not until the late 1980's and early 1990's that high-solids anaerobic digestion (HS-AD) technologies (those designed to operate with a TS content > 15%) were developed in Europe, following increased landfill taxation, banning of organics disposal in landfills, and mandated source-separation of organic waste (De Baere and Mattheeuws, 2014). Since then, HS-AD of the organic fraction of municipal solid waste (OFMSW) has developed rapidly in Europe (De Baere and Mattheeuws, 2014). A simple schematic of HS-AD for the recovery of resources from OFMSW is shown in Figure 1.1 (Zupančič and Grilc, 2012). In some cases, OFMSW, especially the food waste fraction, has been integrated into L-AD systems at municipal or industrial wastewater treatment plants (Rapport et al., 2008). However, in stand-alone systems specifically for OFMSW, HS-AD technologies are largely preferred over L-AD because of the many advantages they offer (Table 1.1.) and the ease of pairing them with aerobic composting operations.

In Europe, approximately 70% of the installed capacity for AD since 2009 has been HS-AD, and in the Netherlands and Belgium approximately 80% of all composting operations incorporate AD as a primary treatment (De Baere and Mattheeuws, 2014). In the US; however, HS-AD has been stifled by the low cost of landfilling and the lack of legislative incentives for alternative OFMSW management (Rapport et al., 2008; van Haaren et al., 2010; Li et al., 2011). Only a fraction of US states have landfill diversion goals or organics disposal bans and source-separation of organic waste is only required in a few locations (Goldstein, 2014; EREF, 2015a). Nevertheless, the first commercial HS-AD facility was constructed in the US in 2012 at the University of Wisconsin Oshkosh. Since then, legislative incentives have increased in the US, resulting in increased development of HS-AD projects and a growing number of HS-AD technology vendors doing business across the country (EREF, 2015a). The trend of increased legislative incentive is expected to continue to accelerate and HS-AD is projected to emerge as a leading OFMSW recycling technology (De Baere and Mattheeuws, 2014; RWI, 2013; EREF, 2015a).

A number of Life Cycle Assessments (LCAs) have been conducted to quantify the environmental sustainability of AD for MSW (Haight, 2005; Edelmann et al., 2005; Sundqvist, 2005; Kim and Kim, 2010; CIWMB, 2009; Zaman, 2009; Morris et al., 2011; Levis and Barlaz, 2011; Bernstad and la Cour Jansen, 2012). AD provides environmental advantages over waste-to-energy (WTE), landfill with landfill gas to energy (LFGTE), bioreactor landfill with LFGTE, and advanced thermal treatment (gasification and pyrolysis) by more efficiently recovering energy from OFMSW. When paired with source-separation (to ensure high-quality feedstocks) and aerobic composting, AD provides advantages over composting alone by enabling energy recovery and reducing emissions of volatile organic compounds (VOCs) and ammonia (De Baere, 1999). These advantages, combined with efforts to reduce GHG emission, are motivating research to improve the economic competitiveness and adoption of HS-AD technologies.

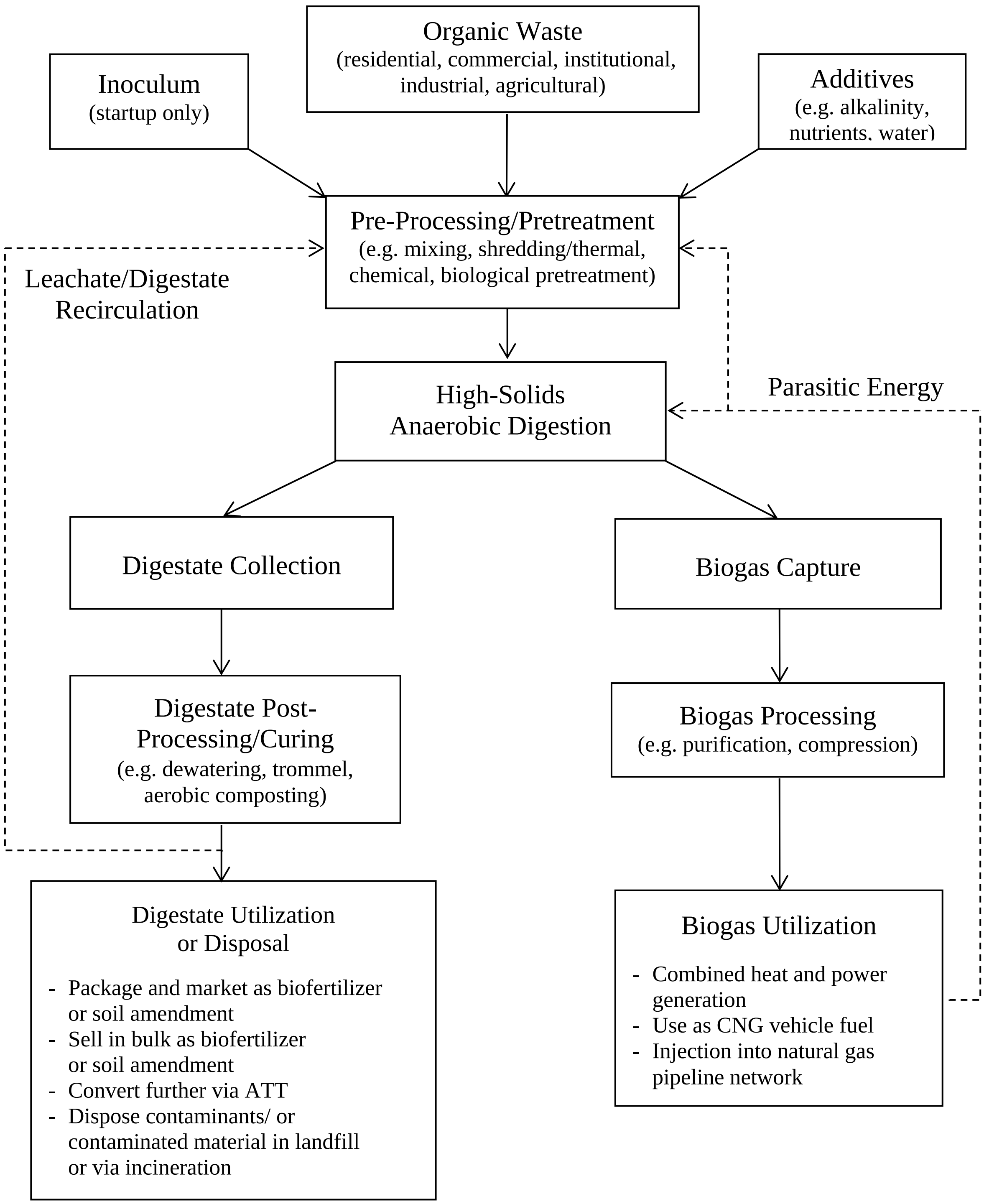


Figure 1.1. HS-AD of OFMSW schematic (from Zupančič and Grilc, 2012 CC BY 3.0 License © The Authors).

Table 1.1. Benefits of AD and advantages and disadvantages of HS-AD vs. L-AD.

Benefits of AD	**Summary**	**Reference(s)**
Enables Energy Recovery	AD is an energy positive process. The production of biogas containing CH_4 enables direct combustion for heating, lighting, cooking, conversion to electricity in combustion engines, production of compressed natural gas for use in vehicles, or injection into the natural gas pipeline network.	Owens and Chynoweth, 1993; Tchobanoglous et al., 2003; Khanal, 2008; Li et al., 2011; Kothari et al., 2014
Enables Nutrient Recovery	Valuable nutrients, especially N and P, are present in high concentrations in the liquid/solid byproducts of AD and can be recovered through post-processing (e.g. trommel and composting/curing of the digestate).	Owens and Chynoweth, 1993; Khanal, 2008; Li et al., 2011; Kothari et al., 2014
Mass/Volume Reduction	Up to 50% substrate mass and volume reduction can be achieved through AD. Because anaerobic microorganisms are slower growing than aerobic, less excess biomass is produced in AD.	Tchobanoglous et al., 2003; Li et al., 2011; Kothari et al., 2014
Destruction of Pathogens	Long term exposure to high temperatures in a microbiologically competitive anaerobic environment ensures reliable pathogen destruction/inactivation.	Wilkie, 2005; Khanal, 2008
Reduced GHG Emissions	AD significantly reduces GHG emissions through capture and energy conversion CH_4 which otherwise would have been emitted through degradation of organic waste in uncontrolled environments or as fugitive emissions in landfills; additional offsets can be achieved through offsetting fossil-fuel derived electricity consumption.	Owens and Chynoweth, 1993; Tchobanoglous et al., 2003; Edelmann et al., 2005; Li et al., 2011; Kothari et al., 2014
Reduced Odors	AD in enclosed reactors with biogas capture yields little odor.	Wilkie, 2005; Khanal, 2008
Advantages of HS-AD vs. L-AD		
Reduced Energy Consumption	Less energy used for heating and internal mixing yields lower parasitic energy losses and higher overall energy efficiency.	Li et al., 2011; Kothari et al., 2014.
Reduced Water Use	Zero or minimal water addition is required in HS-AD, leachate is often recirculated, and minimal excess leachate production results in reduced side-stream treatment costs.	Li et al., 2011; Kothari et al., 2014.
Reduced Reactor Size	The reduced moisture content and capacity for HS-AD systems to handle greater organic loading rates yield lower required reactor volumes for given loading/biogas yield rates.	Guendouz et al., 2010; Li et al., 2011; Kothari et al., 2014.
Reduced Post-Processing	The compost-like digestate byproduct of HS-AD requires only minor post-processing (trommel/sieve and composting/curing) whereas L-AD byproduct first requires dewatering.	Li et al., 2011; Kothari et al., 2014.
No Waste Stratification	In L-AD stratification of FOG and fibrous materials can create operational challenges. This does not occur in HS-AD systems.	Guendouz et al., 2010.
Disadvantages of HS-AD vs. L-AD		
More Inoculum Required	Lower moisture content can yield reduced microbe-substrate contact resulting in greater inoculation requirements.	Li et al., 2011.
Reduced Homogeneity	Lower moisture content reduces mixing capabilities and homogeneity of digester contents yielding spatial variations in process efficiency.	Kothari et al., 2014.
Longer Retention Times	Although retention times in HS-AD systems are often similar to those of liquid systems (~20 days), up to three times longer retention times are needed in HS-AD in some cases due to slower mass transport.	Li et al., 2011; Kothari et al., 2014.

The overall goal of this research project was to investigate the potential for biogas production in Florida from OFMSW using HS-AD. The specific objectives of this research project were to:

1) Evaluate the most appropriate technologies for implementing HS-AD of OFMSW in Florida (Section 2).

2) Carry out fundamental research at bench- and pilot-scale to improve the biodegradability of lignocellulosic waste through co-digestion with pulp and paper sludge (Section 3).

3) Identify potential sites, collaborators, and funding sources for a large-scale HS-AD demonstration project in Florida (Section 4).

A comprehensive review of the development of HS-AD, development trends, and the state-of-the-art of HS-AD was carried out to enable well-informed identification of appropriate technologies for implementing HS-AD of OFMSW in Florida (Section 2). Two sets of experiments comprising several phases of bench- and pilot-scale laboratory experiments were carried out to explore potential methods to improve the overall efficiency of HS-AD, including studies aiming to improve the biodegradability of lignocellulosic waste through inoculation with P&P sludge and studies aiming to identify favorable co-digestion strategies (as reported in Section 3). Findings from the fundamental research and the assessment of the state-of-the-art of HS-AD were then utilized in combination with input solicited from Florida solid waste management industry professionals to identify potential sites, collaborators, and funding sources for a large-scale HS-AD demonstration project in Florida (Section 4).

2.0 OBJECTIVE 1: STATE-OF-THE-ART OF HS-AD

2.1 Introduction

A comprehensive review of HS-AD development and trends in implementation was conducted. This assessment elucidates HS-AD technology types on the market, HS-AD technologies and vendors in the United States and trends in HS-AD implementation in Europe and the US. The information obtained from the assessment allows for the prediction of future trends and well-informed identification of appropriate technologies for implementation of HS-AD in Florida.

2.2 Methodology

Information sources included "grey" and published literature, discussions with industry professionals and technology vendors, and visits to facilities in the US and the Netherlands.

2.3 Results and Discussion

HS-AD systems are classified according to loading type (continuous, batch), number of stages (single-stage, multi-stage) and temperature (mesophilic, thermophilic) (Rapport et al., 2008). HS-AD systems can also be classified by feedstock (SS-OFMSW, MS-OFMSW, mixed MSW) and whether they process a single substrate (OFMSW) or are codigesting (e.g. OFMSW with biosolids) (De Baere and Mattheeuws, 2014). Figure 2.1 illustrates AD system "types" based on these classifications. Table 2.1 summarizes advantages and disadvantages of different systems.

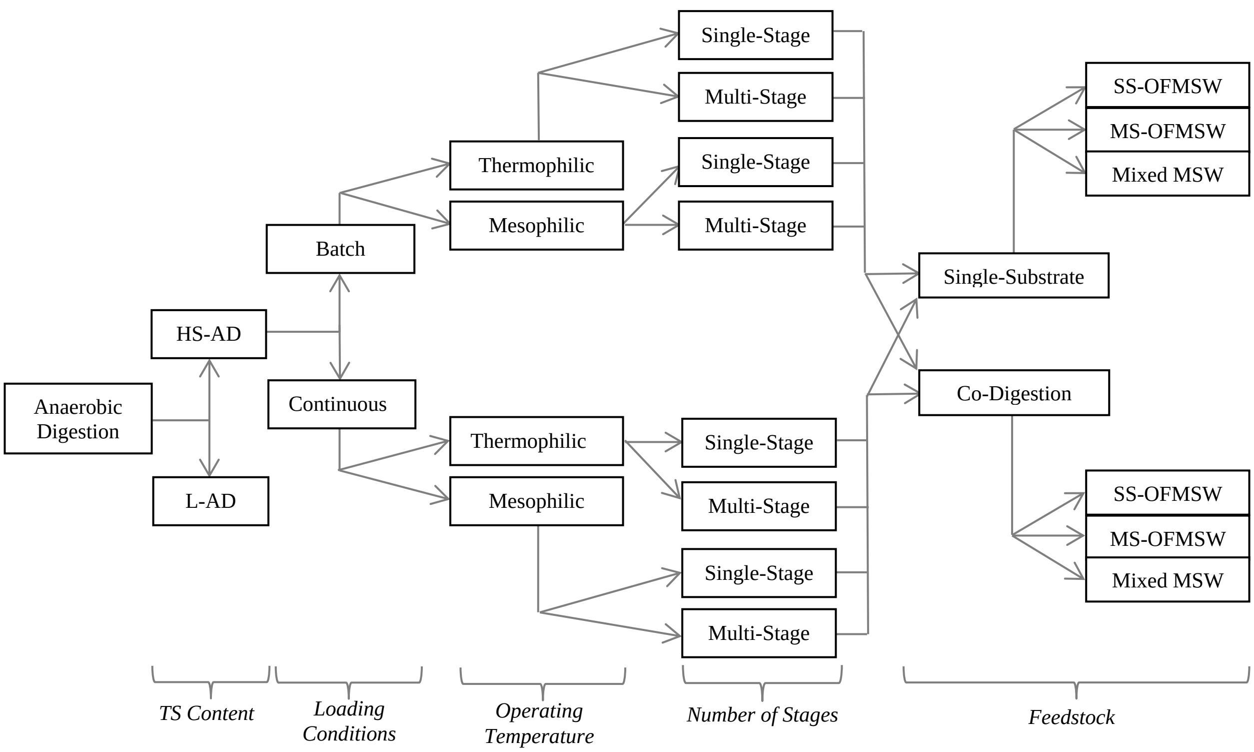


Figure 2.1. Possible AD system "types" based on predominant system classifications.

Table 2.1. Technical, biological, and environmental/economic advantages and disadvantages of AD technologies for OFMSW by classification (adapted from Rapport et al., 2008).

System	Criteria	Advantages	Disadvantages
Batch vs. Continuous	Technical	Simplifies material handling; reduced pre-processing/treatment requirements	Compaction within digester can reduce percolation and percolate recirculation capabilities
	Biological	Separation of hydrolysis and methanogenesis; higher rate and extent of digestion than landfill bioreactors	Variable biogas production with time; reduced process control
	Economic and Environmental	Low capital cost; low O&M costs; lower overall impact	Less complete degradation
Multi-stage vs. Single-stage	Technical	More operationally flexible	Complex design and materials handling
	Biological	Can tolerate high loading rates and fluctuations in loading rates	Can be difficult to achieve true separation of phases in digesters
	Economic and Environmental	Can yield higher digestion efficiencies	Increases capital and O&M costs
Thermophilic vs. Mesophilic	Technical	Requires minimal change in design (heat transfer systems)	Requires more heat transfer equipment
	Biological	Improves digestion efficiency; improves pathogen destruction	Greater risk of process inhibition with thermophilic systems
	Economic and Environmental	Improves bioenergy production rate and marketability of compost	Thermophilic systems require greater heat input
Co-digestion vs. Single Substrate	Technical	Requires no change in design	Requires increased preprocessing
	Biological	Enables optimization of environmental conditions which can improve bioconversion rates	Greater potential for variation in feedstock characteristics and shock inhibition
	Economic and Environmental	Can yield significant enhancements in bioenergy generation	Can increase the economic and environmental costs of waste collection
Source Separated OFMSW vs. Mixed MSW	Technical	Collection is simple with mixed MSW, and feedstock contamination is of little importance	Collection schemes for SS-OFMSW can be challenging; minor contamination (e.g. glass) can pose a problem for digestate reuse
	Biological	Source separation reduces variation in feedstock characteristics and yields more consistent conditions and performance	Processing mixed MSW poses threats of contamination with strong inhibitory compounds
	Economic and Environmental	Less energy is needed for mixed MSW collection; less energy is needed for processing source separated waste and more energy and nutrients are recovered	Processing mixed MSW increases energy input requirements and reduces bioenergy yields and nutrient recovery potential

Continuous HS-AD systems are normally loaded daily, with fresh material going in one end and digested material coming out the other. These systems are configured as large plug-flow type reactors. Batch systems normally consist of multiple "garage" or "shipping container" type reactors that are loaded, sealed, and left to digest for a specified amount of time until they are unloaded (Rapport et al., 2008). Single-stage systems use a single reactor for the entire AD process, whereas multi-stage systems use two or more reactors with varying environmental conditions and retention times to separately optimize different phases of the AD process (e.g. hydrolysis and acidogenesis in one reactor and acetogenesis and methanogenesis in a subsequent reactor) (Deublein and Steinhauser, 2008). Multistage systems sometimes feature both HS-AD and L-AD (e.g. hydrolysis, acidogenesis, and acetogenesis via HS-AD and methanogenesis via L-AD) (Deublein and Steinhauser, 2008). Mesophilic AD systems have operating temperatures ranging from 35-40 °C, whereas thermophilic systems have operating temperatures ranging from 50-55 °C. Some multi-stage systems have different operating temperatures for each stage (e.g. mesophilic first-stage and thermophilic second stage) (Lin et al., 2013).

De Baere and Mattheeuws (2014) provided a review of trends in AD of OFMSW in Europe, which is summarized in Table 2.2. As of 2014, there were 244 full-scale AD plants for processing OFMSW, with a total capacity of ~ 8 million TPY, 62% of installed AD in Europe was HS-AD and the remaining 38% was L-AD. Installed capacity (TPY) for Europe by country included: Germany (~2 million), Spain (~1.6 million), France (>1 million), Netherlands (>750,000), Italy (>500,000), UK (>500,000), Switzerland (>300,000), with smaller installed capacities reported for Belgium, Portugal, Austria, Poland, Norway, Denmark, Malta, Sweden, Luxemburg, and Finland. A map of biogas facilities in the UK can be found at http://www.biogas-info.co.uk/resources/biogas-map/. HS-AD is preferred over L-AD for processing OFMSW due to their economic and environmental advantages, and this trend is expected to continue in the future (De Baere and Mattheeuws, 2014). The majority of AD systems in Europe as of 2014 were continuous systems; however, batch systems have been increasing in popularity since 2009 due to their simplicity and low cost (De Baere and Mattheeuws, 2014). Single-stage systems made up approximately 93% of AD capacity in 2014, with only 7% being multi-stage (two-stage). Implementation of multi-stage systems has been continuously declining because their benefits do not justify their higher capital and operating costs (De Baere and Mattheeuws, 2014). Mesophilic digestion accounted for 67% of AD in Europe in 2014, but thermophilic digestion is becoming increasingly common and is expected to surpass mesophilic digestion as it is now considered mature and has been shown to yield net economic benefits (De Baere and Mattheeuws, 2014).

With respect to feedstock, single substrate digestion (OFMSW) accounted for 89% of AD in 2014, with co-digestion (e.g. OFMSW with wastewater biosolids or livestock wastes) representing only 11% of installed capacity (De Baere and Mattheeuws, 2014). The longstanding trend has been from co-digestion to single substrate digestion, as "stand-alone" systems tailored to process OFMSW have become increasingly common. More recently, there has been a slight increase in co-digestion, as facilities in the agro-industrial sector have demonstrated the potential economic advantages of co-digestion (De Baere and Mattheeuws, 2014). With respect to source-separation, 55% of European AD systems in 2014 were processing SS-OFMSW while 45% were processing mixed MSW. Increases in capacity for processing SS-OFMSW have been in direct proportion to promulgation of regulations on source-separation of OFMSW in commercial, institutional, and residential settings (De Baere and Mattheeuws, 2014).

Table 2.2. Characterization of AD of OFMSW in Europe (De Baere and Mattheeuws, 2014).

Classification	% of Installed Capacity	Trends	Expected Future Trends
Total Solids Content	62% HS-AD, 38% L-AD	HS-AD systems have been consistently preferred over L-AD systems for processing OFMSW for more than 20 years. 62% of 244 MSW AD facilities in Europe are categorized as HS-AD.	HS-AD will continue to increase in prevalence due to the economic and environmental advantages it offers compared to L-AD.
Loading Conditions	> 50% Continuous	Continuous systems have traditionally dominated the industry, but batch systems have been catching on quickly since 2009.	Batch systems are expected to continue to increase in popularity due to their simplicity and low cost.
Number of Stages	93% Single-Stage, 7% Two-Stage	Multi-stage systems have been continuously in decline since the 1990's.	No immediate changes in this trend are expected due to the higher investment and operating costs that accompany multi-stage systems.
Operating Temperature	67% Mesophilic, 33% Thermophilic	Thermophilic digestion has been becoming increasingly common in the last decade.	Thermophilic capacity is expected to surpass mesophilic capacity because thermophilic systems are now well-proven and yield net economic benefits in most cases.
Co-digestion	89% Single-Substrate, 11% Co-digestion	The trend has been almost unanimously from co-digestion to single substrate digestion, as "dedicated" systems tailored for OFMSW processing have been designed and implemented; however, in recent years there has been a slight rise in co-digestion.	Laboratory research and the agro-industrial sector have demonstrated the potential economic advantages of co-digestion and thus, it may become increasingly common.
Feedstock	55% Source-Separated, 45% Mixed MSW	Increases in capacity for processing source separated waste have been in direct proportion to increases in legislation regulating the source separation of OFMSW.	It is expected that source separation regulations will continue to increase and therefore, digestion of source separated OFMSW will continue to increase.

A detailed database of HS-AD projects in the US is provided in Appendix A. Several pilot-scale and/or demonstration-scale HS-AD projects were constructed prior to 2002, as described by Rapport et al. (2008). The first full-scale demonstration HS-AD system in the US was constructed in Clinton, NC in 2002 (Greer, 2011). The 3,380 TPY facility employs an HS-AD technology (now marketed by Orbit Energy, Inc.) developed by the US Department of Energy National Renewable Energy Laboratory (Greer, 2011). The first commercial HS-AD system in the US was constructed in 2011 at the University of Wisconsin Oshkosh and began operation in 2012 (UW Oshkosh, 2015). Currently, eight full-scale HS-AD facilities are operating in the US, with a total combined capacity of 189,600 TPY. Another 19 HS-AD projects were identified that are in the planning, permitting, or construction phases (see database in Appendix A). The majority of the existing and planned facilities, including the largest HS-AD facility in the country (90,000 TPY in San Jose, CA) are located in California and utilize the SmartFerm technology marketed by Zero Waste Energy, LLC (ZWE, US affiliate of the German company, Eggersmann Group). However, several other vendors have established themselves in the North American HS-AD market (Table 2.3) and several other states have implemented or are planning to implement HS-AD. Figure 2.2 shows the number of HS-AD facilities in the US over time, projected to 2017. Figure 2.3 shows the locations of existing and planned US HS-AD facilities.

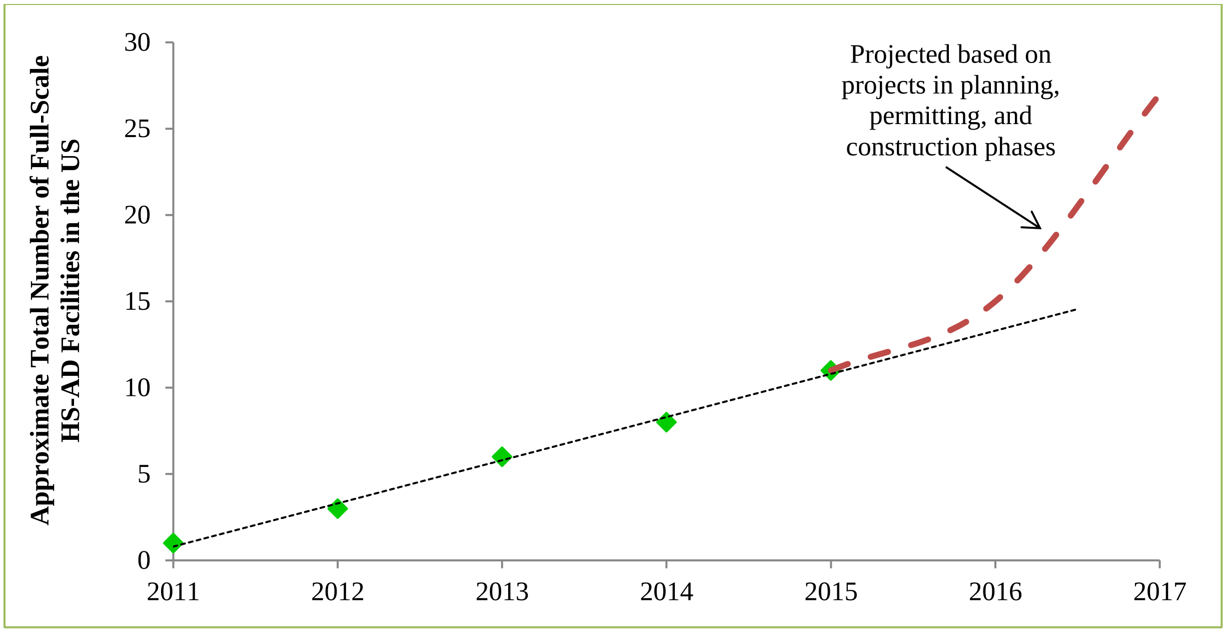


Figure 2.2. Total number of HS-AD facilities in the US versus time, 2011 to 2017 (projected).

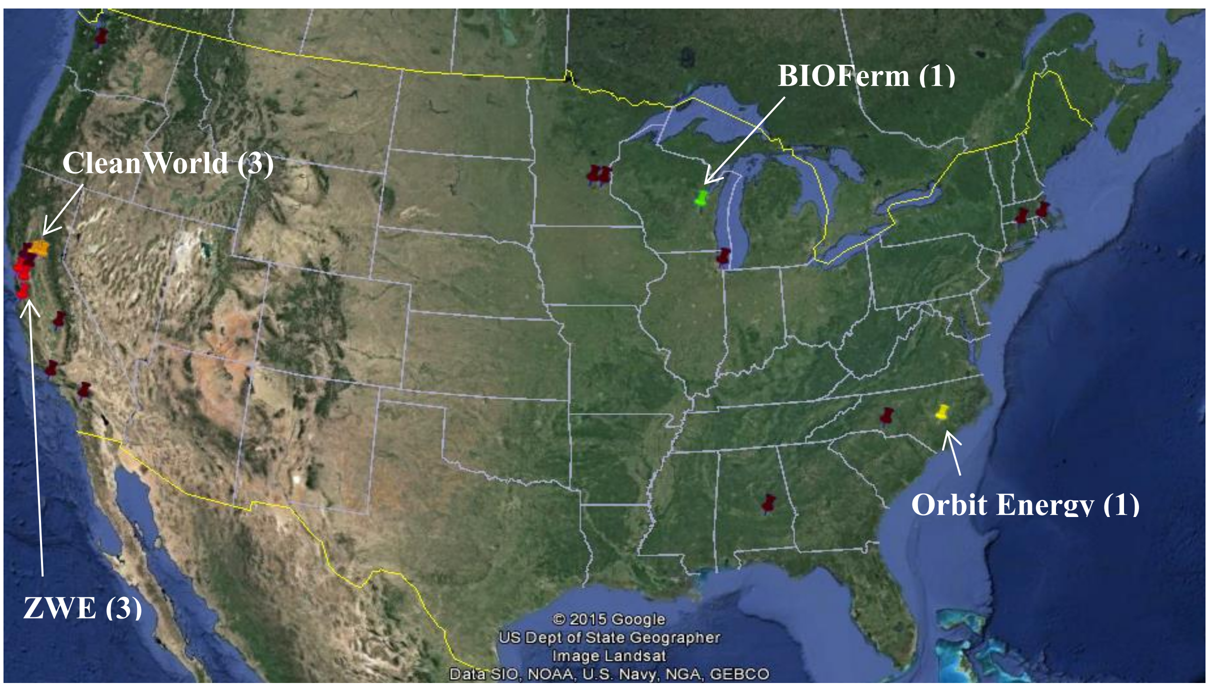


Figure 2.3. Locations of existing and planned HS-AD facilities in the US.

Primary characteristics of HS-AD technologies offered by US vendors are summarized in Table 2.3. The current status and trends in the development of AD of OFMSW in the US are provided in Table 2.4. A database of existing and well-documented planned HS-AD projects in the US is included in Appendix A. According to a recent report by the Environmental Research and Education Foundation (EREF, 2015a), there are currently 181 AD facilities in the US processing OFMSW, with a total OFMSW throughput of 780,000 TPY. Of these facilities, 81 are wastewater treatment plant digesters accepting some food waste or FOG (fats, oils, and greases), with a total throughput of 226,000 TPY (29%), 75 are on-farm digesters accepting food and/or yard waste, with a total throughput of 140,000 TPY (18%), and 25 are stand-alone facilities (designed specifically for processing OFMSW) with a total capacity of 406,000 TPY (52%). It follows that approximately 47% of existing stand-alone capacity for AD of OFMSW is HS-AD (189,600 TPY of 406,000 TPY). However, if all planned AD facilities for OFMSW come online by 2017, HS-AD will be the dominant AD technology type for processing OFMSW in the US, which parallels trends in Europe. With respect to the prevalence of HS-AD systems by other classification categories, 61% of capacity (on a TPY basis) is of the batch variety, 63% is of the single-stage variety, and 95% is of the thermophilic variety.

Table 2.3. Vendors of HS-AD technologies in the US.

Vendor Name	Main Office Location	Founding Year	Primary Partnerships	# of Facilities in Operation in the US	# of Facilities in Development in the US
Zero Waste Energy, LLC	California	2009	Eggersmann Group, Bulk Handling Sys, Environmental Solutions Group	≥ 3	≥ 7
CleanWorld Corporation (formerly CleanWorld Partners, LLC)	California	2009	UC Davis, Synergex	≥ 3	≥ 1
Orbit Energy, Inc.	North Carolina	2002	McGill Environmental	≥ 1	≥ 5
BIOFerm Energy Systems	Wisconsin	2007	Viessmann Group, Schmack Biogas	≥ 1	≥ 1
Organic Waste Systems, Inc.	Belgium (subsid Ohio)	1988	NR	≥ 0	≥ 1
Harvest Power, Inc.	Massachusetts	2008	GICON Bioenergie GmbH	≥ 0	≥ 1
Eisenmann Corporation	Germany (subsid IL)	1977	NR	≥ 0	≥ 2
Turning Earth, LLC./Aikan North America, Inc.	Denmark (subsid GA)	2009	Solum Group, Aikan A/S	≥ 0	≥ 1
EcoCorp, Inc.	Maryland	2000	NR	≥ 0	≥ 0

Note: NR = Not Reported; ≥ 0 indicates that zero facilities were identified, but that it is possible that some exist

Table 2.4. Characteristics of HS-AD technologies available in the US.

Vendor Name	Operating Temperature	TS Content	Loading Conditions	Number of Stages	Retention Time	Parasitic Energy Demand
Zero Waste Energy, LLC[1]	Thermophilic	< 50%	Batch	1	21 days	20%
CleanWorld Corporation (formerly CleanWorld Partners, LLC)[2]	Thermophilic	~10%	Continuous	3	20-30 days	NR
Orbit Energy, Inc.[3]	Thermophilic	< 45%	Continuous	1	"short"	8%
BIOFerm Energy Systems[4]	Mesophilic	25-35%	Batch	1	28 days	5-10%
Organic Waste Systems, Inc.[5]	Thermophilic or Mesophilic	< 50%	Continuous	1	20 days	NR
Harvest Power, Inc.[6]	Thermophilic	NR	Batch	2	≥ 14 days	NR
Eisenmann Corporation[7]	Thermophilic	NR	Continuous	1	NR	NR
Turning Earth, LLC.[8]	Thermophilic	NR	Batch	2	21 days	NR
EcoCorp, Inc.[9]	Thermophilic	35-40%	Continuous	1	20 days	20%

Note: NR = Not Reported; [1]ZWE, 2013; ZWE, 2015; [2]Zhang, 2013; CleanWorld, 2015a; CleanWorld, 2015b; [3]Greer, 2011; Orbit Energy, 2015; [4]BIOFerm, 2014; [5]De Baere, 2012; [6]Harvest Power, 2014; [7]Eisenmann, 2014; [8]Aikan, 2015; [9]EcoCorp, 2015.

Table 2.5. Characterization of AD of OFMSW in the US.

Classification	Current Status	Expected Future Trends
Total Solids Content	Since 2011, the fraction of stand-alone capacity for AD of OFMSW has increased from nearly 0% to around 48% (189,600 TPY of 406,000 TPY).	HS-AD will become the dominant form of AD of OFMSW by 2017 due to the economic and environmental advantages it offers over L-AD.
Loading Conditions	Approximately 61% of HS-AD capacity is currently of the batch variety (116,200 TPY of 189,600 TPY).	14 of the 27 HS-AD systems expected to be in operation by 2017 will be batch systems; no clear trend exists in this respect.
Number of Stages	Around 63% of HS-AD capacity is currently of the single-stage variety (119,600 TPY of 189,600 TPY).	Only 6 of the 27 HS-AD systems expected to be in operation by 2017 will be multi-stage, suggesting that single-stage systems are generally preferred, likely due to their simplicity and low cost.
Operating Temperature	Thermophilic digestion represents the vast majority (>95%) of existing capacity for HS-AD of OFMSW.	Thermophilic digestion is expected to remain the dominant digestion type due to the increased efficiency it offers and demonstrated stability.
Co-Digestion	Currently, 47% of capacity for AD of OFMSW is co-digestion, with 29% being at wastewater treatment plants and 18% being at farms.	The stand-alone capacity for AD of OFMSW is expected to quadruple to 2.5 million tons by 2017 (EREF, 2015a) surpassing co-digestion as the dominant form.
Feedstock	Limited information exists on whether existing facilities are processing mixed, mechanically separated, or source-separated OFMSW.	Increases in mandates on source-separating OFMSW and studies indicating significant economic advantages associated with processing SS-OFMSW over MS-OFMSW suggest that processing source-separated feedstock will be the dominant form of AD of OFMSW.

2.4 Summary of Major Findings

A timeline for the development of HS-AD is provided in Figure 2.4. L-AD is a mature technology for stabilizing organic matter in municipal, agricultural and industrial wastewater, biosolids and sludges. Many L-AD facilities add FOG and source-separated food waste to L-AD systems to enhance energy generation rates. However, OFMSW landfill bans, landfill taxation, and renewable energy incentives in the EU increased sharply in the 1980's, resulting in high demand for alternative OFMSW treatment technologies and spurring the development of HS-AD systems. As legislation continued to increase and source-separation became common, HS-AD became the primary form of OFMSW digestion in the EU. Based on our review of existing projects in the US, implementation of HS-AD began in the US in the early 2000s. Now, with legislation steadily increasing, trends in HS-AD development are mirroring those of the EU, more HS-AD vendors are doing business in the US, implementation is accelerating, and HS-AD capacity is projected to soon surpass L-AD capacity for processing OFMSW.

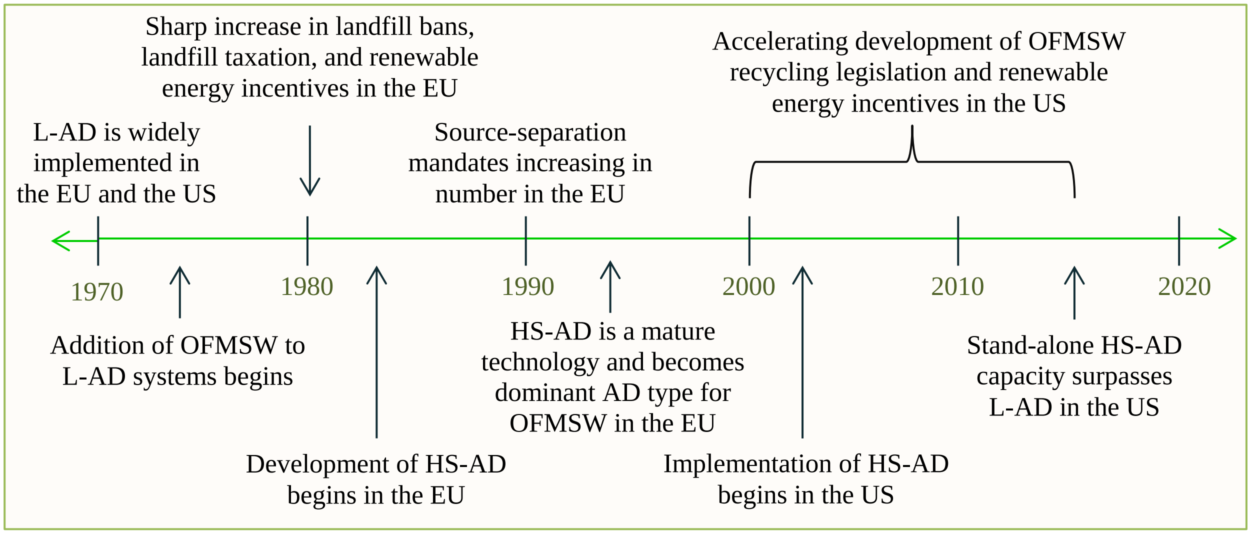


Figure 2.4. Timeline summarizing the development of HS-AD in Europe and the US.

Single-stage, batch-type thermophilic digesters, such as the SmartFerm and BioFerm systems, constitute more than half of the systems operating in the US today. These systems are capable of processing source separated OFMSW (SS-OFMSW), mechanically separated OFMSW (MS-OFMSW), or comingled MSW. The digestate is free of pathogens and is considered compost per the EPA's *Process to Further Reduce Pathogens* (PFRP) program, but requires post-processing to remove contaminants (e.g. trommel). As the most proven form of HS-AD in the US, these systems are considered the most suitable for HS-AD in the state of Florida.

Key factors affecting the economics of HS-AD include the quality and quantity of available feedstock, the cost of feedstock collection and storage, markets for compost, energy, and renewable energy credits (RECs), and the development of public-private partnerships. In general, HS-AD technologies cannot compete with the low cost of landfilling. In San Jose California; however, we observed HS-AD being used at a landfill site for preprocessing comingled MSW before disposal. This practice has the potential to improve energy recovery efficiency, saves landfill space, reduces greenhouse gas emissions, and reduces leachate generation at landfill sites.

3.0 OBJECTIVE 2: ENHANCING BIOENERGY PRODUCTION

3.1 Introduction

This chapter discusses fundamental research carried out to improve the economic sustainability of HS-AD by developing a low cost, low environmental impact process for enhancing methane yields from lignocellulosic materials, such as yard waste. One of the pressing challenges associated with methane production in HS-AD is the low degradability of lignocellulosic wastes (Li et al., 2011). The lignin in these wastes is highly recalcitrant and the association of cellulose and hemicellulose with the lignin acts as a barrier to the microbial populations that perform hydrolytic conversion of cellulose (Tong et al., 1990; Zheng et al., 2014). Thus, HS-AD of lignocellulosic waste requires long retention times to achieve sufficient degradation, which reduces the environmental and economic sustainability of the process (Li et al., 2011). A number of studies have demonstrated that physical, chemical, and/or biological pre-treatment can increase methane yields from lignocellulosic wastes (Vervaeren et al., 2010; Bruni et al., 2010; Kreuger et al., 2011; Zhao et al., 2014). However, recent reviews of pretreatment strategies have concluded that the increased energy production does not justify the environmental and economic costs incurred by these processes in most cases (Mosier et al., 2005; Hendricks and Zeeman, 2009; Zheng et al., 2014; Yang et al., 2015).

A potential low cost, low impact (with respect to energy or chemical inputs or waste generation) strategy for enhancing methane yields from lignocellulosic wastes is bioaugmentation of substrates with microbial populations capable of hydrolyzing lignocellulosic compounds. Flocculent sludge from AD of biosolids from domestic wastewater treatment plants (WW-AD) is the most common source of inoculum used for process start-up in HS-AD systems (Deublein and Steinhauser, 2008) and has been shown to be more effective than other inoculum sources in terms of maximizing methane yields in HS-AD of source-separated OFMSW (Forster-Carneiro et al., 2007). However, the bacteria present in WW-AD sludge are not capable of hydrolyzing lignocellulosics, resulting in slow hydrolysis rates and limited methane yields in HS-AD of yard waste (Sharma et al., 1988; Izumi et al., 2010; Veeken, 2014).

In a prior study carried out in our laboratory, granular anaerobic sludge generated from the treatment of waste from pulp and paper mills (P&P sludge) was identified as a promising inoculum for HS-AD of lignocellulosic waste (Mussoline et al., 2013). P&P sludge contains microbial populations that are acclimated to a lignin-rich waste stream and likely contains hydrolytic communities capable of degrading lignocellulosics (Mussoline et al., 2013; Meyer and Edwards, 2014). Mussoline et al. (2013) investigated the enhancement of methane production from rice straw in HS-AD through bioaugmentation with P&P sludge. The theoretical maximum specific methane yield from rice straw was reached in 92 days of digestion using a substrate to inoculum (S/I) ratio of 1:2 on a wet weight basis. The specific methane yield achieved of 340 L CH_4/kg VS was 47-74% higher than in similar studies using WW-AD inoculum and was comparable to methane yields achieved in studies employing various pretreatment methods. The results indicate that bioaugmentation of agricultural residues with P&P sludge is a promising alternative to pretreatment for enhancing methane production in HS-AD; however, no prior research has been carried out using this strategy to enhance methane production from OFMSW.

The overall goal of this research was to investigate the potential to enhance methane yields from HS-AD of OFMSW using this novel bioaugmentation strategy. Biochemical methane potential (BMP) assays were carried out using yard waste inoculated with P&P and WW-AD sludge. Measurements of concentrations of key indicator compounds in leachate from batch digesters as well as lignin, cellulose, and hemicellulose content of the waste were used to provide additional evidence of enhancement mechanisms. Studies were also carried out to investigate whether the enhancement observed could be sustained through digestate recirculation, which is a common practice in HS-AD systems (Li et al., 2011). Observed methane yield enhancements were compared with enhancements reported in the literature for pretreatment of yard waste using physical, chemical and biological methods.

A pilot-scale HS-AD system was constructed, which was used as a demonstration system and for preliminary pilot-scale experiments exploring the effects of scale on HS-AD. Appendix B includes a photograph and a summary of preliminary data from this system. An additional set of experiments was carried out to investigate co-digestion of yard waste, food waste and waste activated sludge (wastewater biosolids) in HS-AD systems. Wastewater biosolids are a readily available substrate in many regions of the US facing increased regulation and cost of biosolids disposal, including Florida. However, limited information is available on their co-digestion with OFMSW in HS-AD systems. These experiments are currently in progress.

3.2 Methodology

Mixed yard waste (containing branches, leaves, and needles, tree trimmings, shrub trimmings, and other yard debris) was obtained from the University of South Florida campus (Figure 3.1). The waste was shredded using a commercial shredder approximately one week prior to sample collection. Upon collection, the sample was sieved to < 3 mm to improve homogeneity. In full-scale HS-AD systems, grinding of waste to <40 mm particle size is common (De Baere, 2012). P&P sludge from a mill in Matane, Canada was provided by Tembec, a Canadian based manufacturer of forest products. The mesophilic (35ºC) BIOPAQIC anaerobic bioreactor at the Matane mill treats raw pulp and paper wastewater with a total suspended solids content near 200 ppm at a hydraulic retention time of 3.8 hours and generates a granular sludge. WW-AD sludge was obtained from an outflow pipe from a digester at the Howard F. Curren Advanced Wastewater Treatment Facility (HFCAWTF) in Tampa, Florida. HFCAWTF digests a mixture of primary and waste activated sludge under mesophilic conditions with an SRT of 21 days and generates a flocculent sludge. The inocula and substrate were stored at room temperature during the experimental setup.

Experiments were designed based on defined protocols for BMP assays (Owen et al., 1978; Jerger et al., 1982; Owens and Chynoweth, 1993; Angelidaki et al., 2009). Anaerobic digesters were set up in triplicate in 250-mL glass bottles, sealed with metal crimp caps and silicone septa, and placed in a thermostatically-controlled room maintained at 35 ± 2 ºC. The TS content in the digesters was set at 20%, a common TS content for HS-AD (Li et al., 2011). The S/I ratio was set at 1/1 on a wet weight basis, a common relative concentration of inoculum (50% by wet weight) for efficient start-up in batch HS-AD (Rapport et al., 2008; Li et al., 2011; Brown and Li, 2013; Chen et al., 2014). It was assumed that sufficient micronutrient concentrations would be provided by the substrate and inocula, and therefore, no additional nutrients were added to the digesters.

Two phases of batch HS-AD experiments were carried out in series. Figure 3.2 describes the contents of the digesters assembled for all experiments. Phase 1 compared the performance of digesters containing yard waste inoculated with P&P sludge (Phase 1 bioaugmented digesters) with the performance of digesters containing yard waste inoculated with WW-AD sludge (Phase 1 control digesters). Phase 2 compared the performance of digesters containing yard waste inoculated with digestate from Phase 1 bioaugmented digesters (Phase 2 bioaugmented digesters) to the performance of digesters containing yard waste inoculated with digestate from Phase 1 control digesters (Phase 2 control digesters). Four additional digesters were prepared for both the bioaugmented digesters and control digesters during the setup of Phase 1 of batch HS-AD for intermediate chemical analysis as described below. Blank digesters (containing only inocula) were prepared to correct for methane yields from inocula in the bioaugmented and control digesters.

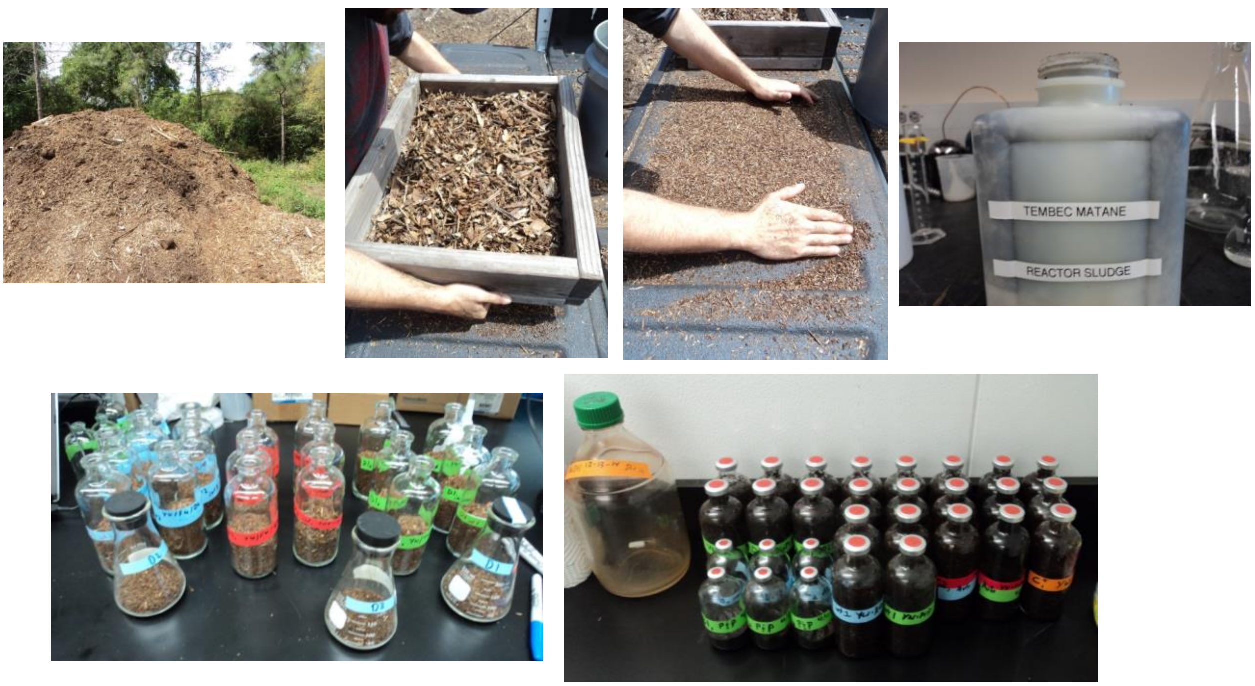


Figure 3.1. Photographs of batch BMP assay set up. Top row: Yard waste pile, screening, screened waste, sludge. Bottom row: set up of materials, finished digesters.

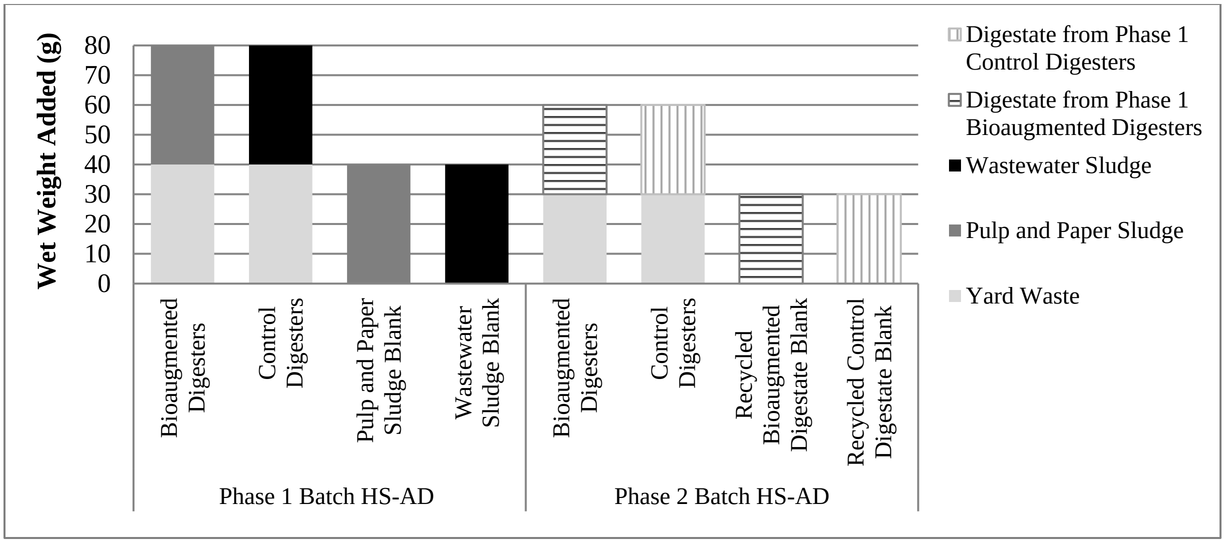


Figure 3.2. Phase 1 and 2 batch HS-AD digester compositions by wet weight.

Biogas was measured using a 50 mL frictionless syringe with a metal luer lock tip (Cadence Science Inc, 5157) equipped with a 25-gauge needle (BD PrecisionGlide 305125) according to previously described procedures (Owen et al., 1978; Jerger et al., 1982; Owens and Chynoweth, 1993). Biogas quality (approximate methane content) was determined by dissolving the carbon dioxide portion of a 20 mL biogas sample into a 3 N NaOH barrier solution and measuring the resulting liquid displacement (in accordance with ASTM D1827-92, 2002). Prior to each biogas measurement, the digesters were shaken vigorously for approximately five seconds to dislodge gas bubbles from the substrate.

Chemical analyses were performed on initial (feedstock) and final (digestate) samples in both Phases 1 and 2 and on intermediate samples in Phase 1 at the end of weeks 1, 3, 6, and 9. Samples were diluted with deionized (DI) water at a 1/2 ratio (mass of sample to volume of DI water), mixed vigorously for three minutes, then centrifuged at 5,000 rpm for five minutes to obtain a representative liquid fraction, as outlined in EPA Method 9045D (EPA, 2004). *Standard Methods* (APHA, 2012) were used to measure supernatant pH (4500-H+B) and concentrations of alkalinity as $CaCO_3$ (2320B), total volatile fatty acids (VFA) as acetic acid (10240), chemical oxygen demand (COD) (5200B), total ammonia nitrogen (TAN) (10031), total nitrogen (TN) (10072), and total phosphorous (TP) (8190). Concentrations, other than pH, were corrected to leachate concentrations based on the measured TS content.

The total mass (wet weight) of the digester contents was measured at the beginning and end of both phases, mass destruction was calculated, and a mass balance was conducted (Appendix C). For both Experiments 1 and 2, TS and VS were measured according to *Standard Methods* (2540) (APHA, 2012). Remaining ash from the volatilization of inoculum samples and digestate samples was diluted and preserved with 1% nitric acid for digestion (72 hours at 50ºC) and elemental analysis (Na, K, Ca, Mg, Fe, Cu, Cr, Ni, Zn, Pb, Co, Mo, Se, and Mn) using a Thermo-Scientific inductively coupled plasma mass spectrometer (ICP-MS). Undigested yard waste and digestate from the bioaugmented digesters and control digesters from the first phase of batch HS-AD were analyzed for lignin, cellulose, and hemicellulose content at the North Carolina State University Environmental Engineering Laboratory using high-performance liquid chromatography (HPLC) as described by Davis (1998). For all analyses, the full contents of the digesters were mixed thoroughly before grab samples were pulled and the mass of grab samples used for the analysis was maximized in order to optimize sample homogeneity/minimize error.

Specific methane yields were calculated by first subtracting the total methane produced in the blank digesters from the total methane produced in the bioaugmented and control digesters to obtain the volume of methane originating from the yard waste. The resulting volume was then adjusted to an equivalent volume at STP. Finally, the adjusted total methane volume (L) was divided by the mass of VS (kg) of yard waste loaded to each digester. Percent enhancement in methane yield was calculated as the percent difference in specific methane yields from bioaugmented digesters and control digesters. Statistical significance was determined by analysis of variance (ANOVA, $\alpha = 0.05$) using Microsoft Excel with $p_{critical} = 0.05$.

3.3 Results and Discussion

TS content (by wet weight), VS content (by wet weight), and alkalinity of yard waste samples and inocula used in Phases 1 and 2 of batch HS-AD experiments are shown in Table 3.1. Elemental characterization of the inocula is shown in Table 3.2. Elements selected were those that have been shown to play important roles in AD. Minimum recommended concentrations and inhibitory concentrations (where applicable) as reported by Deublein and Steinhauser (2008) and Zupančič and Grilc (2012) are shown alongside the results of the elemental analysis (Table 3.2).

Table 3.1. Substrate and inocula alkalinity, total solids content, and volatile solids content.

	Phase 1 Substrate and Inocula			**Phase 2 Substrate and Inocula**		
	Pulp and Paper Sludge	**Wastewater AD Sludge**	**Yard Waste for Phase 1**	**Phase 1 Bioaugmented Digestate**	**Phase 1 Control Digestate**	**Yard Waste for Phase 2**
Alkalinity (mg/L as $CaCo_3$)	2100	580	250	1400	480	130
TS (% of wet weight)	10.0 ± 0.2	0.60 ± 0.03	50.8 ± 3.4	18.5 ± 0.1	23.7 ± 0.3	64.2 ± 0.5
VS (% of TS)	20.5 ± 2.0	3.71 ± 0.36	47.7 ± 4.4	41.5 ± 3.4	44.2 ± 1.7	57.4 ± 1.6

NOTE: All TS and VS values are expressed as averages plus or minus standard deviations of samples run in triplicate.

Table 3.2. Elemental characterization of inocula and minimum and inhibitory concentrations (Deublein and Steinhauser, 2008; Zupančič and Grilc, 2012).

Element	Minimum Recommended Concentration	Inhibitory Concentration	Pulp and Paper Sludge	Wastewater AD Sludge	Phase 1 Bioaugmented Digestate	Phase 1 Control Digestate
Na (mg/kg)	100-200	3500-5500	1180 ± 40	898 ± 21	171 ± 25	84.7 ± 17.4
K (mg/kg)	200-400	3500-4500	382 ± 4	126 ± 3	180 ± 13	178 ± 3
Ca (mg/kg)	100-200	2500-4500	828 ± 20	1230 ± 80	**2370 ± 140**	**2560 ± 70**
Mg (mg/kg)	75-150	1000-1500	84.3 ± 0.7	87.8 ± 4.5	121 ± 10	146 ± 2
Cr (mg/kg)	0.005-50	28-300	0.515 ± 0.005	0.271 ± 0.021	0.128 ± 0.027	0.024 ± 0.012
Fe (mg/kg)	1.0-10	1750	49.7 ± 3.5	61.8 ± 4.5	17.6 ± 2.6	13.2 ± 1.6
Ni (mg/kg)	0.005-0.5	10-300	0.758 ± 0.038	0.232 ± 0.016	1.03 ± 0.066	0.235 ± 0.006
Cu (mg/kg)	> 0	150-300	8.93 ± 0.03	9.01 ± 0.50	2.56 ± 0.13	1.16 ± 0.12
Zn (mg/kg)	> 0	3-400	**113 ± 0**	**7.46 ± 0.48**	**16.8 ± 1.0**	**6.28 ± 0.21**
Pb (mg/kg)	0.02-200	8-340	0.327 ± 0.004	0.606 ± 0.021	0.065 ± 0.018	*0.024 ± 0.012*
Co (mg/kg)	0.06	N/A	0.588 ± 0.030	*0.027 ± 0.002*	0.272 ± 0.017	*0.016 ± 0.000*
Mo (mg/kg)	0.05	N/A	0.475 ± 0.024	0.242 ± 0.012	0.165 ± 0.013	*0.015 ± 0.006*
Se (mg/kg)	0.008	N/A	0.029 ± 0.010	0.125 ± 0.009	0.016 ± 0.007	0.019 ± 0.009
Mn (mg/kg)	0.005-50	1500	7.68 ± 1.87	0.973 ± 0.064	5.16 ± 0.18	5.31 ± 0.578

NOTE: All values are expressed as averages plus or minus standard deviation of samples run in triplicate; potentially inhibitory concentrations are shown in bold; potentially limiting concentrations are shown in italics

Specific methane yields achieved in the Phase 1 bioaugmented and control digesters (Figure 3.3) were 100 ± 2 L CH_4/kg VS and 58 ± 1 L CH_4/kg, respectively. Specific methane yields achieved in the Phase 2 bioaugmented and control digesters (Figure 3.4) were 34 ± 0 L CH_4/kg VS and 21 ± 0 L CH_4/kg VS, respectively. Significant enhancement in methane yield was observed when P&P sludge was used as an inoculum compared with wastewater anaerobic sludge in both Phase 1 (72.7 ± 7.6%, p = 1.03E-3) and Phase 2 (68.5 ± 4.0%, p = 5.15E-7), as shown in Figure 3.5. No significant differences were observed in average biogas quality (based on methane content) in bioaugmented or control digesters, and biogas quality was not significantly different between the two phases. Initial, final, and intermediate chemical analyses results from Phases 1 and 2 are shown in Tables 3.3 and 3.4. Trends observed in the evolution of key chemical parameters in Phase 1 bioaugmented and control digesters (Table 3.3) correspond with observations in methane yields (Figure 3.3).

The lignin, cellulose, and hemicellulose contents (fraction of dry sample) in the digestate from the Phase 1 bioaugmentation digesters were 42.4 ± 0.4%, 10.8 ± 0.4%, and 8.0 ± 0.3%, respectively (Figure 3.6). The lignin, cellulose, and hemicellulose contents in the digestate from the Phase 1 control digesters were 43.0 ± 0.2%, 12.6 ± 0.4%, and 9.3 ± 0.4%, respectively (Figure 3.6). Lignin, cellulose, and hemicellulose contents in the bioaugmented digestate were not significantly different from the control digestate (p = 0.206, p = 0.0518, and p = 0.0624, respectively). However, the average cellulose and hemicellulose contents detected in the bioaugmented digestate were 16.0% and 16.1% lower, respectively, than the average contents detected in the control digestate, and the p-values for these parameters were close to $p_{critical}$.

VS destruction was calculated for both phases of HS-AD but was not significantly different in either phase due to high standard deviations. However, total mass destruction (by wet weight) was also calculated (Figure 3.7) and was significantly higher in bioaugmented than in control digesters for both phases (Phase 1 p = 0.0200 and Phase 2 p = 0.0462). During Phase 1, total mass destruction was 4.67 ± 0.72% and 1.02 ± 0.18%, for bioaugmented and control digesters, respectively. During Phase 2, total mass destruction was 2.88 ± 0.07% and 2.37 ± 0.30%, for bioaugmented and control digesters, respectively. A mass balance was carried out based the initial and final mass of VS and the overall production of methane and carbon dioxide (Appendix C). The percent error in the mass balance for Phase 1 bioaugmented and control digesters and Phase 2 bioaugmented and control digesters was 0.84%, 1.26%, 1.48%, and 1.47%, respectively.

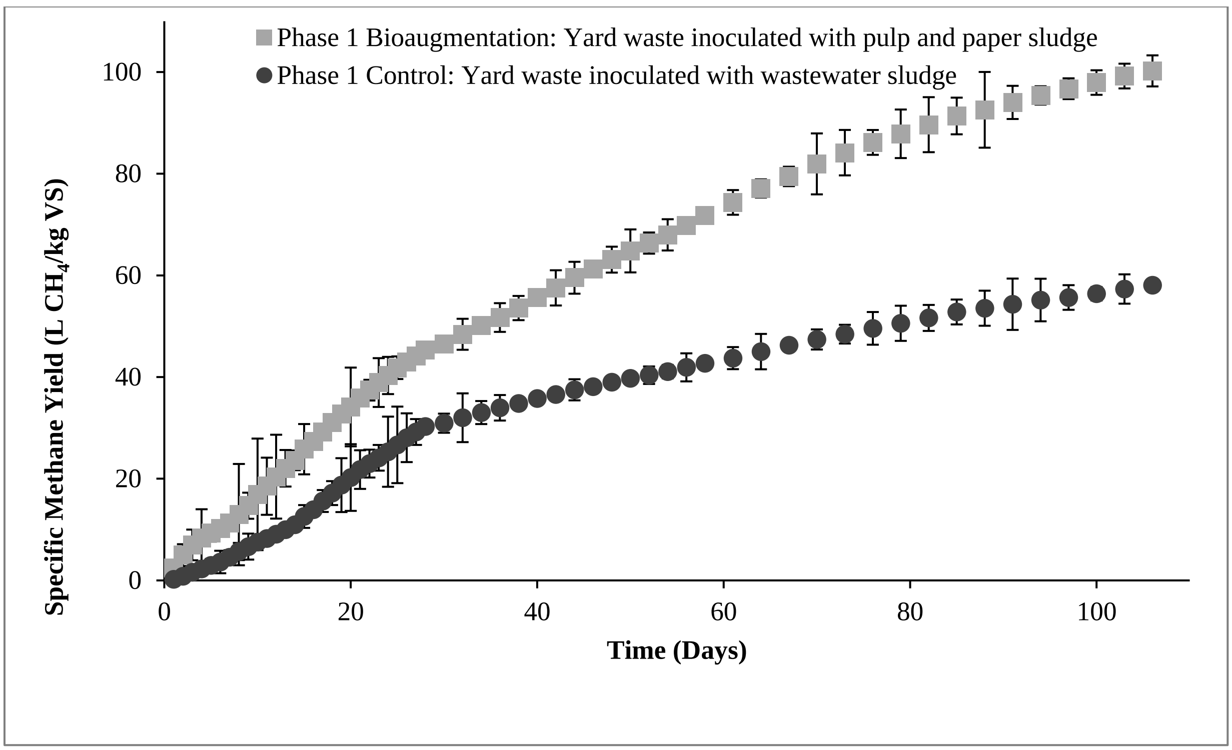


Figure 3.3. Specific methane yields observed in Phase 1 of batch HS-AD over 106 days; error bars represent standard deviations of samples run in triplicate.

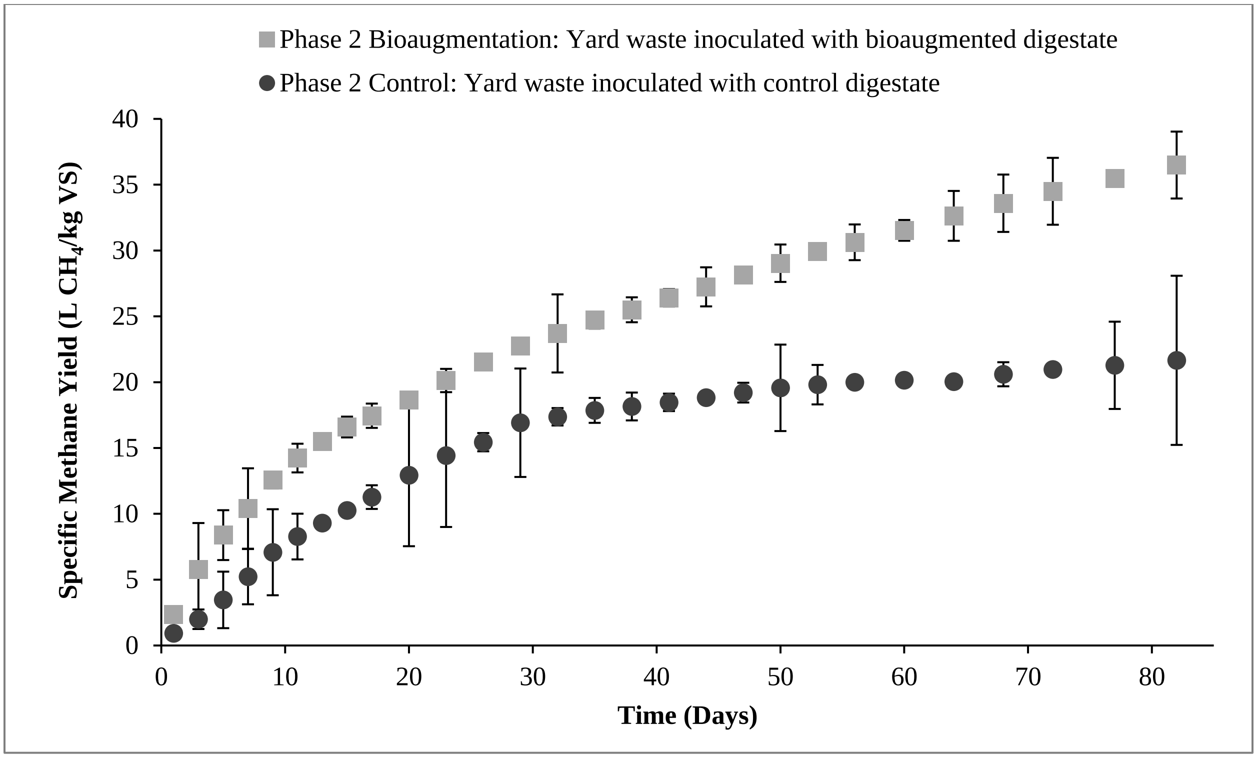


Figure 3.4. Specific methane yields observed in Phase 2 of batch HS-AD over 82 days; error bars represent standard deviations of samples run in triplicate.

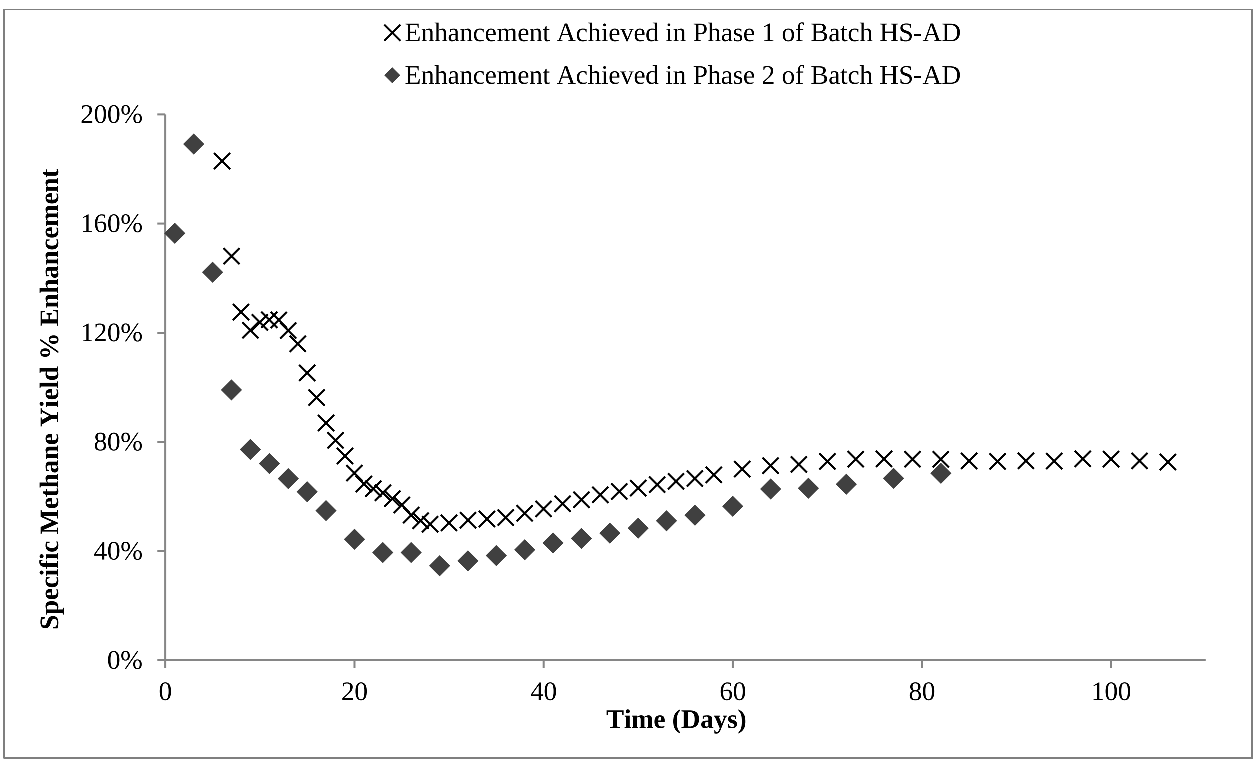


Figure 3.5. Percent enhancement in methane yield achieved in Phases 1 and 2 of batch HS-AD.

Table 3.3. Evolution of pH and concentrations of alkalinity, sCOD, TAN, and VFA in Phase 1.

Digester/Sampling Day		pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L as Acetate)	TAN (mg/L)	sCOD (mg/L)
Phase 1 Bioaugmented Digesters	Initial	7.5	2760	2240 ± 150	340 ± 6	9800 ± 290
	7	7.3	2470	2850 ± 120	370 ± 6	11100 ± 500
	21	7.9	3110	2660 ± 120	441 ± 11	12300 ± 400
	42	8.4	790	2600 ± 190	538 ± 21	9470 ± 230
	63	7.9	1470	2780 ± 220	750 ± 24	4590 ± 280
	Final (106)	8.0	1400	3540 ± 70	725 ± 23	6780 ± 210
Phase 1 Control Digesters	Initial	6.5	960	2330 ± 100	132 ± 12	6820 ± 110
	7	6.3	1290	1450 ± 130	164 ± 2	8270 ± 160
	21	7.5	1150	1360 ± 110	118 ± 7	5060 ± 270
	42	8.0	350	1900 ± 60	129 ± 9	5990 ± 400
	63	7.1	450	2040 ± 210	109 ± 4	3790 ± 60
	Final (106)	6.9	480	1340 ± 10	107 ± 2	2390 ± 40

NOTE: VFA, TAN, and sCOD values are expressed as averages plus or minus standard deviations of samples run in triplicate.

Table 3.4. Phase 2 initial and final pH and concentrations of VFA, TAN, sCOD, and Alkalinity.

Digester/Sampling Day		pH	Alkalinity (mg/L as $CaCO_3$)	VFA (mg/L as Acetate)	TAN (mg/L)	sCOD (mg/L)
Bioaugmented Digesters	Initial	6.9	610	1210 ± 20	215 ± 2	2530 ± 30
	Final (82)	7.7	800	1180 ± 60	370 ± 174	2200 ± 50
Control Digesters	Initial	6.1	180	943 ± 4	53 ± 0	1890 ± 30
	Final (82)	7.4	280	983 ± 123	151 ± 14	1470 ± 60

NOTE: VFA, TAN, and sCOD values are expressed as averages plus or minus standard deviations of samples run in triplicate.

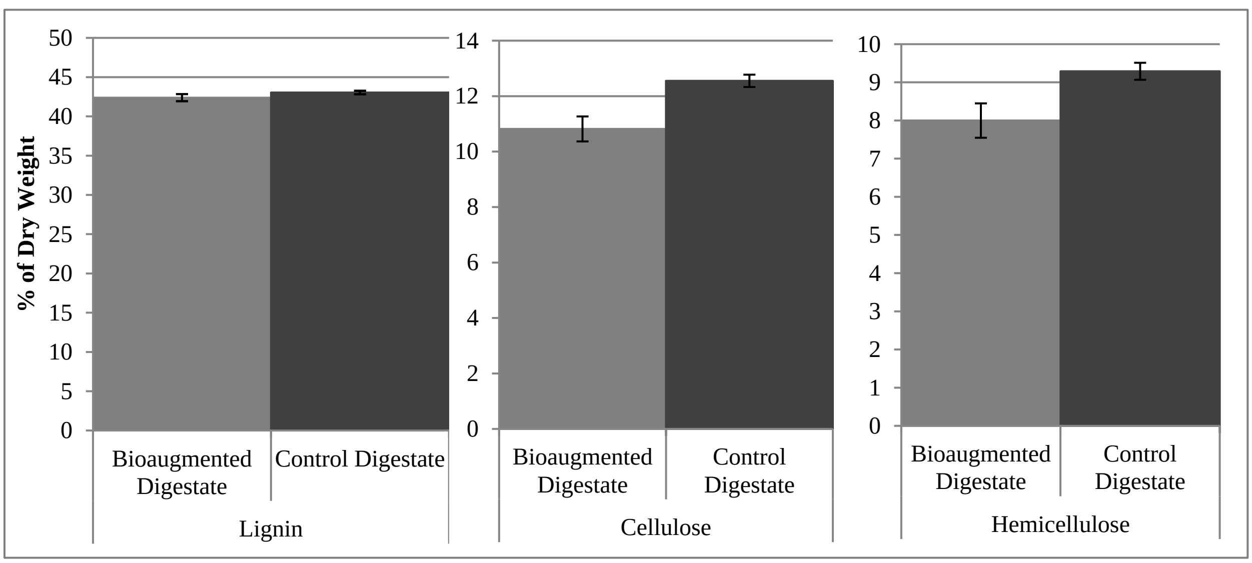


Figure 3.6. Lignin, cellulose, and hemicellulose content in digestate from Phase 1 bioaugmented and control digesters.

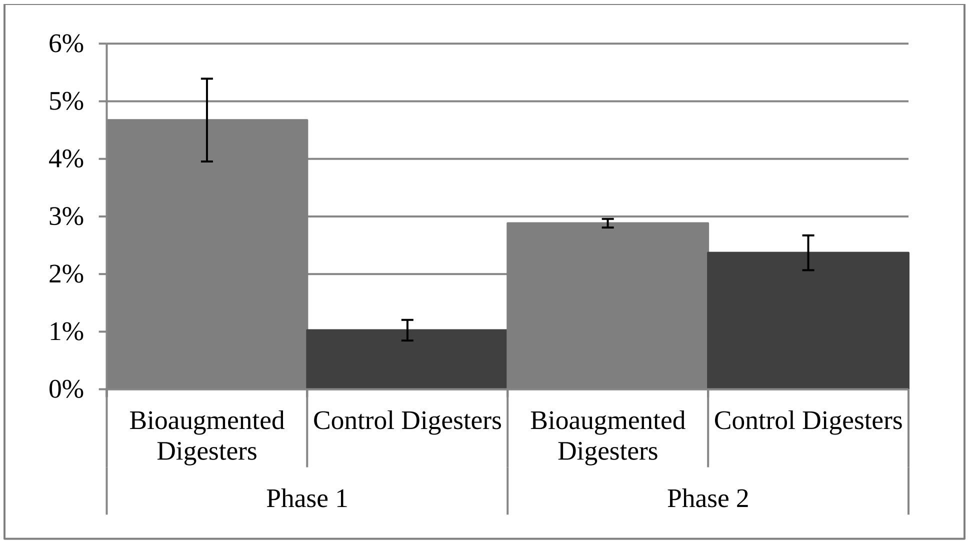


Figure 3.7. Percent total mass destruction in Phases 1 and 2 bioaugmented and control digesters.

3.4 Summary of Major findings

The following is a summary of the major findings of this study:

- A significant enhancement in methane yield from yard waste in HS-AD was achieved via bioaugmentation with P&P sludge as compared with methane yields achieved via inoculation with WW-AD.
- The granular P&P sludge had a higher VS content than the WW-AD sludge. The higher microorganism density likely led to a faster start-up process in the bioaugmented digesters. However, this was expected to have a minimal effect on the cumulative methane yield over the 106-day digestion period.
- The granular P&P sludge had a higher alkalinity than the WW-AD sludge. The lower alkalinity of the WW-AD resulted in a lower buffering capacity and lower pH. This may have inhibited methane yields early in the Phase 1 study (week 1-2), but as trends in pH show, should not have caused inhibition thereafter.
- The trace element concentrations in both the granular P&P sludge and WW-AD meet most minimum concentration requirements and do not exceed most inhibitory concentrations for AD. However, concentrations of certain elements (molybdenum, selenium, cobalt, lead, zinc and calcium) did fall short of or exceed critical concentrations, more so in the control digesters than in the bioaugmented digesters. This may have contributed to the observed differences in methane yields.
- The concentrations of the heavy metals in the Phase 1 digestate were less than both European and US regulatory standards (WRAP, 2010 and Brinton et al., 2000) for safe application of compost/digestate in agriculture.
- Specific methane yields achieved in both Phases of this study fell within ranges reported in the literature for HS-AD of yard waste (Jerger et al., 1982; Owens and Chynoweth, 1993; Brown and Li, 2013; Zhao et al., 2014). Differences in specific methane yields

compared with other studies are attributed to the specific substrate characteristics (e.g. plant species, branches versus leaves, elemental composition, and presence of lignocellulosics).

- No significant differences were observed in the percent enhancement achieved through inoculation with fresh P&P sludge (72.7 ± 7.6%) or digestate (68.5 ± 4.0%), indicating that the enhancement could be sustained by inoculating subsequent batches of yard waste with digestate, as is done in full-scale facilities (Li et al., 2011).
- The substantial decrease in specific methane yields observed in the second phase of batch HS-AD may have been due to the recalcitrance of yard waste samples carried over from the first phase and/or differences in micronutrient concentrations. Raw yard waste samples should be tested for lignocellulosic contents in future studies to enable direct comparison of specific methane yields by correcting according to relative lignin to cellulose/hemicellulose ratios. (Specific methane yields are reported on a per mass of VS added basis, which would lead one to believe that yields between experiments should be directly comparable, but with lignocellulosic wastes that is not the case. Lignin, cellulose, and hemicellulose are all VS, but the cellulose and hemicellulose can significantly contribute to methane yields when dissociated from the lignin, whereas the lignin cannot contribute to methane yields because it is highly recalcitrant in anaerobic systems.)
- The increase in VFA, TAN and sCOD in the first three weeks of bioaugmented digesters indicated that the P&P sludge improved the hydrolysis efficiency of the substrates. The VFA and ammonia concentrations were not inhibitory factors for either set of digesters.
- It is expected that the microbial populations that would dominate in an anaerobic system treating lignocellulosic-rich pulp and paper mill waste would include species that can effectively hydrolyze lignocellulosic compounds. WW-AD sludge is less likely to contain a high density microorganisms capable of hydrolyzing lignocellulosic compounds (Migneault et al., 2011; Zorpas et al., 2011). These observations are consistent with the observed increase in reduction in cellulose and hemicellulose contents in the Phase 1 bioaugmented digesters compared with controls.
- Bioaugmentation with P&P sludge resulted in higher biogas methane content (57 ± 2% in Phase 1 and 59 ± 1% in Phase 2), compared with literature results from bioaugmentation of AD with rumen cultures (Lopes et al., 2004; Hu and Yu, 2005).
- The enhancements achieved in this study (68.5 – 72.7%) were comparable to enhancements reported in various pretreatment studies; however, the minimal impact of this strategy with respect to overall operational costs and environmental impacts make it an attractive alternative to pretreatment.
- Additional research is needed to expand on the findings of this study, including investigating the effects of bioaugmentation with P&P sludge with varying substrates and S/I ratios, further investigation of the mechanisms responsible for the observed methane yield enhancements (microbial communities, alkalinity, and micronutrient concentrations) and research aimed at optimizing the integration of this strategy into full-scale HS-AD systems.

4.0 OBJECTIVE 3: IMPLEMENTATION OF HS-AD IN FLORIDA

4.1 Introduction

HS-AD is particularly applicable to Florida because of the large population, high energy demands, a statewide recycling goal of 75% by 2020, and a current food waste recycling rate of about 7% (FDEP, 2015a). The warm climate may be economically advantageous for AD because high ambient temperatures reduce the amount of heat energy needed to maintain internal operating temperatures (Tchobanoglous et al., 2003). However, collection and storage of putrescible waste in warm climates incur higher costs. The specific objectives of this part of the study were to: (1) Identify locations where HS-AD implementation would be most suitable in Florida based on OFMSW generation and recycling rates and existing MSW infrastructure; (2) Quantify the current economic and environment incentives for HS-AD implementation in Florida and identify key barriers; and (3) Provide policy recommendations and outline possible strategies for improving the economic competitiveness of HS-AD in Florida.

4.2 Methodology

This assessment was conducted using existing information on OFMSW generation, disposal and recycling rates, OFMSW recycling infrastructure, and policies relevant to OFMSW recycling in Florida. Data were obtained from FDEP (FDEP, 2011; 2013; 2015a; 2015b) and other sources (Kessler, 2009; Dieleman, 2015). As FDEP reports generation and recycling rates on a per-county basis, the assessment was carried out on a per county basis. The availability of large quantities of minimally contaminated food and yard waste in close proximity to HS-AD system is one of the most critical factors affecting the economic feasibility of HS-AD (Rapport et al., 2008; Rogoff and Clark, 2014). Therefore, counties with < 100,000 people were not addressed in this assessment. Energy and nutrient recoveries attainable through HS-AD were estimated from values obtained from “grey” and published literature and reported values from industry (Table 4.2). GHG offsets were based on calculated electricity production potential (Table 4.3), approximate GHG offsets achievable per unit electricity produced via HS-AD (SGC, 2012), and documented GHG emissions per unit of electricity generated via the existing electricity grid (EPA, 2013b). Policy recommendations and strategies for improving the competitiveness of HS-AD were derived from “grey” and published literature and industry sources (RIS, 2005; PIS, 2008, Rapport et al., 2008; FIE, 2009; Rogoff and Clark, 2014; CalRecycle, 2014b; EPA, 2015d).

4.3 Results and Discussion

According to the FDEP (2015), 34.4 million tons of MSW were collected in Florida in 2014, nearly 20% of which was OFMSW (2.2 million tons food waste, 3.7 million tons yard waste). Figure 4.1 shows the categorized composition and management of MSW in Florida in 2014. Figure 4.2 displays the counties of Florida, categorized by population and 2013 recycling rates.

In 2008, the Florida Legislature enacted House Bill 7135, establishing a new statewide recycling goal of 75% to be achieved by 2020. As of 2014, statewide food and yard waste recycling rates in Florida were 7% and 51%, respectively (FDEP, 2015a). Considering the current recycling rates and the relative fractions of food and yard waste generated in Florida of 7% and 12% (of total MSW generation), respectively, Florida's statewide recycling rate could be increased by ~ 13% (from 50% to 63%) through OFMSW recycling. FDEP defines recycling as "any process by which solid waste, or materials that would otherwise become solid waste, are collected, separated, or processed and reused or returned to use in the form of raw materials or products" (Florida Statute 403.703). Florida Statute 403.7032 states that "solid waste used for the production of renewable energy" qualifies as recycling. FDEP defines renewable energy as "electrical energy produced from a method that uses one or more of the following fuels or energy sources: hydrogen produced from sources other than fossil fuels, *biomass*, solar energy, geothermal energy, wind energy, ocean energy, and hydroelectric power." Biomass is defined by the FDEP as "a power source that is comprised of, but not limited to, combustible residues or gases from forest products manufacturing, waste, byproducts, or products from agricultural and orchard crops, waste or coproducts from livestock and poultry operations, waste or byproducts from food processing, urban wood waste, municipal solid waste, municipal liquid waste treatment operations, and landfill gas" (Florida Statue 366.91). From these definitions, WTE and LFGTE count as recycling along with conventional recycling (metals, plastics, and glass), composting, AD, and bioenergy generation via advanced thermal treatment. This renewable energy is factored into overall recycling rates, with every MWh of energy generated from waste counting as one ton of waste recycled (or 1.25 tons for counties with high conventional recycling rates) (FDEP, 2015a). Note that the FDEP's definition of recycling conflicts with EPA's, which counts incineration and landfilling as disposal in all cases (EPA, 2015a).

The majority of yard waste recycling in Florida is accomplished through separate collection and management at yard waste processing centers, where the material is shredded and distributed for use as mulch (garden/landscape bedding), process fuel, or alternative daily landfill cover. According to FDEP's Source Separated Organics Processing Facility Database, there are 273 facilities permitted to process yard waste, all but 56 of which are permitted to recycle yard waste (FDEP, 2015b). HS-AD can potentially be paired with this type of yard waste recycling as an initial recycling step for energy recovery (Sawatdeenarunat et al., 2015). All other existing infrastructure for OFMSW recycling (L-AD, compost, bioenergy, WTE, and LFGTE facilities) that could be identified in Florida was mapped using Google Earth (Figure 4.3).

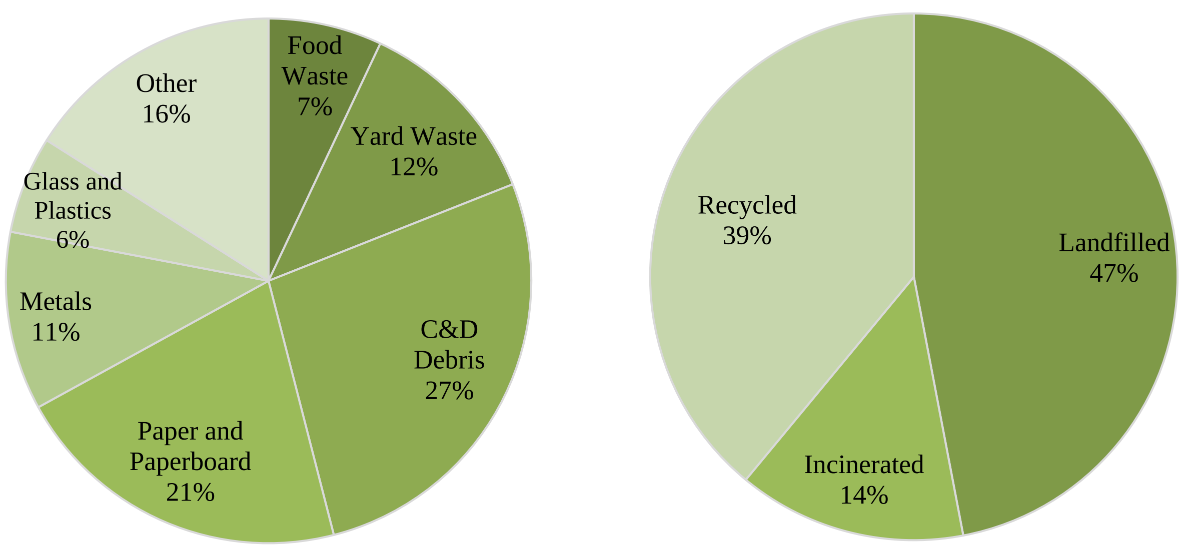


Figure 4.1. 2014 composition and management of MSW in Florida (adapted from FDEP, 2015).

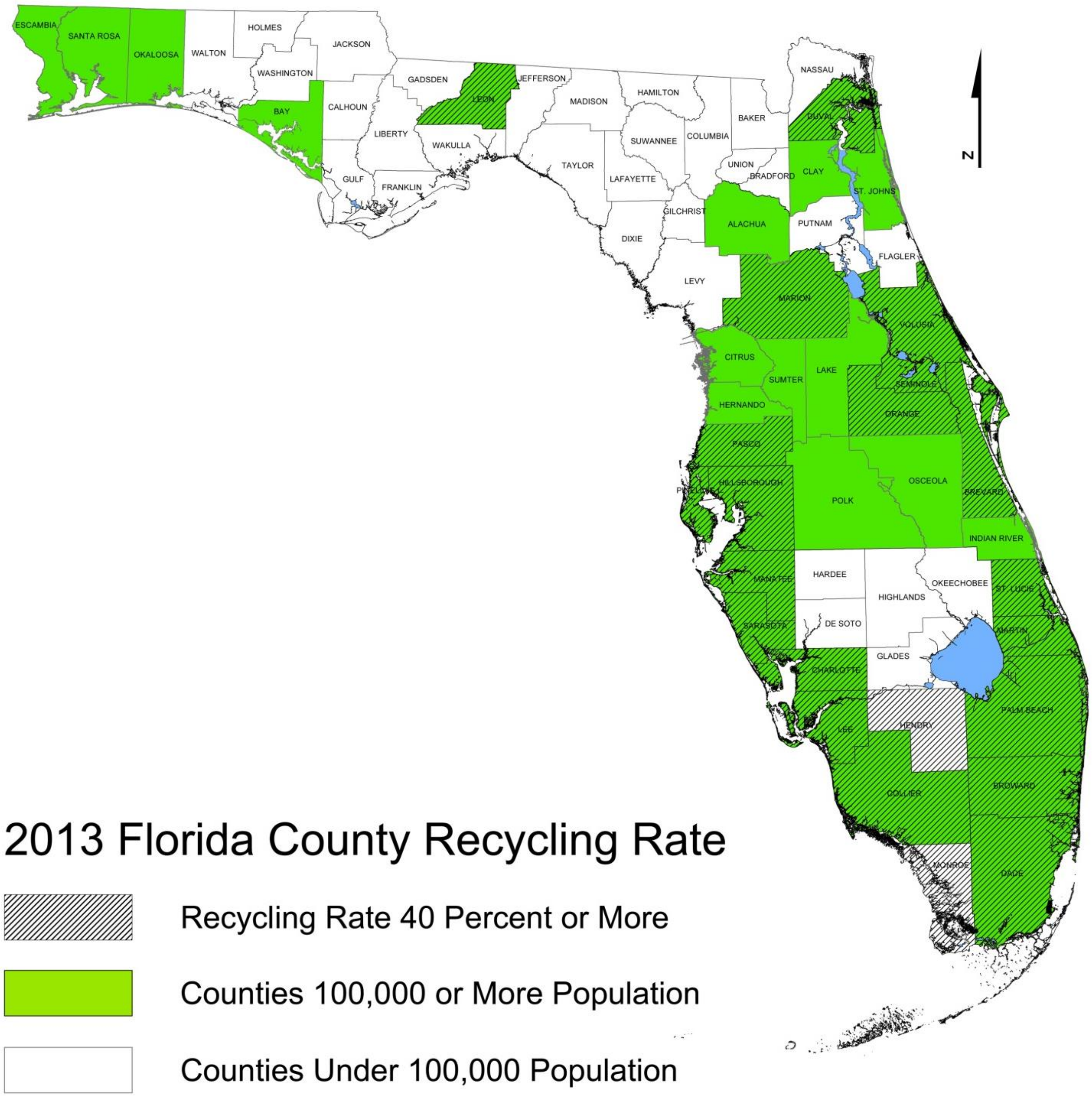


Figure 4.2. Florida counties classified by population and recycling rate as of 2013 (Price, 2015).

Composting is one of the most common technologies for OFMSW recycling in the US (EPA, 2015a). The FDEP encourages local governments to provide public education on composting and develop organics source-separation and composting programs (Florida Statute 403.706). Florida Statute 403.714 states that state agencies are responsible for the development of compost markets and "are *required* to procure compost products when they can be substituted for, and cost no more than, regular soil amendment products." However, composting in Florida has been slow to develop due to a lack of markets for compost products (Kessler, 2009). In 2008, only four permitted composting facilities existed in the state. The only other significant forms of food waste recycling were recovery via a network of collection services, food banks, and soup kitchens and animal feed production from preconsumer food waste (one facility) (Kessler, 2009). However, with the help of the Florida Organics Recycling Center for Excellence (FORCE), the enactment of the 75% recycling goal bill in 2008, and revised regulation allowing for the combined composting of yard and food waste, the number of active permitted composting facilities increased to 24 by 2012, with 10 registered to accept both food and yard waste (Kessler, 2009; Zimms and Ver Eecke, 2012).

Currently, there are 14 active permitted "source-separated organics composting" facilities listed in the FDEP database (FDEP, 2015b). Of these facilities, 13 are permitted to accept yard waste, 12 are permitted to accept "vegetative waste" and 11 are permitted to process "pre-consumer vegetative waste" (FDEP, 2015b), which is defined as source-separated vegetative solid waste from commercial, institutional, industrial or agricultural operations that is not considered yard trash, and has not come in contact with animal products or byproducts or with the end user. The only facility that is not permitted to compost vegetative waste or pre-consumer vegetative waste (My World Nursery) was the only facility that was confirmed to *not* be actively composting. Based on these numbers and this assumption, the total number of permitted composting facilities has decreased since 2012, but the number of facilities processing both food and yard wastes has increased. Several additional facilities that claim to be actively composting were identified through web searches and inquiries with industry professionals, including: George B. Wittmer Associates, Inc. facility (Nassau County), Okeechobee Landfill, JFE-Brighton Regional Composting facility (Brighton Seminole Indian Reservation), and MW Horticulture Recycling (two locations in Lee County) (Wittmer, 2015; WM, 2015; McGill, 2015; MWHR, 2015).

The Reedy Creek Improvement District (RCID) composting facility is the only permitted facility not permitted to accept yard waste. Though initially a yard and food waste composting facility and still permitted as a "source-separated organics composting" facility, RCID is now the state's first and only AD system operated for processing OFMSW. The system, which began operation in 2012, is an L-AD system co-located with the district's wastewater treatment plant (WWTP). This allows for low-cost transfer of biosolids from the WWTP to the L-AD system and centrate (leachate/percolate) from the L-AD system to the WWTP after nitrogen (N) and phosphorous (P) removal (Sorensen, 2014). Although the system is of the L-AD variety, it sets a precedent for AD of OFMSW in Florida. The system has a processing capacity of 130,000 tons per year (TPY), processes source-separated food waste fats, oils, and greases (FOG) from nearby industrial, commercial, and institutional sources and biosolids from the WWTP. The system produces 3.2 MW of electrical energy, 2.2 MW of recoverable heat via a CAT combined heat and power (CHP) engine-generator system, and approximately 6,600 TPY of granular fertilizer product that meets EPA AA standards for a product containing biosolids (Sorensen, 2014). The facility is also listed by the FDEP as a permitted "Bioenergy" facility (FDEP, 2011).

Several other bioenergy projects (wood-fired power and advanced thermal treatment) have been considered in Florida in recent years, with 22 separate permitted projects listed by the FDEP (2011). Of the 22 permitted bioenergy projects, however, only a few have come to fruition: Gainesville Renewable Energy Center (100 MW wood-fired power), INEOS New Plant Bioenergy (hybrid gasification-fermentation 8 million gallons per year [MGY] ethanol production), and Brooksville Central Power and Lime (70 MW wood-fired power). The FDEP (2011) lists four of the 22 permits as cancelled or withdrawn, but web searches reveal that several other projects have been canceled. For example, the Saint Lucie Plasma Gasification project and the Verenium Ethanol project in Highland County were cancelled due to economic challenges (Blandford, 2012; Lane, 2012) and the Adage wood-fired power plant was cancelled due to public opposition (Sheehan et al., 2011). The high capital cost, technical complexity, and lack of well-established economic/cost-benefit data of bioenergy projects relative to alternative technologies such as WTE are key hurdles that must be overcome for further development of advanced thermal treatment projects (EREF, 2013).

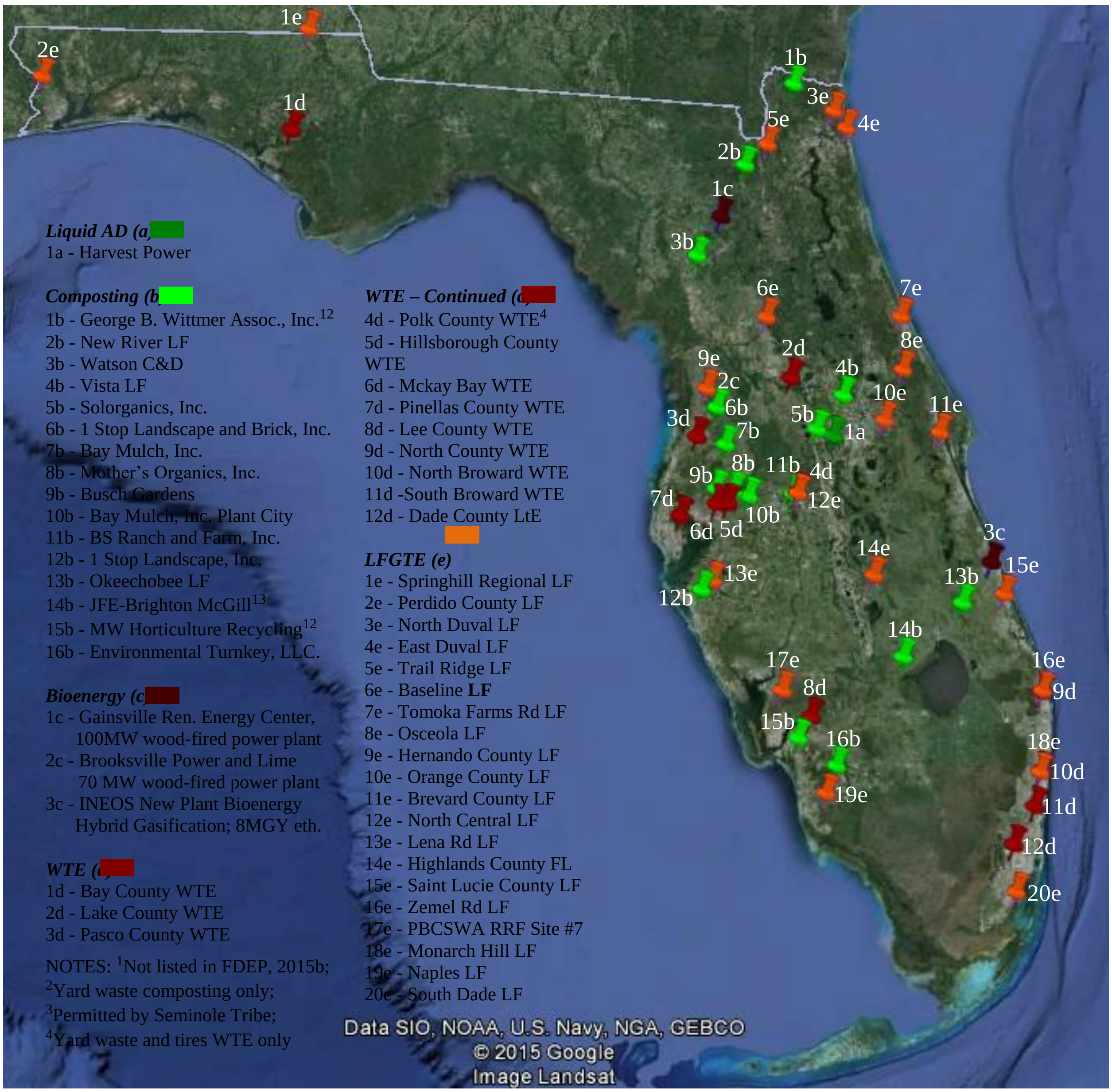


Figure 4.3. OFMSW recycling, WTE and LFGTE facilities in Florida. Note that yard waste processing centers are not shown.

Florida has a longstanding reputation for WTE development, with 12 of the 80 WTE plants in operation in the US (as of 2013) located in the state (FDEP, 2013; Wheelabrator, 2015; EPA, 2015a). The state's 13th WTE facility became operational in 2015 in West Palm Beach – the first

WTE plant to be constructed in the US in more than 20 years (Williams, 2015). Florida is also among leading states in terms of LFGTE, with 20 landfills currently equipped for LFGTE, 18 of which produce electricity and four of which do direct use (two produce electricity and do direct use) (Dieleman, 2015). Another three landfills have plans to implement LFGTE systems (Central County LF, North Dade LF, and Saint Cloud City LF) and another 13 are considered as candidate landfills for future LFGTE projects (Dieleman, 2015). As previously mentioned, this form of "recycling" does not fall within traditional definitions, and by many accounts, reduces incentives for waste reduction and traditional recycling. More research is needed to understand the compatibility of HS-AD with existing Florida MSW infrastructure.

Based on the potential for bioenergy production, GHG emissions reductions and nutrient recovery, nine counties were identified as most suitable for HS-AD implementation in this study. Miami-Dade, Broward, Palm Beach, Hillsborough, Orange, Pinellas, Duval, and Lee are the top eight most populated counties in Florida and consistently rank in the top nine with respect to OFMSW generation (total amount) and disposal (unrecycled amount), as shown in Table 4.1. Alachua County, the home county of the University of Florida and the 23rd most populated county in the state, ranks 10th in terms of OFMSW generation and 7th in terms of unrecycled OFMSW. Of these counties, all had reached 40% overall recycling rates by 2013 except Alachua (Table 4.1) and each has a mix of OFMSW recycling infrastructure, but none have significant capacity for recycling food waste. Each county, except Hillsborough and Pinellas, has at least one landfill with LFGTE and each, except Alachua, Orange, and Duval, have at least one WTE facility. However, only two of these counties have an existing bioenergy plant (Alachua and Orange) and few have composting facilities (Alachua, Orange, Hillsborough, and Lee).

A number of suitable locations were identified for full-scale HS-AD demonstration projects. For example, the University of South Florida generates large quantities of OFMSW and is surrounded by industrial, commercial, and institutional sources of additional OFMSW (several hospitals, grocery stores, and elementary schools), the majority of which is transported and processed at the Hillsborough County Resource Recovery Facility (WTE with separate yard waste processing). This could serve as a centralized site for an educational demonstration facility. HS-AD could also be synergistically paired with existing MSW management infrastructure, including material recovery facilities, landfills with LFGTE, composting facilities, and most bioenergy facilities. HS-AD can be paired with composting operations to enable energy recovery, reduce waste volume, and increase total facility throughput/capacity (De Baere and Mattheeuws, 2014; Kraemer and Gamble, 2014), as is common in the Netherlands and Belgium (De Baere and Mattheeuws, 2014). Specific candidate composting operations could include the Okeechobee Landfill site, which has the capacity to process 30,000 TPY of source-separated OFMSW, and the Vista Landfill site in Orlando County, which is permitted to process 45,000 TPY of OFSMW and was processing approximately 22,000 TPY as of 2012 (Zimms and Ver Eecke, 2012).

Landfills equipped with LFGTE are also suitable for an HS-AD demonstration project. The advantage of this strategy is that biogas from HS-AD systems at landfill sites can be tied into existing LFGTE infrastructure to reduce the capital costs, improve energy recovery efficiency at landfills, simplify collection schemes for HS-AD, reduce waste volume, and utilize existing leachate system infrastructure for the disposal of digestate (in cases where feedstocks are mixed MSW or mechanically-separated OFMSW) (Rapport et al., 2008; Zaman, 2009; Li et al., 2011).

There are at least three existing HS-AD systems in California, for example, that are located at or adjacent to landfills (Monterey, San Jose, and Davis). The development of bioenergy facilities is somewhat in competition with HS-AD, because both technologies partly depend on yard waste as a feedstock. However, as outlined by Sawatdeenarunat et al. (2015) and Pan et al. (2015), AD yard waste can still be used as a feedstock for bioconversion (thermal and/or chemical).

Table 4.1. Yard waste and food waste generation and recycling in 2014 in Florida counties with populations greater than 100,000, ranked in descending order by population (FDEP, 2015a).

County	Yard Waste			Food Waste			Potential Feedstock			
	Generated	Recycled	Recycling Rate	Generated	Recycled	Recycling Rate	Total		Unrecycled	
							Amount	Rank	Amount	Rank
Miami-Dade	517	363	70%	178	0	0%	695	1	332	2
Broward	190	29	15%	193	5.9	3%	383	4	348	1
Palm Beach	208	48	23%	120	0.7	1%	328	7	279	4
Hillsborough	187	118	63%	117	4.4	4%	304	8	182	8
Orange	103	68	66%	324	75	23%	427	2	284	3
Pinellas	248	165	67%	159	3.6	2%	407	3	238	6
Duval	271	104	38%	99	1.2	1%	370	5	265	5
Lee	158	104	66%	121	0.7	1%	279	9	174	9
Polk	62	42	68%	74	2.6	4%	136	15	91	13
Brevard	322	283	88%	40	0.9	2%	362	6	78	14
Volusia	68	46	68%	83	2.0	2%	151	13	103	12
Pasco	46	19	41%	38	0.9	2%	84	19	64	17
Seminole	73	45	62%	41	1.6	4%	114	17	67	16
Sarasota	77	65	84%	41	4.1	10%	118	16	49	22
Manatee	103	29	28%	44	0	0%	147	14	118	10
Marion	48	23	48%	21	0.9	4%	69	22	45	23
Collier	128	127	99%	42	1.2	3%	170	11	42	24
Lake	33	1	3%	19	0.3	2%	52	25	51	21
Escambia	41	10	24%	24	0	0%	65	23	55	19
Osceola	18	0	0%	16	0	0%	34	29	34	26
St. Lucie	20	3	15%	12	0.6	5%	32	31	28	27
Leon	46	15	33%	27	2.3	9%	73	20	56	18
Alachua	198	19	10%	24	0.3	1%	222	10	203	7
St. Johns	54	16	30%	17	0.1	1%	71	21	55	20
Clay	24	24	100%	20	0.3	2%	44	28	20	31
Okaloosa	29	18	62%	16	0.5	3%	45	27	27	28
Hernando	26	11	42%	6.5	0.6	9%	33	30	21	30
Bay	24	5	21%	23	0.6	3%	47	26	41	25
Charlotte	40	35	88%	17	0.7	4%	57	24	21	29
Santa Rosa	15	4	27%	6.8	0.3	4%	22	32	18	32
Martin	107	4	4%	48	42	88%	155	12	109	11
Indian River	84	25	30%	19	0.7	4%	103	18	77	15
Citrus	11	10	91%	11	0.6	5%	22	32	11	34
Sumter	9	0	0%	6.7	0.4	6%	16	34	15	33

Note: Values are expressed in thousands of tons per year (excluding percentages and ranks); "Unrecycled" values were calculated by subtracting amount recycled from amount generated; WTE and LFGTE recycling credits are *not* included in these numbers, so the "Unrecycled" quantities are representative of the amount disposed via incineration and landfilling

Environmental incentives for nutrient and energy recovery, GHG offsets, and associated economic incentives, were estimated using 2014 statewide food and yard waste generation rates of 2.2 million tons and 3.7 million tons, respectively (FDEP, 2015a; Table 4.2). Total energy recoverable from food and yard waste is > 500 MW (4,000 GWh/year; Table 4.3). If the CH_4 generated were used in combined heat and power (CHP) units, this translates to an annual electricity generation potential of ~ 175 MW (1,500 GWh/year), with a portion of the remaining energy (~ 40%) being recoverable heat for maintaining internal temperatures of HS-AD systems. Alternatively, if CH_4 were converted to compressed natural gas (CNG), ~ 80 million diesel gallon equivalents (DGE) of CNG could be produced. To put this in context, Florida currently generates a total of 246,000 GWh/year of electricity, 5,000 GWh/year of which is renewable (EIA, 2015a), and consumes 688 million DGE of CNG per year as vehicle fuel (EIA, 2015b). Thus, either ~0.6% of Florida's electricity demand could be fulfilled, increasing statewide renewable electricity generation by ~ 30%, or ~ 11.5% of CNG vehicle fuel demand could be fulfilled (Table 4.3). Assuming the recovered energy would be used to produce electricity and 20% parasitic energy demand, excess electricity (1,200 GWh/year) could generate > $120M in revenue annually (at $0.10/kWh) not including GHG offsets or nutrient recovery. However, reported electricity revenues are quite variable. At the time of writing this report, Palm Beach County reported 0.048/kWh and Miami-Dade County reported $0.10-0.12/kWh (Schert, J. personal communication).

Table 4.2. Assumed values for quantifying the environmental and economic incentive for implementation of HS-AD for OFMSW recycling in Florida.

Parameter(s)	Assumed Value(s)	Reference(s)
VS Content	Food Waste = 15% by wet weight Yard Waste = 60% by wet weight	Kothari et al., 2014
Average Biogas Yield	Food Waste = 0.5 m^3/kg VS Yard Waste = 0.3 m^3/kg VS	Kothari et al., 2014
Biogas Quality	60% CH_4	Kothari et al., 2014
Energy Equivalence of CH_4 and Diesel Fuel	9.7 kWh/m^3 CH_4 9.8 kWh/L Diesel	SGC, 2012
Combined Heat and Power Conversion Efficiency	35% to electricity ~40% to heat	SGC, 2012
CNG Conversion Efficiency	67%	ZWE, 2013b
GHG Offsets from Substituting Fossil Fuel	100% - 120%	SGC, 2012
Value of Carbon Credits	Voluntary Market Rate = $4.90/MTCO$_2$E Total Value (including ecological offsets) = $664/MTCO$_2$E	ICROA, 2014
Mass Destruction in HS-AD	40%	BIOFerm, 2014a
Bioavailable Nutrient Content of HS-AD Digestate	N = 1% by dry weight P = 0.5% by dry weight	Hartz, 2009
Agricultural Value of Nutrients	N = $0.26/kg N P = $0.14/kg P	WERF, 2011

Table: 4.3. Approximate energy recovery potential through HS-AD of OFMSW in Florida.

	Yard Waste	Food Waste	Total
Assumed Generation Rate (short tons/year) =	3,700,000	2,200,000	5,900,000
Assumed Volatile Solids Fraction (% by wet weight) =	0.60	0.15	
Assumed Biogas Generation (m^3/kg VS) =	0.30	0.50	
Total Energy Content (GWh/year) =	3,520	870	4,390
Total Electricity Generation Potential (GWh/year) =	1,230	300	1,530
Total Electricity Generation in Florida (GWh/year) =			246,200
Fraction of Florida Electricity Demand Fulfilled =	0.5%	0.1%	0.6%
CNG Generation (DGE/year) =	63,400,000	15,700,000	79,100,000
Total CNG Consumption in Florida (DGE/year) =			688,000,000
Fraction of Florida CNG Demand Fulfilled =	9.2%	2.3%	11.5%

Note: Assumes 9.7 kWh-m^{-3} CH_4, 9.8 kWh-L^{-1}diesel, 35% electrical conversion efficiency, and 67% CNG conversion efficiency; mass conversion factor = 907 kg per short ton

According to the US EPA (EPA, 2013b), Florida's electricity-based GHG emissions in 2013 accumulated to 103.4 million metric tons of carbon dioxide equivalents, which translates to approximately 430 metric tons per GWh of electricity produced. Applying an assumed 100% reduction in GHG emissions resulting from substituting energy from the existing energy grid with biogas-derived energy (SGC, 2012) to the estimated electricity production potential through HS-AD of OFSMW of 1,535 GWh/year, an estimated GHG offset potential of 660,000 metric TPY of CO_2 equivalents ($MTCO_2E$/year) could be obtained. If these offsets were sold as carbon credits in the voluntary market, an additional $3.2M worth of annual revenue could be generated (at 4.90MTCO_2$/year, based on globalcarbonproject.org database). When taking into account the economic value of the ecological benefits associated with GHG offsets, the value increases to over $400M per year (at 664MTCO_2$/year). Assuming 40% mass reduction in the HS-AD process, approximately 3.5 million TPY of soil amendment could be generated, equating to at least 7,000 TPY and 3,500 TPY of recoverable N and P (Table 4.4), respectively. Based on a value of bioavailable N and P contents in compost of 1.0% and 0.5%, respectively), or $2.1M per year worth of fertilizer offsets (at $0.26/kg N and $0.14/kg P). Note that fertilizer value calculations were based on data from the UC Davis Solution Center for Nutrient Management (http://ucanr.edu/sites/Nutrient_Management_Solutions). In addition, because capital costs are not included in these estimates, they can be scaled up or down by inputting alternative annual food waste and yard waste processing values (contact PI Ergas sergas@usf.edu for spreadsheets).

Table 4.4. Nitrogen and phosphorous recovery potential through HS-AD of OFMSW in Florida.

	Nitrogen	Phosphorous
Assumed Digestate Generation Rate (short tons/year) =	3,540,000	3,540,000
Assumed Total Solids Content (%) =	20%	20%
Assumed Available Fraction (%) =	1.0%	0.5%
Nutrient Recovery Potential (short tons/year) =	7,080	3,540

Note: Assumes 40% mass reduction in HS-AD; mass conversion factor = 907 kg per short ton

With regard to potential project funding sources, the INEOS bioenergy plant in Indian River County (Figure 4.3) was partially funded by the US Department of Energy, as was the HS-AD system that began operation in 2012 at the University of Wisconsin Oshkosh. US EPA and the USDA have existing and forthcoming programs for funding biogas projects (USDA/EPA/DOE, 2014). Florida based grant programs also exist for MSW management, recycling, and renewable energy projects. For example, the FDEP has an Innovative Recycling/Waste Reduction Grant

Program, a Florida Recycling Loan Program, and a Small County Consolidated Solid Waste Grant Program, and the Florida Department of Agriculture and Consumer Services offers funding through their Research and Development Bioenergy Grant Program. Other potential funding sources include private industry, as demonstrated in other US HS-AD projects. The partnerships developed for the Harvest Power L-AD facility (between the owner, the technology vendor, and the utility company – who agreed to purchase the energy generated by the facility) is an example of a partnership for economically sustainable AD of OFMSW (Rapport et al., 2008).

SCS Engineers conducted an economic analysis for the purpose of estimating tipping fees required to ensure economically sustainable HS-AD operation (Rogoff and Clark, 2014). The analysis included total capital costs (including design, permitting, materials, equipment, and construction), operations and maintenance, inflation and financing. Because of the low market value of compost in Florida, revenue from compost and GHG offsets were neglected, and break-even tipping fees were calculated for four different scenarios (Table 4.5). The results showed that HS-AD becomes economically competitive with increases in processing capacity and that energy sales are a critical factor. The authors mention that when incorporating revenues from GHG offsets (e.g. carbon credits or renewable energy certificates [RECs]), HS-AD projects could reliably yield short pay-back periods and provide returns on investments for developers. The authors further concluded that several factors would have to converge for HS-AD to be economically feasible in Florida, including: high quantities of quality feedstock, high power costs, utility economic incentives, markets for compost, markets for carbon credits and/or RECs, and bans on organics disposal in landfills. This conclusion parallels those drawn in multiple economic analyses of this kind (RIS, 2005; PIS, 2008, Rapport et al., 2008; FIE, 2009; RWI, 2013; Rogoff and Clark, 2014).

To provide context to the results shown in Table 4.5, the World Bank (2012) reports that the costs of landfilling, incineration, composting, and AD in high income countries per ton of waste processed range from $40-100, $70-200, $35-90, and $65-150, respectively. Landfilling is the lowest cost management option, composting is sometimes comparable, and all other options are significantly more expensive. In the US, average nationwide landfill tipping fees in 2013 were $49.78 per ton, down slightly from $49.99 per ton in 2012 (EPA, 2015a). In Florida in 2013, the average landfill tipping fee was $43.65 and the lowest rate in the state was $25.50 (CEP, 2014).

Table 4.5. Break-even tipping fees for HS-AD project scenarios (Rogoff and Clark, 2014).

Scenario	Plant Capacity	Electricity Production	Tipping Fee Required
1	5,000 TPY	None	$45.92 - $53.16
2	5,000 TPY	203 kWh/ton @ $0.1044/kWh	$8.76 - $31.97
3	10,000 TPY	None	$40.73 - $48.53
4	10,000 TPY	203 kWh/ton @ $0.1044/kWh	$3.57 - $27.34

Improvements in HS-AD technology have the potential to improve the economic outlook for HS-AD. Certain HS-AD technologies have been shown to have lower parasitic energy demands (see Section 2.3.3.) and certain technologies have been shown to generate higher biogas yields. Co-digestion of food and yard waste at certain ratios, have been shown to improve environmental conditions (e.g. C/N ratio and feedstock porosity) and enhance system performance. Other co-digestion strategies, such as incorporation of biosolids as a co-substrate, can provide enhanced revenue in the form of increased tipping fees. Biosolids management in Florida is an increasingly expensive endeavor with relatively limited capacity for L-AD of biosolids, land application regulations becoming increasingly stringent, and the costs of biosolids disposal in landfills being very high (Forbes Jr., 2011). Phase II of this research will specifically investigate the potential for incorporating biosolids with yard and food waste in HS-AD systems, including life cycle environmental impacts and costs. Pretreatment or bioaugmentation strategies can effectively improve the biodegradability of lignocellulosic wastes (e.g. yard waste and agriculture plant residues), providing significant enhancement in energy recovery (see Chapter 3).

Market-related factors that could improve the economics of HS-AD include markets for compost and carbon credits and/or RECs and energy markets (energy costs and demand for renewables). Increases in energy costs would have positive effects on the economics of HS-AD and have negative effects on the economics of energy consuming management technologies (composting and landfill without LFGTE), resulting in improved competitiveness of HS-AD. Energy costs and demand for renewables are influenced by policy, as are compost and carbon credit/REC markets. Policy has the potential to influence numerous key factors such as demand for alternative OFMSW management infrastructure (i.e. landfill bans) and quality of feedstock for HS-AD (i.e. source-separation). However, more research is needed on the sustainability of source separation of putrescible waste in Florida due to the warm climate. Policies that have resulted in improved OFMSW management in other regions are as follows:

- Landfill bans on OFMSW (yard and food waste) including those with LFGTE. Diverting OFMSW has resulted in reduced fugitive methane emissions and reduced landfill leachate generation. As described by Yasar and Celik (2016). According to the EPA, "the promotion of LFG energy is not in conflict with the promotion of organic waste diversion" (EPA, 2015d).
- Mandates on source-separation of OFMSW by appropriate sources (residential, commercial, industrial, institutional). According to a study of a full-scale facility in Italy (Bolzonella et al., 2006b), energy recovery efficiency increased by a factor of three by processing source-separated OFMSW over systems processing mechanically-separated OFMSW.
- Pay-as-you-throw policies, recycling programs, and other progressive MSW management programs that increase incentives for waste reduction and recycling and facilitate the transformation of the existing disposal-based MSW framework to a recovery-based system. California's Extended Producer Responsibility policy, for example, makes "producers" responsible for end-of-life product disposal costs (CalRecycle, 2014b).
- Policies that create incentives for recycling both nutrients and energy from OFMSW (AD) as opposed to recycling only energy (LFGTE, WTE, advanced thermal treatment) or only nutrients (composting). In other words, policies that account for environmental impacts and offsets of various recycling methods, such that there is an incentive to recycle paper, plastic, and glass via conventional recovery methods rather than incinerating the material. WTE and landfilling with LFGTE should not be counted as recycling.
- Establishment of Renewable Portfolio Standards that enhance incentives for renewable energy generation and growth of REC markets. A majority of states (29) now have Renewable Portfolio Standards and another eight have voluntary targets (NREL, 2014). RECs, Renewable Identification Numbers (RINs), and carbon credits play significant roles in the economics of renewable energy generation, including through HS-AD.

4.4 Summary of Major Findings

The objective of this study was to evaluate the potential for HS-AD implementation in Florida. There is a great opportunity for the implementation of OFMSW recycling infrastructure in the state. Based on current recycling rates of food and yard waste of 7% and 51%, respectively, and the relative fractions (of total MSW generated) of food waste and yard waste of 7% and 12%, respectively, Florida's statewide recycling rate could be increased by nearly 13% (from 50% to 63%). Note that these rough estimates were developed based on an unrealistic assumption that 100% OFMSW recycling rates could be achieved. Additional cost life cycle cost assessments will be performed in Phase II of this research. Each of the eight most populated counties in the state – Miami-Dade, Broward, Palm Beach, Hillsborough, Orange, Pinellas, Duval, and Lee – consistently rank in the top nine counties in the state with respect to OFMSW disposal/availability for use as feedstock in HS-AD. A ninth county that was identified as particularly promising for HS-AD implementation was Alachua County, the home county of the University of Florida and the 23rd most populated county in the state. More research is needed to understand the compatibility of HS-AD with existing MSW infrastructure, particularly WTE.

A rough estimate of environmental and economic incentives for implementing HS-AD for OFMSW management in the state were estimated, again assuming 100% of OFMSW were to be processed via HS-AD (although this could be adjusted for any scale/processing capacity). Based on 2014 food waste and yard waste generation, approximately 500 MW (4,000 GWh/year) of energy could be recovered from OFMSW via HS-AD, equating to approximately 175 MW (1,500 GWh/year) of electricity (~ 0.6% of Florida's electricity demand) and 325 MW of usable heat energy if the methane were to be used in CHP units, or equating to nearly 80 million DGEs of CNG (~ 11.5% of Florida's CNG vehicle fuel demand) if the methane were to be converted to CNG. Additionally, more than 7,000 tons of nitrogen and 3,500 tons of phosphorous could be recovered annually and at least 660,000 metric tons of GHG emissions (as carbon dioxide equivalents) could be offset.

A number of policy changes should be considered for the potential benefits associated with HS-AD implementation to be realized. As seen in Europe and California, banning organics disposal in landfills, mandating source-separation of OFMSW by all generation sources, and creating incentives for renewable energy generation are the policy actions that have had the greatest influence on the rate of development of HS-AD capacity for OFMSW recycling. Other recommendations include the development of "Pay as You Throw" programs, recycling programs, Extended Producer Responsibility policies, and other policies for incentivizing waste reduction and recycling and creating economic value for the environmental benefits of various recycling options. A final recommendation is to establish a Florida Renewable Portfolio Standard to enhance incentives for renewable energy generation and growth of REC markets. A number of grant and loan programs were identified for project funding, public-private partnerships are becoming the norm in the recycling industry, and waste management frameworks are steadily transforming to recovery-based as opposed to the traditional disposal-based systems.

Additional research that should be carried out includes comprehensive LCA studies to identify optimal integrated recycling approaches for specific waste streams in specific contexts, studies to develop/identify effective strategies for facilitating source separation and optimizing organics collection for warm climates, and research on optimizing HS-AD system design and co-digestion strategies.

5.0 CONCLUSIONS

HS-AD is a promising technology for OFMSW because of the many environmental and economic advantages it offers. HS-AD efficiently recovers energy from OFMSW and is easily paired with composting to enable the recovery of nutrients. In the process, GHG emissions that would result from uncontrolled or partially controlled degradation of OFMSW are avoided. GHG emissions are also offset by the substitution of fossil-fuel derived energy with biomethane, which can be used for heating, electricity generation, and/or vehicle fuel. By reducing the nutrient strength of landfill leachate, diversion of OFMSW from landfills to HS-AD facilities reduces eutrophication impacts on the environment or additional energy and chemical inputs needed for removing N and P from leachate streams at wastewater treatment facilities. The recovery and use of nutrients as fertilizer also reduces the impacts of inorganic fertilizer production on the nitrogen cycle (Haber-Bosch process) and depletion of mineral P reservoirs. However, trends in the development of HS-AD in Europe and discussions with practitioners involved with successful HS-AD projects in the US revealed that the optimization of HS-AD technologies, expansion of regulatory drivers, and development of public-private partnerships are necessary for accelerating the transition.

For this research, published and grey literature were reviewed, HS-AD facilities in California and the Netherlands were toured, interviews were conducted with MSW management professionals, and laboratory experiments were carried out. The specific objectives were to: (1) evaluate the most appropriate technologies for implementing HS-AD of OFMSW in Florida, (2) carry out fundamental research at bench- and pilot-scale to improve the biodegradability of lignocellulosic waste through co-digestion with P&P, and (3) identify potential sites, collaborators, and funding sources for a large-scale HS-AD demonstration project in Florida.

State-of-the-art of HS-AD (Section 2): The types of HS-AD technologies available, US vendors and trends in HS-AD implementation in Europe and the US were identified. AD of OFMSW in Europe, especially HS-AD, is a mature technology. As of 2014, there were 244 full-scale AD facilities treating OFMSW in Europe, with a total capacity of approximately 8 million tons per year (TPY); 89% of capacity was "stand-alone" (systems treating *only* OFMSW), 62% was HS-AD, and 70% installed since 2009 was HS-AD. Approximately 55% of capacity in Europe treats source-separated substrates as opposed to mixed or mechanically-separated substrates, because it has been shown to improve energy and nutrient recovery efficiency in HS-AD systems.

Trends in HS-AD of OFMSW in the US have paralleled those in the EU. There are currently 181 AD facilities treating OFMSW, with a total capacity of approximately 780,000 TPY, 52% of capacity is stand-alone (25 facilities), and 24% is HS-AD (8 facilities), with the remainder being stand-alone L-AD or L-AD co-digestion at wastewater treatment plants or on-farm systems. However, the number of US HS-AD facilities is growing, from one in 2011 to eight in 2015. It is projected that HS-AD will be the dominant form of AD of OFMSW by 2017, with at least another 19 full-scale HS-AD systems expected to come online. In general, batch, thermophilic, single-stage systems are the dominant HS-AD system types being developed in the US. However, continuous and multi-stage systems are also available. There are at least nine vendors of HS-AD technologies in the US, four of which have facilities in operation and another four have projects in the planning, permitting, or construction phases. No single technology vendor has emerged as dominant in the industry at this time. HS-AD is economically competitive with composting or alternative conversion technologies, such as WTE and advanced thermal treatment. However, it is unlikely that AD can compete with the low cost of landfilling without significant legislative and policy changes. The primary factors that govern the economic sustainability of HS-AD projects are local waste disposal tipping fees, the quality and quantity of available feedstock, the cost of feedstock collection and storage, local markets for energy and compost, and legislative incentives with regard to renewable energy generation (e.g. RPS) and alternative OFMSW management (e.g. landfill bans and source-separation requirements/incentives). A final critical factor affecting the feasibility of HS-AD is development of public-private partnerships.

Enhancing Bioenergy Production (Section 3): A significant enhancement in methane yield from yard waste in HS-AD was achieved via bioaugmentation with P&P sludge as compared to methane yields achieved with a conventional inoculum. Trends in chemical data support the hypothesis that the observed enhancement was a result of the hydrolytic communities in the P&P sludge possessing a superior ability to hydrolyze lignocellulosics. The observed enhancement in methane yield was also sustained in a subsequent phase of batch HS-AD via inoculation with digestate from the first phase of digestion, suggesting that this method may have potential to yield prolonged benefits with respect to process efficiency and net energy recovery. The enhancements achieved in this study (68-73%) are comparable to enhancements reported in various pretreatment studies. The minimal impact of this strategy with respect to overall operational costs and environmental impacts make it an attractive alternative to pretreatment. In addition to the bioaugmentation studies, a number of preliminary co-digestion studies were performed. These studies showed that addition of biosolids to HS-AD had the potential to increase biogas production and improve system revenues. The addition of oyster shells to HS-AD has the potential to improve process stability and performance.

HS-AD implementation in Florida (Section 4): In Florida, there is a lack of organics recycling infrastructure. Based on the analysis carried out in this report, the statewide recycling rate could be increased by as much as 13% through HS-AD implementation. Nutrient recovery could reach 7,000 and 3,500 TPY of bioavailable N and P, respectively. Approximately 500 MW of energy could be generated from this waste stream, which translates to either 175 MW of electricity (approximately 660,000 metric tons of CO_2 equivalents per year) and 325 MW of heat, or to nearly 80 million diesel gallon equivalents of compressed natural gas. Based on the criteria of potential for bioenergy production, GHG emissions reductions and nutrient recovery, Miami-Dade, Broward, Palm Beach, Hillsborough, Orange, Pinellas, Duval, Lee, and Alachua counties are the most feasible counties for HS-AD implementation. However, more research is needed to understand the compatibility of HS-AD with existing MSW infrastructure, particularly WTE. Initial demonstration projects should be located at universities and/or existing composting and landfill sites. However, the low costs of energy and landfilling in Florida, lack of legislation incentivizing organics recycling, and lack of markets for compost and RECs make the economics of HS-AD particularly challenging. In addition, more research is needed on the sustainability of source separation of putrescible waste in warm climates, such as Florida. Policies that have the potential to promote the transition from the current disposal-based waste management paradigm toward a recovery-based paradigm include bans on landfilling organics, source-separation mandates, pay-as-you-throw policies, and extended producer responsibility policies.

BIBLIOGRAPHY

Adekunle, K.F., Okolie, J.A. 2015. A Review of Biochemical Process of Anaerobic Digestion. Advances in Bioscience and Biotechnology, 6, 205-212.

Agarwal, S.K. 2005. Advanced Environmental Biotechnology A.P.H, Publishing Corporation New-Delhi. pp: 46, 58.

Aikan (Aikan North America, Inc.). 2015. Batch Processing. How it Works. http://www.aikantechnology.com/how-it-works/batch-processing.html.

Amani, T., Nosrati, M., Sreekrishnan, T.R. 2010. Anaerobic digestion from the viewpoint of microbiological, chemical, and operational aspects - a review. Environmental Reviews, 18, 255-278. doi: 10.1139/A10-011.

Amirta R., Tanabe T., Watanabe T., Honda Y., Kuwahara M., Watanabe T. 2006. Methane fermentation of Japanese cedar wood pretreated with a white rot fungus, Ceriporiopsis subvermispora. J Biotechnol;123:71e7.

Angelidaki, I., Ahring, B.K. 2000. Methods for increasing the biogas potential from the recalcitrant organic matter contained in manure. Water Sci. Technol. 41.3, 189e194.

Angelidaki, I., Alves, M., Bolzonella, D., Borzacconi, L., Campos, J.L., Guwy, A.J., Kalyuzhnyi, S., Jenicek, P., van Lier, J.B. 2009. Defining the biomethane potential (BMP) of solid organic wastes and energy crops: a proposed protocol for batch assays. Water Sci. Technol. 59 (5), 927–934.

Ansari, A.A., Gill S.S. 2014. Eutrophication: Causes, Consequences and Control. Volume 2. Springer Science, Business Media Dordrecht. doi:10.1007/978-94-007-7814-6_5.

Antonopoulou G., Stamatelatou K., Lyberatos G. 2010. Exploitation of rapeseed and sunflower residues for methane generation through anaerobic digestion: the effect of pretreatment. Chem Eng Trans;20:253e8.

APHA (American Public Health Association). 2012. Standard Methods for the Examination of Water and Wastewater 20th ed. American Public Health Association/American Water Works Association/Water Environment Federation, Washington DC.

Ares, E. 2012. The Renewables Obligation. The Renewables Obligation. House of Commons Library, Science and Environment Section SN/SC/5870. http://researchbriefings.parliament.uk/ResearchBriefing/Summary/SN0 5870.

Astrup, T.F., Tonini, D., Turconi, R., Boldrin, A. 2014. Life cycle assessment of thermal Waste-to-Energy technologies: Review and recommendations. Waste Management, 37, 104-15, doi: 10.1016/j.wasman.20 14.06.011.

Bagi, Z., Acs, N., Balint, B., Horvath, L., Dobo, K., Perei, K.R., Rakhely, G., Kovas, K.L. 2007. Biological intensification of biogas production. Appl. Microbiol. Biotechnol. 76, 473e482.

Bai Y., Li W., Chen C., Liao P. 2010. Biological pretreatment of cotton stalks and domestication of inocula in biogas fermentation. Microbiol China;37: 513e9.

Bernstad, A., la Cour Jansen, J. 2012. Review of comparative LCAs of food waste management systems – Current status and potential improvements. Waste Management 32, 2439–2455.

BioCycle. 2013. New NYC Food Waste Recycling Law will have a National Impact, Say American Biogas and Composting Groups. BioCycle Breaking News. Washington, DC.

BIOFerm (BIOFerm Energy Systems). 2014a. BIOFerm Dry Fermentation. Anaerobic Digestion Systems for Solid Input Materials. http://www.biofermenergy.com/wp-content/uploads/2014/03/2014_BIOFerm-Dry-Fermentation_Batch-System-Digester_BIOFerm-Energy-Systems.pdf.

BIOFerm (BIOFerm Energy Systems). 2014b. BIOFerm EUCOlino. The Compact Plug and Play Biogas Plant from Schmack Biogas. http://www.biofermenergy.com/wp-content/uploads/2011/11/EUCOlino-Flyer.pdf.

Blandford, L.K. 2012. St. Lucie officials decide to terminate Geoplasma contract. Journal Media Group. TC Palm. http://www.tcpalm.com/business/st-lucie-officials-to-decide-today-whether-to.

Bogner, J., M. Abdelrafie Ahmed, C. Diaz, A. Faaij, Q. Gao, S. Hashimoto, K. Mareckova, R. Pipatti, T. Zhang. 2007. Waste Management, In Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R. Dave, L.A. Meyer (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Bolzonella, D., Battistoni, P., Susini, C., Cecchi, F. 2006a. Anaerobic codigestion of waste activated sludge and OFMSW: the experiences of Viareggio and Trevisoplants (Italy). Water Sci Technol;53:203–11.

Bolzonella, D., Pavan, P., Mace, S., Cecchi, F. 2006b. Dry anaerobic digestion of differently sorted organic municipal solid waste: a full-scale experience. Water Science and Technology;53(8):23–32.

Bouallagui, H., Touhami, Y., Cheikh, R.B., Hamdi, M. 2005. Bioreactor performance in anaerobic digestion of fruit and vegetable wastes. Process Biochem. 40, 989–995.

Boulanger, A., Pinet, E., Bouix, M., Bouchez, T., Mansour, A. A. 2012. Effect of inoculum to substrate ratio (I/S) on municipal solid waste anaerobic degradation kinetics and potential. Waste Management 32 ; 2258–2265.

Brinton, W.F. 2000. Compost Quality Standards & Guidelines. Prepared by Woods End Research Laboratory for New York State Association of Recyclers. http://compost.css.cornell.edu/Brinton.pdf.

Brown, D., Li, Y. 2013. Solid state anaerobic co-digestion of yard waste and food waste for biogas production. Bioresource Technology 127, 275–280.

Brückner C., Weiss D., Mildner U. 2007. Mundgerechtere bakterienkost. Bauern Ztg;36:48e9.

Bruni E., Jensen A.P., Angelidaki I. 2010. Comparative study of mechanical, hydrothermal, chemical and enzymatic treatments of digested biofibers to improve biogas production. J Bioresour Technol;101:8713e7.

Burton, C. H., Turner, C. 2003. Manure management: Treatment strategies for sustainable agriculture. Silsoe: Silsoe Research Institute.

CalRecycle. 2002. Food Waste Recovery: A Model for Local Government Recycling and Waste Reduction. http://www.calrecycle.ca.gov/publications/Documents/LocalAsst/31002001.pdf.

CalRecycle. 2014a. California Anaerobic Digestion Projecs (a partial list, October, 2014). http://www.calrecycle.ca.gov/organics/conversion/ADProjects.pdf.

CalRecycle. 2014b. Extended Producer Responsibility (EPR) and Stewardship. Frequently Asked Questions. http://www.calrecycle.ca.gov/epr/FAQs.htm.

Ceballos, G., Ehrlich, P.R., Barnosky, A.D., García, A., Pringle, R.M., Palmer, T.M. 2015. Accelerated modern human–induced species losses: Entering the sixth mass extinction. Sci. Adv. 1, e1400253.

Cecchi, F., Traverso, P.G., Mata-Alvarez, J., Clancy, J., Zaror, C. 1988. State of the art of R&D in the anaerobic digestion process of municipal solid waste in Europe. Biomass 16, 257±284.

CEP (Clean Energy Project, Inc.). 2014. Landfill Tipping Fees in USA. http://www.cleanenergyprojects.com/Landfill-Tipping-Fees-in-USA-2013.html.

Cesaro A., Nadeeo V., Amodio V., Belgiorno V. 2012. Enhanced biogas production from anaerobic codigestion of solid waste by sonolysis. Ultrason Sonochem;19:596e600.

Chandra R., Takeuchi H., Hasegawa T. 2012a. Hydrothermal pretreatment of rice straw biomass: a potential and promising method for enhanced methane production. Appl Energy;94:129e40.

Chandra R., Takeuchi H., Hasegawa T., Kumar R. 2012b. Improving biodegradability and biogas production of wheat straw substrates using sodium hydroxide and hydrothermal pretreatments. Energy;43:273e82.

Chen, Y., Cheng, J.J., Creamer, K.S., 2008. Inhibition of anaerobic digestion process: a review. Bioresour. Technol. 99 (10), 4044–4064.

Chen, X., Yan, W., Sheng, K., Sanati, M. 2014. Comparison of high-solids to liquid anaerobic co-digestion of food waste and green waste. Bioresource Technology 154, 215–221.

Cho J.K., Park S.C., Chang H.N. 1995. Biochemical methane potential and solid-state anaerobic-digestion of Korean food wastes. Bioresource Technology; 52(3):245–53.

Chum, H., Faaij, A., Moreira, J., Berndes, G., Dhamija, P., Dong, H., Gabrielle, B., Goss Eng, A., Lucht, W., Mapako, M., Masera Cerutti, O., McIntyre, T., Minowa, T., Pingoud, K. 2011. Bioenergy. In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation [O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss, S. Kadner, T. Zwickel, P. Eickemeier, G. Hansen, S. Schlömer, C. von Stechow (eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Cirne, D.G., Bjornsson, L., Alves, M., Mattiasson, B. 2006. Effects of bioaugmentation by an anaerobic lipolytic bacterium on anaerobic digestion of lipid-rich waste. J. Chem. Technol. Biotechnol. 81, 1745e1752.

CIWMB (California Integrated Waste Management Board). 2009. Life Cycle Assessment and Economic Analysis of Organic Waste Management and Greenhouse Gas Reduction Options. Prepared for CIWMB by RTI International, R.W. Beck, Sally Brown, Matthew Cotton, Sacramento, CA.

CleanWorld. 2012. CleanWorld Sacramento BioDigester. http://www.cleanworld.com/wp-content/uploads/2012/04 /SacProjectProfilewebversion.pdf.

CleanWorld. 2015a. Personal Communication with Brad Jacobson, CleanWorld Business Development. May 7, 2015. Davis, CA.

CleanWorld. 2015b. About CleanWorld. http://www.cleanworld.com/about/.

Crittenden, J.C., R.R. Trussell, D.H. Hand, K.J. Howe, and G. Tchobanoglous. Water Treatment Principles and Design, 3rd ed. John Wiley and Sons, New York. ISBN 0-470-40539-2. 2012.

Davis, M.W. 1998. A rapid modified method for compositional carbohydrate analysis of lignocellulosics by high pH anion-exchange chromatography with pulsed amperometric detection (HPAEC/ PAD). J. Wood Chem. Technol. 18 (2), 235–252.

De Baere, L. 2012. The Dranco Technology: A Unique Digestion Technology for Solid Organic Waste. Organic Waste Systems. http://www.ows.be/wp-content/uploads/2013/02/The-DRANCO-technology-2012.pdf.

De Baere, L., Mattheeuws, B. 2014. Anaerobic digestion of the organic fraction of municipal solid waste in Europe - Status, experience and prospects in: Waste Management, Vol 3: Recycling and Recovery, Vol. 3, TK, pp. 517-526.

del Real Olvera, J., Lopez-Lopez, A. 2012. Biogas Production from Anaerobic Treatment of AgroIndustrial Wastewater, Biogas, Dr. Sunil Kumar (Ed.), ISBN: 978-953-51-0204-5, InTech, Available from: http://www.intechopen.com/books/biogas/biogas-production-from-anaerobic-treatment-of-agro-industrialwastewater.

Delgenés, J.P., Penaud, V., Moletta, R. 2002. Pretreatments for the enhancement of anaerobic digestion of solid wastes. Chapter 8. In: Biomethanization of the organic fraction of municipal solid wastes. IWA Publishing; pp. 201e28.

Deublein, D., Steinhauser, A. 2008. Biogas from waste and renewable resources. Weinheim, Willey-VCH Verlag GmbH & Co. KGaA.

Dieleman, B. 2015. Innovative Uses of LFG Energy. From the Florida SWANA Winter Waste Conference. http://www.swanafl.org/Resources/Events/2015%20Winter%20Conference/Presentations/Dieleman.pdf.

DOE (U.S. Department of Energy). 2013. Anaerobic Digestion Basics. Office of Energy Efficiency and Renewable Energy. Washington, DC. http://energy.gov/eere/energybasics/articles/anaerobic-digestion-basics.

DOE (U.S. Department of Energy). 2015a. Energy Incentive Programs. Office of Energy Efficiency and Renewable Energy. Washington, DC. http://energy.gov/eere/femp/energy-incentive-programs.

DOE (U.S. Department of Energy). 2015b. Green Power Markets. The Green Power Network. Energy Efficiency and Renewable Energy. http://apps3.eere.energy.gov/greenpower/markets/certificates.shtml?page=5.

Drennan, M.F., DiStefano, T.D. 2010. Characterization of the curing process from high-solids anaerobic digestion. Bioresource Technology 101, 537–544.

DSIRE (Database of State Incentives for Renewables and Efficiency). 2015. Find Policies and Incentives by State. NC Clean Energy Technology Center. NC State University. In Collaboration with the U.S. Department of Energy. Washington, DC. http://www.dsireusa.org/.

EcoCorp. 2015. Technology. http://www.ecocorp.com/Technology.html.

Edelmann, W., Baier, U., Engeli, H. 2005. Environmental aspects of the anaerobic digestion of the organic fraction of municipal solid wastes and of agricultural wastes. U.B.a.H.E. Water Sci Technol.; 52 (1-2):203-8.

Eisenmann. 2012. Sustainability in the Urban Environment through Anaerobic Digestion. An Overview of how one Urban Farm is Fighting the Food Desert Epidimic by Utilizing Anaeoribc Digestion to Create a Net-Zero Energy System. http://cdn2.hubspot.net/hub/133998/file-17443629-pdf/docs/eisenmann_-_sustainability_in_an_ urban_environment_through_anaerobic_digestion.pdf.

Eisenmann. 2014. Maximizing Biogas Production for CR&R's Fleet of Collection Vehicles Eisenmann's high solids anaerobic digestion technology to convert organic waste to compressed natural gas. Eisenmann Press Release. http://cdn2.hubspot.net/hub/133998/file-632006819-pdf/docs/crr_and_eisenmann_ad_project_upd ate_-_04-2014.pdf.

EIA (U.S. Energy Information Administration). 2015a. Florida. State Profile Overview. http://www.eia.gov/state/?sid=FL#tabs-4.

EIA (U.S. Energy Information Administration). 2015b. Florida. Nature Gas Data. http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_sfl_a.htm.

EPA (U.S. Environmental Protection Agency). 1992. The Consumer's Handbook for Reducing Solid Waste. EPA530-K-92-003. http://nepis.epa.gov/Exe/ZyPDF.cgi/10000MD0.PDF?Dockey=10000MD0.PDF.

EPA (U.S. Environmental Protection Agency). 1997. Pay-As-You-Throw Success Stories. EPA530-F-97-007. http://www.epa.gov/wastes/conserve/tools/payt/pdf/paytss.pdf.

EPA (U.S. Environmental Protection Agency). 2004. Method 9045D – Soil and Waste pH. Revision 4. http://www.caslab.com/EPA-Methods/PDF/EPA-Method-9045D.pdf.

EPA (U.S. Environmental Protection Agency). 2008. Renewable Energy Certificates. EPA's Green Power Partnership. Washington, DC. http://www.epa.gov/greenpower/documents/gpp_basics- recs.pdf.

EPA (U.S. Environmental Protection Agency). 2009. Opportunities to Reduce Greenhouse Gas Emissions through Materials and Land Management Practices. Office of Solid Waste and Emergency Response. http://www.epa.gov/oswer/docs/ghg_land_and_materials_management.pdf.

EPA (U.S. Environmental Protection Agency). 2011. Introduction to the National Pretreatment Program. Office of Wastewater Management. http://water.epa.gov/polwaste/npdes/pretreatment/upload/pretreatment_program_intro_2011.pdf.

EPA (U.S. Environmental Protection Agency). 2012a. Reducing Waste. Green Homes. http://www.epa.gov/gree nhomes/ReduceWaste.htm.

EPA (U.S. Environmental Protection Agency). 2012b. State of Practice of Emerging Waste Conversion Technologies. Prepared by RTI international. EPA 600/R-12/705. http://nepis.epa.gov/Adobe/PDF/P10 0FBUS.pdf.

EPA (U.S. Environmental Protection Agency). 2013a. State Recycling Tax Incentives. Wastes – Resource Conservation – Recycling Market Development. http://www.epa.gov/osw/conserve/tools/rmd/bizasst/rec-tax.htm.

EPA (U.S. Environmental Protection Agency). 2013b. State Level CO_2 Emissions from Fossil Fuel Combustion. http://epa.gov/statelocalclimate/documents/pdf/CO2FFC_2013.pdf.

EPA (U.S. Environmental Protection Agency). 2015a. Advancing Sustainable Materials Management: Facts and Figures 2013. Assessing Trends in Generation, Recycling and Disposal in the United States. Office of Resource Conservation and Recovery (5306P). EPA530-R-15-002.

EPA (U.S. Environmental Protection Agency). 2015b. Tax Incentives. Wastes – Resource Conservation – Recycling Market Development. http://www.epa.gov/wastes/conserve /tools/rmd/bizasst/tax-ince.htm.

EPA (U.S. Environmental Protection Agency). 2015c. Clean Power Plan. http://www2.epa.gov/cleanpowerplan.

EPA (U.S. Environmental Protection Agency). 2015d. Regulatory Impact Analysis for the Proposed Revisions to the Emission Guidelines for Existing Sources and Supplemental Proposed New Source Performance Standards in the Municipal Solid Waste Landfills Sector. http://www.epa.gov/airtoxics/landfill/20150810_landfills_ ria.pdf.

EPEM (Environmental Planning, Engineering & Management). 2015. AD 5: Complete Dry AD (Dry Fermentation). Database of Waste Management Technologies. Waste C Control. http://www.epem.gr/waste-c-control/database/html/AD-05.htm.

EREF (The Environmental Research & Education Foundation). 2013. Summary of Waste Conversion Technologies. Prepared for NEWMOA by Bryan Staley. http://www.newmoa.org/events/docs/112_109/EREF_MSW_Conversion_Techs_Aug2013.pdf.

EREF (The Environmental Research & Education Foundation). 2015a. Anaerobic Digestion of Municipal Solid Waste: Report on the State of Practice. www.erefdn.org.

EREF (The Environmental Research & Education Foundation). 2015b. Using Municipal Solid Waste as a Biofuel Feedstock. www.erefdn.org.

Fabián, R.M., Gourdon, R. 1999. Effect of baling on the behavior of domestic wastes: laboratory study on the role of pH in biodegradation. Bioresour. Technol. 69, 15–22.

Faulkner, T. 2015. R.I.'s First Anaerobic Digester Expected by the End of the Year. Blue Sphere ECORI News. http://bluespherecorporate.com/r-i-s-first-anaerobic-digester-expected-by-end-of-year/.

FDEP (Florida Department of Environmental Protection). 2011. Emission Sources – Bioenergy. http://www.dep.state.fl.us/air/emission/bioenergy.htm.

FDEP (Florida Department of Environmental Protection). 2013. Florida Waste-to-Energy Facilities. http://www.dep.state.fl.us/waste/quick_topics/publications/shw/solid_waste/ WTE_Contacts-2013.pdf.

FDEP (Florida Department of Environmental Protection). 2015a. Solid Waste Management in Florida 2014 Annual Report. http://www.dep.state.fl.us/waste/categories/recycling/ SWreportdata/14_data.htm.

FDEP (Florida Department of Environmental Protection). 2015b. Yard Trash Transfer Stations, Yard Trash Recycling Facilities, Manure Blending Facilities, and Manure/Animal Byproducts/Vegetative Waste Composting Facilities Currently Registered OR Operation is Addressed Under a Permit.

https://fldeploc.dep.state.fl.us/www_wacs/Reports/Yard_Trash_Processors_current_webupdates.asp.

Fernandez J., Perez M., Romero L.I. 2008. Effect of substrate concentration on dry mesophilic anaerobic digestion of organic fraction of municipal solid waste (OFMSW). Bioresource Technology;99 (14):6075–80.

FIE (Foth Infrastructure & Environment, LLC). 2009. Source Separated Organic Materials Anaerobic Digestion Feasibility Study. Project ID 09R007. Ramsey Washington Counties Resource Recovery Project Board and St. Paul Port Authority. St. Paul. Minnesota.

Fletcher, K. 2015. California energy commission awards biogas project $5 million. Biomass Magazine. http://biomassmagazine.com/articles/11418/california-energy-commission-awards-biogas-project-5-million.

Forbes Jr., R.H. 2011. The Changing Landscape of Biosolids Management in Florida: The 21st Century's First Decade & Predictions for the Next One. Florida Water Resources Journal. http://fwrj.com/techarticles/0611%20tech4.pdf.

Forster-Carneiro, T., Pe´rez, M., Romero L.I., Sales D. 2007. Dry–thermophilic anaerobic digestion of organic fraction of the municipal solid waste: focusing on the inoculum sources. BioresourTechnol; 98: 3, 195–203.

Fox M.H., Noike T., Ohki T. 2003. Alkaline subcritical-water treatment and alkaline heat treatment for the increase in biodegradability of newsprint waste. Water Sci Technol;48:77e84.

Franjo C.F., Ledo J.P., Anon J.A.R., Regueira L.N. 1992. Calorific value of municipal solid waste. Environ Technol; 13:1085–9.

Frost & Sullivan (Frost & Sullivan, Inc.). 2013. CEO 360 Degree Perspective on the Global Pulp and Paper Water and Wastewater Treatment Market. Frost & Sullivan's Environmental Research and Consulting. Report e Paulina Szyplinska.

Gerardi, M.H. 2003. The microbiology of anaerobic digesters electronic resource. Hoboken, N.J: Wiley-Interscience.

Gerhardt M., Pelenc V., Bäuml M. 2007. Application of hydrolytic enzymes in the agricultural biogas production: results from practical applications in Germany. Biotechnol J;2:1481e4.

Ghanem, I.I.I., Guowei, G., Jinfu, Z. 2001. Leachate production and disposal of kitchen food solid wastes by dry fermentation for biogas generation. Renew. Energy 23 (3-4), 673–684.

GMI (Global Methane Initiative). 2014. A Global Perspective of Anaerobic Digestion Policies and Incentives. Global Methane Initiative Agricultural Subcommittee.

Goldstein, N. 2014. Food Waste Collection Innovations. BioCycle July, 2014, Vol. 55, No. 6, p. 46. http://www.biocycle.net/2014/07/15/food-waste-collection-innovations/.

Gollakota, K.G., Meher, K.K. 1988. Effect of particle size, temperature, loading rate and stirring on biogas production from castor cake.Biol.Wastes 24, 243–249.

Greer, D. 2011. Digester Developers Target Mixed Organic Waste Streams. BioCycle August, 2011, Vol. 52, No. 8, p. 53. http://www.biocycle.net/2011/08/16/digester-developers-target-mixed-organic-waste-streams/.

Guendouz, J., Buffiore, P., Cacho, J., Carrore, M., Delgenes, J. P. 2010. Dry anaerobic digestion in batch mode: Design and operation of a laboratory-scale, completely mixed reactor. Waste Management, 30 (10), 1768-1771.

Gunaseelan, V.N. 1997. Anaerobic Digestion of Biomass for Methane Production: A Review. Biomass and Bioenergy Vol. 13, Nos. l/2, pp. 833114. PII: SO961-9534(97)00020-2.

Haight, M. 2005. Assessing the environmental burdens of anaerobic digestion in comparison to alternative options for managing the biodegradable fraction of municipal solid wastes. Water Sci and Technol. 52(1-2): p. 553-559.

Hartz, T.K. 2009. Nutrient Value of Compost. University of California, Davis, Vegetable Research and Information Center. http://vric.ucdavis.edu/events/2009_osfm_symposium/UC%20Organic%20Symposium%20010609%2005b%20Hartz.pdf.

Harvest Power. 2014. Clean Energy Fund: Urban Renewal Bioenergy Production. Public Project Report. Fraser Richmond Soil & Fibre, Ltd. Richmond, BC. http://www.harvestpower.com/wp-content/uploads/2014/10/Harvest-Fraser-Richmond-Organics-CEF-Outreach-Report-EN.pdf.

Hendrix, A.T.W.M., Zeeman, G. 2009. Pretreatments to enhance the digestibility of lignocellulosic biomass. Bioresource Technology 100; 10–18.

Heo, N.H., Park, S.C., Kang, H. 2004. Effects of mixture ratio and hydraulic retention time on single-stage anaerobic co-digestion of food waste and waste activated sludge. J. Environ. Sci. Health A39 (7), 1739–1756.

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 Theses Department of Civil & Environmental Engineering, University of South Florida; http://scholarcommons.usf.edu/etd/5883.

Hjorth M, Gränitz K, Adamsen APS, Møller HB. 2011. Extrusion as a pretreatment to increase biogas production. Bioresour Technol;102:4989e94.

Holt, E., Bird, L. 2005. Emerging Markets for Renewable Energy Certificates: Opportunities and Challenges. National Renewable Energy Laboratory. Operated for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy by Midwest Research

Institute, Battelle. Contract No. DE-AC36-99-GO10337. http://apps3.eere.energy.gov/greenpower/resources/pdfs/37388.pdf.

Hood, J. 2014. UK experience of the Renewable Transport Fuel Obligation (RTFO) and policies to promote the development of waste-derived and advanced biofuels. Low Carbon Fuels Strategy Department for Transport of the United Kingdom. European Biofuels Technology Platform 6th Stakeholder Plenary Meeting Tuesday 14th October 2014, Brussels. http://www.biofuelstp.eu/spm6/docs/jonathan-hood.pdf.

Hu, Z.H., Yu, H.Q. 2005. Application of rumen microorganisms for enhanced anaerobic degradation of corn stover. Process Biochem. 40, 2371–2377.

Hulshoff Pol, L.W., de Castro Lopes, S.I., Lettinga, G., Lens, P.N. 2004. Anaerobic sludge granulation. Water Research; Volume 38, Issue 6, March 2004, Pages 1376-1389. doi:10.1016/j.watres.2003.12.002.

HWMA (Humboldt Waste Management Association). 2013. Permitting Tool Kit for Food Waste Anaerobic Digesters. US EPA Region 9. http://www.epa.gov/region9/organics/ad/hwma-permitting-toolkit.pdf.

ICROA (International Carbon Reduction and Offset Alliance). 2014. Unblocking the Hidden Value to Carbon Offsetting. http://www.icroa.org/42/icroa-research.

IPCC (International Panel on Climate Change). 2014. Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1132 pp.

Izumi, K., Okishio, Y.K., Nagao, N., Niwa, C., Yamamoto, S., Toda, T. 2010. Effects of particle size on anaerobic digestion of food waste. Int. Biodeterior. Biodegrad. 64 (7), 601–608.

Jackowiak D., Bassard D., Pauss A., Ribeiro T. 2011a. Optimisation of a microwave pretreatment of wheat straw for methane production. Bioresour Technol;102:6750e6.

Jackowiak D., Frigon J.C., Ribeiro T., Pauss A., Guiot S. 2011b. Enhancing solubilisation and methane production kinetic of switchgrass by microwave pretreatment. Bioresour Technol;102:3535e40.

Jerger, D.E., Dolenc, D.A., Chynoweth D.P. 1982. Bioconversion of woody biomass as a renewable source of energy. Biotechnol Bioeng Symp, 1982;12:2, 33–48.

Kaparaju, P., Rintala, J. 2005. Anaerobic co-digestion of potato tuber and its industrial by-products with pig manure. Resources Conservation and Recycling, 43(2) 175-188. doi: 10.1016/j.resconrec.2004.06.001.

Kaparaju P., Luostarinen S., Kalmari E., Kalmari J., Rintala J. 2002. Co-digestion of energy crops and industrial confectionery by-products with cow manure: batch scale and farm-scale evaluation. Water Sci Technol;45:275e80.

Karagiannidis, A., Perkoulidis, G. 2009. A multi-criteria ranking of different technologies for the anaerobic digestion for energy recovery of the organic fraction of municipal solid wastes. Bioresour. Technol. 100, 2355–2360.

Kato, M.T., Field, J.A., Versteeg, P., Lettinga, G. 1994. Feasibility of expanded granular sludge bed reactors for the anaerobic treatment of low-strength soluble wastewaters. Biotechnol. Bioeng. 44 (4), 469e479.

Kayhanian, M. 1994. Performance of a high-solids anaerobic digestion process under various ammonia concentrations. J. Chem. Tech. Biotechnol. 59, 349–352.

Kessler (Kessler Consulting, Inc.). 2009. The Greening of Florida: A Solid Waste Management Roadmap. Prepared for the City of Tallahassee under Innovative Recycling and Waste Reduction Grant IG8-18.

Khanal, S. 2008. Anaerobic biotechnology for bioenergy production principles and applications. Hoboken: John Wiley & Sons, Inc.

Kim, M. H., Kim, J.W. 2010. Comparison through a LCA evaluation analysis of food waste disposal options from the perspective of global warming and resource recovery. Science of the Total Environment. 408(19): p. 3998-4006.

Kinyua, M.N. 2013. "Effect of Solids Retention Time on the Denitrification Potential of Anaerobically Digested Swine Waste". Graduate Theses and Dissertations. http://scholarcommons.usf.edu/etd/4520.

Kirkels, A., Verbong, G. 2011. Biomass gasifi cation: Still promising? A 30-year global overview. Renewable and Sustainable Energy Reviews, 15(1), pp. 471-481.

Kobayashi F., Take H., Asada C., Nakamura Y. 2004. Methane production from steam exploded bamboo. J Biosci Bioeng;97:426e8.

Kothari, R., Pandey, A.K., Kumar, S., Tyagi, V.V., Tyagi, S.K. 2014. Different aspects of dry anaerobic digestion for bio-energy: An overview. Renewable and Sustainable Energy Reviews. 39, 174-195.

Kraemer, T., Gamble, S. 2014. Integrating Anaeroibc Digestion with Composting. BioCycle, Vol. 55, No. 10, p. 32. http://www.biocycle.net/2014/11/18/integrating-anaerobic-digestion-with-composting/.

Kreuger E., Sipos B., Zacchi G., Svensson S.E., Björnsson L. 2011. Bioconversion of industrial hemp to ethanol and methane: the benefits of steam pretreatment and co-production. Bioresour Technol;102:3457e65.

Kumar, J. A., Li, J.Z., He, J.E., Chang, S., Jha, A.K. 2010. Optimization of Dry Anaerobic Fermentation of Solid Organic Wastes. Advanced Materials Research, Vols. 113-116, pp. 740-743.

Lane, J. 2012. The October Surprise: BP Cancels Plans for US Cellulosic Ethanol Plant. Biodigest Fuels. http://www.biofuelsdigest.com/bdigest/2012/10/26/the-october-surprise-bp-cancels-plans-for-us-cellulosic-ethanol-plant/.

Lens, P., Hamelers, B., Hoitink, H., Bidlingmaier, W. 2004. Resource Recovery and Reuse in Organic Solid Waste Management. IWA Publishing. London, United Kingdom.

Levis, J.W., Barlaz, M.A. 2011. What is the Most Environmentally Friendly Way to Treat Commercial Food Waste? Environ Sci Technol. 45(17): 7438-7444.

Li, Y., Park, S., Zhu, J. 2011. Solid-state anaerobic digestion for methane production from organic wastes. Renewable and Sustainable Energy Reviews 15: 821–826.

Liew L.N., Shi J., Li Y. 2011. Enhancing the solid-state anaerobic digestion of fallen leaves through simultaneous alkaline treatment. Bioresour Technol;102:8828e34.

Lin Y., Wang D., Wang L. 2010. Biological pretreatment enhances biogas production in the anaerobic digestion of pulp and paper sludge. Waste Manag Res;28:800e10.

Liu, T., Sung, S. 2002. Ammonia inhibition on thermophilic acetoclastic methanogens. Water Sci. Technol. 45, 113–120.

Lo, Y.C., Saratale, G.D., Chen, W.M., Bai, M.D., Chang, J.S. 2009. Isolation of cellulose hydrolytic bacteria and applications of the cellulolytic enzymes for cellulosic biohydrogen production. Enzyme and Microbial Technology;44:417–25.

Lopes, W.S., Leite, V.D., Prasad, S. 2004. Influence of inoculum on performance of anaerobic reactors for treating municipal solid waste. Bioresource Technol. 94, 261–266.

Lu Y., Lai Q., Zhang C., Zhao H., Ma K., Zhao X., et al. 2009. Characteristics of hydrogen and methane production from corn stalks by an augmented two- or three-stage anaerobic fermentation process. Bioresour Technol;100:2889e95.

Mackulak, T., Prousek, J., Svorc, L., Drtil, M. 2012. Increase of biogas production from pretreated hay and leaves using wood-rotting fungi. Chem Pap;66: 649e53.

Mata-Alvarez, J., Dosta, J., Romero-Güiza, M.S., Fonoll, X., Peces, M., Astals, S. 2014. A critical review on anaerobic co-digestion achievements between 2010 and 2013. Renewable and Sustainable Energy Reviews, 36, 412–427.

Madigan, M.T., Martinko, J.M., Bender, K.S., Buckley, D.H., Stahl, D.A. 2014. Brock Biology of Microorganisms, 14th Edition, Pearson, Boston.

Massé, D., Droste, R. 2000. Comprehensive model of anaerobic digestion of swine manure slurry in a sequencing batch reactor. Water Research, 34(12), 3087-3106. doi: 10.1016/S0043-1354(00)00064-6.

McGill (McGill Environmental Systems of NC, Inc.). 2015. The JFE-Brighton Regional Composting Facility. http://www.mcgillcompost.com/jfe-brighton-composting.

Mensink, M. 2007. Speaking the same language the way forward in tracking industrial energy efficiency and CO2 emissions. In: International Council of Forest & Paper Associations, Presentation at Expert Review Workshop, International Energy Agency, Paris. www.icfpa.org.

Meyer, T., Edwards, E.A. 2014. Anaeroibc digestion of pulp and paper mill wastewater and sludge. Water Research; Volume 65, 15 Nov 2014, Pages 321-349. doi:10.1016/j.watres.2014.07.022.

MH-Carbon. 2013. An introduction to Carbon Credits. ECO_2 – Trading for the Future. http://www.redd-monitor.org/wp-content/uploads/2013/01/MH-Carbon-Invest.pdf.

Michalska K., Miazek K., Krzystek L., Ledakowicz S. 2012. Influence of pretreatment with Fenton’s reagent on biogas production and methane yield from lignocellulosic biomass. Bioresour Technol;119:72e8.

Migneault, S., Koubaa, A., Riedl, B., Nadji, H., Deng, J., Zhang, S.Y. 2011. Binderless fiberboard made from primary and secondary pulp and paper sludge. Wood Fiber Sci. 43 (2), 180e193.

Mirahmadi K., Kabir M.M., Jeihanipour A., Karimi K., Taherzadehm M.J. 2010. Alkaline pretreatment of spruce and birch to improve bioethanol and biogas production. BioResources;5:928e38.

Molnar, L. and Bartha, I. 1988. High solids anaerobic fermentation for biogas compost production. Biomass, 16, 173-182.

Monlau F., Latrille E., Da Costa A.C., Steyer J.P., Carrere H. 2013. Enhancement of methane production from sunflower oil cakes by dilute acid pretreatment. Appl Energy;102:1105e13.

Moorhead, K.K., Nordstedt, R.A. 1993. Batch anaerobic digestion of water hyacinth: effects of particle size, plant nitrogen content and inoculum volume.Bioresour.Technol.44 (1), 71–76.

Morris, J., Matthews, H.S., Morawski, M. 2011. Review of LCAs on Organics Management Methods & Development of an Environmental Hierarchy. Alberta Environment Edmonton, AB.

Mosier, N., Wyman, C., Dale, B., Elander, R., Lee, Y.Y., Holtzapple, M., Ladisch, M. 2005. Feature of promising technologies for pretreatment of lignocellulosic biomass. Bioresource Technology 96; 673–686.

Mussoline, W., Esposito, G., Lens, P., Spagni, A., Giordano, A. 2013. Enhanced methane production from rice straw co-digested with anaerobic sludge from pulp and paper mill treatment process. Bioresour Technol, 148, 135-143.

Muthangya M., Mshandete A.M., Kivaisi A.K. 2009. Two-stage fungal pre-treatment for improved biogas production from sisal leaf decortication residues. Int J Mol Sci;10:4805e15.

MWHR (MW Horticulture Recycling Facility, Inc.). 2015. Press Release 8/14/15. https://www.mwhorticulturerecycling.com/.

NNFCC (National Non-Food Crops Centre). 2015. Biogas Map. The Official Information Portal on Anaerobic Digestion. http://www.biogas-info.co.uk/resources/biogas-map/.

NREL (National Renewable Energy Laboratory). 2014. Renewable Portfolio Standards. Operated for the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy by the Alliance for Sustainable Energy LLC. http://www.nrel.gov/docs/gen/fy14/62350.pdf

Oakley, S. M. 2005. Manual de Desino y Operacion de Rellenos Sanitarios en Honduras. Tegucigalpa, Honduras. USAID.

O'Flaherty, V., Colleran, E., 1999. Effect of sulphate addition on volatile fatty acid and ethanol degradation in an anaerobic hybrid reactor. I: process disturbance and remediation. Bioresour. Technol. 68, 101e107.

O'Flaherty, V., Colohan, S., Mulkerrins, D., Colleran, E. 1999. Effect of sulphate addition on volatile fatty acid and ethanol degradation in an anaerobic hybrid reactor. II: microbial interactions and toxic effects. Bioresour. Technol. 68, 109e120.

Oleszkiewicz J., Poggi-Varaldo H.M. 1997. High solids anaerobic digestion of mixed municipal and industrial waste. J Environ Eng;123:1087–92.

Orbit Energy. 2015. Orbit Energy Inc. Sustainability Responsibility Security. Orbit Energy Renewable Power. http://www.environmentcouncilri.org/sites/default/files/Orbit%20 Energy_RI_Compost%20Conference.pdf.

O-Thong S., Boe K., Angelidaki I. 2012. Thermophilic anaerobic co-digestion of oil palm empty fruit bunches with palm oil mill effluent for efficient biogas production. Appl Energy;93:648e54.

Owen, W.F., Stuckey, D.C., Healy, J.B., Young, L.Y., Mccarty. P.L. 1979. Bioassay for monitoring biochemical methane potential and anaerobic toxicity. Water Res., 13, pp. 485–492.

Owens, J.M., Chynoweth, D.P., 1993. Biochemical methane potential of municipal solid waste (MSW) components. Water Sci. Technol. 27 (2), 1–14.

OWS (Organic Waste Systems). 2015. Personal Communication with Norma McDonald on May 27, 2015.

Pan, S., Du, M.A., Huang, I., Liu, I., Chang, E., Chiang, P. 2015. Strategies on implementation of waste-to-energy (WTE) supply chain for circular economy system: a review. In Press. doi:10.1016/j.jclepro.2015.06.124.

Pandey, A. 2003. Solid-state fermentation, Biochem. Eng. J. 13; 81–84.

Peng, X., Börner, R.A., Nges, I.A., Liu, J. 2014. Impact of bioaugmentation on biochemical methane potential for wheat straw with addition of Clostridium cellulolyticum Bioresource Technology 152; 567–571.

Peñuelas, J., Sardans, J., Rivas-ubach, A. and Janssens, I. A. 2012. The human-induced imbalance between C, N and P in Earth's life system. Global Change Biology, 18: 3–6. doi: 10.1111/j.1365-2486.2011.02568.x.

Petersson A., Thomsen M.H., Hauggaard-Nielsen H., Thomsen A.B. 2007. Potential bioethanol and biogas production using lignocellulosic biomass from winter rye, oilseed rape and faba bean. Biomass Bioenergy;31:812e9.

PIS (Pytheas Investors Service). 2008. Treatment of Municipal Solid Waste – Anaerobic Digestion Technologies. www.pytheas.net.

Price, J.L. 2015. Florida 2013 Recycling Rate Image. Florida Department of Environmental Protection. http://www.dep.state.fl.us/waste/categories/recycling/images/2013_rate.jpg.

Rapport, J., Zhang, R., Jenkins, B.M., and Williams, R.B. 2008. Current anaerobic digestion technologies used for treatment of municipal organic solid waste. University of California, Davis: Contractor Report to the California Integrated Waste Management Board.

Redman, G. 2010. A Detailed Economic Assessment of Anaerobic Digestion Technology and its Sustainability to UK Farming and Waste Systems. 2nd Edition. The Andersons Center. Leicestershire. UK.

RIS (RIS International Ltd., in association with MacViro Consultants Inc.). 2005. Feasibility of Generating Green Power through Anaerobic Digestion of Garden Refuse from the Sacramento Area. SMUD Advanced Renewable and Distributed Generation Program. Sacramento, CA.

RISE-AT (Regional Information Service Centre for South East Asia on Appropriate Technology). 1998. Review of current status of Anaerobic Digestion Technology for treatment of MSW. http://www.ist.cmu.ac.th/riseat/documents/adreview.pdf.

Rogoff, M. J., Clark, B.J. 2014. Anaerobic Digestion – What Are the Economics? Waste Advantage Magazine. July 2014. 22-25.

Romano R.T., Zhang R.H., Teter S., McGarvey J.A. 2009. The effect of enzyme addition on anaerobic digestion of jose tall wheat grass. Bioresour Technol;100:4564e71.

Ruiz, A. 2014. California Alternative Energy and Advanced Transportation Financing Authority. Request to Approve Resolution Amendment for Sales and Use Tax Exclusion Award to Change the Participating Party. Recology Bioenergy Application No. 14-SM006. http://www.treasurer.ca.gov/caeatfa/staff/2014/ 20140715/4a.pdf.

RWI (Renewable Waste Intelligence). 2013. Business Analysis of Anaerobic Digestion in the USA.

Sans, C., Mata-Alvarez, J., Cecchi, F., Pavan, P. 1995. Volatile fatty-acids production by mesophilic fermentation of mechanically-sorted urban organic wastes in a plug-flow reactor. Bioresource Technology; 51(1): 89–96.

Sawatdeenarunat, C., Surendra, K.C., Takara, D., Oechsner, H., Khanal, S.K. Anaerobic digestion of lignocellulosic biomass: Challenges and opportunities. Bioresource Technology 178; 178–186.

Schievano, A., D'Imporzano, G., Malagutti, L., Fragail, E., Ruboni, G., Adani, F., 2010. Evaluating inhibition conditions in high-solids anaerobic digestion of organic fraction of municipal solid waste. Bioresour. Technol. 101, 5728–5732.

Schnurer, A. and Jarvis, A. 2009. Microbiological Handbook for Biogas Plant. Swedish Waste Management, Swedish Gas Centre, Malmö, 1-74.

Sengupta, S., Ergas, S. J., Lopez-Luna, E. 2007. Investigation of solid-phase buffers for sulfur-oxidizing autotrophic denitrification, Water Environ. Res. 79; 2519–2526.

SGC (Svenskt, Gastekniskt, Center AB). 2012. Basic Data on Biogas. 2nd Edition. ISBN: 978-91-85207-10-7. Sweden. http://eks.standout.se/userfiles/file/BiogasSydost/BioMethaneRegions/BasicDataonBiogas2012-komprimerad.pdf.

Sharma, S.K., Mishra, I.M., Sharma, M.P., Saini, J.S. 1988. Effect of particle size on biogas generation from biomass residues. Biomass, 17, No. 4, pp. 251-263.

Sheehan, M., Chirillo, S., Schlossberg, J., Sammons, W., Leonard, M. 2011. Biomass Electricity: Clean Energy Subsidies for a Dirty Industry The case for ending taxpayer and ratepayer subsidies that harm public health, environment, climate, and forests. Produced by the Biomass Accountability Project in collaboration with the Energy Justice Network. http://www.pfpi.net/wp-content/uploads/2011/06/BAP-Biomass-Projects-Report.pdf.

Song Z.L., Yang G.H., Guo Y., Zhang T. 2012. Comparison of two chemical pretreatments of rice straw for biogas production by anaerobic digestion. Bioresources;7:3223e36.

Sorensen, M. 2014. Codigestion in Central Florida. BioCycle, Vol. 55, No.3, p. 48. http://www.biocycle.net/2014/03/28/codigestion-in-central-florida/.

Sparks, K. 1998. Tax Credits: An Incentive for Recycling? Resource Recycling Magazine. http://www.epa.gov/wastes/conserve/tools/rmd/docs/taxcred.pdf.

Sundqvist, J.O. 2005. How should municipal solid waste be treated-a system study of incineration material recycling, anaerobic digestion and composting. Swedish Environmental Research Institute.

Tamaru, T., Miyake, H., Kuroda, K., Nakanishi, A., Kawade, Y., Yamamoto, K., Uemura, M., Fujita, Y., Doi, R.H., Ueda, M. 2010. Genome sequence of the cellulosome-producing mesophilic organism Clostridium cellulovorans. 743B, J. Bacteriol., vol. 192, pp. 901-2.

Tale, V.P., Maki, J.S., Zitomer, D.H. 2015. Bioaugmentation of overloaded anaerobic digesters restores function and archaeal community. Water Research 70, 138, e147.

Take H., Andou Y., Nakamura Y., Kobayashi F., Kurimoto Y., Kuwahara M. 2006. Production of methane gas from Japanese cedar chips pretreated by various delignification methods. Biochem Eng J;28:30e5.

Tchobanoglous, G., Theisen, H., and Vigil, S. 1993. Integrated Solid Waste Management. McGraw-Hill, New York.

Tchobanoglous, G., Kreith, F. 2002. Handbook of Solid Waste Management. Second Edition. McGraw-Hill, New York.

Tchobanoglous, G., Burton, F. L., Stensel, H. D. 2003. Wastewater engineering: Treatment and reuse (4th ed. / revised by George Tchobanoglous, Franklin L. Burton, H., David, Stensel.). Boston, MA.: McGraw-Hill. New York.

Teghammar A., Yngvesson J., Lundin M., Taherzadeh M.J., Horvath I.S. 2010. Pretreatment of paper tube residuals for improved biogas production. Bioresour Technol;101:1206e12.

Tong, X., Smith, L.H., McCarty, P.L., 1990. Methane fermentation of selected lignocellulosic materials. Biomass 21, 239–255.

Townsend, T. G., Powell, J., Jain, P., Xu, Q., Tolaymat, T., Reinhart, D. 2015. Waste and Landfill Fundamentals. In Sustainable Practices for Landfill Design and Operation (pp. 13-34). Springer New York.

Turning Earth (Turning Earth, LLC.). 2014. Turning Earth Central Connecticut. http://turningearthllc.com/turning-earth-central-connecticut/.

Uellendahl H., Wang G., Moller H.B., Jorgensen U., Skiadas I.V., Gavala H.N., et al. 2008. Energy balance and cost-benefit analysis of biogas production from perennial energy crops pretreated by wet oxidation. Water Sci Technol;58(9):1841e7.

UN (United Nations). 2015. Sustainable Development Goals. Goal 12: Ensure sustainable consumption and production patterns. http://www.un.org/sustainabledevelopment/sustainable-consumption-production/.

UNEP (United Nations Environment Programme). 2009. Developing Integrated Solid Waste Management Plan Training Manual. Volume 3: Targets and Issues of Concern for ISWM. Division of Technology, Industry and Economics, International Environmental

Technology Centre, Osaka/Shiga, Japan. http://www.unep.org/ietc/Portals/136/Publications/Waste%20Management/ISWMPlan_Vol3.pdf.

UNEP (United Nations Environment Programme). 2015. Global Waste Management Outlook. http://www.unep.org/ietc/Portals/136/Publications/Waste%20Management/GWMO%20report/GWMO%20full%20report.pdf.

UNESCAP (United Nations Economic and Social Commission for Asia and the Pacific). 2013. United Kingdom's Climate Change Levy. Addressing Competitiveness in introducing ETR. Case Study. Low Carbon Green Growth Roadmap for Asia and the Pacific. http://www.unescap.org/sites/default/files/48.%20CS-United-Kingdom-climate-change-levy.pdf.

UNESCO (United Nations Educational, Scientific, and Cultural Organization). 2015. Green the Nutrient Economy and Reduce Ocean Hypoxia through a Policy, Regulatory and Economic Instruments to Promote Nutrient Efficiency and Recovery. http://www.unesco.org/new/en/natural-sciences/ioc-oceans/priority-areas/rio-20-ocean/10-proposals-for-the-ocean/2c-nutrient-efficiency-and-recovery/.

USDA (U.S. Department of Agriculture). 2013. Economics, Statistics, and Market Information System, Agricultural Prices: January 31, 1964 to April 30, 2012.

USDA/EPA/DOE (U.S. Department of Agriculture, U.S. Environmental Protection Agency, U.S. Department of Energy). 2014. Biogas Opportunities Roadmap. http://www.epa.gov/climatechange/Downloads/Biogas-Roadmap.pdf.

UW Oshkosh. 2015. UW Oshkosh Urban Anaerobic Dry Biogas Systems. Innovation in Sustainability and Renewable Energy. http://www.uwosh.edu/biodigester/About/uw-oshkosh-biodigester.

VALORGAS. 2010. Seventh Frame Programme Theme Energy.2009.3.2.2 Biowaste as feedstock for 2nd generation. D2.1: Compositional analysis of food waste from study sites in geographically distinct regions of Europe. http://www.valorgas.soton.ac.uk/Deliverables/111129_VALORGAS_241334_D5-1_Final_version.pdf.

van Haaren, R., Themelis, N., Goldstein, N. 2010. 17th Nationwide Survey of MSW Management in the U.S. The State of Garbage in America. A joint study by BioCycle and the Earth Engineering Center of Columbia University. Updated 10 – 2014. http://www.seas.columbia.edu/earth/wtert/sofos/SOG2010.pdf.

Vandenburgh, S. R., Ellis, T. G. 2002. Effect of varying solids concentration and organic loading on the performance of temperature phased anaerobic digestion process. Water Environment Research, 74(2), 142-148. doi: 10.2175/106143002X139857.

Vandevivere, P., De Baere, L., Verstraete, W. 2002. Types of anaerobic digesters for solid wastes, in Biomethanization of the Organic Fraction of Municipal Solid Wastes, J. Mata-Alvarez, Editor. IWA Publishing: Barcelona. p. 111-140.

Veeken, A. 2014. Personal Communication with Adrie Veeken, European Federation of Waste Management and Environmental Services (FEAD), Attero. October 13th, 2014.

Veeken, A. 2014. Personal Communication with Adrie Veeken, European Federation of Waste Management and Environmental Services (FEAD), Attero. October 7th, 2015.

Veeken, A., Hamelers, B. 1999. Effects of temperature on hydrolysis rates of selected biowaste components. Bioresource Technology 69 249±254.

Veeken, A., Hamelers, B. 2000. Effects of substrate-seed mixing and leachate recirculation on solid state digestion of biowaste. Water Science and Technology Vol 41 No 3 pp 255–262.

Vervaeren H., Hostyn K., Ghekiere G., Willems B. 2010. Biological ensilage additives as pretreatment for maize to increase the biogas production. Renew Energy;35:2089e93.

Wang H.J., Wang H. 2010. Alkaline hydrothermal pretreatment for the increase in biodegradability of leaves waste. In: Hao JM, Li JH, Hu HL, editors. Selected proceedings of the fifth international conference on waste management and technology (ICWMT 5). Irvin, California: Sci Res Publ, Inc-Srp; pp. 166e9.

Ward, A.J., Hobbs, P.J., Holliman, P.J., Jones, D.L. 2008. Optimization of the anaerobic digestion of agricultural resources. Bioresour. Technol. 99, 7928–7940.

WCED (World Commission on Environment and Development). 1987. Our Common Future. Oxford: Oxford University Press. p. 27. ISBN 019282080X.

WERF (Water Environment Research Foundation). 2011. Nutrient Recovery State of the Knowledge as of December 2010.

Westerman, P., Veal, M., Cheng, J., Zering, K. 2008. Carbon Credits for Methane Collection and Combustion. North Carolina Cooperative Extension. North Carolina. http://www.bae.ncsu.edu/extension/ext-publications/waste/animal/ag-708-methane-westerman.pdf.

Wheelabrator (Wheelabrator Ridge Energy, Inc.). 2015. Plant Facts. http://www.wtienergy.com/plants/independent-power/wheelabrator-ridge-energy-inc/.

Wilkie, A. C. 2005. Anaerobic digestion: Biology and benefits. Ithaca, NY, USA: Natural Resource, Agriculture, and Engineering Service, Cornell University.

Williams, T. 2015. Garbage Incinerators Make Comeback, Kindling Both Garbage and Debate. The New York Times. http://www.nytimes.com/2015/01/11/us/garbage-incinerators-make-comeback-kindling-both-garbage-and-debate.html?_r=0#.

Wittmer (George B. Wittmer Associates, Inc.). 2015. Products. http://www.wittmer-agricycle.com/Products.html.

World Bank. 2012. Hoornweg, D., Bhada-Tata P. What a Waste: A Global Review of Solid Waste Management. No. 15. Urban Development Series Knowledge Papers. Urban Development & Local Government Unit. The World Bank. Washington, DC, USA.

WM (Waste Management, Inc.). 2015. Personal Communication with Chris Bolyard, Manager, Waste Management, Inc., Florida. Oct. 4, 2015.

WRAP (Water & Resources Action Programme). 2010. Specification for whole digestate, separated digestate, separated liquor and separated fibre derived from the anaerobic digestion of source-segregated biodegradable materials, Publicly Available Specification (PAS) 110, U.K. http://www.langagead.com/images/pdf/PAS-110[1]%20 Specification.pdf.

WTERT (Waste-to-Energy Research and Technology Council). 2014. FAQ. Earth Engineering Center. Columbia University. http://www.seas.columbia.edu/earth/wtert/faq.html.

WWI (The Worldwatch Institute). 2013. State of the World 2013. Is Sustainability Still Possible? Island Press. Washington, DC. ISBN 13: 978-1-61091-449-9.

Xiao W.P., Clarkson W.W. 1997. Acid solubilization of lignin and bioconversion of treated newsprint to methane. Biodegradation;8:61e6.

Yang, L., Xu, F., Ge, X., Li, Y. 2015. Challenges and strategies for solid-state anaerobic digestion of lignocellulosic biomass. Renewable and Sustainable Energy Reviews, 44, 824–834. doi: 10.1016/j.rser.2015.01.002.

Yenigün, O., Demirel, B. 2013. Ammonia inhibition in anaerobic digestion: A review. Process Biochemistry 48, 901–911.

Yepsen, R. 2015. BioCycle Nationwide Survey: Residential Food Waste Collection in the US. BioCycle, Vol. 56, No. 1, p. 53.

Yokoyama, S., Matsumura, Y. 2008. The Asian Biomass Handbook: A Guide for Biomass Production and Utilization. The Japan Institute of Energy, Tokyo, Japan, 326 pp.

Yue, Z., Li, W., Yu, H. 2013. Application of rumen microorganisms for anaerobic bioconversion of lignocellulosic biomass. Volume 128, January 2013, Pages 738–744. doi:10.1016/j.biortech.2012.11.073.

Zaman, A. U. 2009. Life Cycle Environmental Assessment of Municipal Solid Waste to Energy Technologies. Global Journal of Environmental Research 3 (3): 155-163.

Zhang, R., El-Mashad, H.M., Hartman, K., Wang, F., Liu, G., Choate, C., Gamble, P. 2007. Characterization of food waste as feedstock for anaerobic digestion Bioresource Technology 98, 929–935.

Zhang, Q., He, J., Tian, M., Mao, Z., Tang, L., Zhang, J., et al. 2011. Enhancement of methane production from cassava residues by biological pretreatment using a constructed microbial consortium. Bioresour Technol;102:8899e906.

Zhang, R. 2013. United States Patent Application Publication, Pub. No.: US 2013/0260433. patentimages.storage.googleapis.com/pdfs/US20130260433.pdf.

Zhao, J., Zheng, Y., Li, Y. 2014. Fungal pretreatment of yard trimmings for enhancement of methane yield from solid-state anaerobic digestion. Bioresour Technol; 156:176–81.

Zheng, Y., Zhao, J., Xu, F., Li, Y. 2014. Pretreatment of lignocellulosic biomass for enhanced biogas production. Progress in Energy and Combustion Science 42 35e53.

Zhiying, Y., Zilin, S., Dong, Li., Yuexiang, Y., Xiaofeng, L., Tao, Z. 2015. The effects of initial substrate concentration, C/N ratio, and temperature on solid-state anaerobic digestion from composting rice straw. Bioresource Technology 177, 266–273. doi: 10.1016/j.biortech.2014.11.089.

Zhong W., Zhang Z., Luo Y., Sun S., Qiao W., Xiao M. 2011. Effect of biological pretreatments in enhancing corn straw biogas production. Bioresour Technol;102:11177e82.

Zieminski K., Romanowska I., Kowalska M. 2012. Enzymatic pretreatment of lignocellulosic wastes to improve biogas production. Waste Manag;32: 1131e7.

Zimms, M., Ver Eecke, D. 2012. Food Waste Composting Progress in the Southeast. BioCycle. Vol. 53, No. 10, p. 20. http://www.biocycle.net/2012/10/25/food-waste-composting-progress-in-the-southeast/.

Zorpas, A.A., Inglezakis, V., Koumi, C., Voukalli, I. 2011. Domestic sewage sludge (DSS) characteristics from wastewater treatment plant (WWTP) operation in warm climates conditions. A 7 years project. In: Proceedings of the 3rd International CEMEPE & SECOTOX Conference, Skiathos, Greece, June 19e24.

Zupančič, G.D., Uranjek-Ževart, N., Roš, M. 2008. Full-scale anaerobic co-digestion of organic waste and municipal sludge. Biomass Bioenergy; 32:162–7.

Zupančič, G.D., Grilc, V. 2012. Anaerobic Treatment and Biogas Production from Organic Waste, Management of Organic Waste, Dr. Sunil Kumar (Ed.), ISBN: 978-953-307-925-7, InTech, Available from: http://www.intechopen.com/books/management-of-organic-waste/anaerobic-treatment-and-biogas-productionfrom-organic-wastes.

ZWE (Zero Waste Energy, LLC.). 2013a. Our Projects. http://zerowasteenergy.com/what-we-do/our-projects/.

ZWE (Zero Waste Energy, LLC.). 2013b. Our Solutions. Dry Anaerobic Digestion. http://zerowasteenergy.com/our-solutions/dry-anaerobic-digestion/.

ZWE (Zero Waste Energy, LLC). 2015. Personal Communication with Chris Axton, ZWE Monterey Facility Manager. May 5, 2015. Monterey, CA.

APPENDIX A. DATABASE OF HS-AD PROJECTS IN THE US.

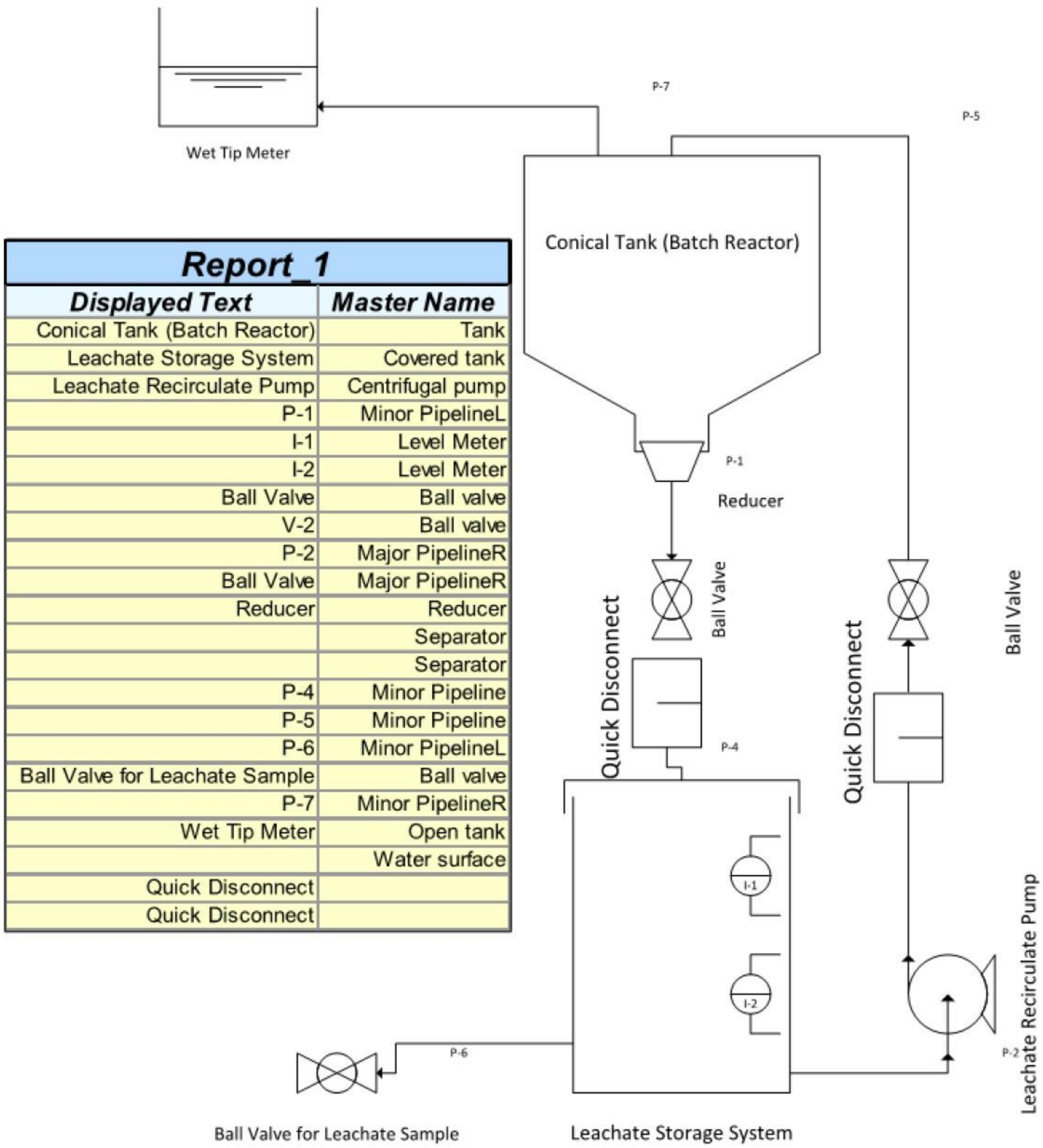
Location	Company/ Design	Funding Sources	Start-up	Capacity	Cost	Gas Utilization	Digestate Utilization	Source(s)
Clinton, NC	Orbit Energy	NR	2002	3,400 TPY	NR	CHP: unspecified	Marketed as Class A compost	Orbit Energy, 2015
Oshkosh, WI	BioFerm Energy Systems	Midwestern Disaster Area Revenue Bond, State of Wisconsin grant, U.S. Department of Energy grant, the U.S. Treasury Section 1603 grant	2012	10,000 TPY	$5 M	CHP: 370 kW, surplus electricity sold to Wisconsin Public Service	Sold as soil amendment	UW Oshkosh, 2015
Sacramento, CA (Am. River Packaging)	CleanWorld Corporation	Five Star Bank, Central Valley Community Bank, the California Energy Commission, CalRecycle, Synergex	2012	40,000 TPY	NR	CNG: up to 700,000 diesel gallon equiv./yr	NR	CleanWorld, 2012; CleanWorld, 2015b
Monterey, CA	Zero Waste Energy	NR	2013	5,000 TPY	NR	CHP: 100 kW, surplus electricity sold to neighboring wastewater treatment plant	2,200 TPY sold to local farmers	ZWE, 2013a
San Jose, CA	Zero Waste Energy	NR	2013	90,000 TPY	NR	CHP: 1.6 MW, surplus electricity sold to neighboring wastewater treatment plant	NR	ZWE, 2013a
Davis, CA	CleanWorld Corporation	First Northern Bank, CalRecycle, the U.S. Department of Energy	2013	20,000 TPY	NR	Microturbines: 640 kW	Liquid fertilizer, onsite composting is expected soon	CleanWorld, 2015b
South San Francisco, CA	Zero Waste Energy	NR	2014	11,200 TPY	NR	CNG: 120,000 diesel gallon equiv./yr	NR	ZWE, 2013a.
Sacramento, CA	CleanWorld Corporation	NR	2014	10,000 TPY, Expanding to 40,000	NR	NR	NR	CalRecycle, 2014a; CleanWorld, 2015b
Perris, CA	Eisenmann Corporation	NR	2015 (projected), under construction	80,000 TPY, may expand to 300,000	NR	CNG: up to 1,000,000 diesel gallon equiv./yr	NR	CalRecycle, 2014a; Eisenmann, 2012; Eisenmann, 2014
Chicago, IL	Eisenmann Corporation	Illinois Department of Commerce and Economic Opportunity (DCEO); Partnership with The Plant	2015 (projected)	5,000 TPY, may expand to 11,000	NR	CHP: 200 kW	NR	Eisenmann, 2012; Eisenmann, 2014
Tulare, CA	Harvest Power	California Energy Commission grant; Partnership with Colony Energy Partners	2015 (projected), permitting	Up to 182,500 TPY	$25-30M (projected)	CNG: up to 2,800,000 diesel gallon equiv./yr + CHP	NR	CalRecycle, 2014a; Fletcher, 2015

Appendix A (Continued)

Location	Company/ Design	Funding Sources	Start-up	Capacity	Cost	Gas Utilization	Digestate Utilization	Source(s)
Montgomery, AL	Zero Waste Energy	Partnership with IREP (Infinitus Renewable Energy Park) and the City of Montgomery	Phase 1 (MRF) began in 2015	12,500 TPY	NR	CNG: 130,000-150,000 diesel gallon equiv./yr	NR	ZWE, 2013a
Vacaville, CA	Organic Waste Systems	California Energy Commission grant; California Alternative Energy and Advanced Transportation Financing Authority	2016 (projected), permitting	65,000 TPY	$26 M (projected)	CNG: 1,100,000 diesel gallon equiv./yr (projected)	40,000 TPY liquid and solid fertilizer	CalRecycle, 2014a; Ruiz, 2014; OWS, 2015
Hartford, CT	Turning Earth	NR	2016 (projected)	50,000 TPY	$20M (projected)	CHP: 1.4 MW	40,000 cubic yards of compost to be marketed	Turning Earth, 2014
Johnston, RI	Orbit Energy	Partnership with National Grid and Blue Sphere Corporation	2016 (projected)	91,250 TPY	$18.9M	CHP: 3.2 MW	13,000 -14,600 TPY of compost to be marketed	Faulkner, 2015; Orbit Energy 2015
Des Moines, WA	Orbit Energy	Partnership with Puget Sound Energy	2016 (projected)	NR	NR	CHP: 4.5 MW	NR	Orbit Energy, 2015
Charlotte, NC	Orbit Energy	Partnership with Duke Energy and Blue Sphere Corporation	2017 (projected)	NR	NR	CHP: 4.8 MW	NR	Orbit Energy, 2015
Napa, CA	Zero Waste Energy	California Energy Commission grant; City of Napa; Napa Recycling and Waste Services, LLC.	2017 (projected)	25,000 TPY	NR	CNG: 330,000 diesel gallon equiv./yr	20,447 TPY of compost to sell to local farmers	ZWE, 2013a
Oxnard, CA	Zero Waste Energy	Partnership with Agromin, Inc.	2017 (projected)	20,000 TPY	NR	NR	NR	ZWE, 2013a
San Leandro, CA	Zero Waste Energy	NR	2017 (projected)	20,000 TPY	NR	NR	NR	ZWE, 2013a
Contra Costa County, CA	Zero Waste Energy	NR	2017 (projected)	20,000 TPY	NR	NR	NR	ZWE, 2013a
Delano, MN	Zero Waste Energy	NR	2017 (projected)	40,000 TPY	NR	NR	NR	ZWE, 2013a
Minneapolis, MN	Zero Waste Energy	NR	2017 (projected)	30,000 TPY	NR	NR	NR	ZWE, 2013a

APPENDIX B. PILOT-SCALE HS-AD

An additional line of experiments are planned to be conducted at the pilot-scale using a 10-gallon percolate recirculating HS-AD system that was designed by George Dick. Figure B1 shows the process flow diagram and parts list of the pilot-scale system and Figure B2 shows the fully constructed system. One preliminary study was conducted using yard waste inoculated with wastewater sludge, during which 16 days of biogas data was collected (Figure B3) before challenges were encountered with gas leakage and biogas measurement via wet-tip meter. Efforts are ongoing to develop sound operational techniques for pilot-scale experiments.



Report_1	
Displayed Text	**Master Name**
Conical Tank (Batch Reactor)	Tank
Leachate Storage System	Covered tank
Leachate Recirculate Pump	Centrifugal pump
P-1	Minor PipelineL
I-1	Level Meter
I-2	Level Meter
Ball Valve	Ball valve
V-2	Ball valve
P-2	Major PipelineR
Ball Valve	Major PipelineR
Reducer	Reducer
	Separator
	Separator
P-4	Minor Pipeline
P-5	Minor Pipeline
P-6	Minor PipelineL
Ball Valve for Leachate Sample	Ball valve
P-7	Minor PipelineR
Wet Tip Meter	Open tank
	Water surface
Quick Disconnect	
Quick Disconnect	

Figure B1: Pilot-scale HS-AD system process flow diagram and parts list.

Figure B2: Photograph of fully-constructed 10-gallon pilot-scale HS-AD system.

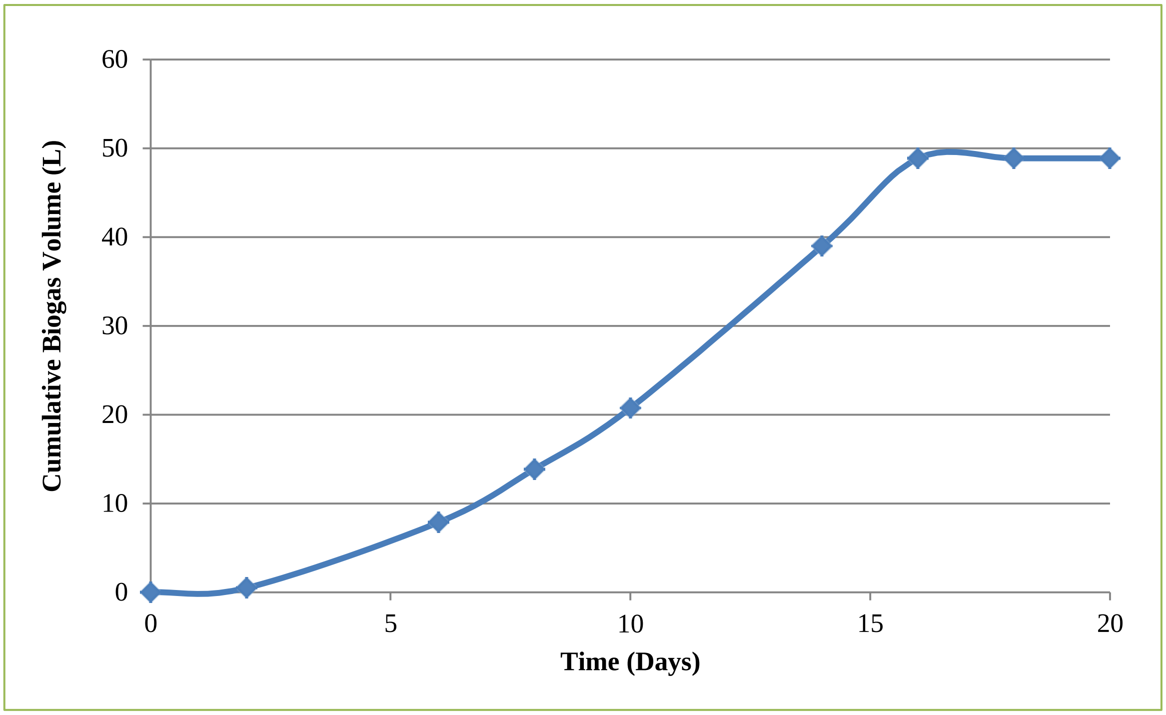


Figure B3: Cumulative biogas data from preliminary pilot-scale HS-AD experiment.

APPENDIX C: BENCH-SCALE BATCH HS-AD MASS BALANCE

A mass balance was conducted for Phases 1 and 2 of bench-scale batch HS-AD using the measured initial and final masses of feedstock (mass in) and digestate (mass out), the measured volume of methane generated by the digesters, the calculated carbon dioxide volume generated by the digesters, and the densities of methane and carbon dioxide at 35°C. The mass balance assumes that all of the non-methane biogas generated by the digesters is carbon dioxide (i.e. error associated with non-methane and non-carbon dioxide fractions of the biogas generated by the digesters is negligible). The idea behind the mass balance is that the change in mass in the digesters from the beginning to the end of the study should be within an acceptable error (<2%) of the mass of biogas generated over the course of the study. If this is the case, it validates that there was no significant error in the study with regard to biogas volume and quality measurements. The mass balance is shown below. The slight % error in the mass balance likely resulted from human error in biogas volume measurements.

Mass In = Mass Out

Mass of Feedstock (M1) = Mass of Digestate (M2) + Mass of CH_4 (M3) + Mass of CO_2 (M4)

% Error = ABS[M1 – (M2+M3+M4)] ÷ M1 x 100%

	Phase 1		Phase 2	
	Bioaugmented	Control	Bioaugmented	Control
Mass In = Initial Mass = M1 (g)	**122.00**	**102.50**	**124.00**	**132.00**
M2, Average Final Mass (g)	*116.30*	*101.45*	*120.43*	*128.87*
Average Volume of CH_4 Generated (L)	2.175	1.09	0.854	0.583
M3, Mass of CH_4 assuming 0.656 g/L (g)	*1.43*	*0.72*	*0.56*	*0.38*
Average Volume of CO_2 Generated (L)	1.641	0.822	0.593	0.405
M4, Mass of CO_2 assuming 1.98 g/L (g)	*3.25*	*1.63*	*1.18*	*0.80*
Mass Out = M2+M3+M4 (g)	**120.98**	**103.79**	**122.16**	**130.06**
% Error	0.84%	1.26%	1.48%	1.47%