Phase II Bioenergy Production from MSW by High Solids Anaerobic Digestion

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Energy Recovery from MSW

- Waste to Energy (WtE)→Incineration
    - Food and yard waste: High moisture and nitrogen content

      ➔ Low calorific value, environmental problems (e.g., dioxin and NOx)

- Landfills: Biogas production via recirculation of leachate for the entire waste stream
    - Fugitive methane emissions
    - High ammonia, COD, and salinity in leachate

- High Solids Anaerobic Digestion (HS-AD)
    - Breaks down of biodegradable material by microorganisms in the absence of oxygen
    - ≥ 15% total solids content
    - Reduced digester size
    - Lower parasitic energy losses
    - Improved leachate quality
    - Higher quality biogas

Smartferm process (ZWE), Marina, CA, US

Challenges and Opportunities for HS-AD

P.1. High Volatile Fatty Acid (VFA)

→ pH ↓: Inhibits methanogens

S.1. Alkalinity source needed to help maintain neutral pH (e.g. oyster shells)

S.2. Reduction of organic loading rate (e.g. substrate to inoculum ratio)

P.2. High N content of substrate

→ NH_3/NH_4^+ ↑: Inhibits methanogens

S.1. Co-digestion of wastes to maintain the optimum C/N ratio (20-30/1)

Challenges & Opportunities for HS-AD

- **Why Biosolids?**
  - High biosolids availability due to population growth and wastewater regulations
  - Restrictions land application of biosolids
  - Lack of biosolids AD infrastructure in US (~38% of biosolids treated by L-AD)
  - High cost of biosolids disposal in landfills and incineration
    - $110-650 per dry ton for landfill
    - $300-500 per dry ton for incineration

Phase II: Goal & Objectives

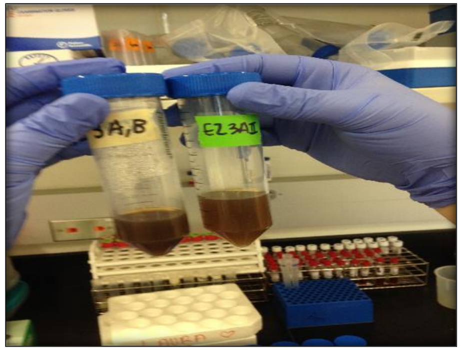
- **Overall goal**: Improve environmental and economic sustainability of HS-AD of organic fraction of municipal solids waste (OFMSW) in Florida

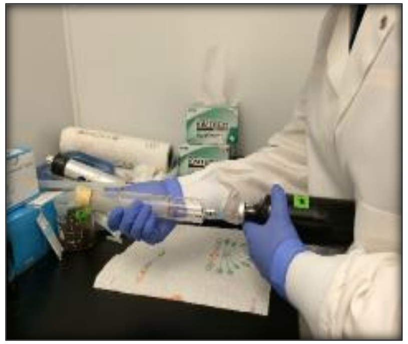
- **Specific Objectives**
  - **Objective 1:** Investigate the performance of HS-AD of OFMSW with varying substrate ratios and temperature
  - **Objective 2:** Conduct life cycle assessment (LCA) to evaluate environmental impacts and benefits for HS-AD of OFMSW
  - **Objective 3:** Compare HS-AD with other waste management options (e.g. landfilling, waste to energy, composting) to ensure economic sustainability

Objective 1: Investigate HS-AD Performance

- **Objective 1:** Investigate the performance of HS-AD of OFMSW with varying substrate ratios and temperatures

  - Effects of biosolids addition on HS-AD of food waste and yard waste
  - Effects of substrate/substrate ratios (food waste, yard waste, and biosolids)
  - Effects of substrate/inoculum ratios (1.2, 2.5, & 3.8 based on VS)
  - Effects of operating temperature (35ºC vs. 55ºC)





Materials & Methods: Experiment (1)

Food waste

Yard waste

Biosolids & Inoculum

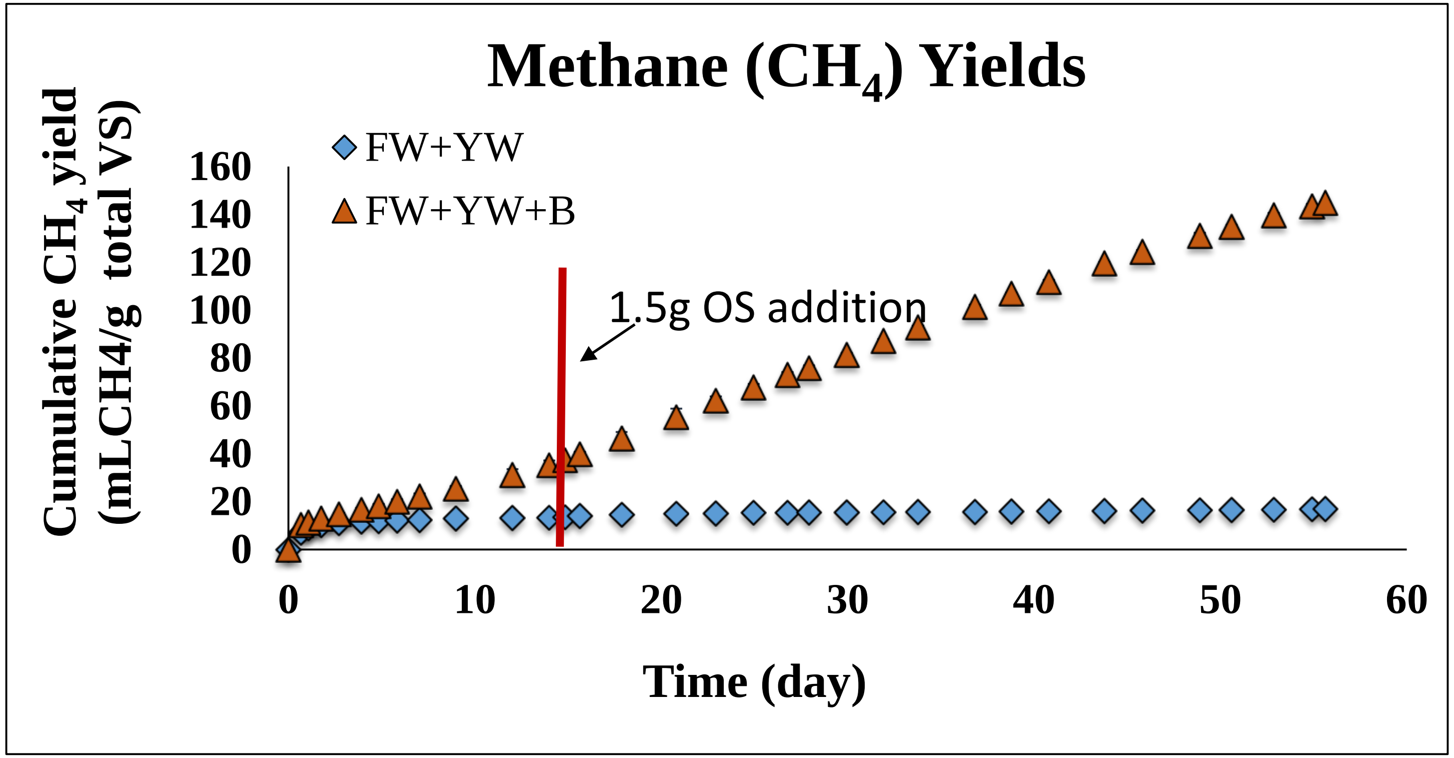
Material and Methods: Experiment (2)

- **Bio-Methane Potential (BMP) Set –Up**

	1st Set	**2nd Set**	**3rd Set**	**4th Set**
Temperature (°C)	35	35	35	35 & 55
Alkalinity source addition	Oyster shells	Oyster shells/Sodium bicarbonate		
Substrate ratios (%)	FW/YW=50:50 FW/YW/B=33:33:33	FW/YW/B= 33:33:33 FW/YW/B=23:62:15	FW/YW/B=23:62:15	FW/YW/B=23:62:15
Inoculum type	Non-acclimated	Non-acclimated	Acclimated	Acclimated
S/I ratios (Volatile Solids basis)	2.7	1	1.2 2.5 3.8	1

- **Analytical Methods**: Total Solid (TS), Volatile Solid (VS), pH, Alkalinity, soluble COD (sCOD), VFA, Total Nitrogen (TN), NH_4^+-N, and Biogas/CH_4 content

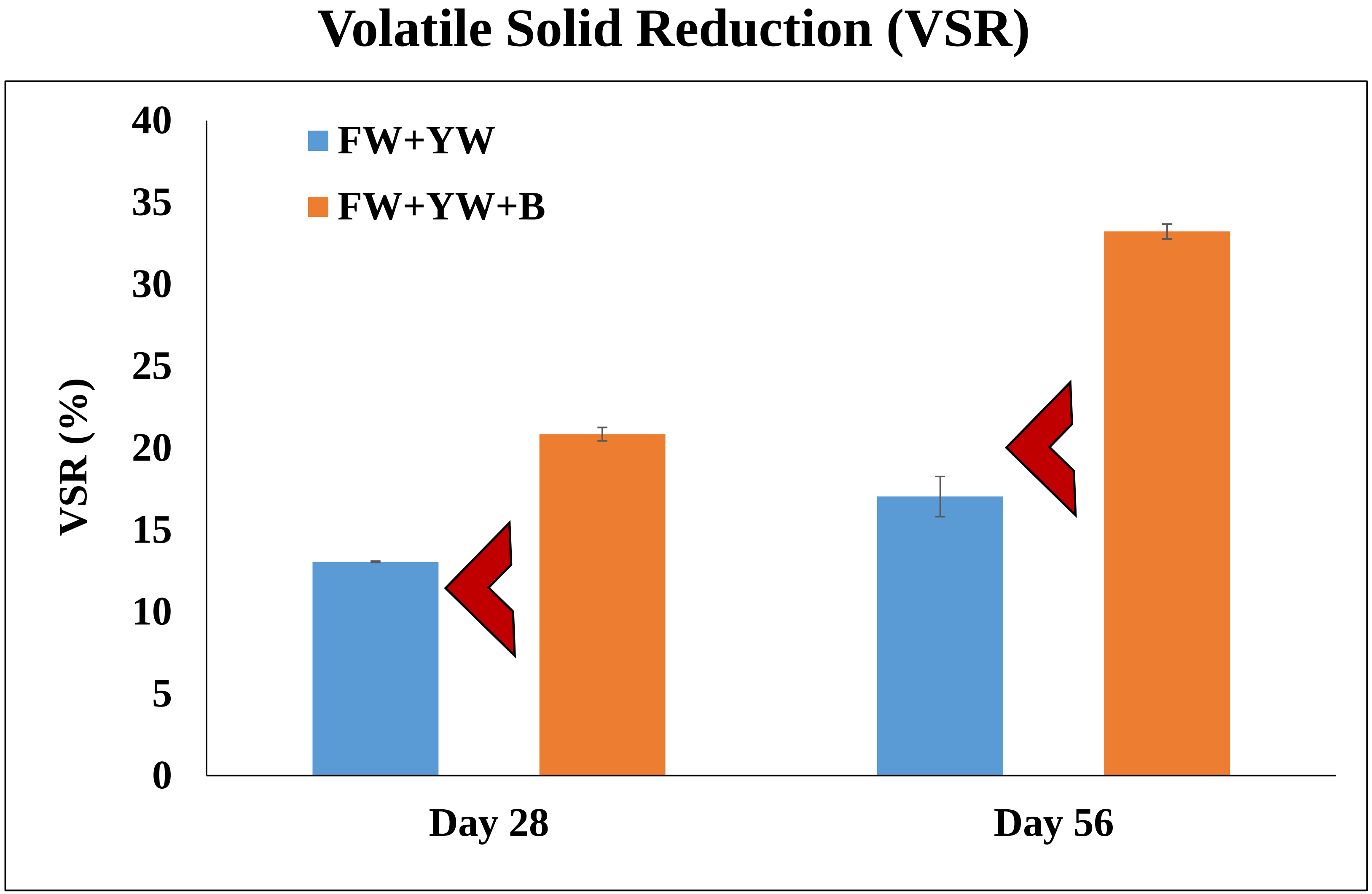
Results: 1. Effect of Biosolids Addition (1)



- Low pH during the start-up period
  - Crushed oyster shells addition
    → Improved alkalinity
- Low CH_4 yield of FW+YW
  → High VFA concentrations (>10,000 mg/L)
- CH_4 yields higher with biosolids

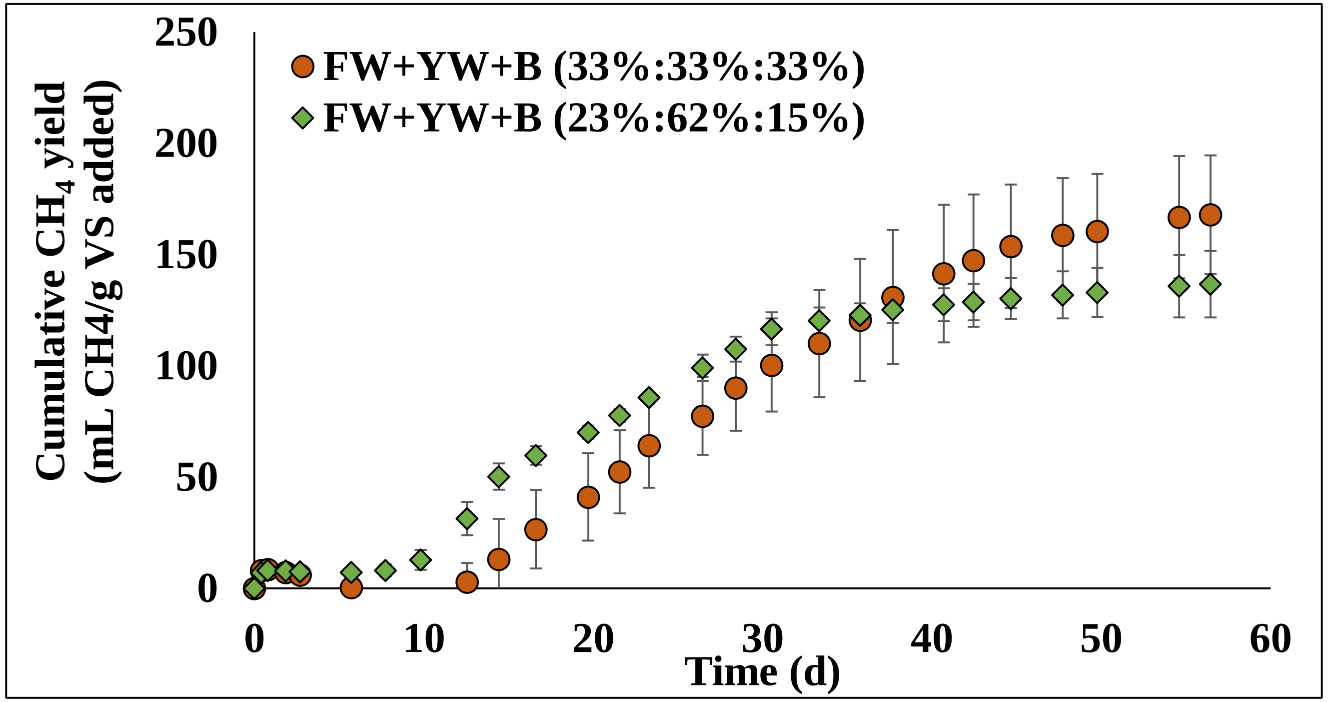
Item	FW+YW				FW+YW+B			
	Day 0	Day 14	Day 28	Day 56	Day 0	Day 14	Day 28	Day 56
pH	6.99	5.13	5.37	5.36	6.95	5.69	7.88	8.59
VFA (mg/L)	1,722 (±359)	17,914 (±1,583)	21,611 (±231)	22,067 (±109)	3,449 (±112)	15,612 (±787)	11,238 (±1,447)	4,427 (±2,428)
Alkalinity (mg $CaCO_3$/L)	550 (±6)	933 (±59)	5,396 (±96)	6,230 (±240)	563 (±19)	485 (±109)	6,318 (±702)	9,302 (±2,000)

Results: 1. Effect of Biosolids Addition (2)

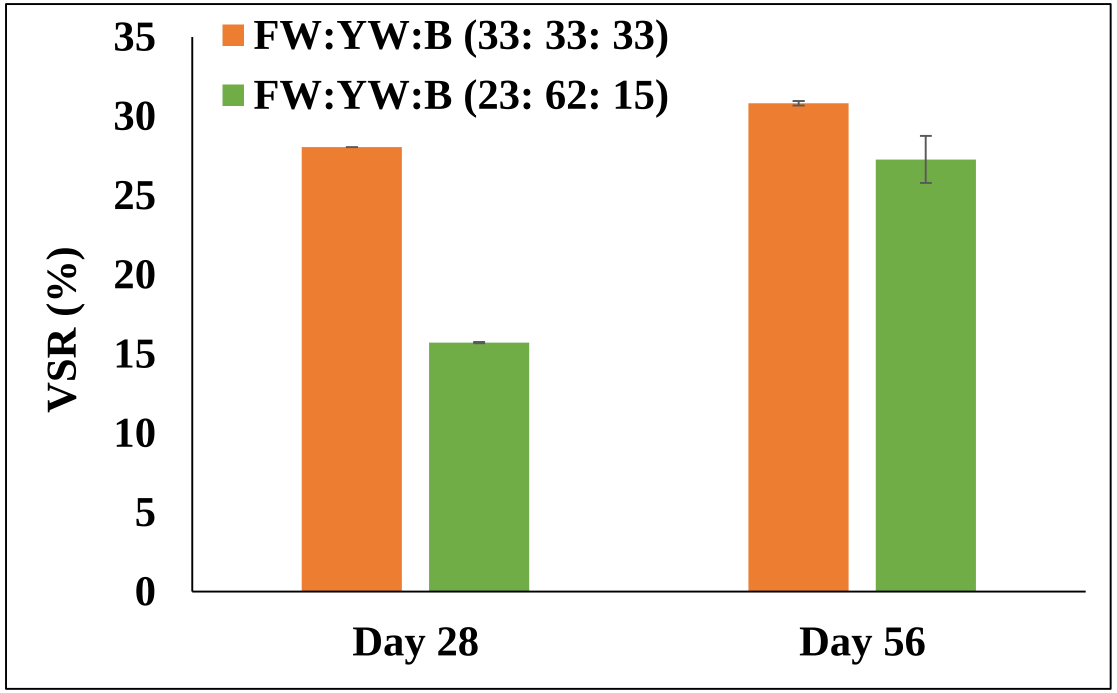


Results: 2. Effect of Substrate Ratios

Methane (CH_4) Yields

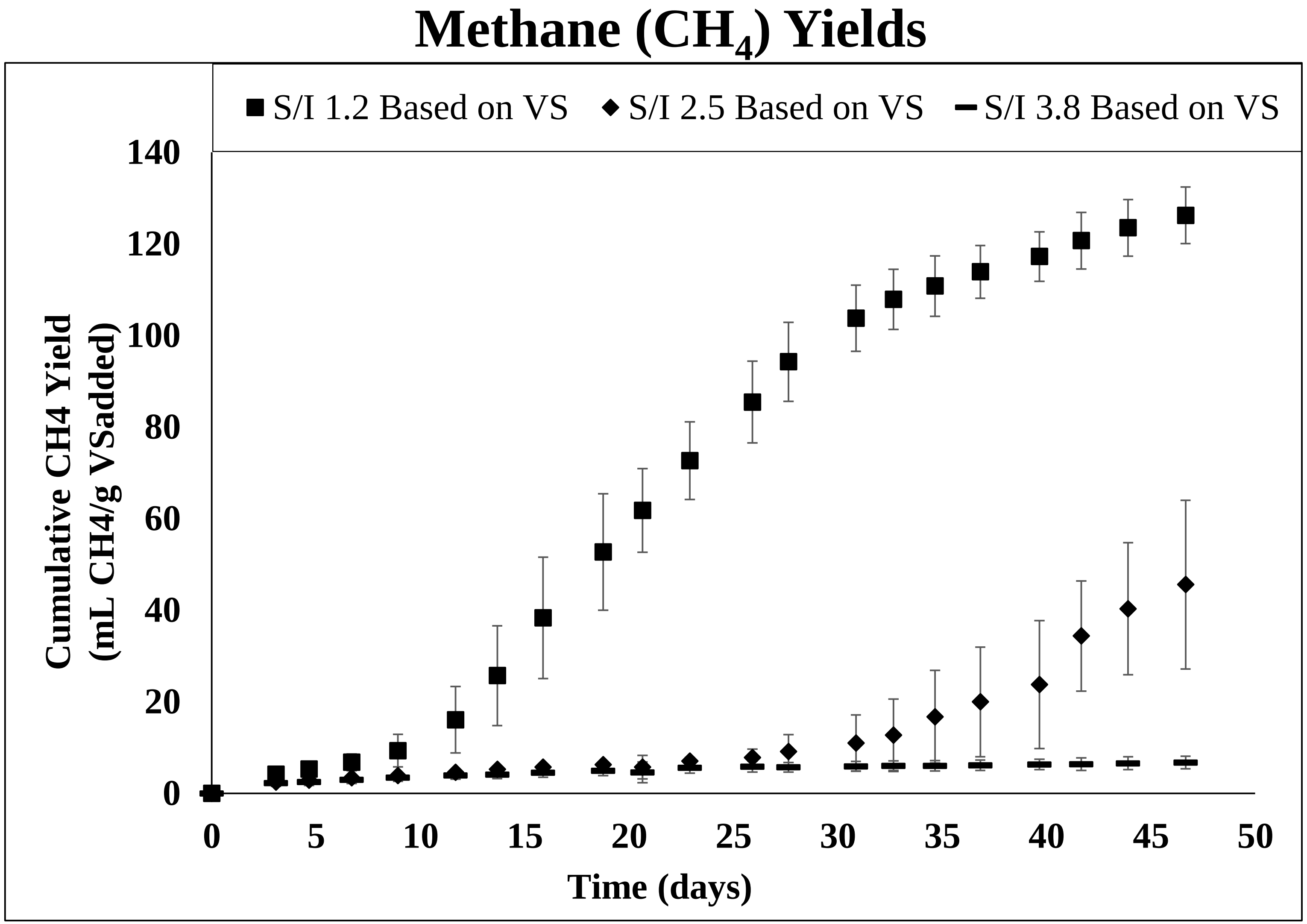


Volatile Solid Reduction (VSR)



- Before 35 days, the digester with more YW resulted in higher CH_4 yield ← **Less pH variation**
- After 35 days, the digester with more YW resulted in lower CH_4 yield ← **Lignin**
- HS-AD with the ratio reflecting available amounts of wastes in Hillsborough County had a comparable VSR during 56 days

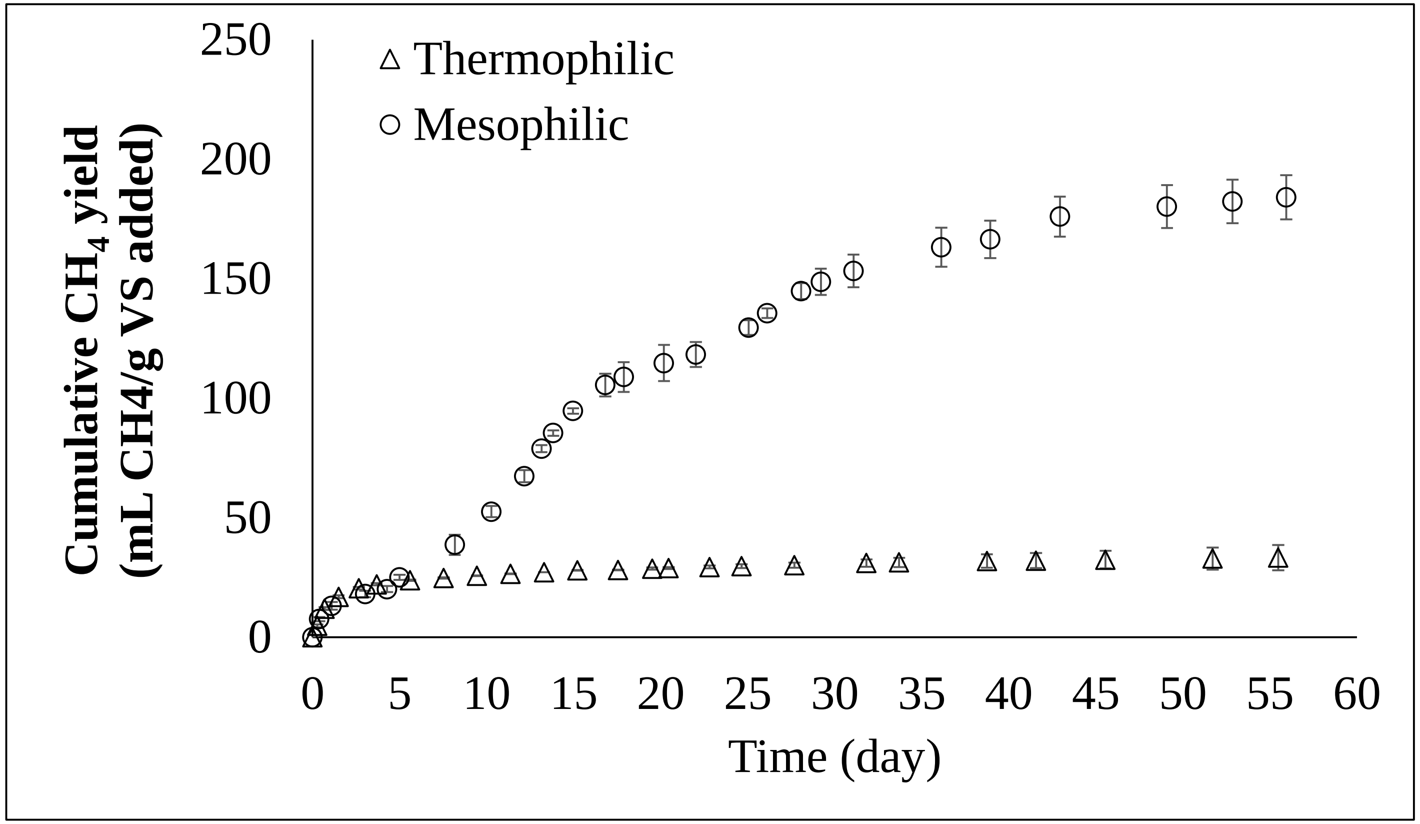
Results: 3. Effect of Substrate/Inoculum (S/I) Ratios



- Balanced S/I ratios important to CH_4 yield
  - Digestate recirculation to head of digester
- Day 48
  - S/I 3.8 mixture had high VFA concentration (>13,850 mg/L)
  - the S/I 1.2 mixture had the lowest NH_3 concentration <1,520 mg/L)

Results: 4. Effect of Temperature

Methane (CH_4) Yields



- Higher CH_4 yield under mesophilic conditions
- Inhibition in thermophilic BMPs due to:
  - VFA accumulation
  - High NH_3 concentrations

→ Currently repeating experiments

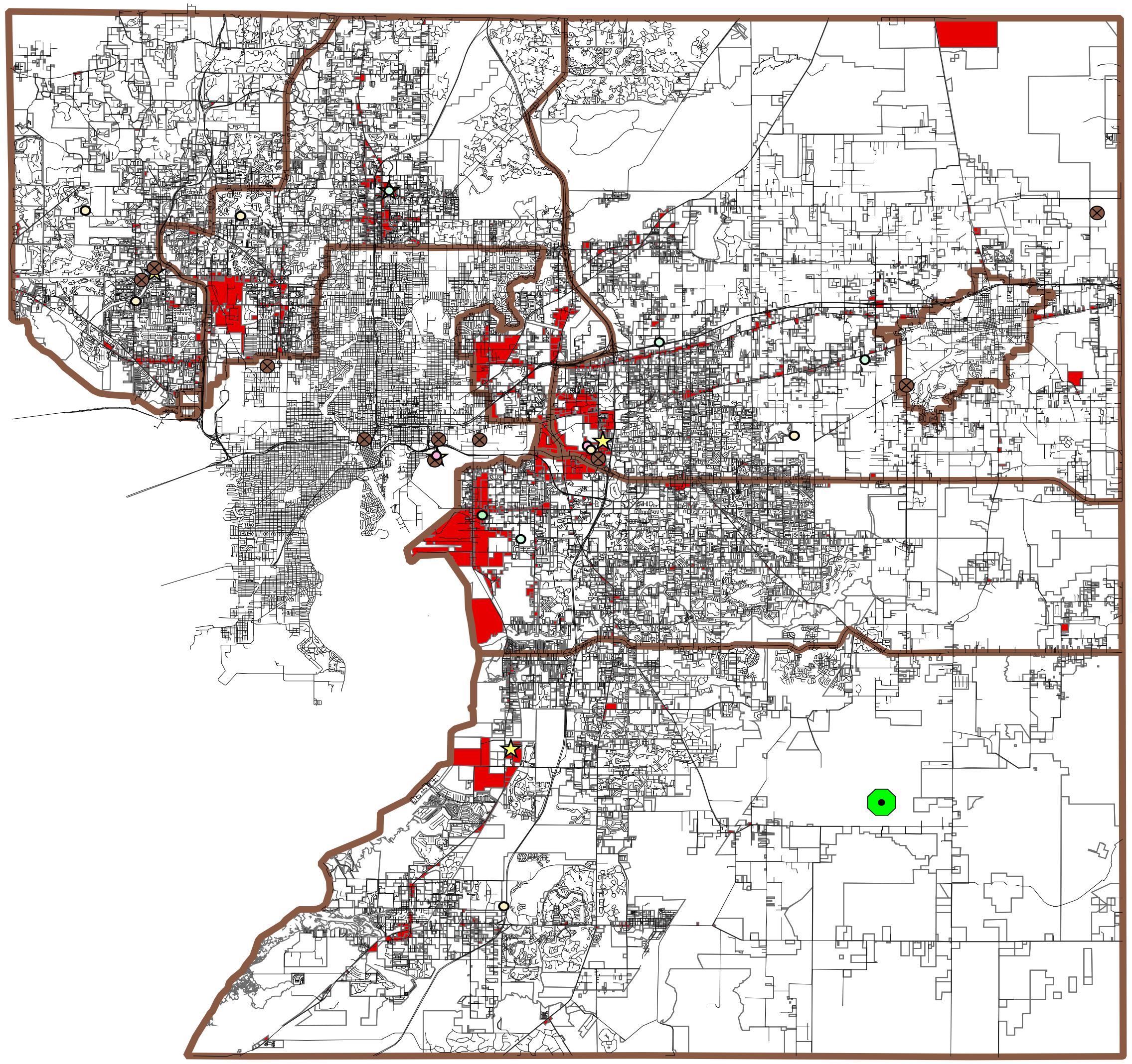
Major Findings from Objective 1

- Addition of Biosolids improves CH_4 yields in HS-AD of OFMSW:
  - Better conditions during start-up
  - Higher buffering capacity due to ammonium from biosolids degradation
  - Better volatile solids reduction
- Increasing portion of YW improved CH_4 yield before 35 days, but resulted in lower cumulative methane yields after 35 days:
  - Reduce the risk of VFA inhibition
  - Lower biodegradation due to lignin content
- S/I ratio 1.2 based on VS provided the greatest cumulative CH_4 yield
- High temperature results were inconclusive

Objective 2: Life Cycle Assessment of HS-AD

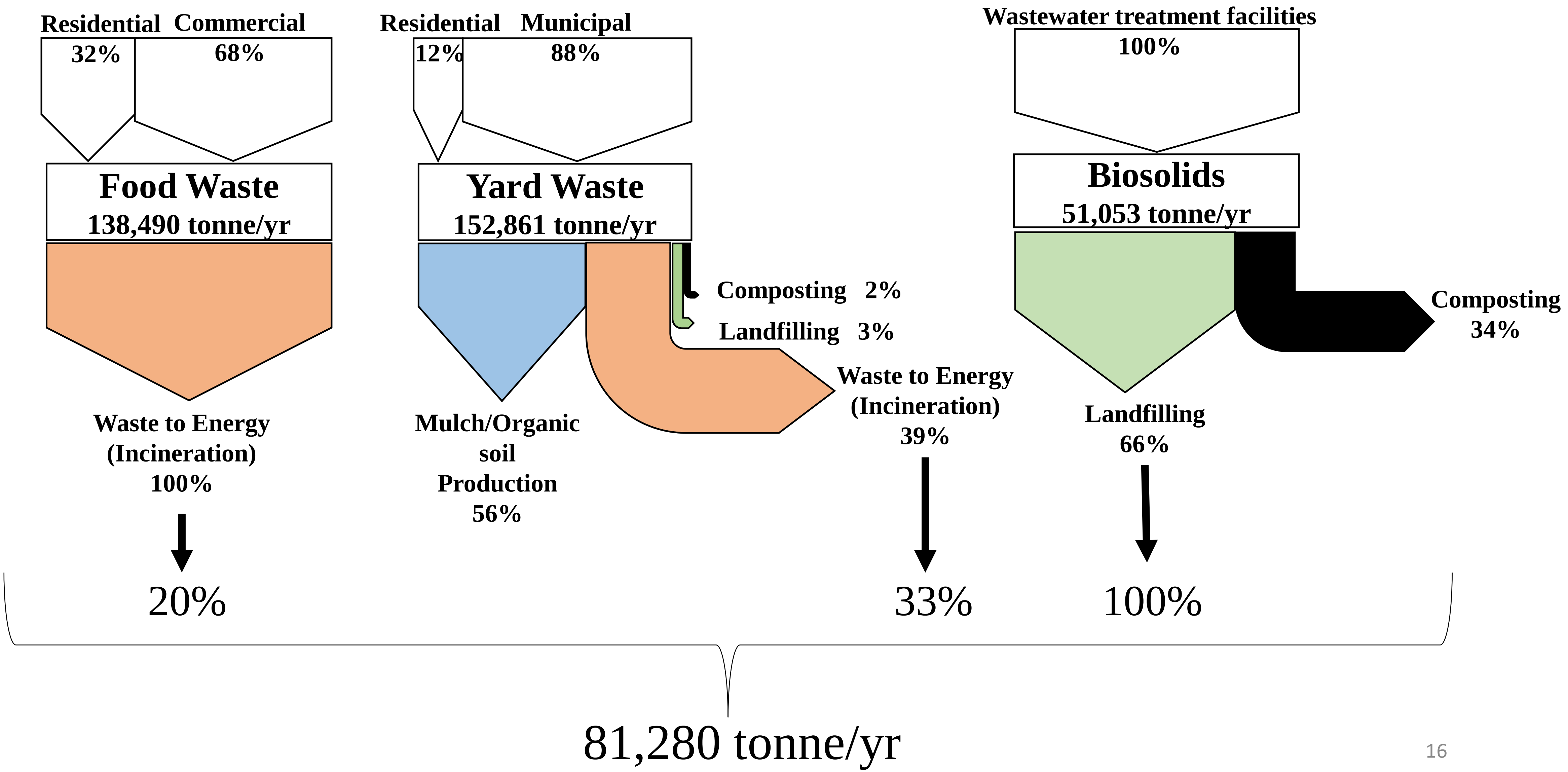
- **Objective 2:** Conduct life cycle assessment (LCA) to assess environmental impact and benefits for HS-AD of OFMSW

- **Study area:** Hillsborough County, FL
- **Considered waste**
  - Food waste from commercial area
  - Yard waste
  - Biosolids

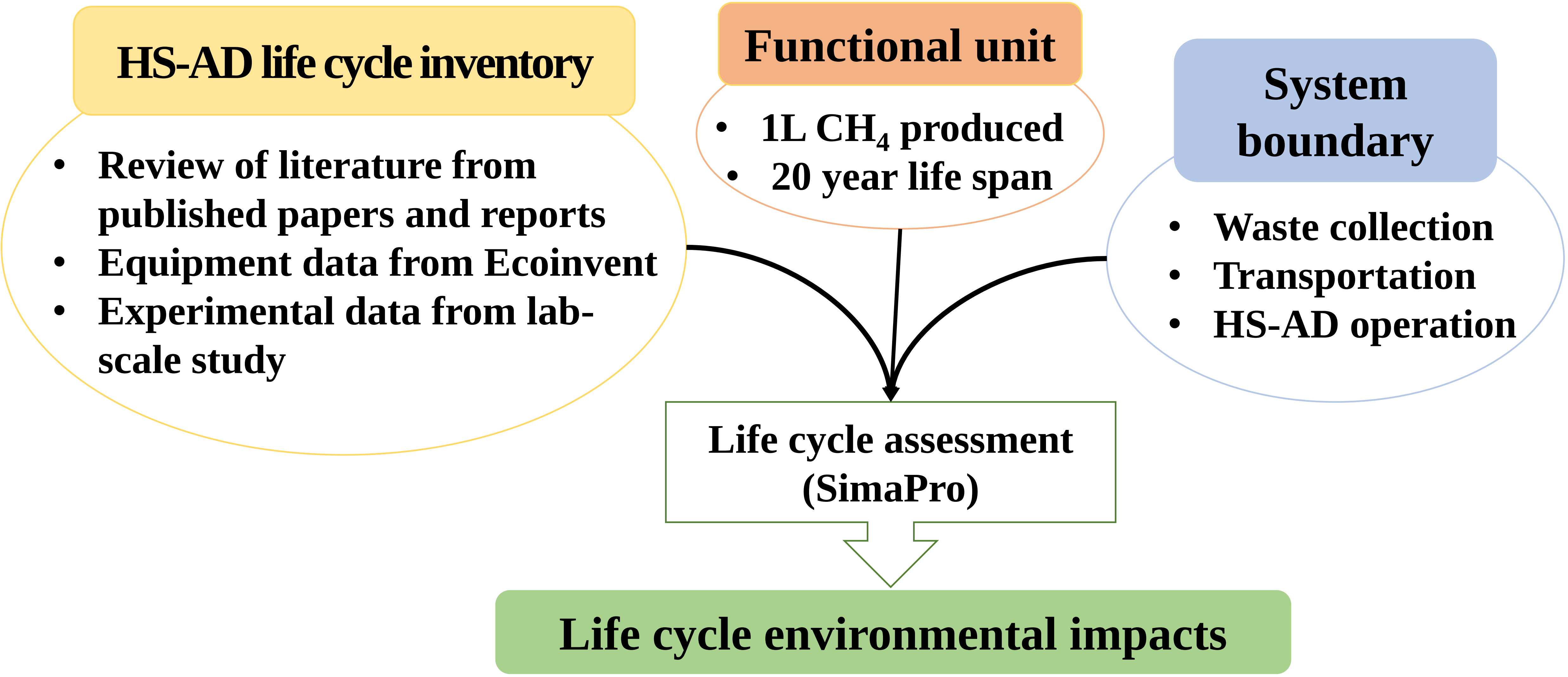


GIS map of Hillsborough County, FL

Available Amounts of Waste in Hillsborough County

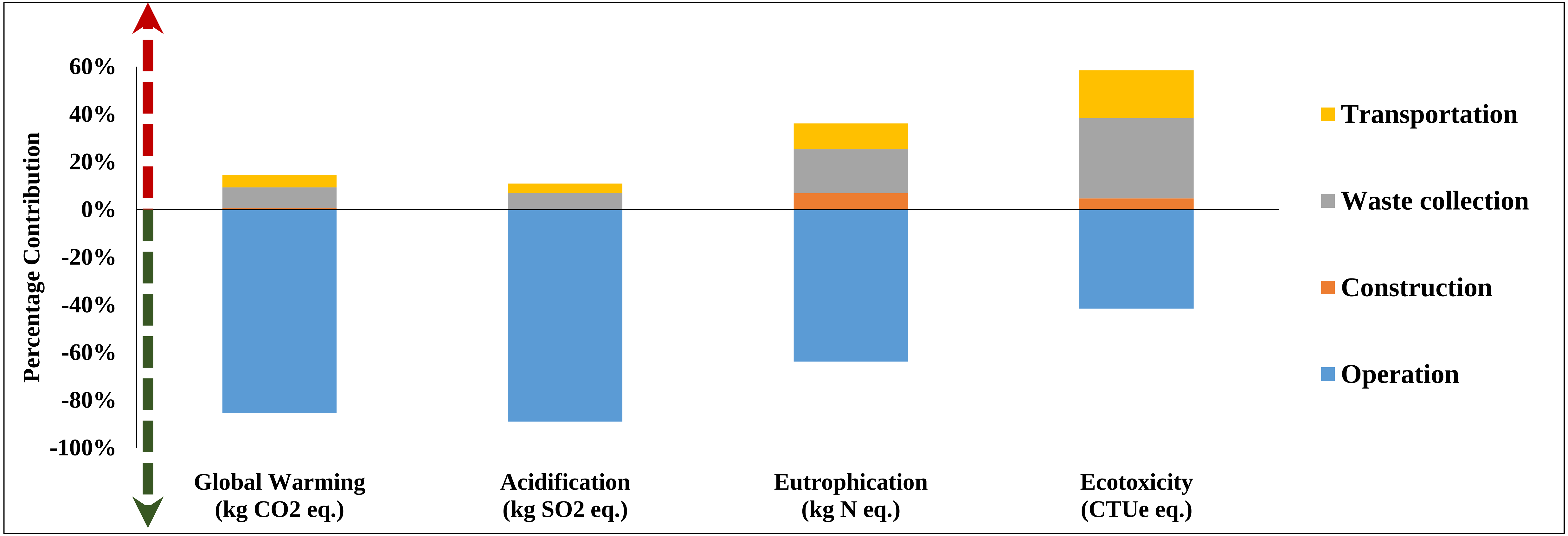


Materials & Methods



Life Cycle Environmental Impacts and Benefits of HS-AD

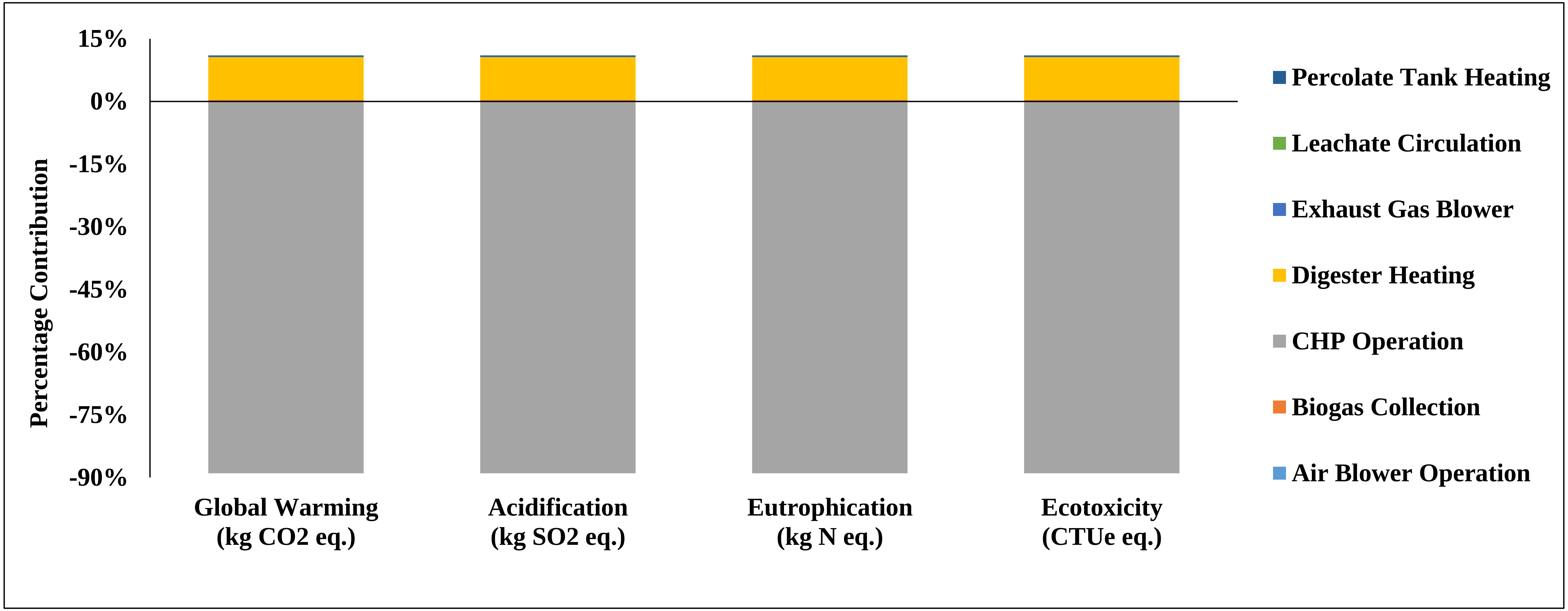
Environmental impacts



Environmental benefits

Environmental Impacts and Benefits of HS-AD

HS-AD Operation phase of HS-AD



***CHP: Combined heat and power system**

Major Findings from Objective 2

- HS-AD can provide environmental benefits:
  - Benefits mainly associated with HS-AD operation
    - Environmental benefits resulted from energy and nutrient recovery
  - Waste collection is the largest contributor to impacts, especially eutrophication and ecotoxicity
  - Construction phase contribution is low compared with others

Objective 3: Life Cycle Cost Analysis of HS-AD

- **Objective 3:** Compare HS-AD with other waste management options to ensure economic sustainability.

- **Full-scale scenarios in Hillsborough County Florida**
- **Capacity of each option**: 81,280 tonne/yr
- **Considered life span:** 20 years
- **Life Cycle Cost (LCC)**: present value method

Waste to Energy (Incineration)

HS-AD

Landfilling

Composting (Windrow)

Material & Methods

- **Life Cycle Cost (LCC, $)**

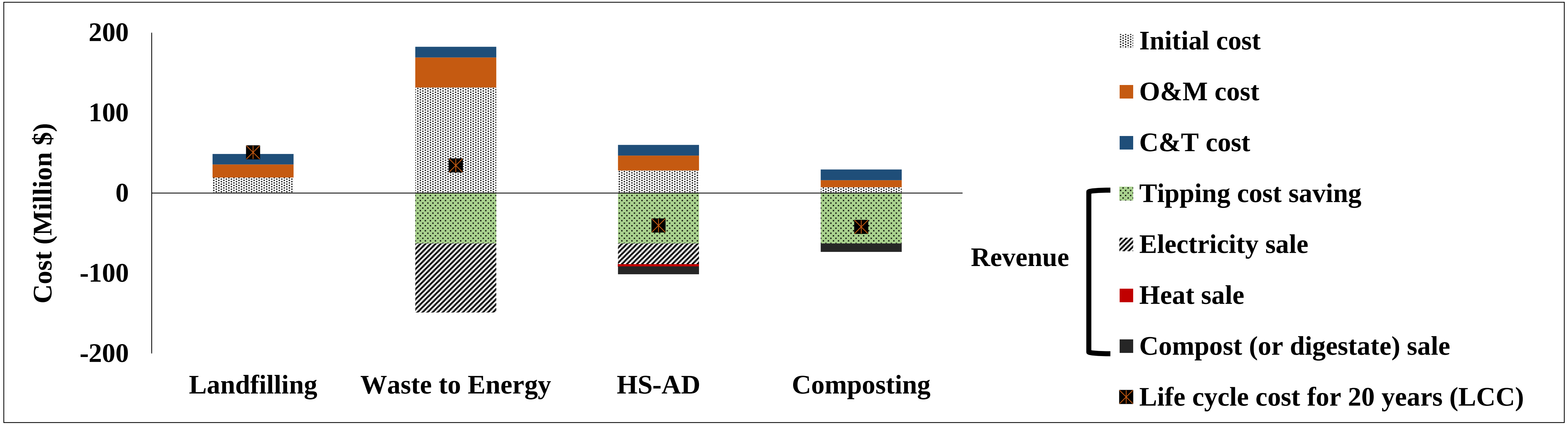
$$LCC = C_I + C_{O\&M} \times UPV + C_{C\&T} \times UPV$$
$$-(C_{R,h} \times UPV + C_{R,e} \times UPV^* + C_{R,d} \times UPV + C_{R,t} \times UPV)$$

C_I: Initial Cost w/o land acquisition cost
$C_{O\&M}$: Costs for Operation & Maintenance
$C_{C\&T}$: Costs for Collection and Transportation
$C_{R,h}$, $C_{R,d}$, $C_{R,t}$ & $C_{R,e}$: Revenues from beneficial products: Heat, Digestate (or Compost), Tipping cost saving & Electricity, respectively
UPV: a uniform present value factor
UPV*: a non-uniform present value factor

- **Uncertainty analysis of LCC considering land acquisition cost**
  - Monte Carlo simulation with 1,000 iterations
  - Land acquisition cost in Hillsborough County

Results: Life Cycle Cost Analysis (1)

- Life cycle costs (w/o land acquisition cost) for different options

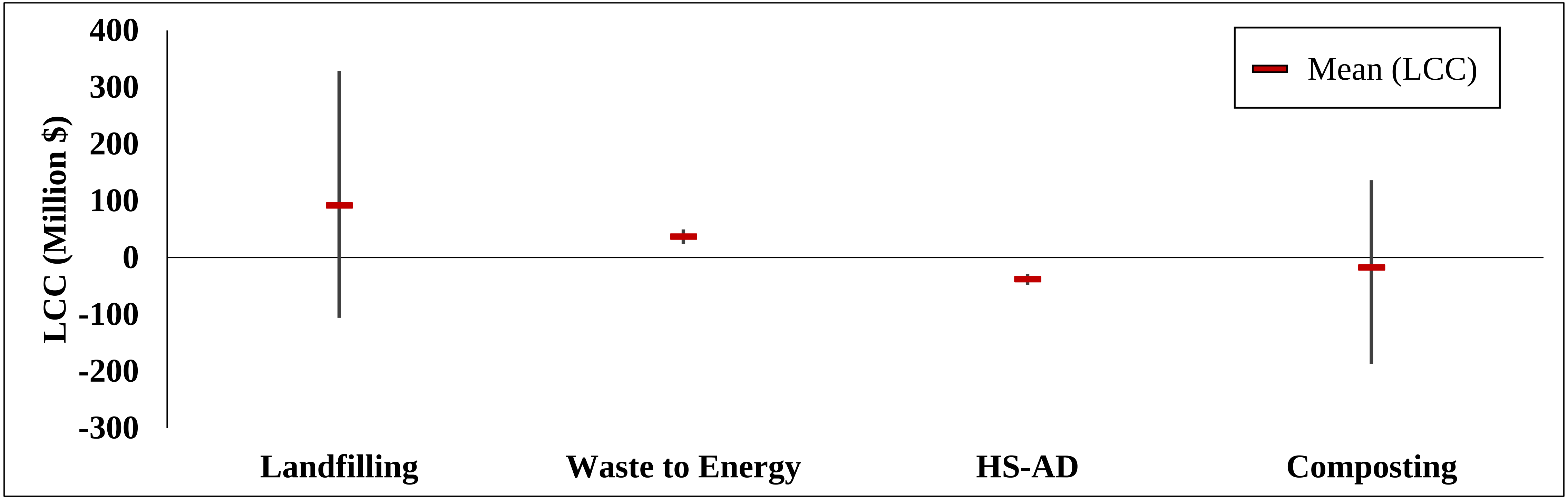


- Cost of revenue: Waste to Energy (WtE) >> HS-AD > Composting
- Largest contributor: Initial cost (Landfilling & WtE)

  Tipping cost saving (HS-AD & Composting)
- The most economical option: Composting due to low initial costs

Results: Life Cycle Cost Analysis (2)

- Uncertainty analysis of Life Cycle Cost (LCC) considering land acquisition



- The most economical option: HS-AD
- LCC variations for composting and landfilling were larger

Major Findings from Objective 3

- Without land acquisition costs:
  - The most economical option was composting due to low initial cost
  - Life cycle cost (LCC) for HS-AD is comparable to composting
  - Tipping cost saving is the largest contributor for HS-AD, followed by initial cost

- With land acquisition cost:
  - The most economical option was HS-AD
  - The LCC variation for composting and landfilling is large because these options require larger land area

Conclusions and Next Steps

Conclusions

- Addition of biosolids in the HS-AD of FW and YW can improve substrate characteristics and increase CH_4 yields
- HS-AD of FW, YW, and biosolids can provide environmental and economic benefits via energy and compost recovery
- HS-AD can improve the environmental and economic sustainability of solid waste management in Hillsborough County, FL

Next steps

- Thermophilic BMP study
- Semi-continuous reactor study
- LCA for other waste management options
- Publications

Practical Benefits for End-Users

- Diversion of OFMSW and biosolids from landfills or incineration
  - Landfills:
    - Reduced fugitive GHG emissions
    - Increase landfill life
    - Improved leachate quality
  - WWTPs:
    - Reduced impact of leachate (side stream) from L-AD on mainstream WWTPs
    - Reduction of the biosolids processing costs for landfilling or incineration
  - Incineration:
    - Improved efficiency of incineration
    - Lower dioxin and NOx production
- Production of high quality biogas
- Production of compost (digestate)

Metrics: Education

Graduate Students and Post-doc:

Name	Rank	Department	Institution
Phillip Dixon	MS	Civil & Environmental Engineering	USF
Gregory Hinds	MS	Civil & Environmental Engineering	USF
Eunyoung Lee	Postdoc	Civil & Environmental Engineering	USF
Meng Wang	Postdoc	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
Deborah S. B. L. Oliveira	Chemical & Biomedical Engineering	USF
Luiza S. B. L. Oliveira	Chemical & Biomedical Engineering	USF
Aleem Waris	Chemical & Biomedical Engineering	USF

Dissemination: Publications & Website

Peer reviewed journal article and book chapter:

- 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.
- Hinds, G.R., Lens, P., Zhang, Q., Ergas, S.J. (2017) Microbial biomethane production from municipal solid waste using high-solids anaerobic digestion, In *Microbial Fuels: Technologies and Applications*, Serge Hiligsmann (Ed), Taylor & Francis, Oxford, UK.

MS Theses:

- Dixon, P. (2018) *Impact of Substrate to Inoculum Ratio on Methane Production in High Solids Anaerobic Digestion (HS-AD) of Food Waste, Yard Waste, and Biosolids*, MS Thesis, USF.
- 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, USF.

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

Phase II Dissemination: Oral Presentations

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

Phase II Dissemination: Posters

- Dixon, P., Waris, A., Lacoff, P., Lee, E., Wang, M., Zhang, Q., Mihelcic, J., and Ergas, S. (2018) Energy From Biosolids and Municipal Solid Waste: Effect of Organic Loading Rate on Methane Yield, *Florida Water Resource Conference* (FWRC), Daytona Beach, FL, April, 2018.
- Oliveira, L.S.B.L., Oliveira, D.S.B.L., Lee, E., Jimenez, E., Ergas, S.J., Zhang, Q. (2018) Life Cycle Assessment for High Solids Anaerobic Digestion of Food Waste, Yard Waste, and Biosolids, *Thirty-Third International Conference on Solid Waste Technology & Management*, Annapolis, MD, March 11-14, 2018.
- Lee, E., Bittencourt, P., Jimenez, E., Casimir, L., Wang, M., Dixon, P., Zhang, Q., and Ergas, S. (2017) High-Solids Anaerobic Co-digestion of Food Waste and Yard Waste with Biosolids for Sustainable Bioenergy Production, *2017 International Summit on Energy Water Food Nexus*, Orlando, FL, October, 2017.
- Dixon, P., Lee, E., Bittencourt, P., Jimenez, E., Casimir, L., Wang, M., Zhang, Q., Ergas, S.J. (2017) Effects of Biosolids Addition and Alkalinity Sources on High-Solids Anaerobic Co-digestion of Food Waste and Green Waste, *Renewable Energy Systems & Sustainability Conference*, Lakeland, FL, July 31-August 1, 2017.
- Dixon, P., Lee, E., Bittencourt, P., Jimenez, E., Casimir, L., Wang, M., Zhang, Q., Ergas, S.J. (2017) Effects of Biosolids Addition and Alkalinity Sources on High-Solids Anaerobic Co-digestion of Food Waste and Green Waste, *SWANA FL 2017 Summer Conference & Hinkley Center Colloquium*, Fort Myers, FL, July 23-25, 2017.
- Bittencourt, P. Jimenez, E. , Dixon, P., Wang, M., Ergas, S.J. (2017) Effects of Alkalinity and Temperature on High-Solids Anaerobic co-Digestion, *USF Undergraduate Research Colloquium*, Tampa, FL, April 6, 2017.

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Questions?

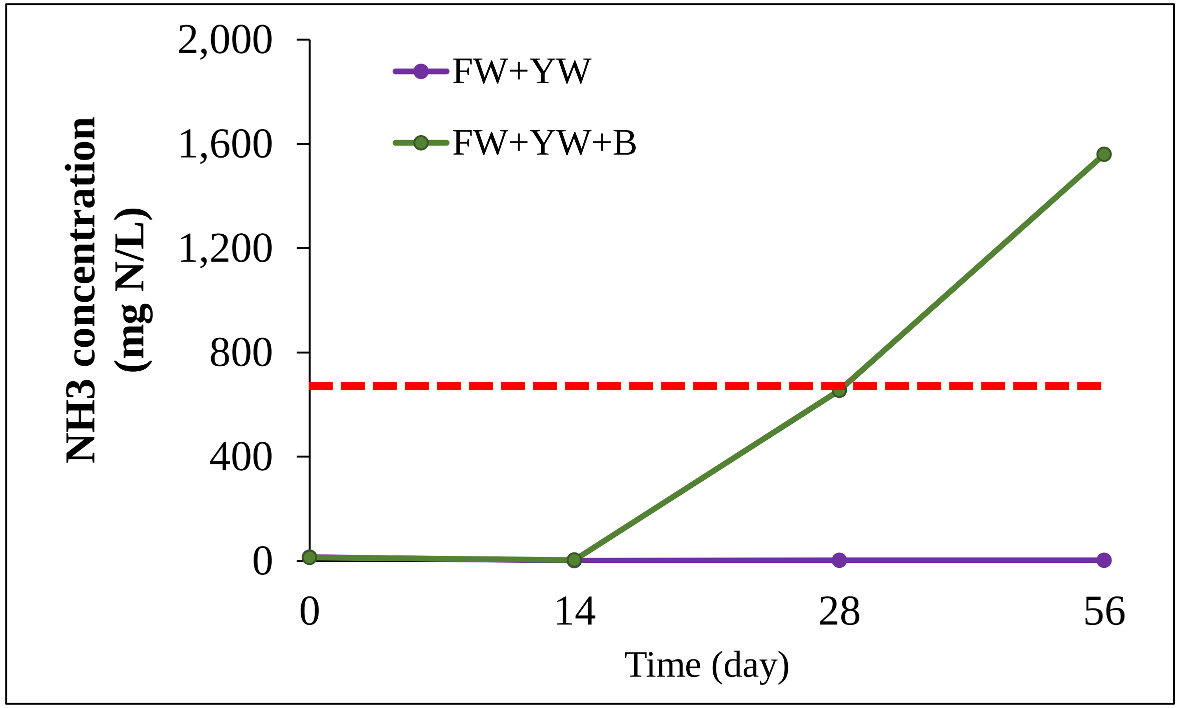
reclaim

water • nutrients • energy

usf-reclaim.org

Results: 1. Effect of Biosolids Addition (2)

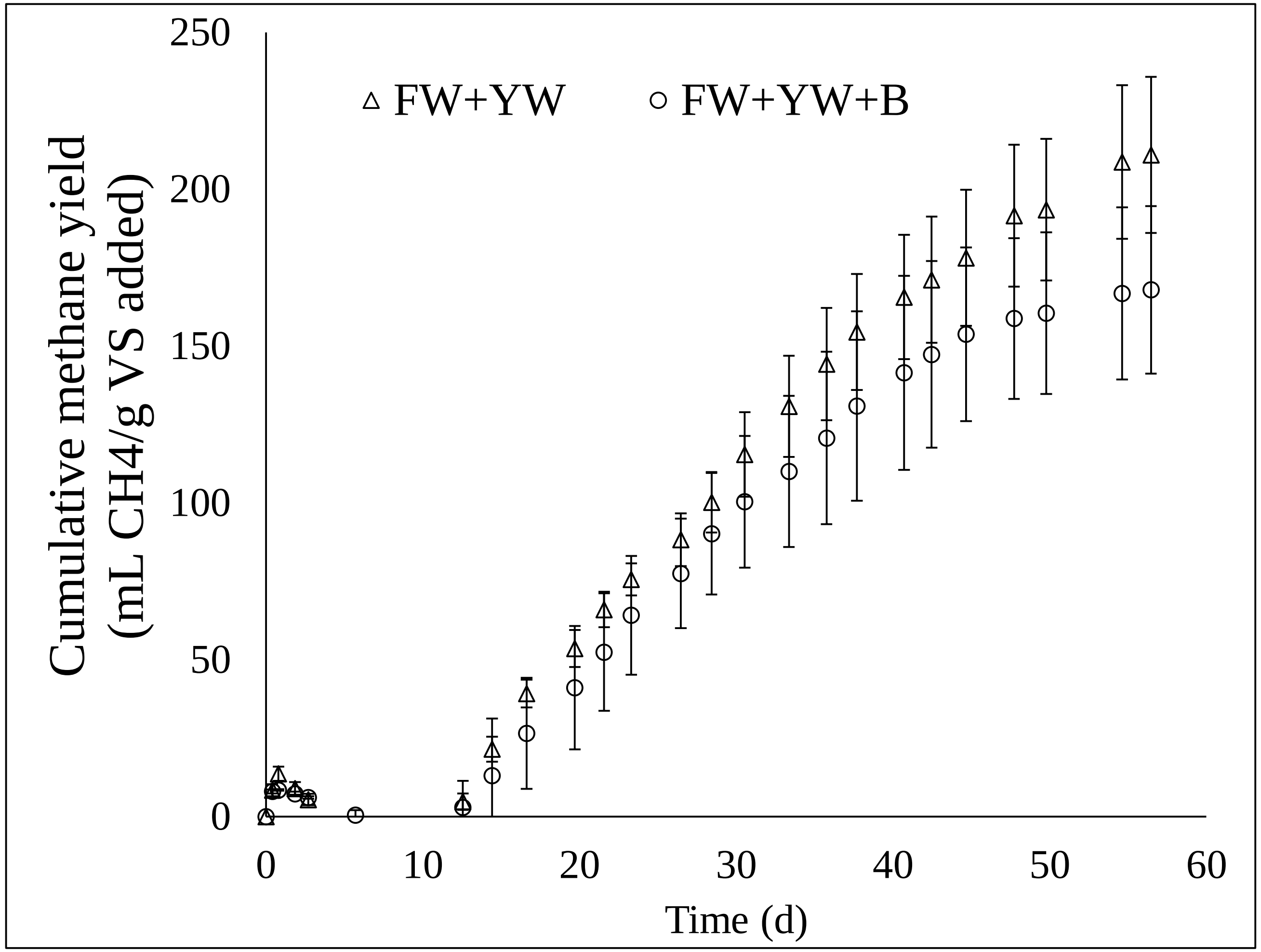
Free Ammonia (NH_3)



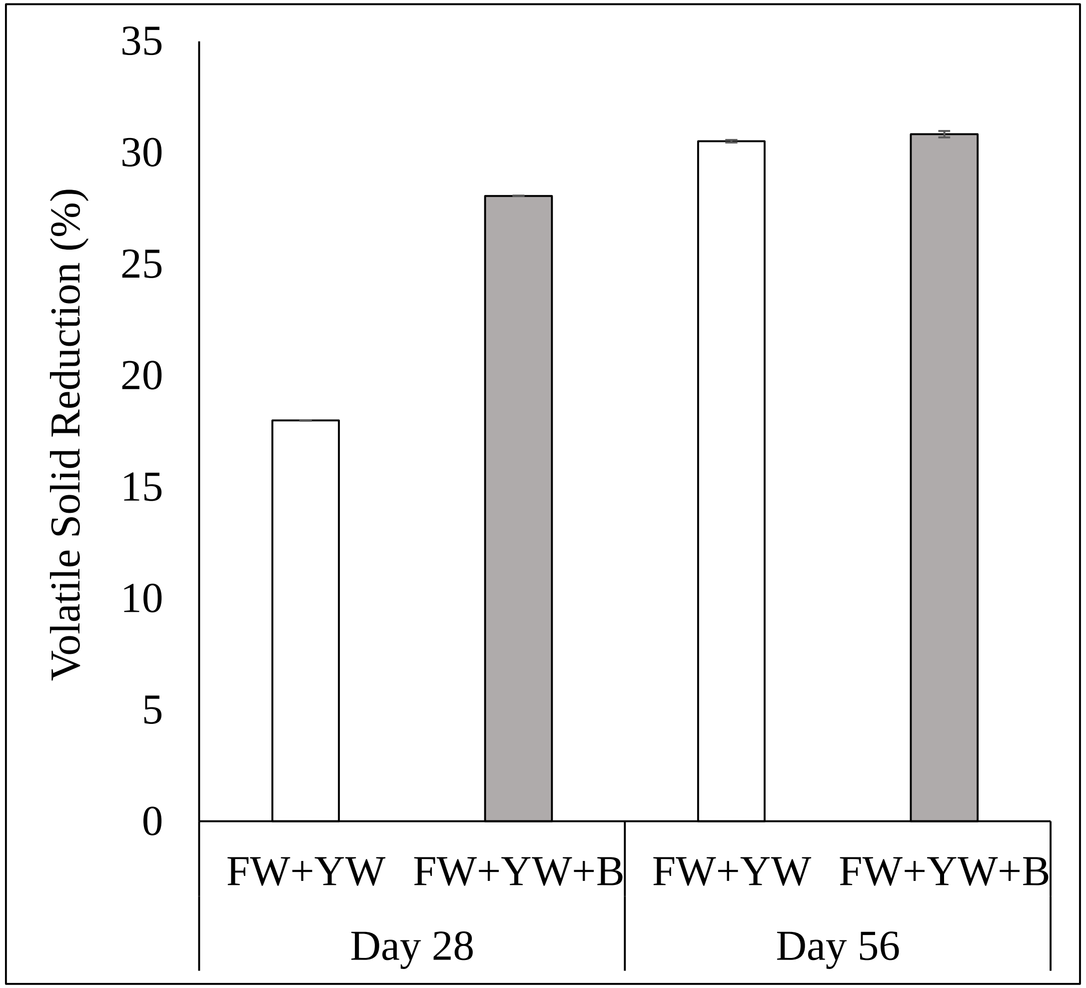
- NH_3-N inhibition > 700-1,100 mg/L (Niu et al., 2013)

Results: 1. Effect of Biosolids Addition (S/I=1)

Methane (CH_4) Yields

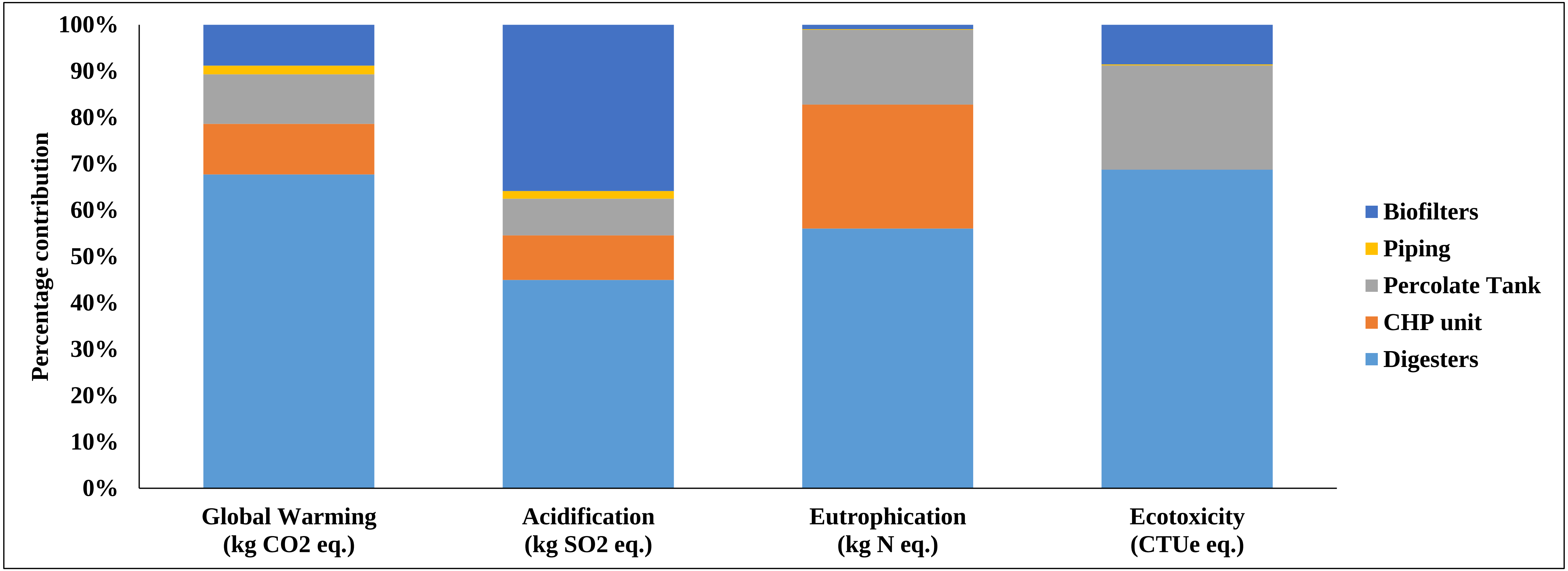


Volatile Solid Reduction



Environmental Impacts of HS-AD

Construction phase of HS-AD



Material & Methods

Input	Value	Reference
Life cycle cost analsis period (yr)	25	This study
Discount or interest rate (%)	1.89	USIR (2017)
Escalation rate (%)	0.65	EERC (2017)
Electricity price ($/kWh)	0.1035	EIA (2017)
Heat rate ($/kWh)	0.0088	Moriarty (2013)
Digestate price ($/tonne)	11.2	Schwarzenegger (2010)
Tipping fee, non-processable solid waste ($/tonne)	31	Hillsborough County (2016)
Tipping fee, processable solid waste ($/tonne)	58	
Collection & Transfer		
Average distance of collection (miles/hual)	211	This study
Average distance of transfer (miles/hual)	58 & 28	This study
A haul loading (tonne)	30	Faucette et al. (2002)
Transportation cost factor ($/miles)	0.8	This study
High Solids Anaerobic Digestion		
HS-AD size (m2)	3500	This study
Methane yield for HS-AD (ml/gVS)	92.89	This study
Voletile Solid reduction (%)	31	This study
Low heating value of methane for HS-AD (KWh/m3)	9.94	Passos and Ferrer (2015)
Combined Heat and Power Efficiency: Heat (%)	49.5	BIOFerm, n.d.
Combined Heat and Power Efficiency: Electricity (%)	37.7	

Input	Value	Reference
Waste to Energy (incineration)		
Waste to Energy (WtE) facility size (m2)	4000	This study
O&M cost factor for WtE ($/tonne)	28	Funk et al. (2013); SWANA (2012)
Percentage of reject after mechanical treatment for WtE (%)	89.39	Fernández-González et al. (2017)
Lower heating value of waste for WtE (MJ/tonne)	8000	Habib et al. (2013)
Composting (Windrow)		
Composting system (Windrow) size (m2)	43100	This study
Compost production ratio (g compost/g wet mass waste)	0.656	Komilis and Ham (2000)
Compost price ($/tonne)	29	Shiralipour and Epstein (2005)
Landfilling		
Landfill size (m2)	72800	This study
Expected life time of landfill (yr)	25	This study
Capital cost factor for landfill ($/acre)	774000	US EPA (2015)
O&M cost factor for landfill ($/tonne)	3.31	US EPA (2015)