UNIVERSITY OF SOUTH FLORIDA

Phase II Bioenergy Production from MSW by High Solids Anaerobic Digestion

Sarina J. Ergas, PhD, PE, BCEE
Qiong Zhang, PhD
Dept. of Civil & Environmental Engineering
USF, Tampa, FL

TAG Kick-Off Meeting
March 28, 2017

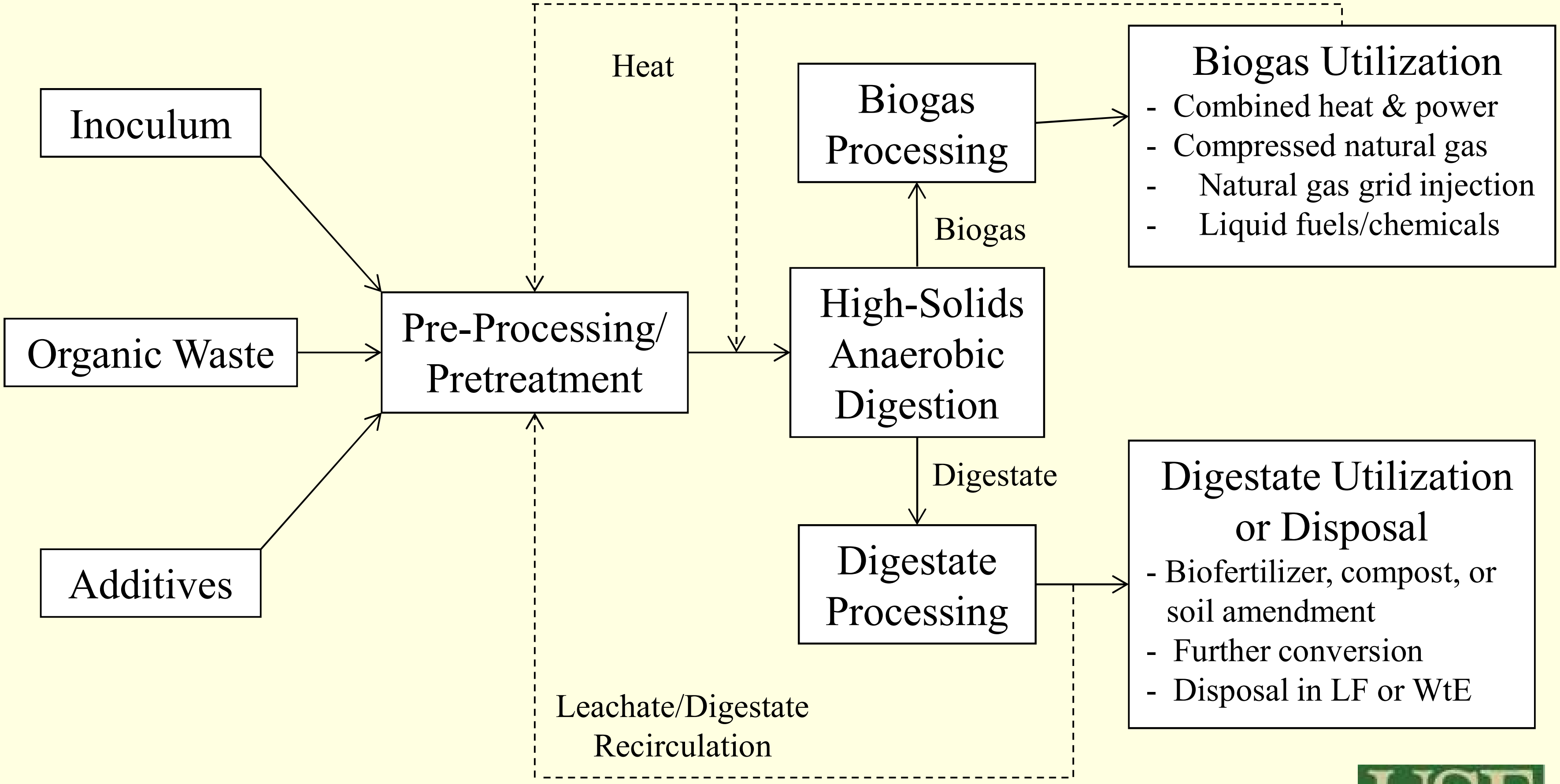
Anaerobic Digestion of MSW

- Common in Europe and increasing in US
- Diversion of organic fraction of MSW (OFMSW) for separate anaerobic digestion (AD)
  - Enhance energy recovery
  - Produce higher quality biogas
  - Reduce GHG emissions
  - Extend landfill life
  - Improved leachate quality
  - Produce a soil amendment (compost)
  - Offsets impacts of inorganic fertilizer production

USF

Intro to HS-AD (a.k.a. SS-AD)

- *Designed to process feedstocks with > 15% total solids content.*



Inoculum

Organic Waste

Additives

Pre-Processing/ Pretreatment

Heat

High-Solids Anaerobic Digestion

Biogas

Biogas Processing

Biogas Utilization
- Combined heat & power
- Compressed natural gas
- Natural gas grid injection
- Liquid fuels/chemicals

Digestate

Digestate Processing

Digestate Utilization or Disposal
- Biofertilizer, compost, or soil amendment
- Further conversion
- Disposal in LF or WtE

Leachate/Digestate Recirculation

USF

Zero Waste Energy, Monterey

USF

Advantages of HS-AD vs. L-AD

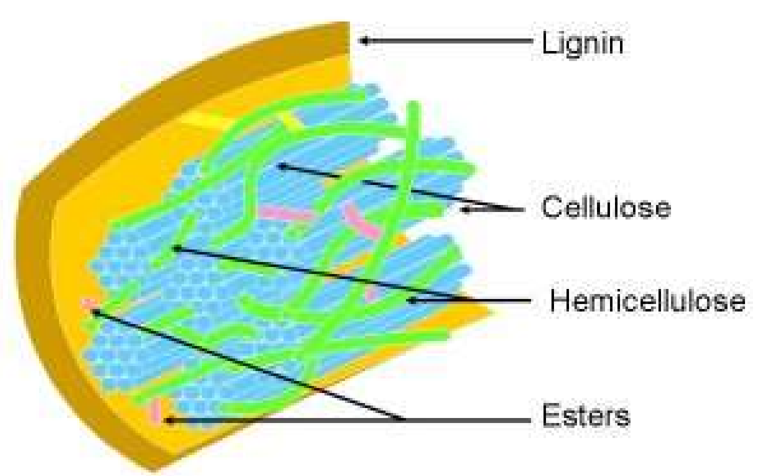
- Reduced parasitic energy demands
- Reduced reactor volume requirements
- Reduced water usage and leachate generation

Sordisep Process, Brecht

BioFERM Process

HS-AD Challenges

- Slow start up times & large reactor volumes:
  - Lignin biodegradation barrier
  - Co-digestion with pulp & paper AD sludge (P&P) potential to increase biogas production.



www.lignofuel.com

- Lack of knowledge among MSW stakeholders.
- Lack of life cycle & economic assessments specifically looking at HS-AD sustainability.

Phase I Obj. 1: What is the state-of-the-art of HS-AD?

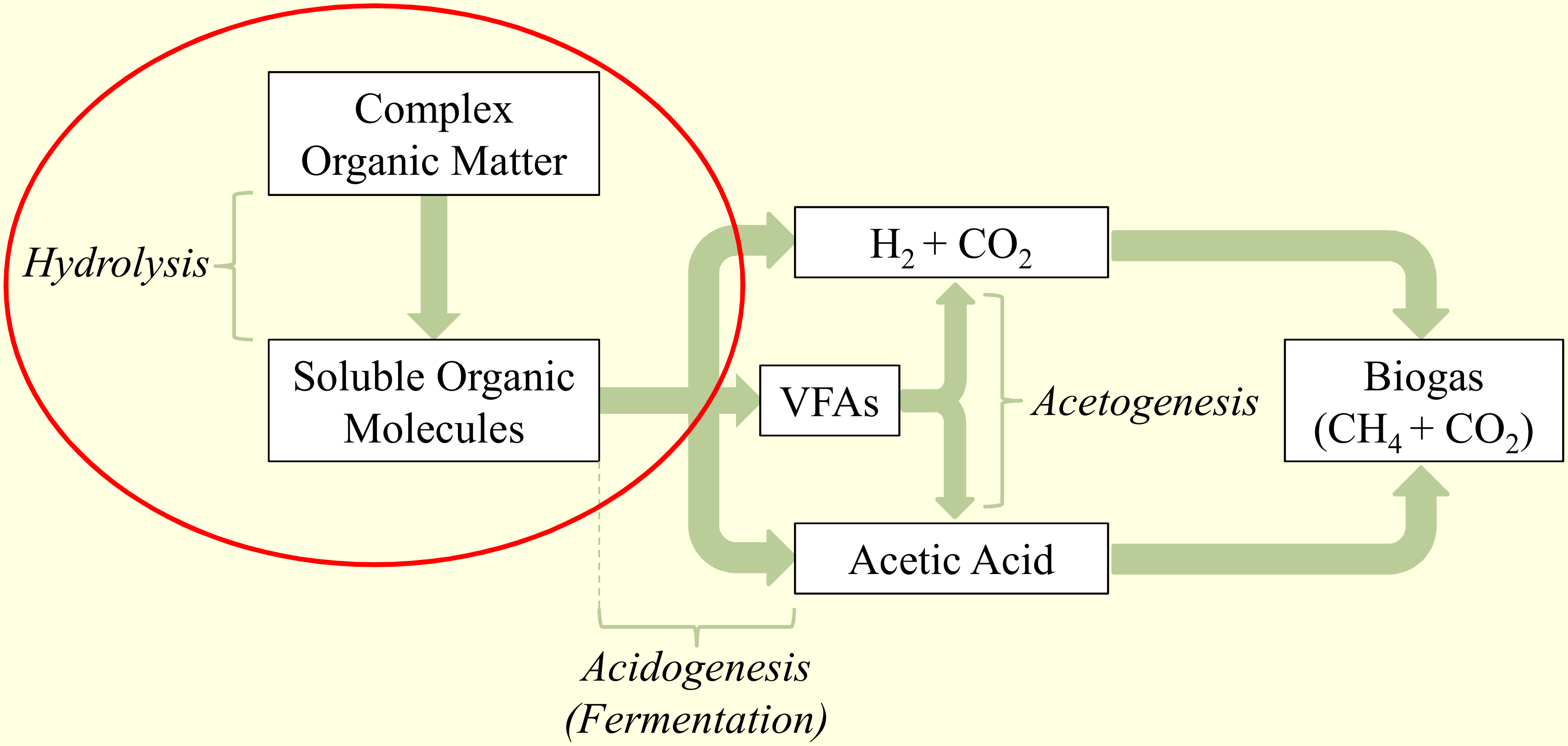
- Goals
  - Understand trends and identify primary drivers in the industry
  - Identify appropriate technologies for implementation in FL
- Methodology
  - Review published and “grey” literature
  - Developed chronological database of US HS-AD projects
  - Visits to facilities in California and the Netherlands

Major Findings Obj. 1

- Policy promoting OFMSW recycling in the US increasing:
  - 20 states now have yard waste landfill bans, 5 have food waste bans
  - 7 have landfill diversion targets
  - Over 200 communities offer separate collection of food waste
  - *Required* source-separation in San Francisco, Seattle, VT, and CT
  - 29 states now have renewable portfolio standards
- HS-AD implementation parallels policy development
  - HS-AD has surpassed L-AD for OSFMW processing capacity
  - CA is leading the way with policy and HS-AD development
- Single-stage, batch, thermophilic, “garage” type systems are the most suitable for Florida
  - Low cost, simple operation, reliable, compost pathogen free

Phase I Obj. 2: Enhancing Bioenergy Production

- The Lignocellulosic Challenge



Complex Organic Matter

Hydrolysis

Soluble Organic Molecules

$H_2 + CO_2$

VFAs

Acetic Acid

Acetogenesis

Biogas ($CH_4 + CO_2$)

Acidogenesis (Fermentation)

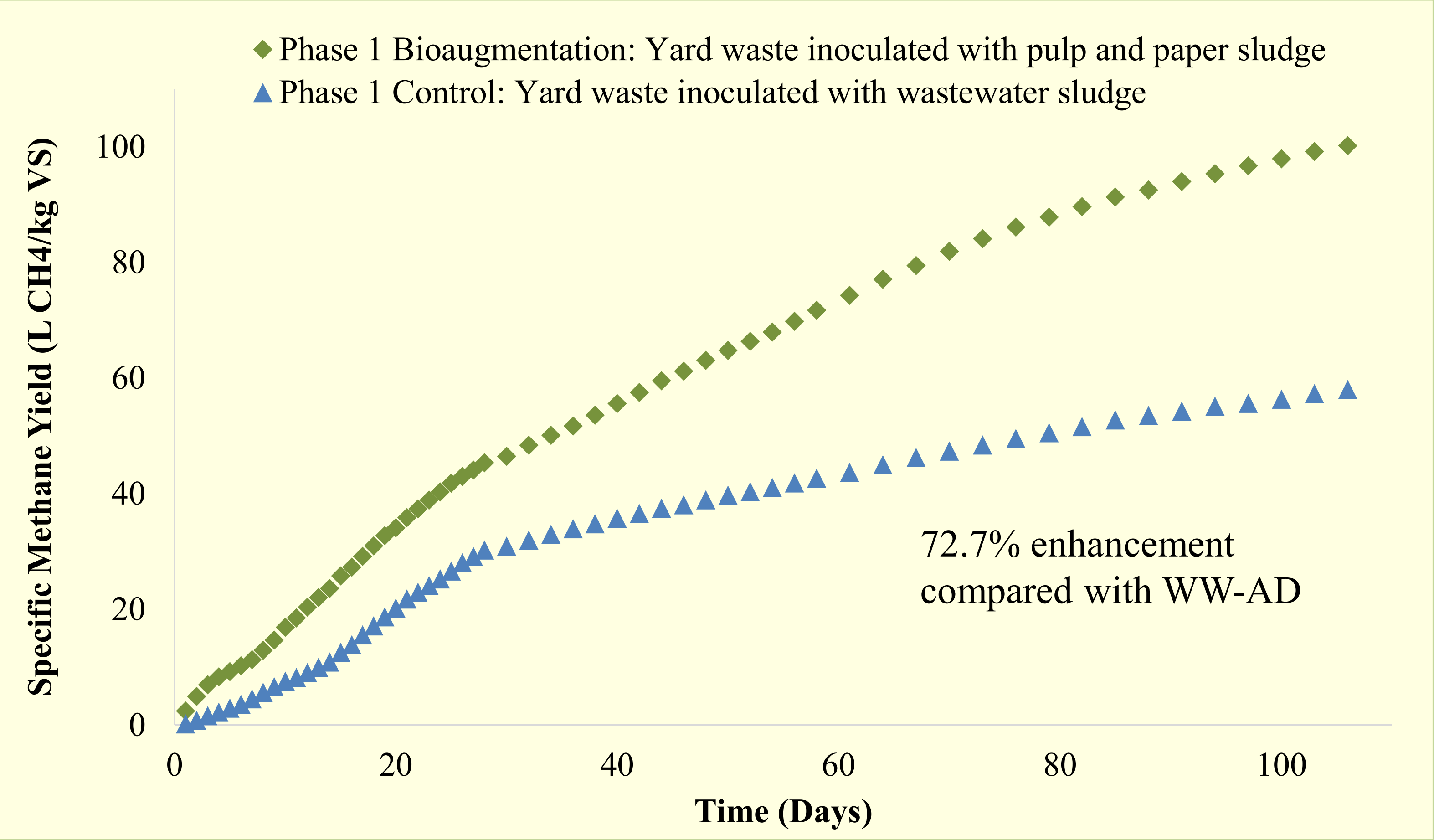
Phase I Obj. 2: Enhancing Bioenergy Production

- Goals
  - Study the effects of bioaugmentation with P&P on methane yields in HS-AD of yard waste
  - Determine whether enhancements can be sustained via digestate recirculation
- Hypothesis
  - Hydrolytic microorganisms in sludge from AD of P&P are adapted to lignocellulosic waste and therefore have a greater capacity to degrade lignocellulosics than a conventional inoculum.

USF

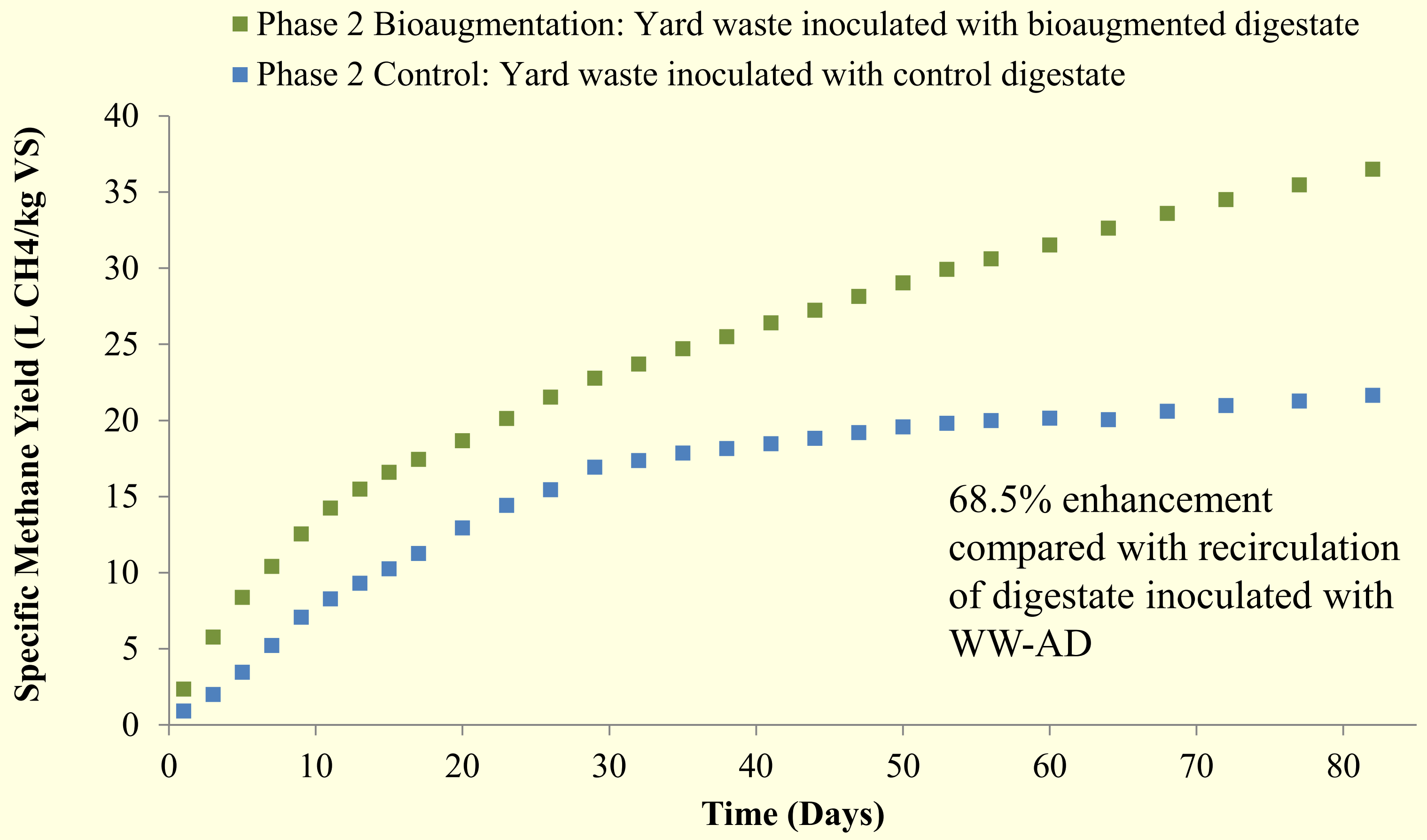
Materials & Methods

Methane Yields – Direct Inoculum



72.7% enhancement compared with WW-AD

Methane Yields - Recirculation



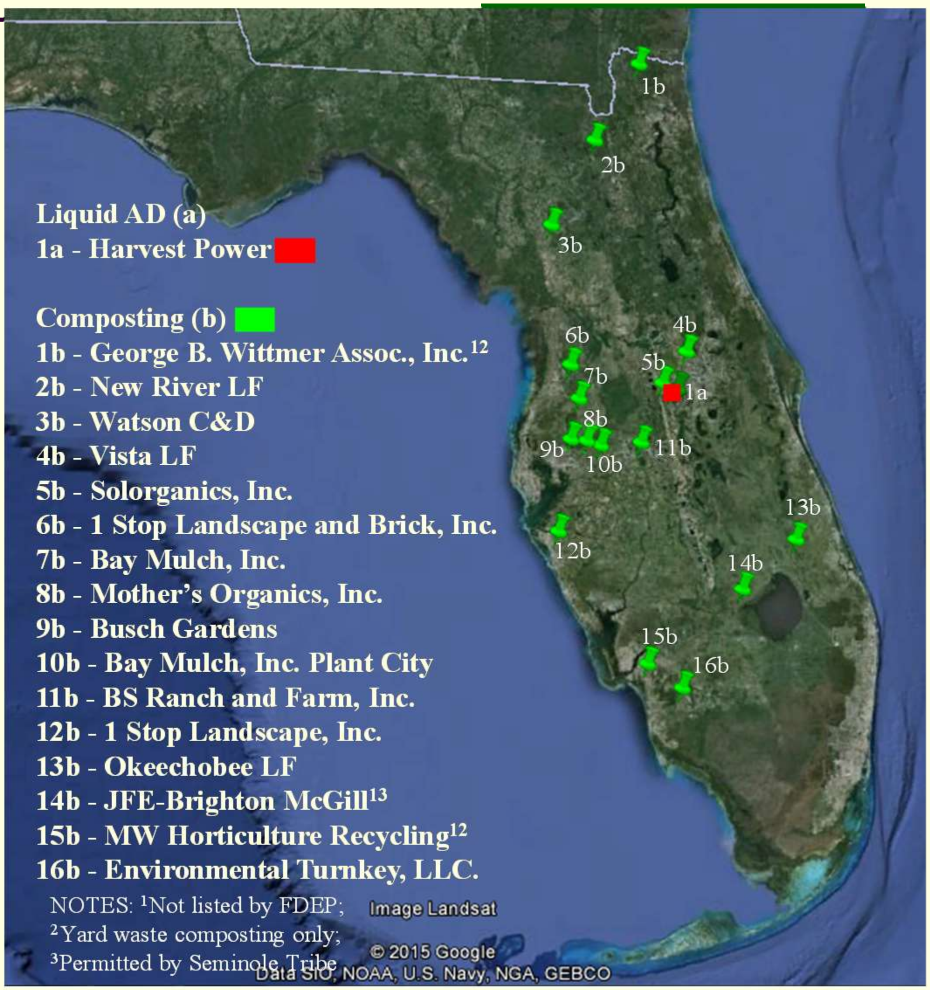
68.5% enhancement compared with recirculation of digestate inoculated with WW-AD

Major Findings Obj. 2

- Significant methane yield enhancements with P&P co-digestion
- Chemical and lignocellulosic data support hypothesis
  - VFA concentrations indicate methanogenesis was rate-limiting in bioaugmented digesters while hydrolysis was limiting in control digesters
  - 16%, 16%, and 2% less lignin, cellulose, and hemicellulose in bioaugmented digestate relative to control digestate
- Comparison with other pre-treatment methods:
  - Potentially lower cost, less energy & chemicals and waste generation than thermal or chemical pretreatment.

Phase I Obj. 3: Potential for HS-AD Implementation in FL

- Goals
  - Identify best FL counties for HS-AD implementation:
    - Existing MSW infrastructure
    - Potential bioenergy production & GHG emissions reductions
    - Potential for nutrient recovery.
  - Evaluate economics and develop policy recommendations.



Liquid AD (a)
1a - Harvest Power 🟥

Composting (b) 🟩
1b - George B. Wittmer Assoc., Inc.[1,2]
2b - New River LF
3b - Watson C&D
4b - Vista LF
5b - Solorganics, Inc.
6b - 1 Stop Landscape and Brick, Inc.
7b - Bay Mulch, Inc.
8b - Mother's Organics, Inc.
9b - Busch Gardens
10b - Bay Mulch, Inc. Plant City
11b - BS Ranch and Farm, Inc.
12b - 1 Stop Landscape, Inc.
13b - Okeechobee LF
14b - JFE-Brighton McGill[1,3]
15b - MW Horticulture Recycling[1,2]
16b - Environmental Turnkey, LLC.

NOTES: [1]Not listed by FDEP;
[2]Yard waste composting only;
[3]Permitted by Seminole Tribe

OFMSW "Recycling" Infrastructure

Incentives for HS-AD in Florida

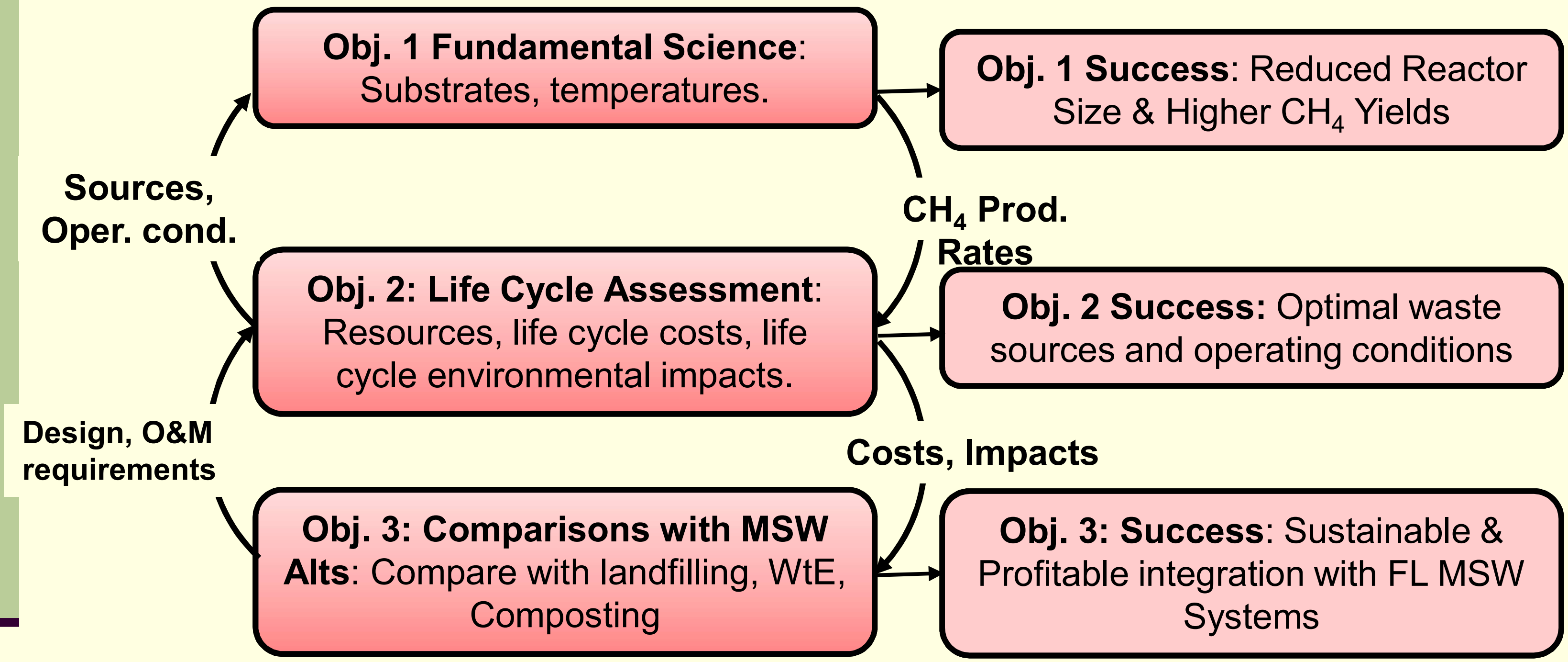
- 75% recycling goal by 2020
  - Current statewide recycling rate = 50%
    - Yard and food waste recycling rates = 51% and 7%, respectively
  - 12% of waste stream is yard waste and 7% is food waste
    - *Up to 13% increase in recycling rate achievable via OFMSW recycling*
- Renewable energy generation
  - Up to 500MW of renewable energy could be produced
    - 175 MW electricity (~1% of FL total demand, > $120M) + 200 MW heat
    - OR: 80 million DGEs of CNG per year (~11.5% of FL total demand)
    - 660,000 MTCO_2E per year offset (~$3.2M - $400M)
- Nutrient recovery
  - Up to 7,000 TPY and 3,500 TPY of N and P, respectively (~$ 2.1M)

Obj. 3 Major Findings

- Outlook is promising, especially in highly populated counties
- Potential environmental and economic benefits are significant
- Economic sustainability is reliant upon numerous factors
    - Local tipping fees
    - Quantity, quality, and proximity of available feedstock
    - Energy and compost markets and renewable energy incentives
    - *Public-private partnerships*
- Legislative incentive has potential to greatly improve the feasibility of HS-AD implementation; recommendations:
    - Bans on landfilling food waste and yard waste
    - Mandated source-separation of food waste and yard waste
    - Policies promoting compost use and renewable energy generation

Phase II: Goals & Objectives

- **The overall goal** is to improve the environmental and economic sustainability of HS-AD of OFMSW in Florida. Specific objectives for Phase II are to:
  - Investigate the performance of HS-AD of OFMSW with varying substrate ratios (yard, food, biosolids) and temperatures (35, 55 °C).
  - Apply life cycle analysis (LCA) to guide the selection of waste sources and operating conditions for HS-AD and
  - Compare HS-AD with other waste management options (e.g., landfilling, waste to energy (WtE), composting) to ensure economic and environmental sustainability.



Obj. 1 Fundamental Science: Substrates, temperatures.

Obj. 1 Success: Reduced Reactor Size & Higher CH_4 Yields

Sources, Oper. cond.

CH_4 Prod. Rates

Obj. 2: Life Cycle Assessment: Resources, life cycle costs, life cycle environmental impacts.

Obj. 2 Success: Optimal waste sources and operating conditions

Design, O&M requirements

Costs, Impacts

Obj. 3: Comparisons with MSW Alts: Compare with landfilling, WtE, Composting

Obj. 3: Success: Sustainable & Profitable integration with FL MSW Systems

Research Plan: Experimental

Stage	**Scale**	**Substrate**	**Temp. °C**	**Effect of:**
I	Bench	YW, FW YW, FW, BS YW, FW, BS, OS	35	BS and OS
II	Bench	YW, FW, BS	35, 55	Temperature
III	Bench	YW/FW/BS	Based on Phase II	Substrate ratios
IV	Pilot	YW, FW, BS		Scale
V	Pilot	Based on LCA		Data for LCA

- Address research gaps identified in Phase I related to biosolids (BS) and alkalinity sources.
- Improved methodology – greater repeatability.
- Provide data for LCA studies.

Research Plan: LCA

- Used to investigate tradeoffs in energy consumed in collection, transport & processing and produced by HS-AD.
- Screening LCA includes collection, transportation & processing in Hillsborough Co.
- Waste sources mapped using GIS to estimate transportation distances.
- Energy for collection & transport - Hillsborough MSW Management System.
- Energy produced from wastes and conditions - literature & experiments.
- System boundary: cradle-to-gate; Functional unit: 1 L CH_4.
- Impact categories: energy demand, GHGs, acidification, eutrophication.
- Screening LCA will guide selection of waste sources and operating conditions for pilot experiments.

Research Plan: Life Cycle Cost Analysis

- Comparison of HS-AD, landfilling, WtE, and composting.
- Comparison based on the dry weight of waste processed since different strategies have different beneficial products, for example (energy, compost).
- MSW infrastructure mapped using GIS to estimate collection and transportation costs.
- LCCA will include infrastructure, O&M, collection and transportation costs and revenue from beneficial products.
- HS-AD infrastructure costs obtained from literature, existing HS-AD installations.
- Cost information for LF, WtE and composting obtained from Hillsborough County's MSW Management System.

Phase II: Preliminary BMPs Assays

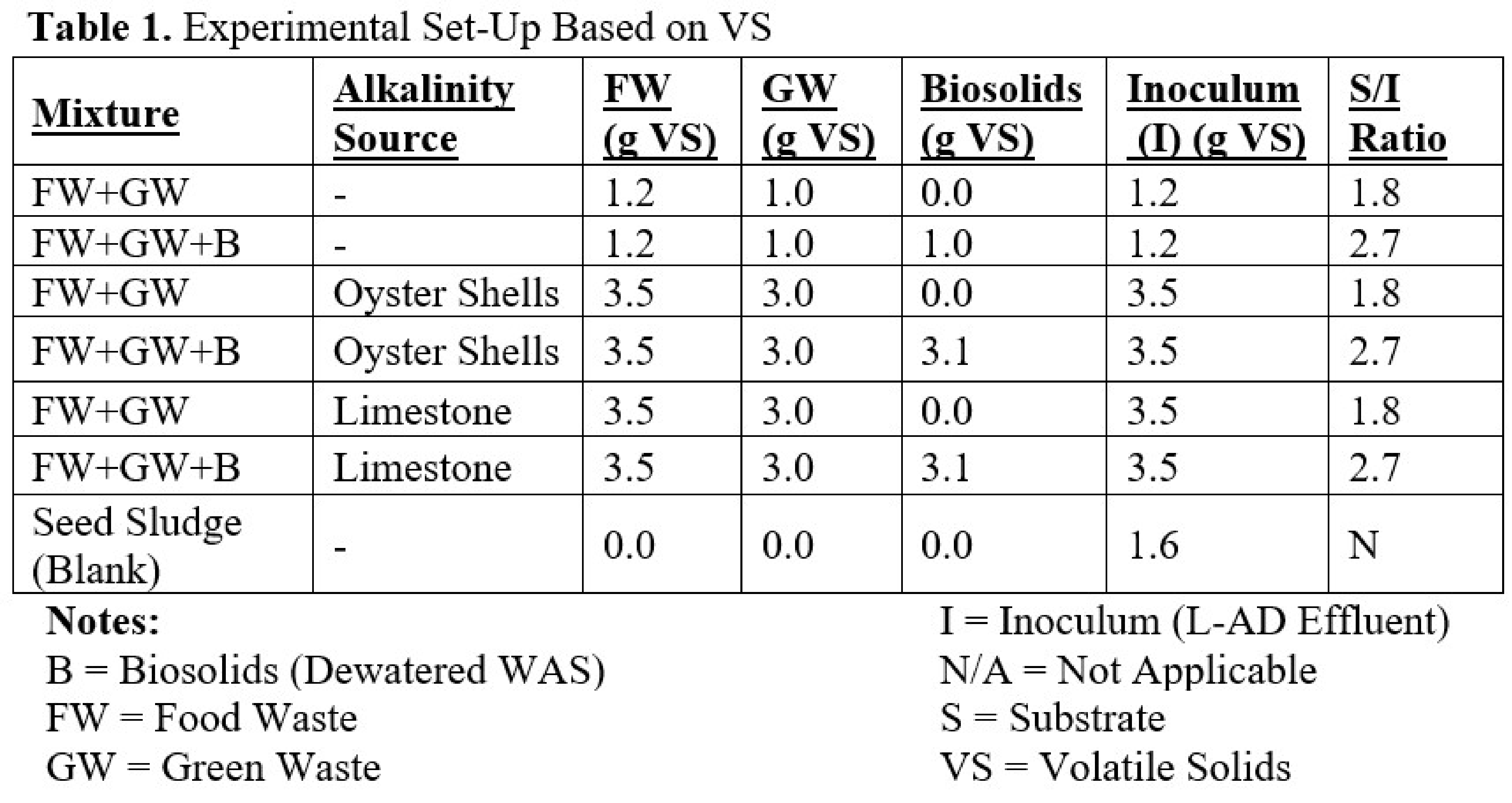


Table 1. Experimental Set-Up Based on VS

Mixture	**Alkalinity Source**	**FW (g VS)**	**GW (g VS)**	**Biosolids (g VS)**	**Inoculum (I) (g VS)**	**S/I Ratio**
FW+GW	-	1.2	1.0	0.0	1.2	1.8
FW+GW+B	-	1.2	1.0	1.0	1.2	2.7
FW+GW	Oyster Shells	3.5	3.0	0.0	3.5	1.8
FW+GW+B	Oyster Shells	3.5	3.0	3.1	3.5	2.7
FW+GW	Limestone	3.5	3.0	0.0	3.5	1.8
FW+GW+B	Limestone	3.5	3.0	3.1	3.5	2.7
Seed Sludge (Blank)	-	0.0	0.0	0.0	1.6	N

Notes:

B = Biosolids (Dewatered WAS)
FW = Food Waste
GW = Green Waste
I = Inoculum (L-AD Effluent)
N/A = Not Applicable
S = Substrate
VS = Volatile Solids

CH_4 Yields for OFMSW With &Without Biosolids

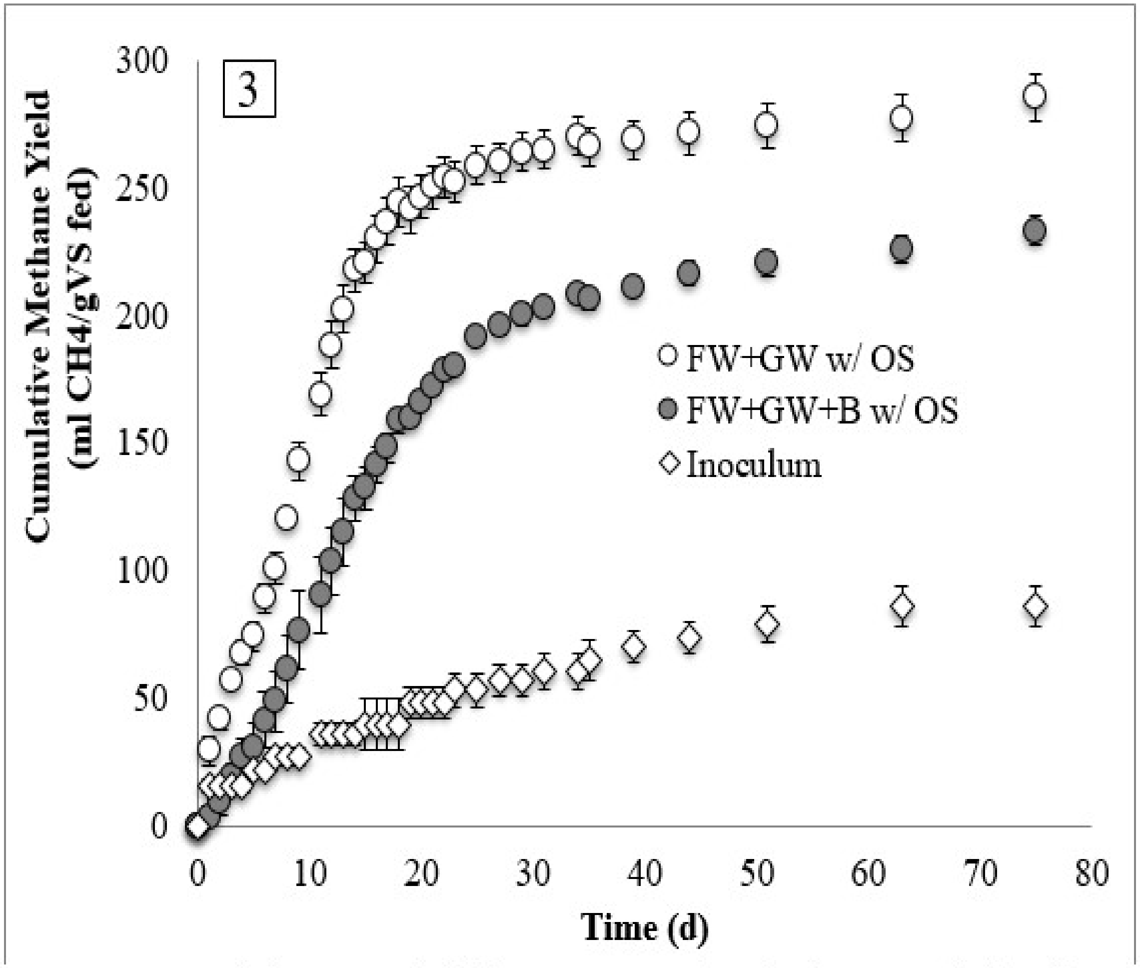


Figure 3. Cumulative CH_4 Yield for FW+GW w/Crushed Oyster Shells with and without Biosolids

- <u>CH_4 Yields Lower When B Added to FW+GW</u>
- May be due to differences in substrate to inoculum ratios (S/I) with and without B
- <u>Advantages of biosolids addition:</u>
    - <u>Increased overall bioenergy production,</u>
    - <u>Recovery of nutrients, and</u>
    - <u>Diversion of biosolids from land application or landfilling</u>

CH_4 Yields With Different Alkalinity Sources

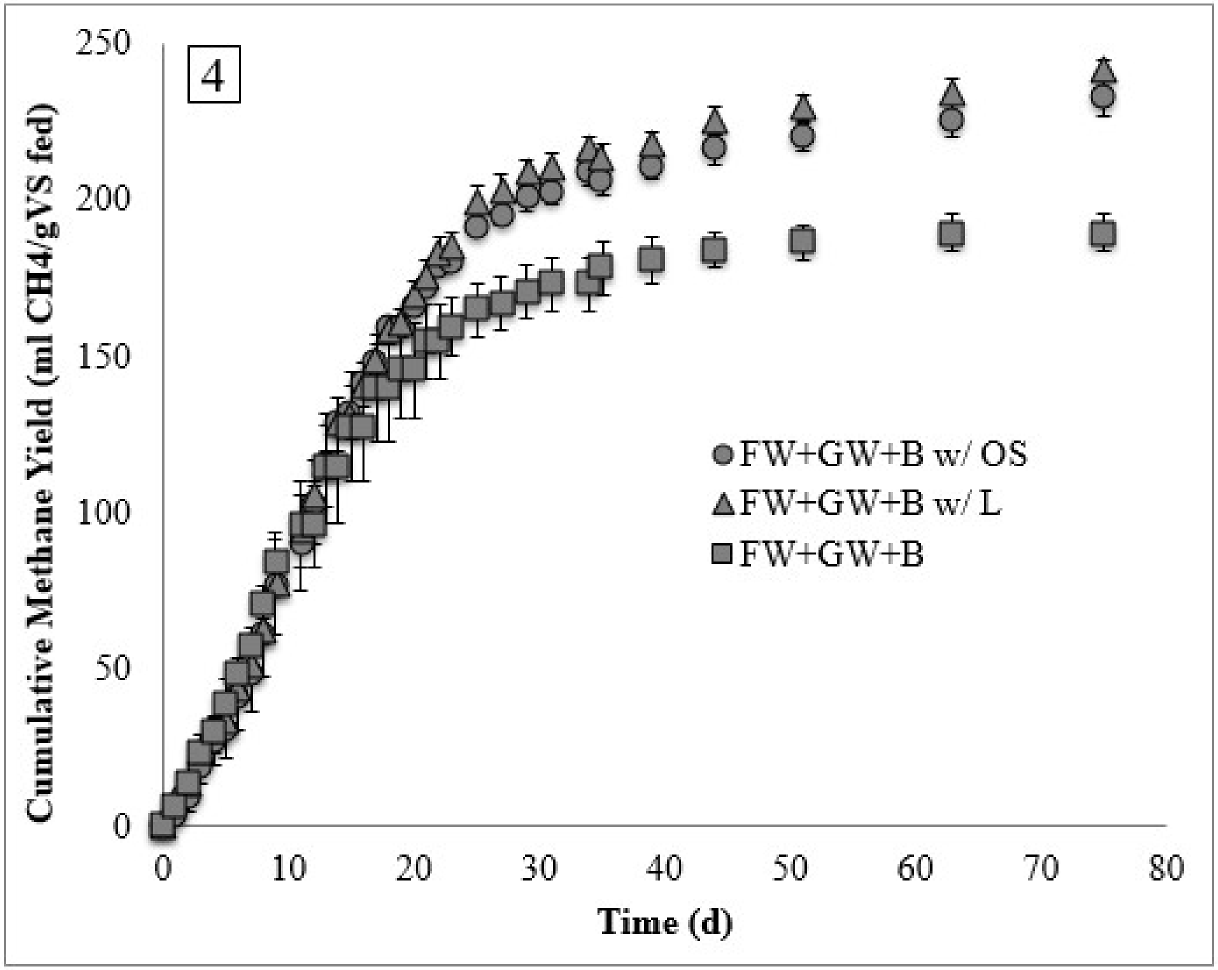
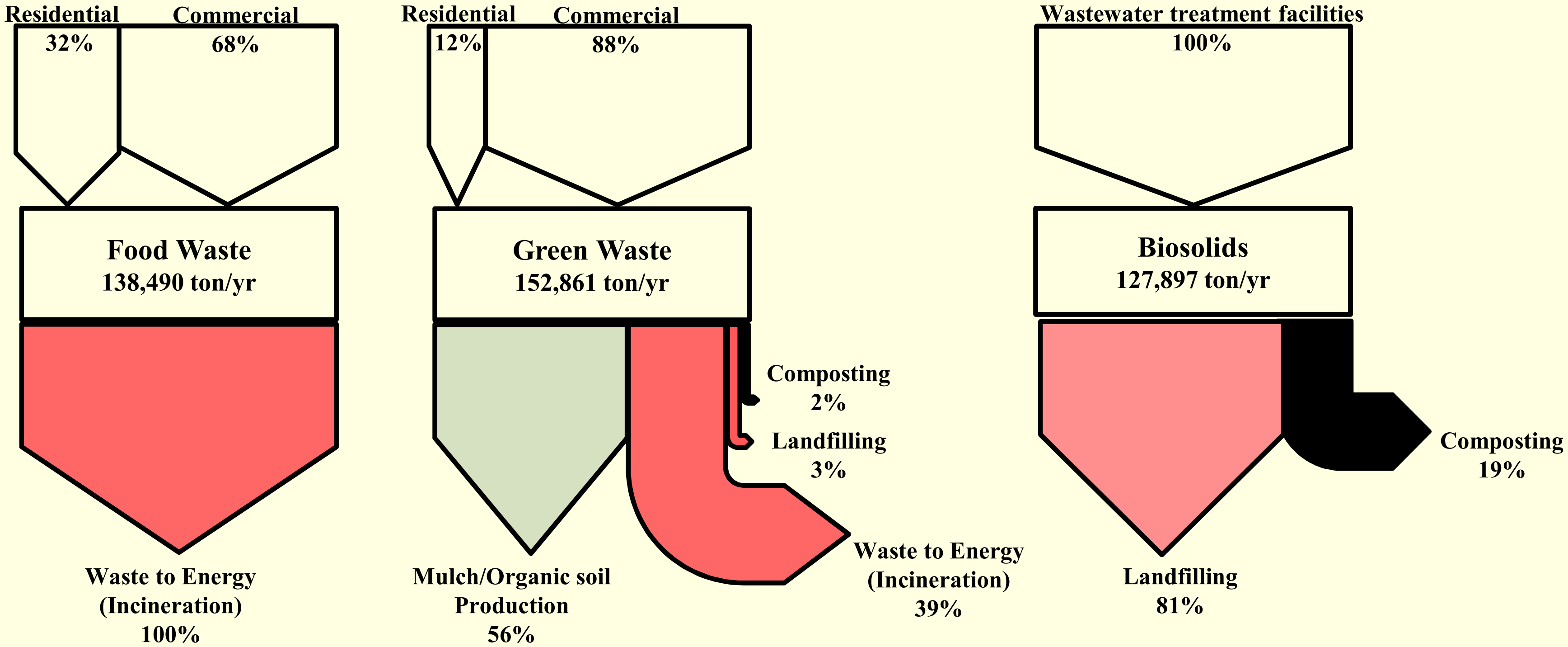


Figure 4. Cumulative CH_4 Yield for FW+GW+B w/Crushed Oyster Shells and Limestone as Alkalinity Sources

- CH_4 Yields Higher With added alkalinity
- May be because of VFA production and localized alkalinity imbalances within micro-niches due to incomplete mixing
- No significant differences between OS and L

Production & Management Flow for FW, GW, & B in 2015 for Hillsborough County



USF

Life Cycle Cost Analysis (LCCA) of HS-AcD

- **Life Cycle Cost (LCC):**

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

where

- C_I: Initial Cost
- $C_{O\&M}$: Operation and Maintenance Cost
- $C_{C\&T}$: Collection and Transportation Cost
- $C_{R,t\&b\&h}$: Revenues from Tipping Fee Saving and Digestate and Heat Sales
- $C_{R,e}$: Revenue from Electricity Sale
- UPV: Uniform Present Value Factor
- UPV*: Non-Uniform Present Value Factor

Parameters Considered in LCCA

Input	**Value**	**Reference**
Discount or Interest Rate (%)	1.9	USIR 2016
Escalation Rate (%)	0.65	EERC 2017
Operation and Maintenance Cost Rate ($/ton)	72	Vavrin et al. 2014
Average Hauling Distance (miles)	50	Assumed
Collection and Transportation Rate ($/mile/ton)	0.1	Faucette et al. 2002
Tipping Fee ($/ton)	20	County 2016
L ($/kg)	1.3	Survey 2017
L Consumption (kg/ton organic wastes)	109	Obtained from our experiments
OS ($/kg)	0	Assumed
OS Consumption (kg/ton organic wastes)	82	Obtained from our experiments
Heating Value (kWh/m^3)	9.94	Passos and Ferrer 2015
Combined Heat and Power Efficiency: Heat (%) Electricity (%)	49.5 37.3	BIOFerm 2017
Electricity Rate ($/kWh)	0.08	EIA 2016
Heat Rate ($/kWh)	0.01	Moriarty 2013
Stabilized B Price ($/ton)	11.2	Schwarzenegger 2010
Life cycle Cost Analysis Period (yr)	25	Assumed

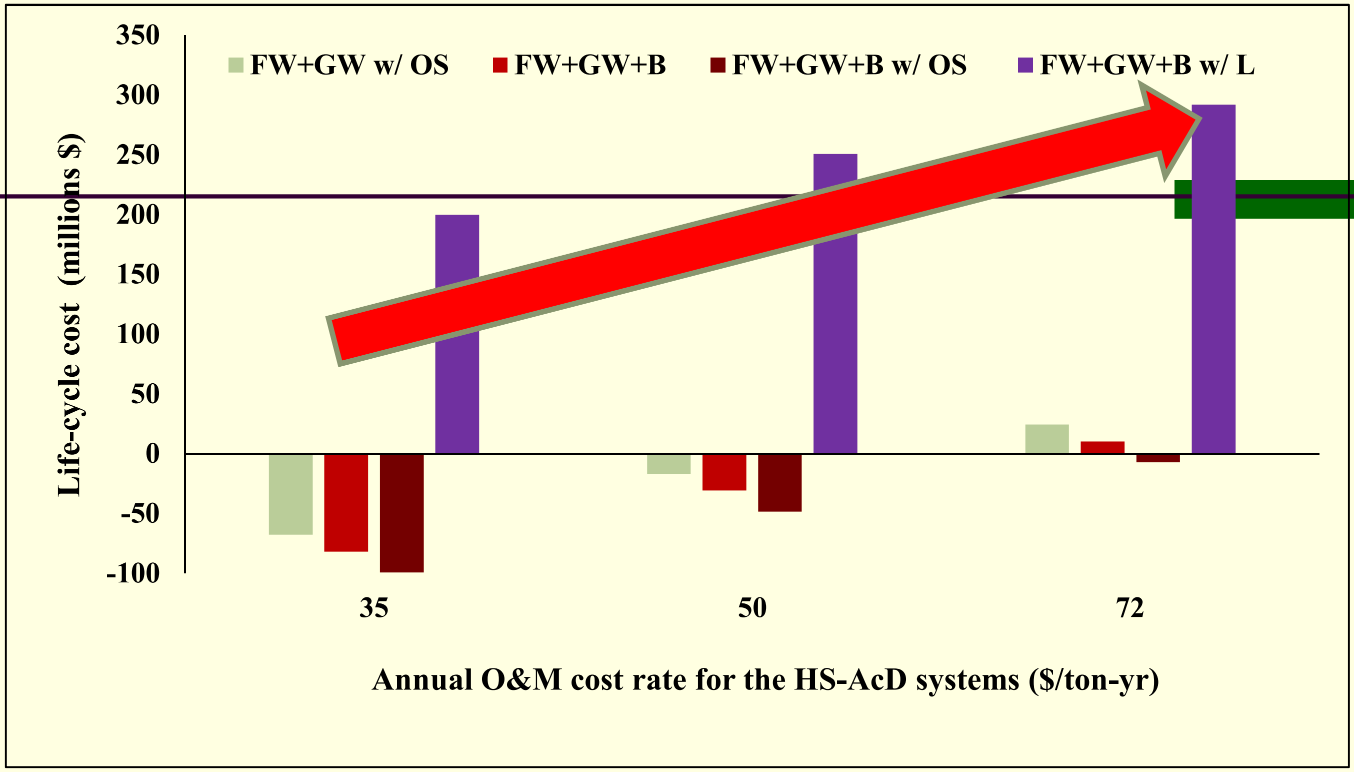
Life Cycle Costs (LCCs) Over 25 years

Item	FW+GW w/OS	FW+GW+B	FW+GW+B w/OS	FW+GW+B w/L
Initial Cost ($)	38,410,000	38,410,000	38,410,000	38,410,000
O&M Cost ($)	174,526,000	174,526,000	174,526,000	491,508,000
C&T Cost ($)	373,000	373,000	373,000	373,000
Tipping Fee Saving ($)	1,978,000	19,896,000	19,896,000	19,896,000
Electricity Sale ($)	145,430,000	142,118,000	157,261,000	173,139,000
Heat Sale ($)	19,638,000	19,190,000	21,235,000	23,379,000
Digestate Sale ($)	21,925,000	21,925,000	22,376,000	22,226,000
Life Cycle Cost (LCC) ($)	**24,339,000**	**10,180,000**	**-7,460,000**	**291,652,000**

LCCA Summary

- Revenues: Electricity Sale >> Heat Sale or Digestate Sale > Tipping Fee Saving
- Tipping Cost Saving:
    - FW+GW w/OS: 5,000 tons/yr (3% of Total GW)
    - Other Options: 5,000 tons/yr (3% of Total GW)+45,300 tons/yr (35% of total B)
- Addition of B Increased HS-AcD Revenues
- FW+GW+B w/L: Highest O&M Cost Due to Limestone Use
- HS-AcD Largest Contributor: O&M Cost
- Most Economical HS-AcD: FW+GW+B w/OS Due to High CH_4 Production

Sensitivity of LCCs



- LCC Results For All Options Increased as the Annual O&M Cost Rate Increased
- Annual O&M Cost Rates Were Significant Factors When Determining Economic Feasibility of Systems
- The Most Economical HS-AcD was FW+GW+B w/OS For All O&M Cost Rates Investigated

Preliminary Study: Conclusions

- Biosolids addition increased overall CH_4 production and revenues
- Alkalinity source addition increased CH_4 yields
  - OS is low-cost waste product (decreased LCC values)
- Most Economically Sustainable Option: HS-AcD of FW+GW+B w/OS
- Diverting OFMSW from landfills potentially improves leachate quality
- Avoiding L-AD of biosolids recovers nutrients and avoids the production of sidestreams requiring further treatment.

Practical Benefits for End-users

- Diversion of organic waste from landfills & land application,
- Higher bioenergy production tha landfills,
- Reduced fugitive GHG emissions,
- Lower leachate production and improved leachate quality
- Reduced impacts of L-AD sidestreams and leachate on mainstream WWTPs.
- Production of compost that can be sold or used by municipal agencies or community members.

Products for sale made from digested materials

http://www.clearhorizonsllc.com/html/products/indexEP.htm

http://www.dailysunnews.com/news/2009/jun/19/local-dairy-going-green-with-enviromoss-product/

http://www.magic-dirt.com/

Metrics: Education

Graduate Students and Post-doc:

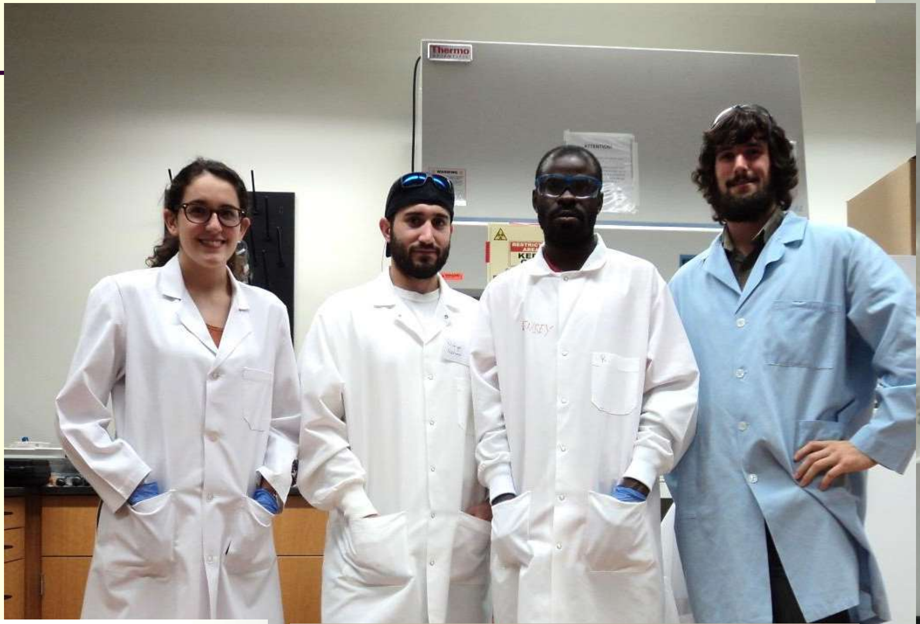
Name	Rank	Department	Institution
Hinds, Gregory*	MS	Civil & Environmental Engineering	USF
Dick, George*	MS	Civil & Environmental Engineering	USF
Wang, Meng	Postdoctoral Researcher	Civil & Environmental Engineering	USF
Anferova, Natalia*	Visiting PhD student	Water Technology & Environmental Eng.	Prague Univ. Chemistry & Technology
Dixon, Phillip	PhD	Civil & Environmental Engineering	USF
Eunyoung Lee	PhD	Civil & Environmental Engineering	USF

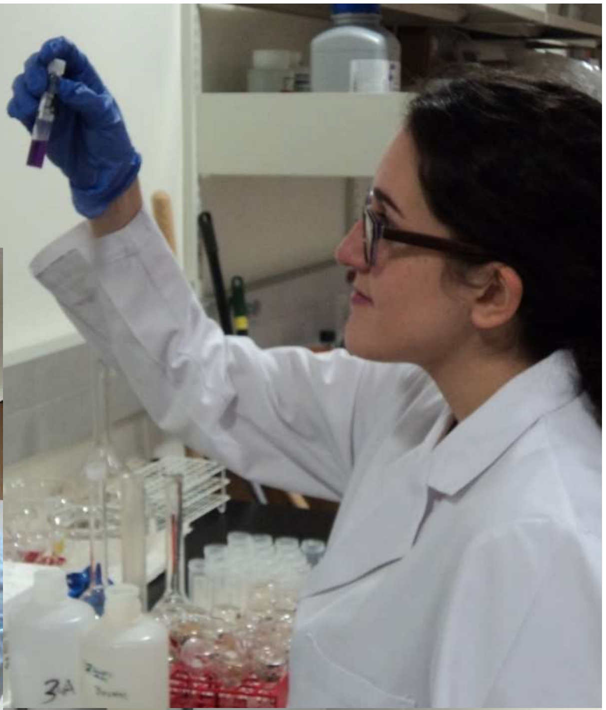
Undergraduates:

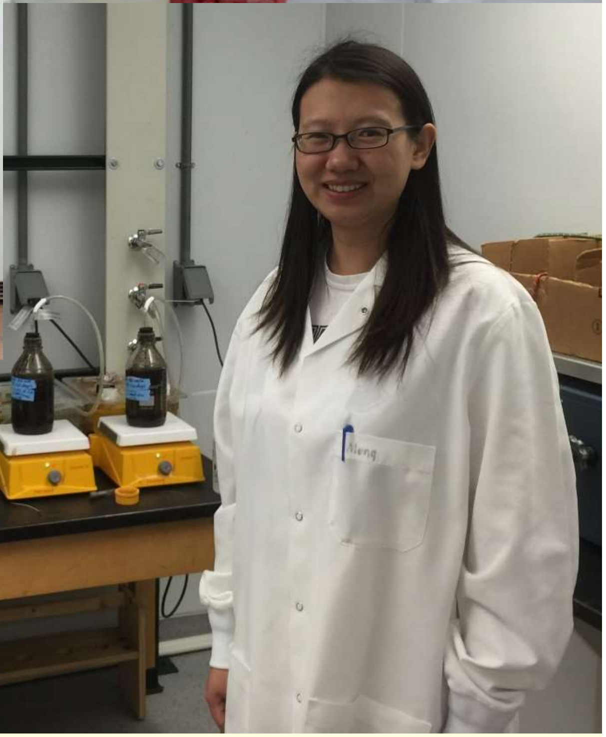
Name	Department	Institution
Ariane Rosario*	Civil & Environmental Engineering	USF
Lensey Casimir	Civil & Environmental Engineering	USF
Paula Bittencourt	Mechanical Engineering	USF
Eduardo Jimenez	Civil & Environmental Engineering	USF

Additional support: USF TA, NSF and USF Scholarships, EU and NSF REU and RET programs.

HS-AD Research Team







K-12 and Community Education

engineering expo

Florida Water Environment Association

American Water Works Association
The Authoritative Resource on Safe Water™

Dissemination: Publications

Peer Reviewed Journal Article:

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

Book Chapter:

- Hinds, G.R., Lens, P., Zhang, Q., Ergas, S.J. (***in press***) 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.

MS Thesis:

- Hinds, G.R. (2015) *High-Solids Anaerobic Digestion of the Organic Fraction of Municipal Solid Waste State of the Art, Outlook in Florida, and Enhancing Methane Yields from Lignocellulosic Wastes*, *MS Thesis*.

Professional Publications:

- Hinds, G.R., Dick, G., Yeh, D.H., Ergas, S.J. (2015) Enhanced methane production from yard waste in solid-state anaerobic digestion, *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.

Website: http://bioenergy-from-waste.eng.usf.edu/

USF

Dissemination: National & International Conferences:

- *Hinds, G.R., Mussoline, W., Dick, G., Yeh, D.H., Ergas, S.J. (2016) Enhanced methane production in solid-state anaerobic digestion through bioaugmentation, *Proc. GWMS;* Jan. 31-Feb. 3, 2016; Indian Wells, CA.
- Ergas, S.J., Hinds, G.R., Anferova, N., Bartáček, J., Yeh, D. (2016) Bioenergy recovery and leachate management through high solids anaerobic digestion of the organic fraction of municipal solid waste, *Proc. World Environmental & Water Resources Congress*; May 22-26, 2016; West Palm Beach, FL.
- Dixon, P., Bittencourt, P., Anferova, N., Jenicek, P., Bartacek, J., Wang, M., Ergas, S.J. (2016) Effects of Biosolids Addition, Microaeration, and Alkalinity Sources on High-Solids Anaerobic Co-digestion (HS-AcD) of Food Waste and Green Waste, Waste-to-Bioenergy: Applications to Urban Areas, 1st International ABWET Conference, Jan. 19-20, Paris, France.
- Dixon, P., Bittencourt, P., Lee, E., Wang, M., Jimenez, E., Zhang, Q., Ergas, S.J. (2017) Effects of Biosolids Addition and Alkalinity Sources on High-Solids Anaerobic co-Digestion (HS-AcD) of Food Waste and Green Waste, *Proc. WEF Residuals and Biosolids Conference*, April 8-11, Seattle, WA.

Regional and State Meetings

Hinds, Gregory. “Bioenergy Production from MSW through SS-AD.” USF, College of Engineering Research Day. **Tampa**, Florida. 19 Nov. 2014.

Hinds, Gregory. “Enhanced Methane Production from Lignocellulosic Waste in SS-AD through Bioaugmentation.” USF, Graduate Student Research Symposium. **Tampa**, Florida. 10 Mar. 2015.

Hinds, Gregory. “Bioenergy Production from MSW through HS-AD: State of the Art and Outlook in Florida.” AEESP Lecture Poster Session USF, **Tampa**, Florida. 13 Nov. 2015.

*Rosario, Ariane. “Enhanced Methane Production from Lignocellulosic Waste in SS-AD through Bioaugmentation.” USF, Undergraduate Research and Arts Colloquium. **Tampa**, Florida. 9 Apr. 2015.

Casimir, Lensey. “SS-AD for the Recovery of Energy and Nutrients from Organic Solid Waste.” USF, NSF REU Research Symposium. **Tampa**, Florida. 29 Jul. 2015.

Casimir, Lensey. “SS-AD for the Recovery of Energy and Nutrients from Organic Solid Waste.” AEESP Lecture Poster Session USF, **Tampa**, Florida. 13 Nov. 2015.

*Dawley, Matthew. “Methane Production by SS-AD Co-digestion of the OFMSW.” USF, NSF RET Research Symposium. **Tampa**, Florida. 29 Jul. 2015.

Casimir, Lensey and Anferova, Natalia. “Enhanced Methane Yield from Yard Waste in HS-AD through Bioaugmentation with P&P.” Hinkley Center Colloquium. **Tallahassee**, Florida. 23 Sep. 2015.

Hinds, Gregory. “Bioenergy Production from MSW through HS-AD: State of the Art and Outlook in Florida.” Hinkley Center Colloquium. **Tallahassee**, Florida. 23 Sep. 2015.

Hinds, Gregory. “Bioenergy Production from MSW through SS-AD.” UCF, AEESP Lecture Poster Session. **Orlando**, Florida. 27 Feb. 2015.

Questions?

reclaim

water • nutrients • energy

usf-reclaim.org

USF