A New High-Solids Anaerobic Digestion System

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Outline

- Anaerobic digestion as an technology of choice converting food wastes to bioenergy and other co-products
- Technical challenge and innovative digester design
- Performance for treating food waste
- Performance for treating green waste
- Conclusions and next step

Observations on AD Technology

- Only biomass conversion process that has been widely adopted world wide;
- Only biomass technology that has little controversial;
- A major bioenergy technology in the near term and a key player in the long term;
- It deserves more attention as it can play bigger roles.

Why Anaerobic Digestion Will Get More Attention

- A resources becomes more relatively limited and environmental concerns increase, recycling and reusing waste becomes more important and feasible;
- As fuels price increases, transporting wastes to a centralized disposal site gets more expensive;
- Feedstock cost and availability are major limiting factors for the development of any biofuel;
- Relative low investment risk.

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Further Develop AD Technology to Better Meet the Demand

Producing products other than methane

Co-product development

- Organic fertilizer
    - Nitrogen
    - Phosphorous
- Fiber for peat moss replacement
- CNG for transportation fuel
- Others

Technology advancement

- Biorefinerying and bioporcessing process
- Employing biotechnology tools
- Applying engineering sciences

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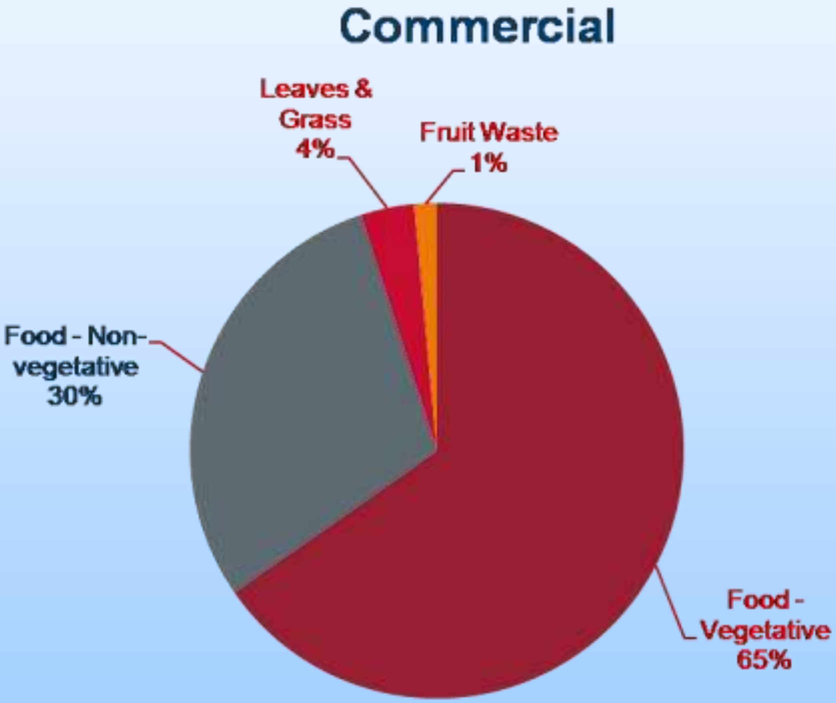
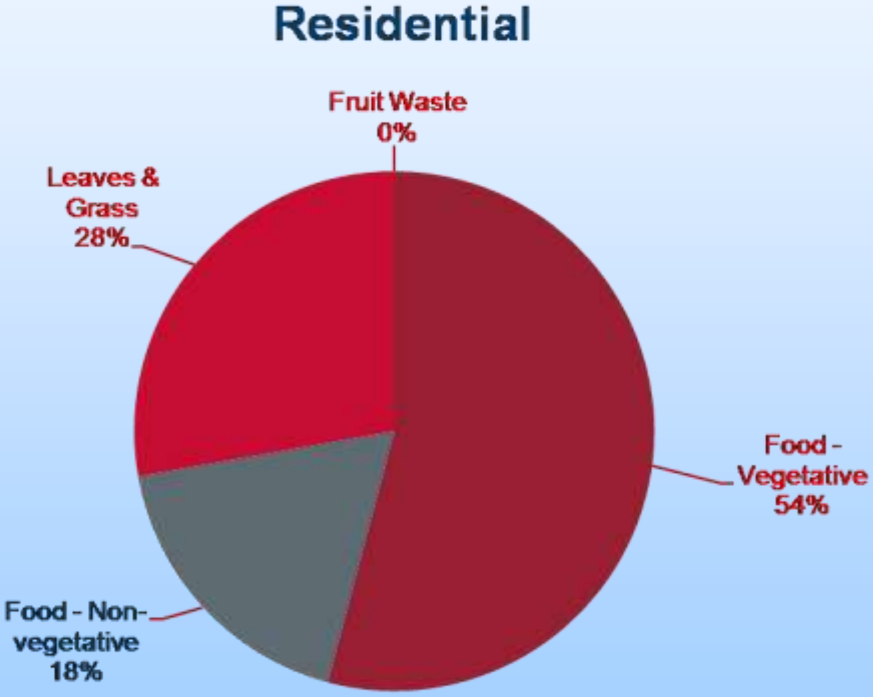
Washington State Organic Wastes



Annual tonnage: 502,090



Annual tonnage: 573,284

** Washington Waste mainly includes food waste and green waste.*

Economic and Environmental Comparison of Current Food Waste Treatment Technologies

Treatment	Costs ($/MT)	Net Costs ($/MT)
Collection + Landfill	140	140
Collection + Incineration	200	180
Collection + Composting	170	170
Collection + Anaerobic Digestion + Composting*	165	50

Diggelmann, Dr. Carol and Dr. Robert K. Ham. Department of Civil and Environmental Engineering – University of Wisconsin. January 1998. “Life-Cycle Comparison of Five Engineered Systems for Managing Food Waste.”

Volatile Compounds	Composting (g/MT)	Composting after Anaerobic Digestion (g/MT)	Percent Reduction
Total VOC + NH_3	747	101	86%

J. Mata-Alvarez, S. Mace and P. Llabres, Anaerobic digestion of organic solid wastes. An overview of research achievements and perspectives. Bioresour Technol, 74 (2000), pp. 3–16.

Common Anaerobic Digester and High Solid Anaerobic Digester (HSAD)

wastes

Municipal Rural Household

High Solid Anaerobic Digester
Total Solid (TS): > 10%

Efficient

Controllable

Green energy

Common Anaerobic Digesters
Total Solid (TS):~5%

Challenges to HSAD Design and Operation

- High solid content, high viscosity, low mass transfer and reaction rate;
- High power consumption for agitation and transportation;
- Inadequate retention time for both solids and liquids due to different reaction rate;
- Inhibition due to high volatile fatty acid (VFA);
- Inhibition due to high ammonia content.

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WSU's Strategies Towards These Challenges

- A unique two-stage design with seed recycling to eliminate VFA inhibition
- Ammonia removal for reducing its inhibition
- An innovative mixing design to minimize energy consumption
- Multiple scale up tests
- Using modeling as an design and analysis tool

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Liquid/Solid Separation in HSAD Reactor

Natural Separation Based on Biogas Floatation and Low Specific Gravity

The first day

The second day

Food waste initial TS 15%

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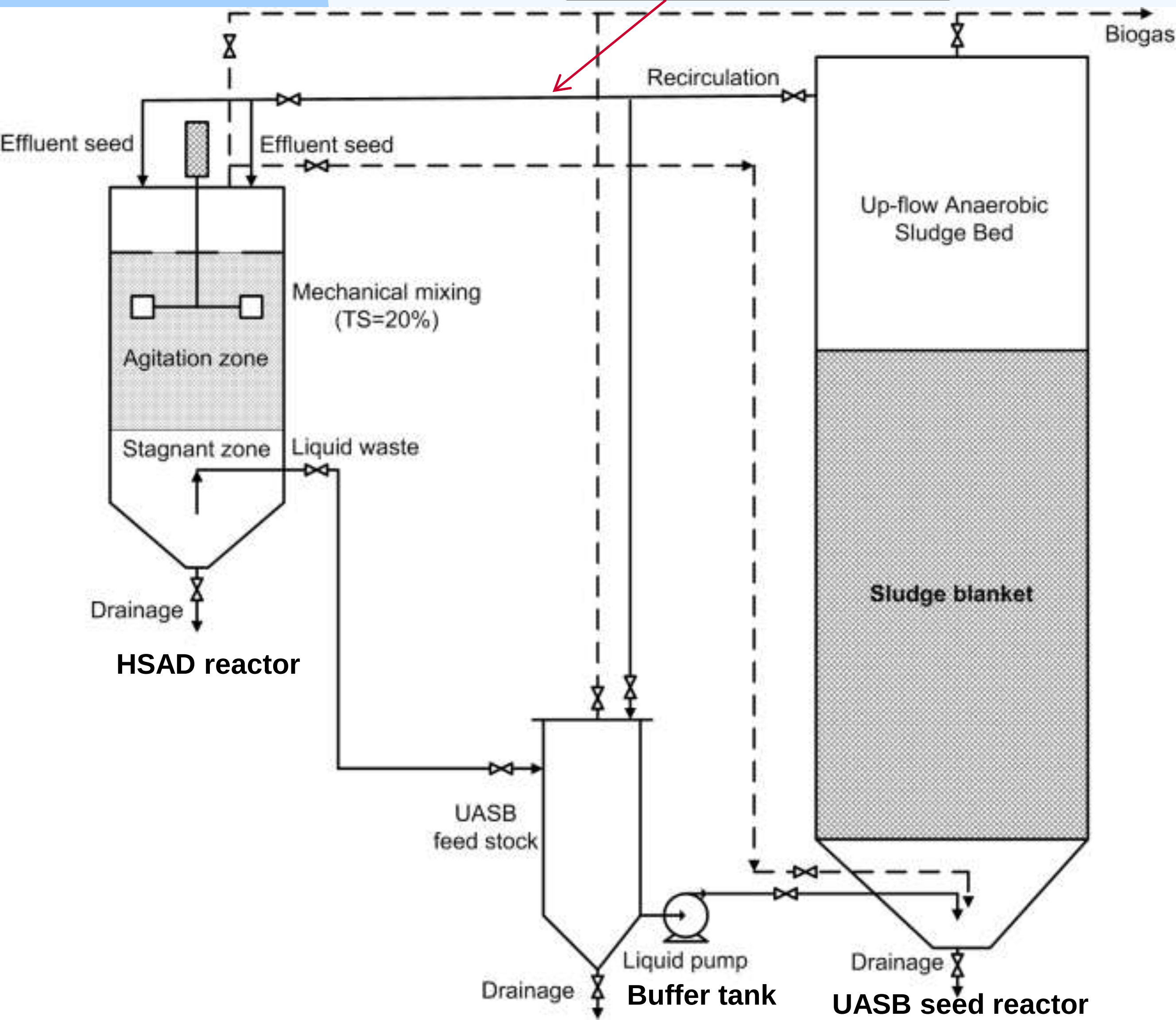
High-solid Anaerobic Digester with Recycling Seeds (HADRS)



Ammonia stripping

HSAD reactor

Buffer tank

UASB seed reactor

One stage and two phase in the first digester

Two stage and two phase in all two digester

Combined three mixing in the first digester: intermittent mechanical mixing, top spraying, and biogas floatation

Combined mixing and pH control strategy

Enhance methane productivity instead of hydrogen

Progress of HSAD at WSU

2006. 07. 01

Lab-scale

2008 (6 gallon)

Integrated Lab-scale

2011 (100 gallon)

Small pilot-scale system

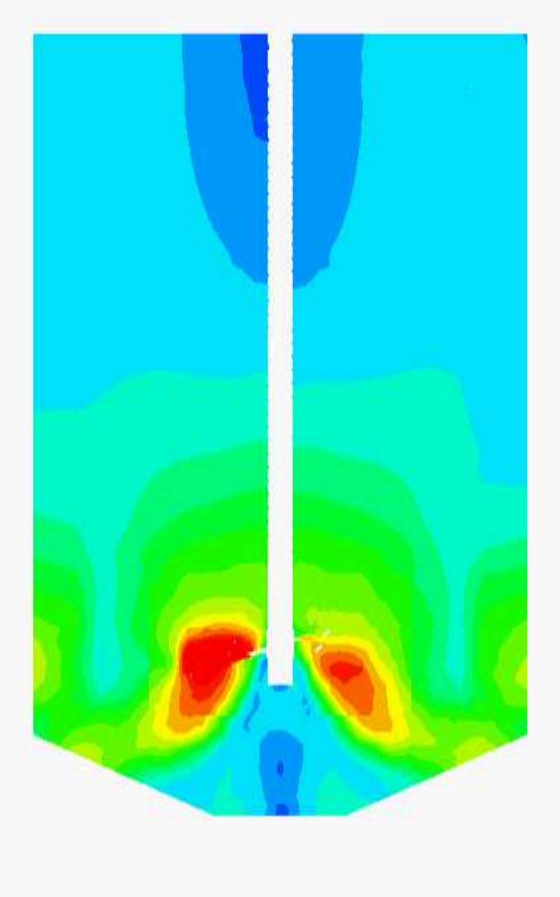
2011 Filed patent

Demonstration
&
Commercializatio

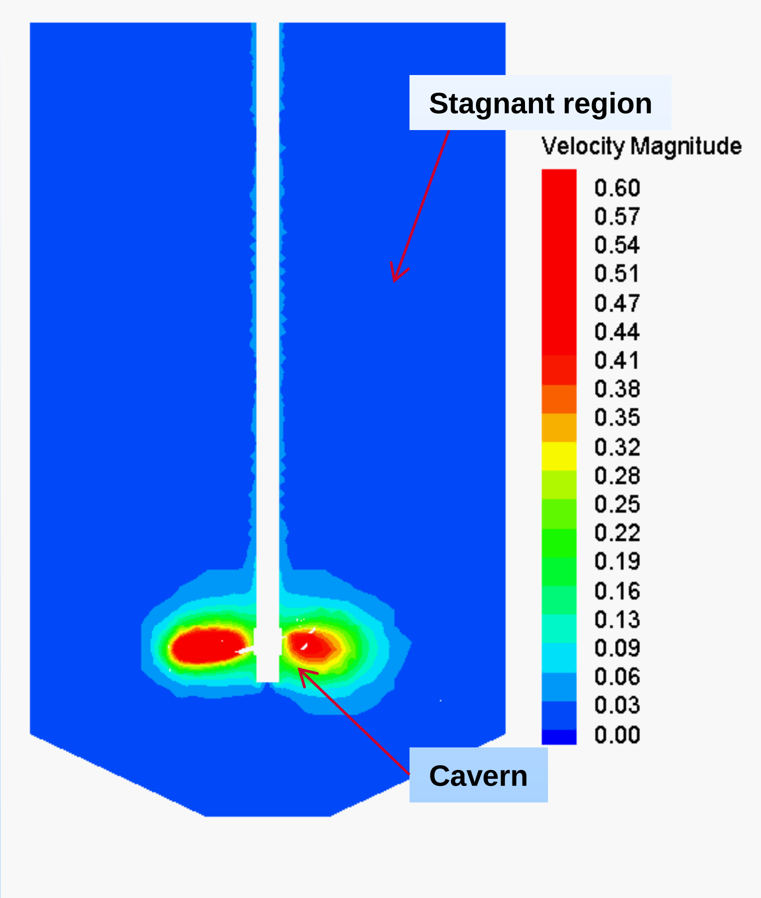
Preparing to construct in Tianjin, China

Design and Optimization Tools

Reactor Design by CFD-FLUENT



- ❖Total Solid (TS)<5%
- ❖Viscosity :9×10^{-4} Pa·s
- ❖Newtonian fluid

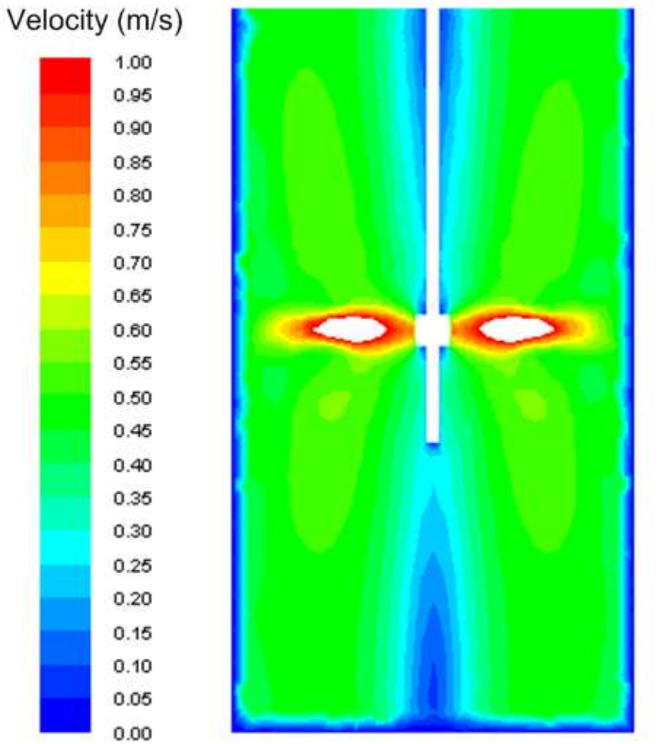


- ❖Total Solid (TS)=10%
- ❖Apparent viscosity
  - – K:16.1 Pa·s^n; n: 0.348
- ❖non-Newtonian fluid

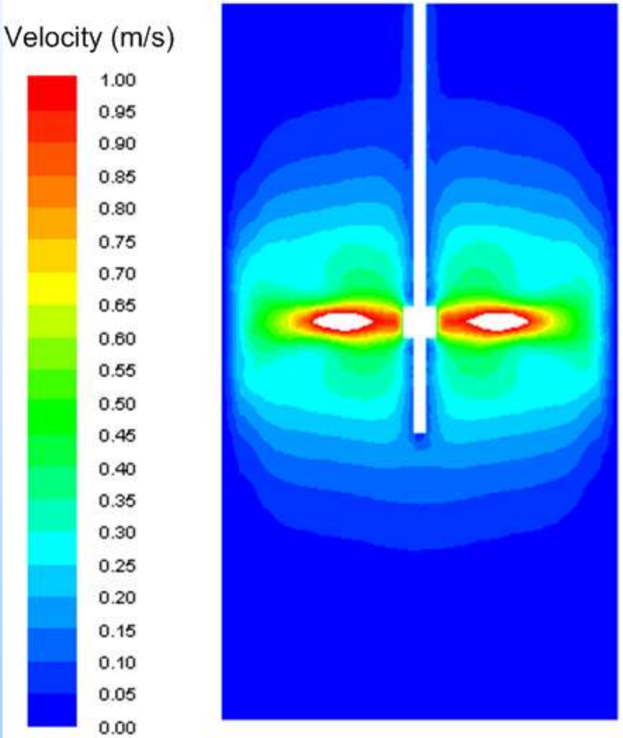
K – Consistency coefficient
n – Power-law index

L. Yu, J. Ma, S. Chen. 'Numerical simulation of mechanical mixing in high solid anaerobic digester'. *Bioresource Technology* 2011, 102(2): 1012–8.

HSAD Reactor Design



TS < 5%



TS = 10%

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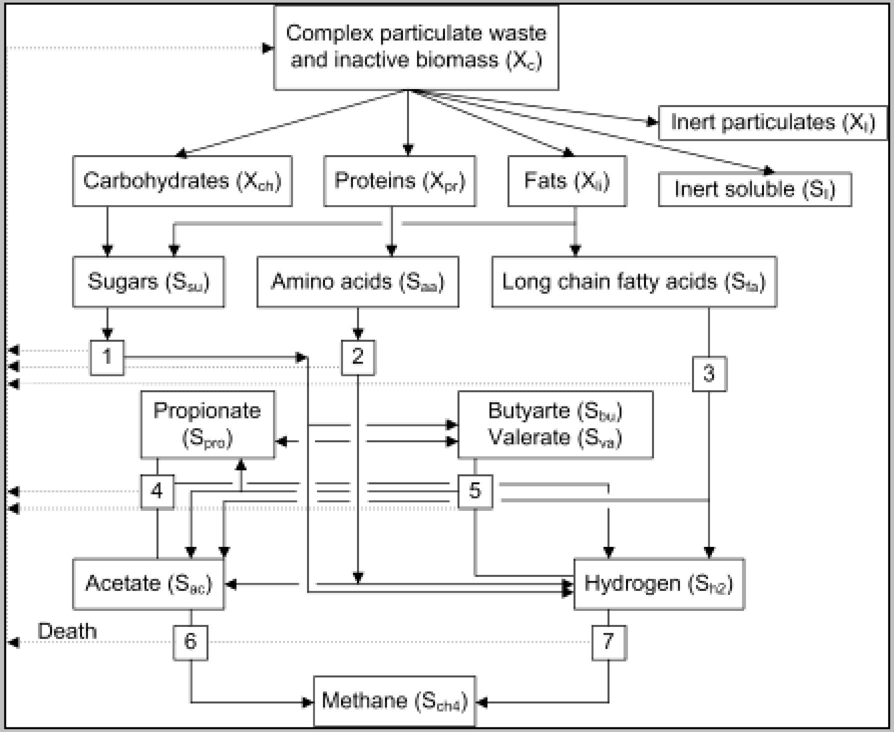
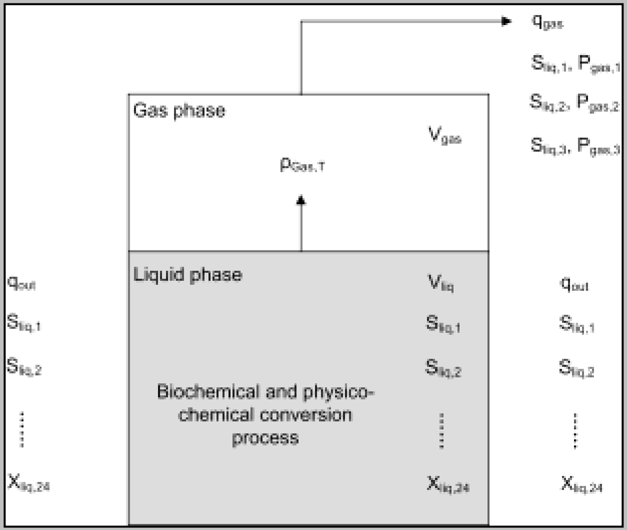
Design and Optimization Tools

Process Simulation by Anaerobic Digestion Model No.1 (ADM1)



Continuous flow stirred tank reactor (CSTR)

$$\frac{dC_{liq,i}}{dt} = \frac{q_{in}C_{in,i} - q_{out}C_{liq,i}}{V_{liq}} + \sum_{j=1-19} r_j v_{i,j}$$



(1) Acidogenesis from sugars

(2) Acidogenesis from amino acid

(3) Acetogenesis from LCFA

(4) Acetogenesis from propionate

(5) Acetogenesis from butyrate and valerate

(6) Aceticlastic methanogenesis

(7) Hydrogenotrophic methanogenesis

L. Yu, Q. Zhao, J. Ma, C. Frea, S. Chen. 'Experimental and modeling study of a two-stage pilot scale high solid anaerobic digester system'. *Bioresource Technology* 2012, 124(11): 8 – 17.

Performance Treating Food Waste

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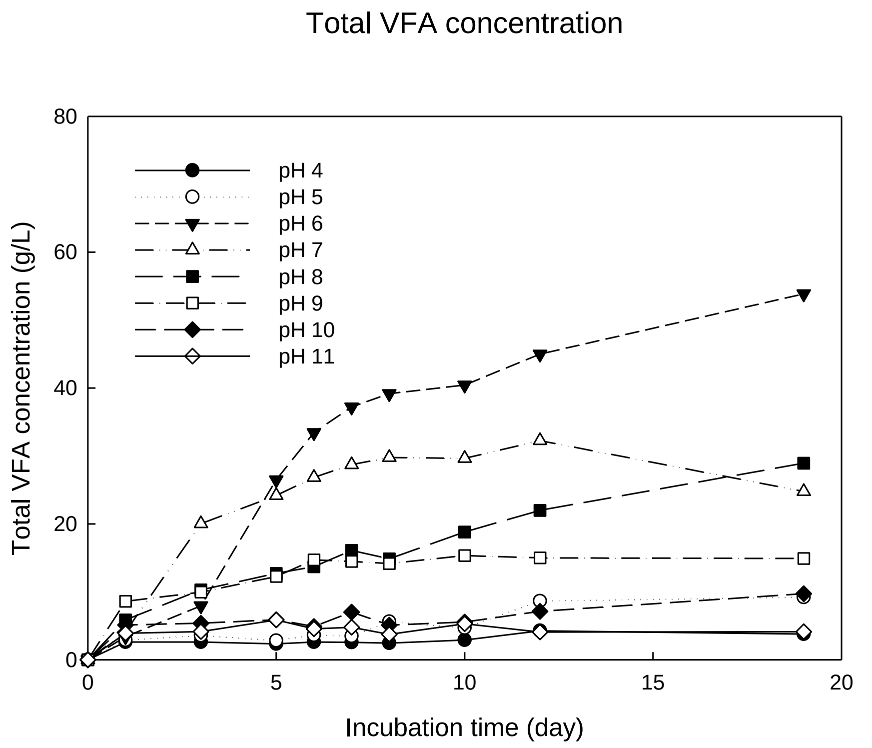
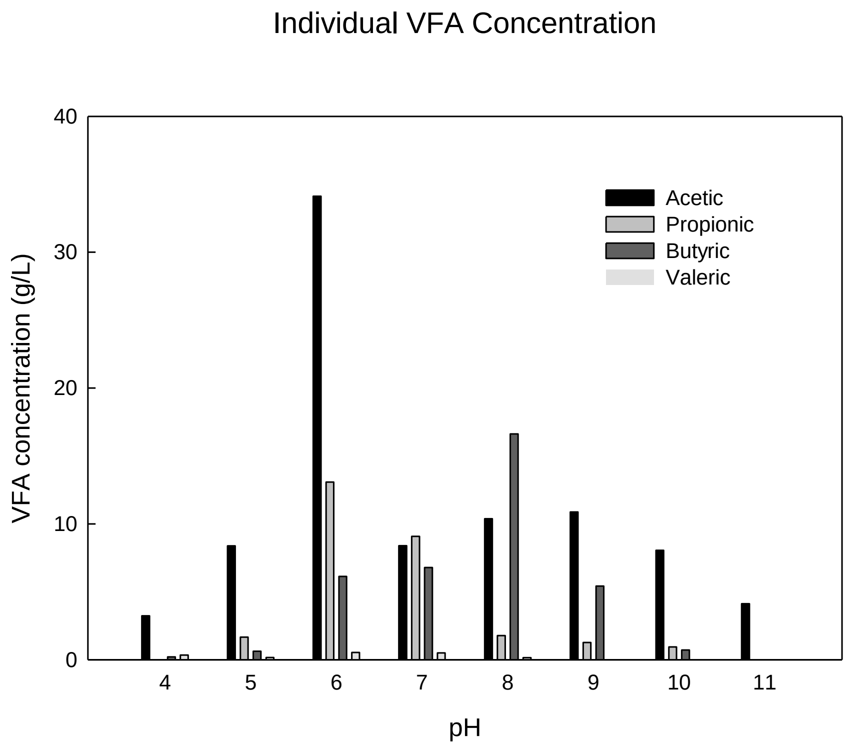
Characteristics of Food waste

Parameters	Unit	Value
Total Solid (TS)	% (w/w)	31.7
Total Volatile Solid (TVS)	% (w/w)	30.0
Total COD	g/L	439.0
Carbohydrate	g/L	176.9
Protein	g/L	99.0
Fat	g/L	24.0
Total Nitrogen	g/L	17.7
Volatile Fatty Acid (VFA)	g/L	10.1

Hydrolysis Optimization in HSAD Reactor

VFA Productivity at Different pH


Total VFA concentration


Individual VFA Concentration

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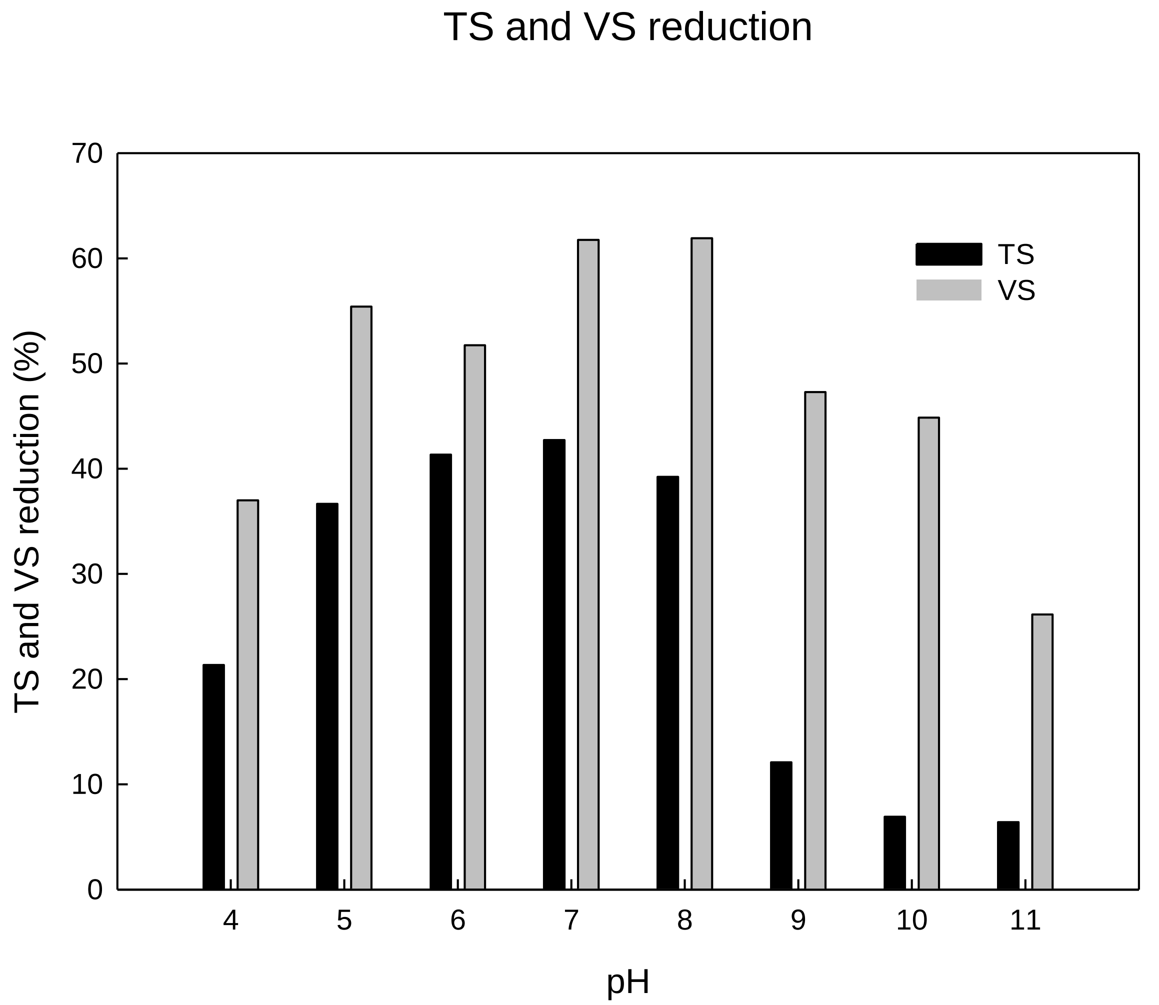
pH 6, maximum VFA concentration: 53.9 g/L;

Excessive acidity or alkalinity reduce VFA production.

Hydrolysis Optimization in HSAD Reactor
TS/VS Reduction at Different pH



pH 7 – 8, TS/VS reduction is maximum

100 Gallon Pilot-scale Performance

Parameters	Unit	Value
Theoretical methane yield	m^3 CH_4/kg VS	0.51
6 Gal experimental methane yield	m^3 CH_4/kg VS	0.4
100 Gal experimental methane yield	m^3 CH_4/kg VS	0.29
Biogas production rate	m^3/m^3/day	3.17
Methane production rate	m^3/m^3/day	2
Methane content	-	63.9%
Total solid reduction	-	43.74%
Volatile solid reduction	-	46.03%
COD removal	-	47.33%

Economic Analysis of the Savings with the HADRS System

Cost and economic benchmarks	HADRS system	Conventional HSAD system	Annual Savings of the HADRS system	
			US\$/kWh	Percentage %
Capital cost including post composting \$/ton	18.89	27.78		
Electricity production rate kWh/ton	113.37	113.37		
Capital cost of solids reactor including post composting \$/kWh	0.17	0.25	0.08	32%
Cost of the seed reactor assuming similar capital cost as solid reactors \$/kWh	0.17		-0.17	
Cost of solids recycle \$/m^3		0.043		
Cost \$/m3 of liquid recycle	0.029			
Recycling cost \$/kWh	0.0011	0.0015	0.0005	33%
Mixing cost solids reactor \$/m^3	4.94	4.94		
Mixing cost solids reactor \$/kWh	0.74	1.1	0.35	32%
Mixing cost for recycled solids blending \$/kWh		0.22	0.22	100%
Total cost production \$/kWh	1.08	1.55	0.48	31%
kWh from food waste in Washington	157M	157M		
Total cost utilizing all food waste in Washington (annual savings)	168M	244M	75M	31%
kWh from all digestible waste in Washington	560M	560M		
Total cost utilizing all digestible waste (annual savings)	602M	870M	268M	31%

Estimated Based on lab-scale data

Performance Treating Green Waste

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Anaerobic Digestion of Green Waste

- **Lawn Grass - kentucky bluegrass (poa pratensis l.)**

- **80% of U.S. households have a private lawn.**
- **27.6 million acres of turf grass in U.S.**
- **21 million acres in home lawns.**
- **Huge source for bioenergy production.**

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Grass Characteristics

- **Density: 136 kg/m^3**
- **Cellulose: 25 – 40%**
- **Hemicellulose: 35 – 50%**
- **Lignin: 10 – 30%**

Easy to be suspended - suitable to use in the HADRS system.

High hemicellulose and lignin contents - Pretreatment will accelerate hydrolysis to fit the high rate system.

Sugar Recovery of Lawn Grass after Pretreatments

Sample	% Free sugar recovery
Untreated grass	0.00± 0.00
Ozone treated grass (10 min)	48.50 ± 2.17
SAA treated grass (24h, 50 ^{0}C)	86.71 ± 0.20
Ozone and SAA treated grass (10 min OZ, 15% NH_4OH, 6 h, 50 ^{0}C)	89.63 ± 2.09

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Anaerobic Digestion with and without Pretreatment

- Analysis of grass waste

Parameters	Unit	Value
Total Solid (TS)	% (w/w)	2.5
Total Volatile Solid (TVS)	% (w/w)	1.7
Total COD	g/L	22.2
Carbohydrate	g/L	7.9
Protein	g/L	5.6
Fat	g/L	-
Total Nitrogen	g/L	0.8
Total Phosphorus	g/L	0.3

Method

- Reactor: 250 ml serum bottle;
- Feed stock: Lawn grass from house yard in Pullman, WA;
- Inoculums: Active sludge;
- Operational mode: Batch
- Inhibition or no inhibition of methanogen to separately study the processes of producing VFA and methane.

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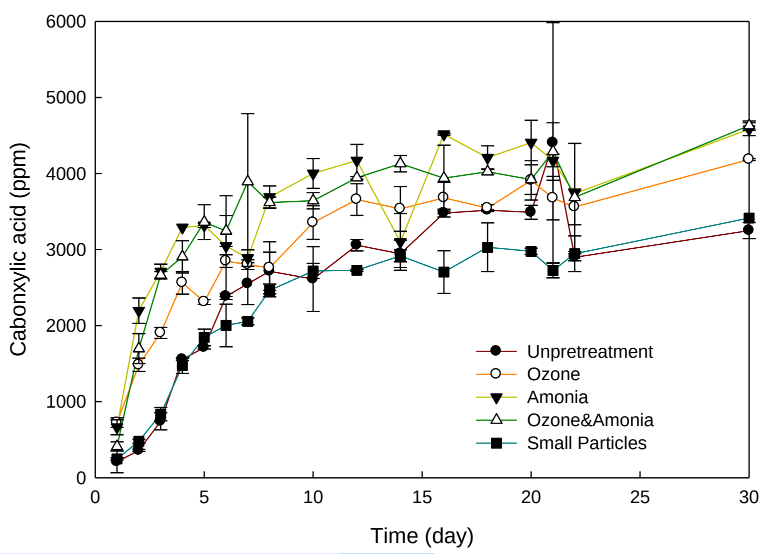
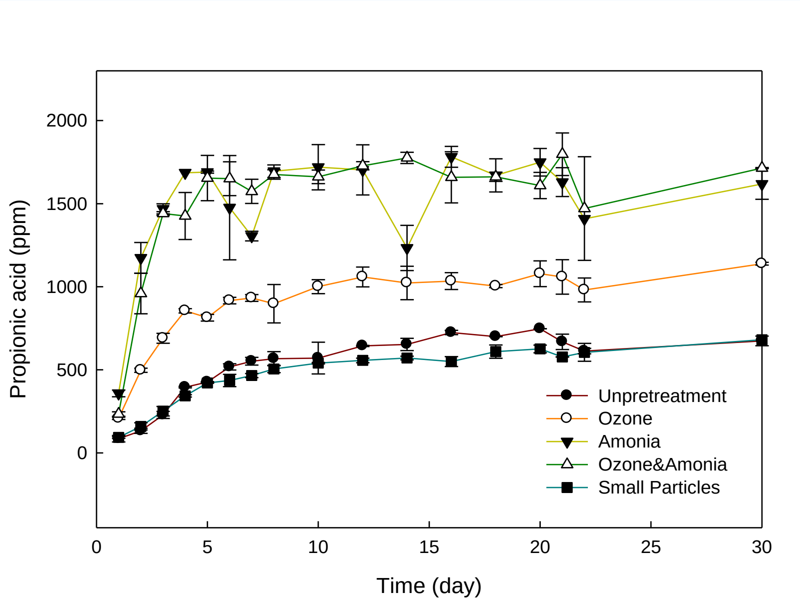
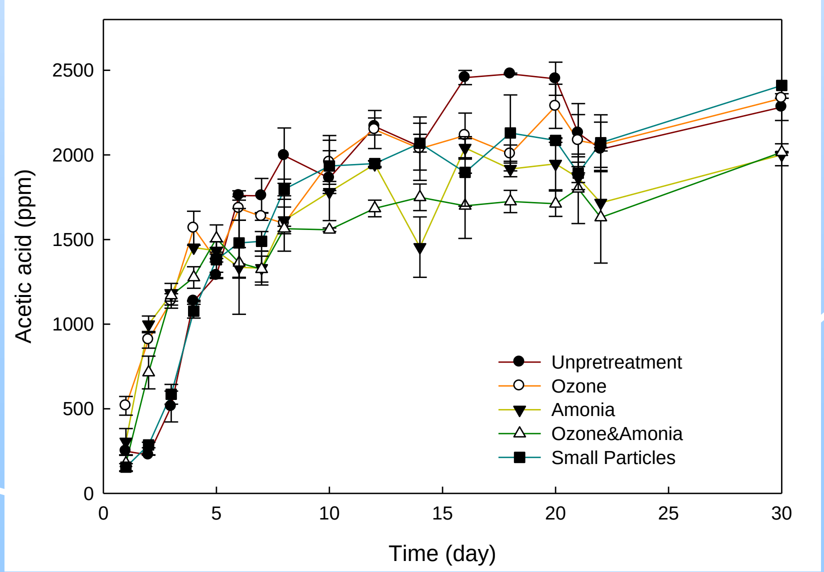
VFA Change with Time







There are significant differences in propionic acid production between unpretreatment and pretreatment; Ammonia and Ozone&Ammonia pretreatment are better

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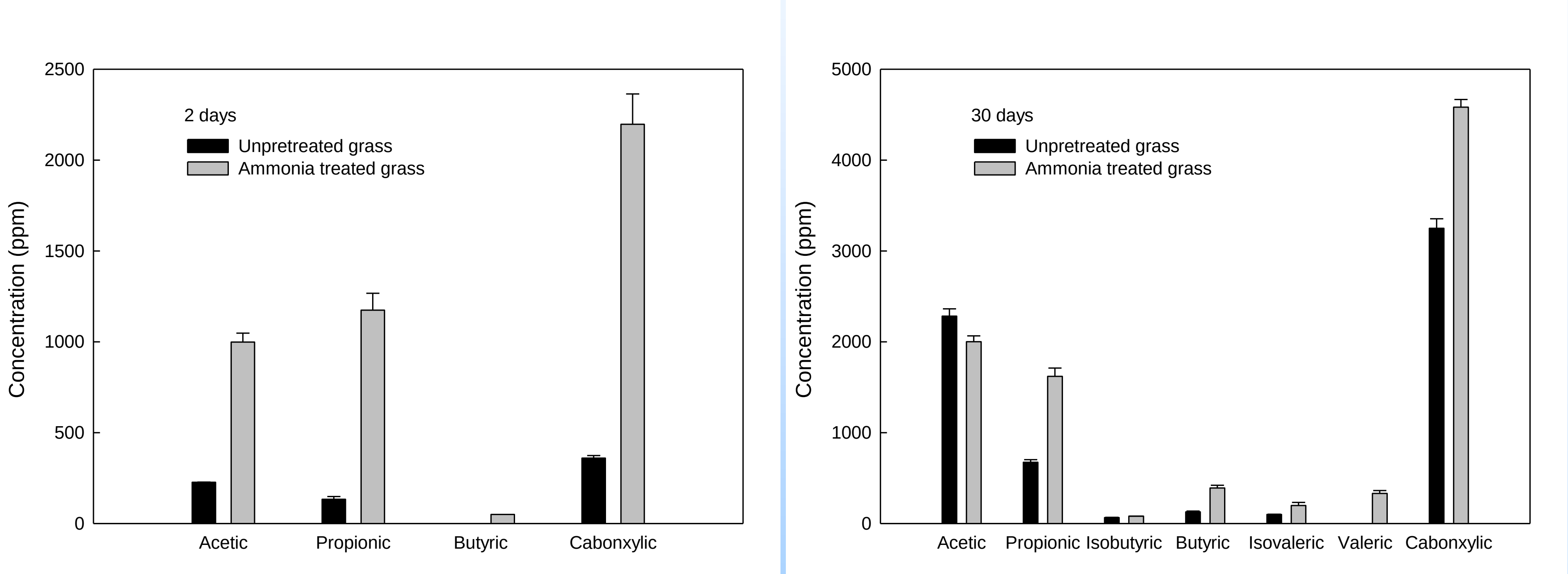
Comparison of VFA with and without Pretreatment



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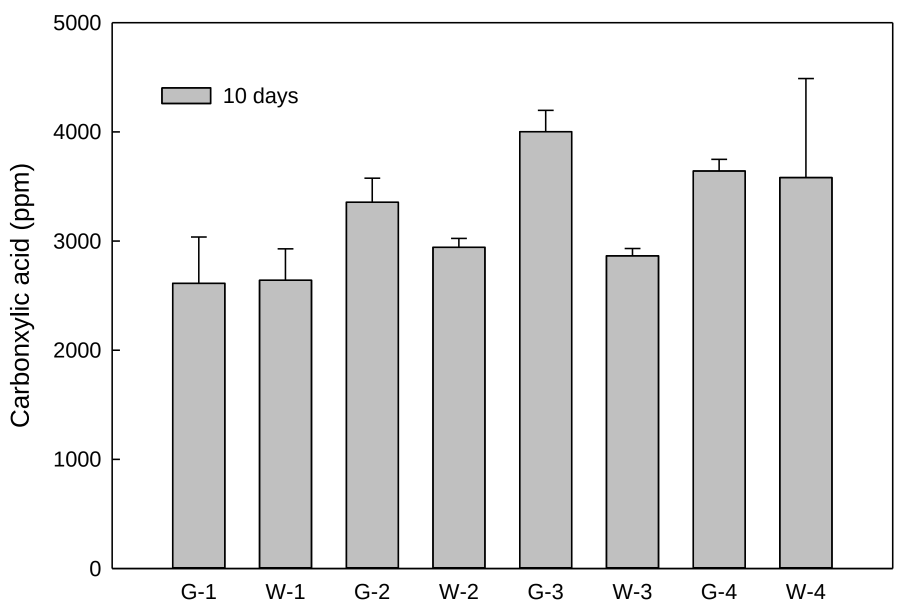
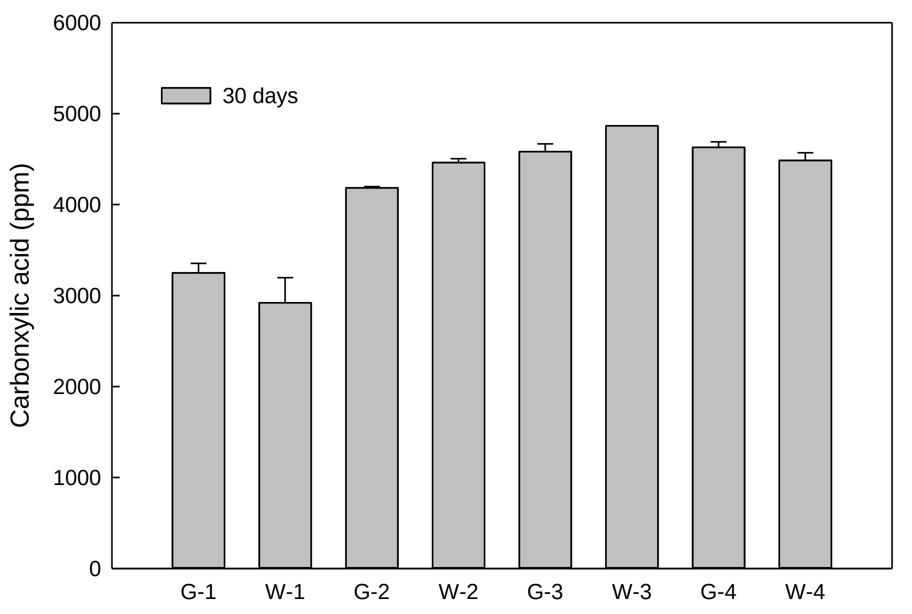
The pretreatment has significant effect on VFA production at shorter days

Comparison of Grass and Wheat Straw





G-1: unpretreated grass; W-1: unpretreated wheat straw
G-2: ozone treated grass; W-2: ozone treated wheat straw
G-3: ammonia treated grass; W-3: ammonia treated wheat straw
G-4: ozone & ammonia treated grass; W-4: ozone & ammonia treated wheat straw

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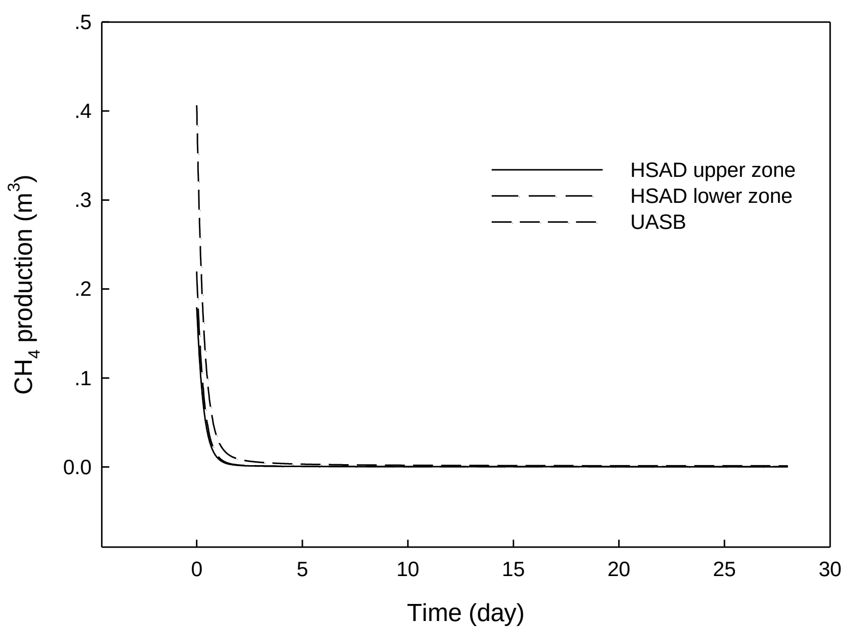
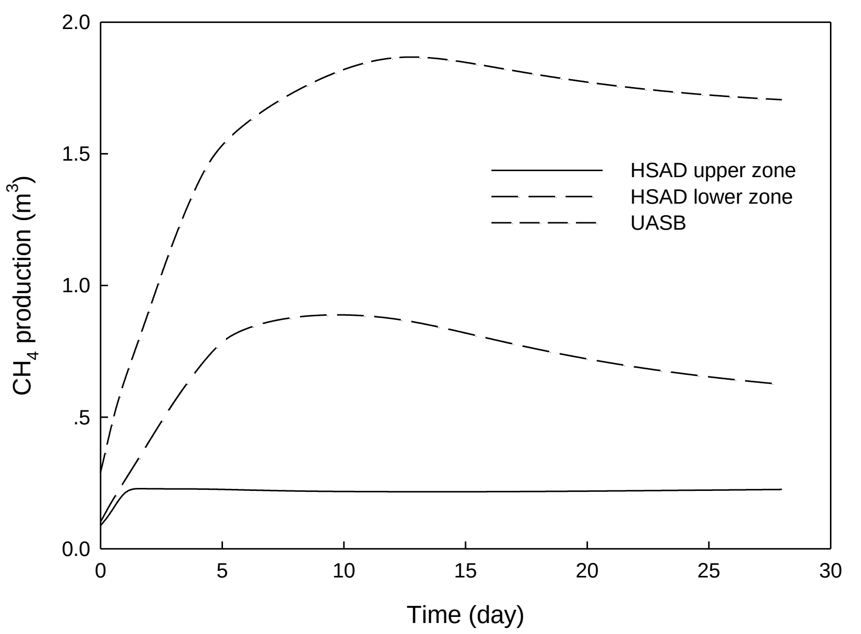
Prediction of Scale-up by 100 Fold

Coefficient of dispersion is 20 m^2/day



Coefficient of dispersion is 2000 m^2/day



Conclusions

- AD is a proper technology for organic waste treatment as it allows for harvesting energy and nutrients while stabilizing the organic materials;
- The WSU’s new AD design has the potential to efficiently treat both food and green wastes;
- Modeling tools and bench scale data are available for scaling up;
- Integration of AD and composting should be explored;
- Collaborations are invited for next level of pilot test/demonstration.

Acknowledgement

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ideas. connections. jobs

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