Anaerobic Digestion Systems on Small- and Medium-sized Farms

Wei Liao

Anaerobic digestion Research and Education Center (ADREC)
Biosystems and Agricultural Engineering, Michigan State University

Manure Management and Utilization Technologies
Purdue University Extension
November 17, 2022

Outline

1. Facts
2. Current practice of agricultural wastes utilization
3. Our strategy of agricultural wastes utilization for small- and medium-sized farms
4. Integrated organic wastes utilization
   - Anaerobic digestion of biogas production
   - Solar-biopower generation
   - Water recycle and nutrient recovery
5. Case studies
6. Conclusions

1. Facts

- 4.5 billion dry tons of agricultural residues annually produced in the world.
- About 1.3 billion tons of food wastes annually produced in the world (approximate 730 million tons of organic wastes discharged to the surface water).
- About 2,200 cubic kilometer of wastewater globally produced per year.

Animal manure
www.wikipedia.com

Food wastes
http://geographyblog.eu/wp/geography-of-food-waste-is-staggering/

Wastewater
http://commons.wikimedia.org/wiki/File:Discharge_pipe.jpg

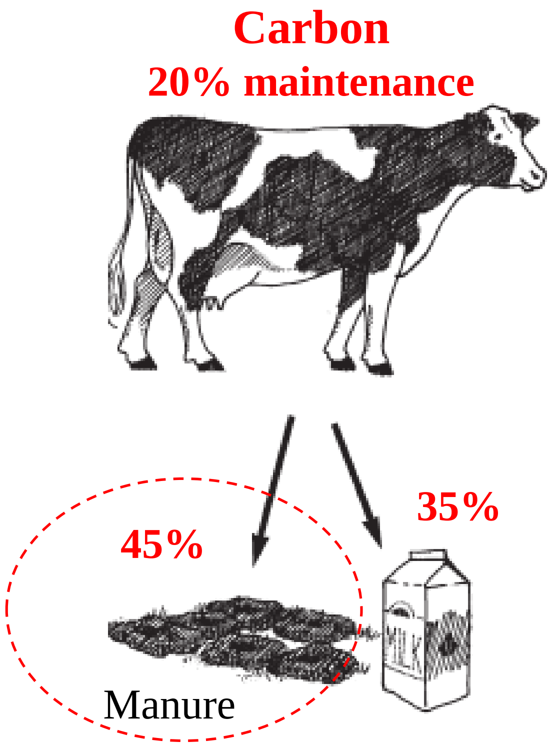
Landfill
http://www.wikipedia.com

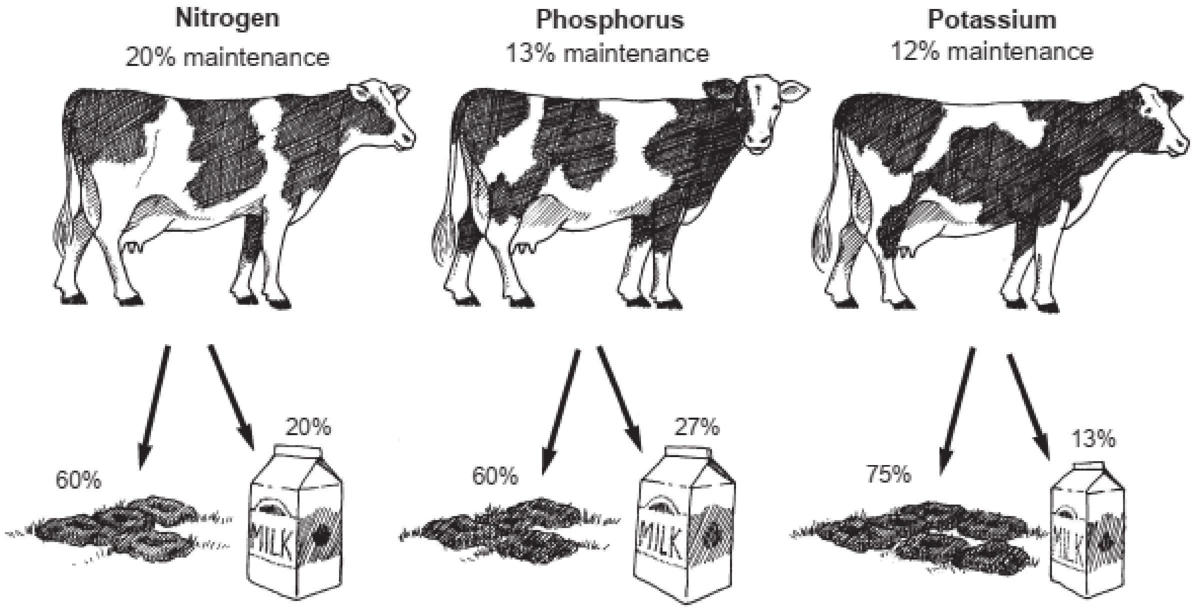
From: United Nations World Water Development Report 2017.
Bentsen, N. S. et al. Progress in Energy and Combustion Science 40, 59-73 (2014).
Melikoglu, M. et al. Cent. Eur. J. Eng. 3(2), 157-164 (2013)

2. Facts

Example: dairy farms and animal manure

- 97% of U.S. dairy farms are owned by family
- Average dairy farm size is 187 cows per dairy farm
- More than 90% of the U.S. dairy farms are small- and medium-sized farms (less than 1,000 cows)
- More than 27 million tons (dry dairy manure) produced in the U.S. annually

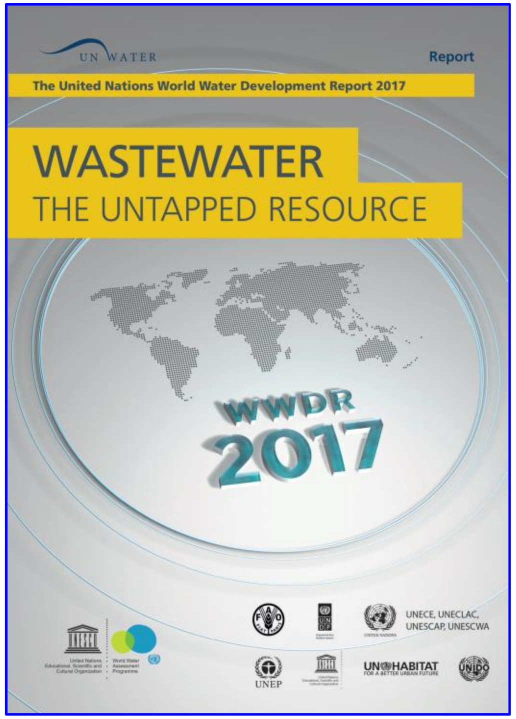


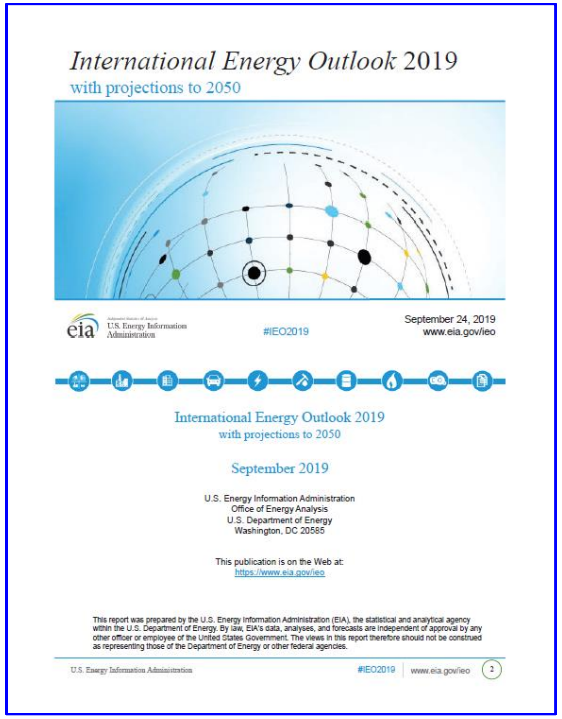


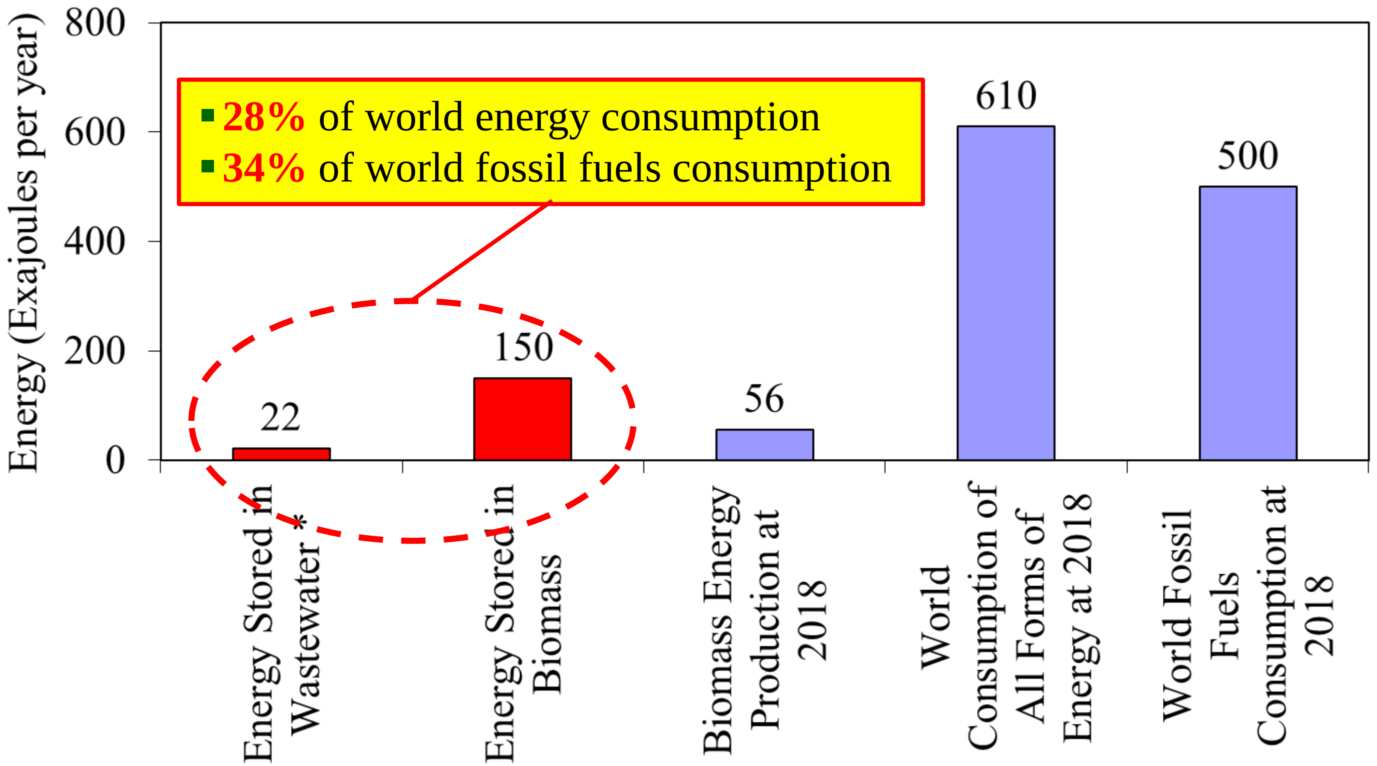
From: J. Hart, et al., Dairy manure as a fertilizer source, , Nutrient management for dairy production, EM8586, 1997
From: J. Blignaut, et al., Agricultural Systems, 195(2022), 103286

2. Facts

Potential of the organic residues and wastewater





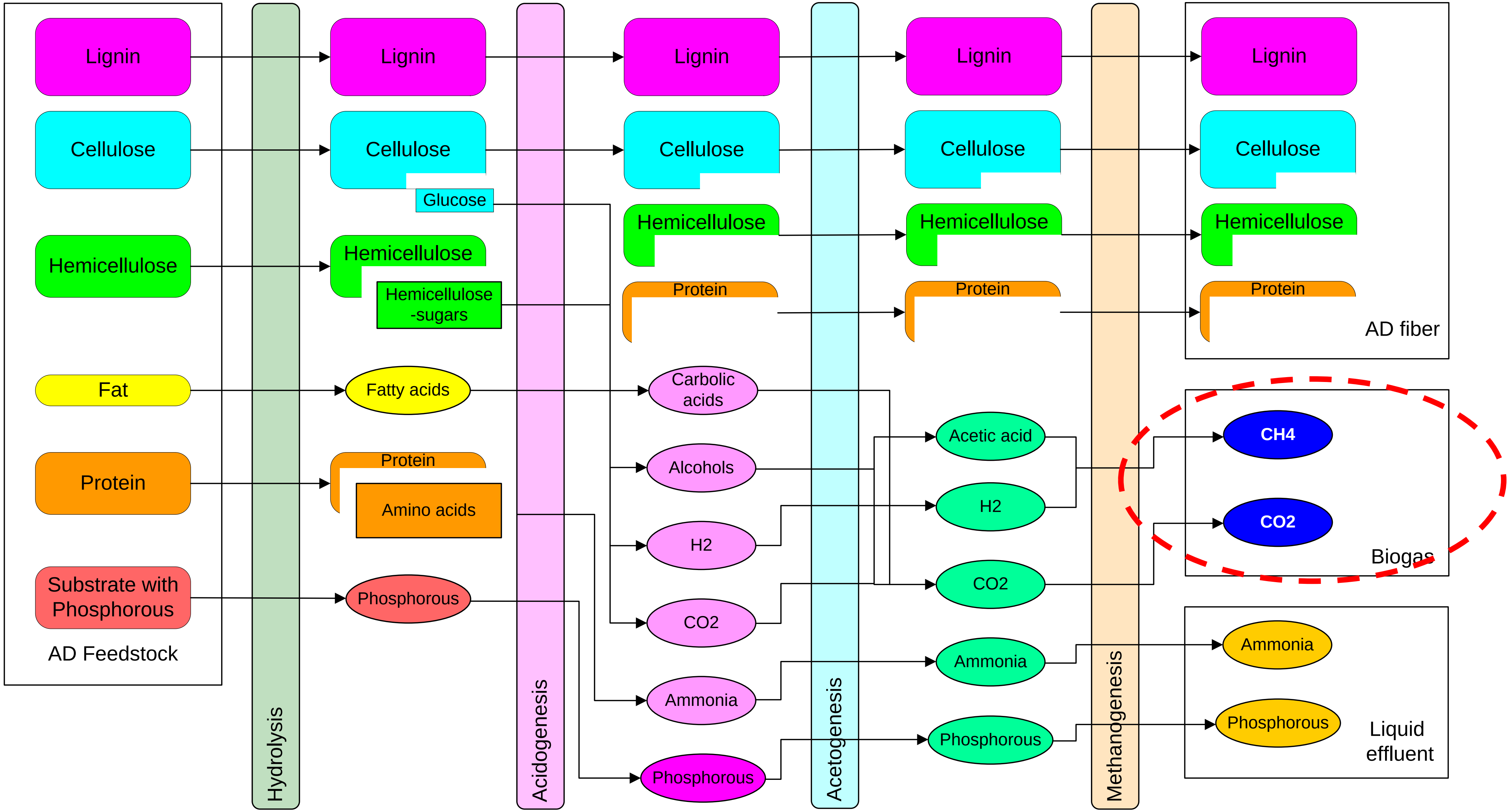


Organic residues have the potential to make a significant contribution to global energy sustainability.

* From: Heidrich, E. et al. Environ. Sci. Technol. 45.827 (2011). The energy content of wastewater is 1 x 10^7 J/cubic meter wastewater.

3. Current practice of agricultural wastes utilization

Anaerobic digestion



MICHIGAN STATE UNIVERSITY

3. Current practice of agricultural wastes utilization

BAE Department of Biosystems and Agricultural Engineering

Biogas – Carbon utilization

Raw biogas → Biogas cleaning → **Clean biogas** → Heat and Electricity

(2-10 inches of water)

Biogas cleaning → Biogas upgrading → **Renewable natural gas (RNG)** → Gas grid injection; Vehicle fuel

Gas grid injection

Vehicle fuel

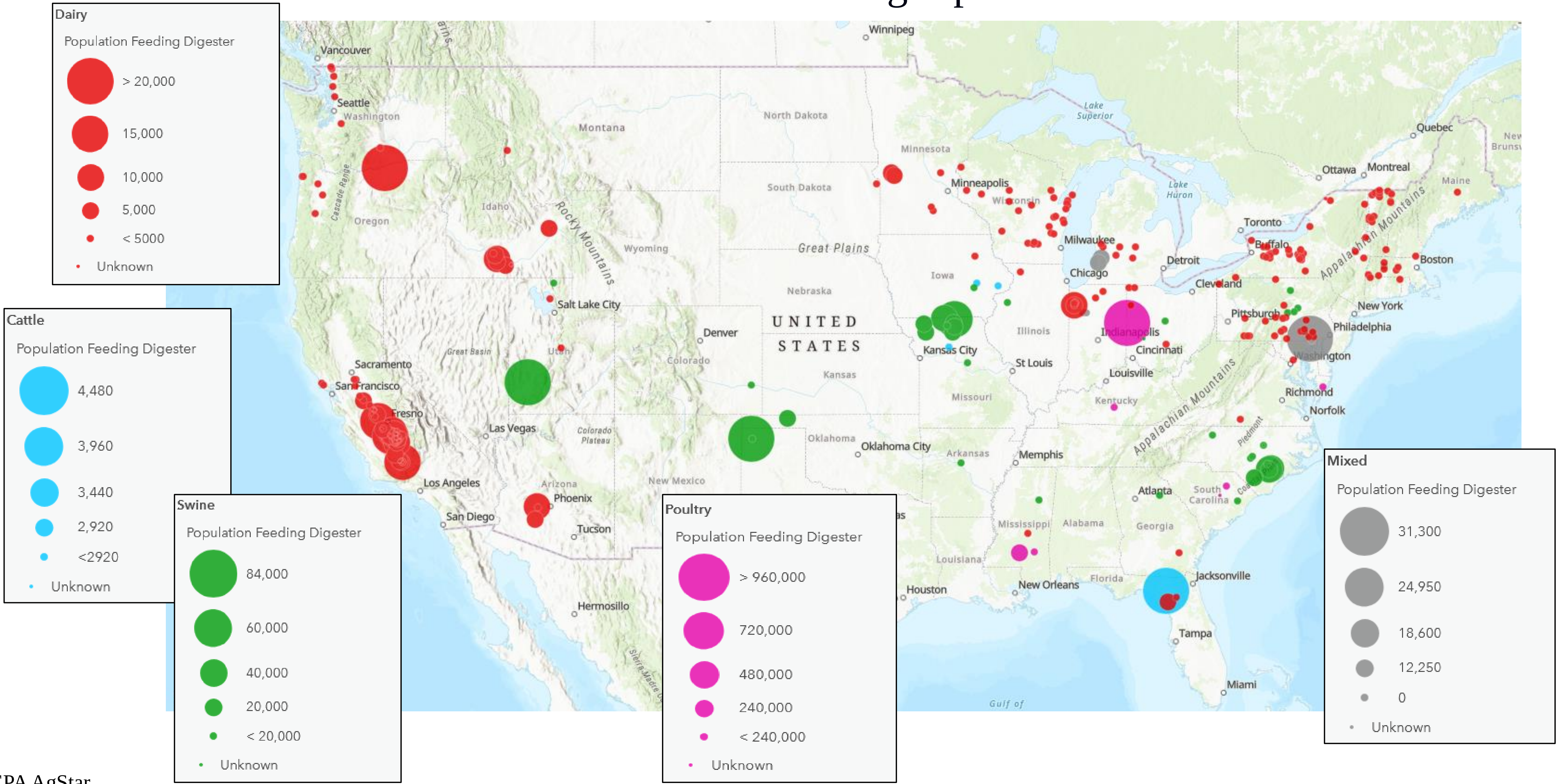
(5 psi)

(100-500 psi)

Carbon utilization of agricultural wastes is not enough for Small- and medium-sized farms !!!

3. Current practice of agricultural wastes utilization

Current farm-based biogas plants



From EPA AgStar

3. Current practice of agricultural wastes utilization

Current operational and potential biogas plants in the U.S.

	Livestock manure	Landfill gas	Wastewater treatment facilities	Total
Currently operational systems	**331**	636	1,241	2,208
Potential biogas systems	**>60,000**	1,086	3,681	64,767

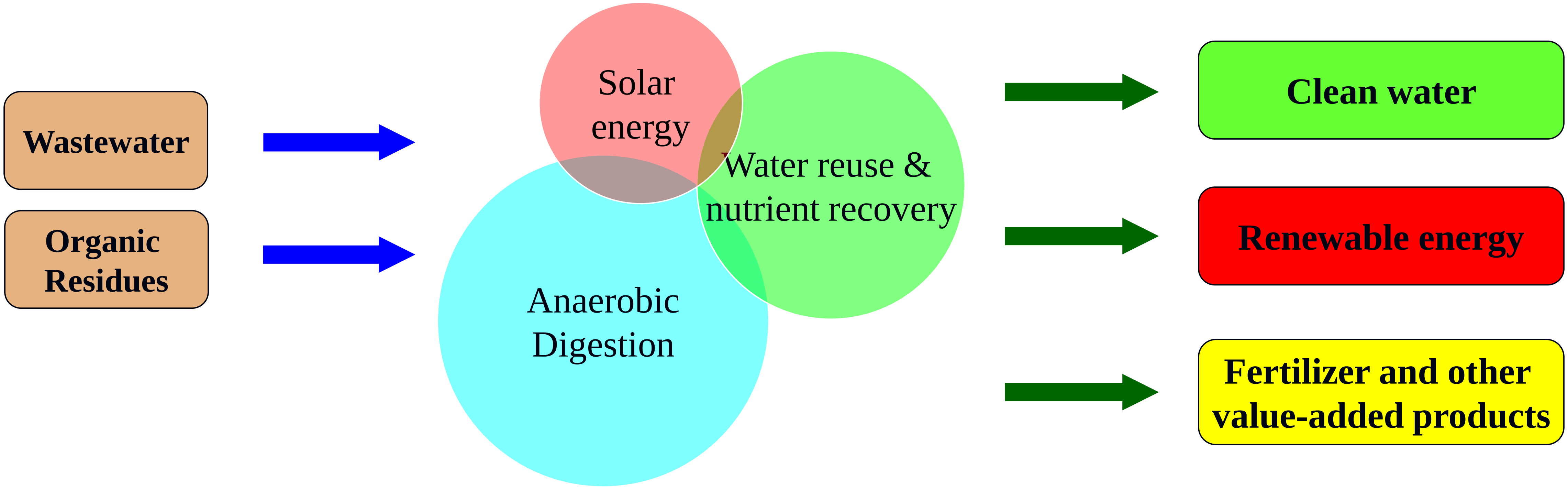
Estimated energy potential from organic wastes in the U.S.

	Livestock manure	Landfill gas	Wastewater treatment facilities	Total
Biogas production potential (billion cubic feet per year)	**257**	284	113	654
Electricity potential (billion kWh/year)	**13.1**	22.5	5.6	41.2
Vehicle fuel (million GGE)	**1031**	1028	441	2499

From EPA AgStar

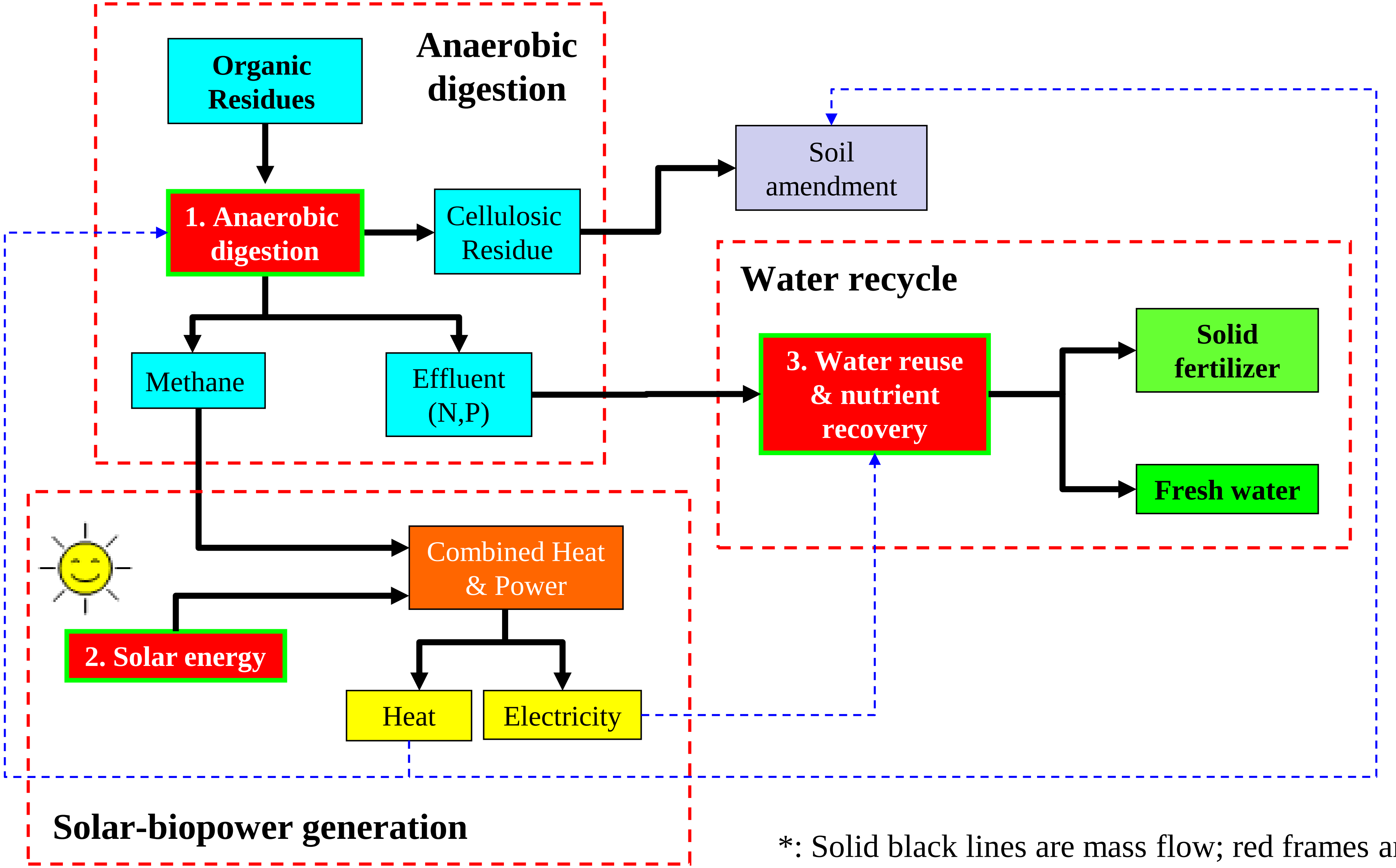
3. Our strategy

Synergistically integrating anaerobic digestion with solar and other technologies creates technically feasible and economically sound system solutions to fully utilize C/N/P in the wastes and address the challenge of organic residues management for small- and medium-sized farms.



4. Integrated organic wastes utilization

Flowchart of the integrated organic wastes utilization

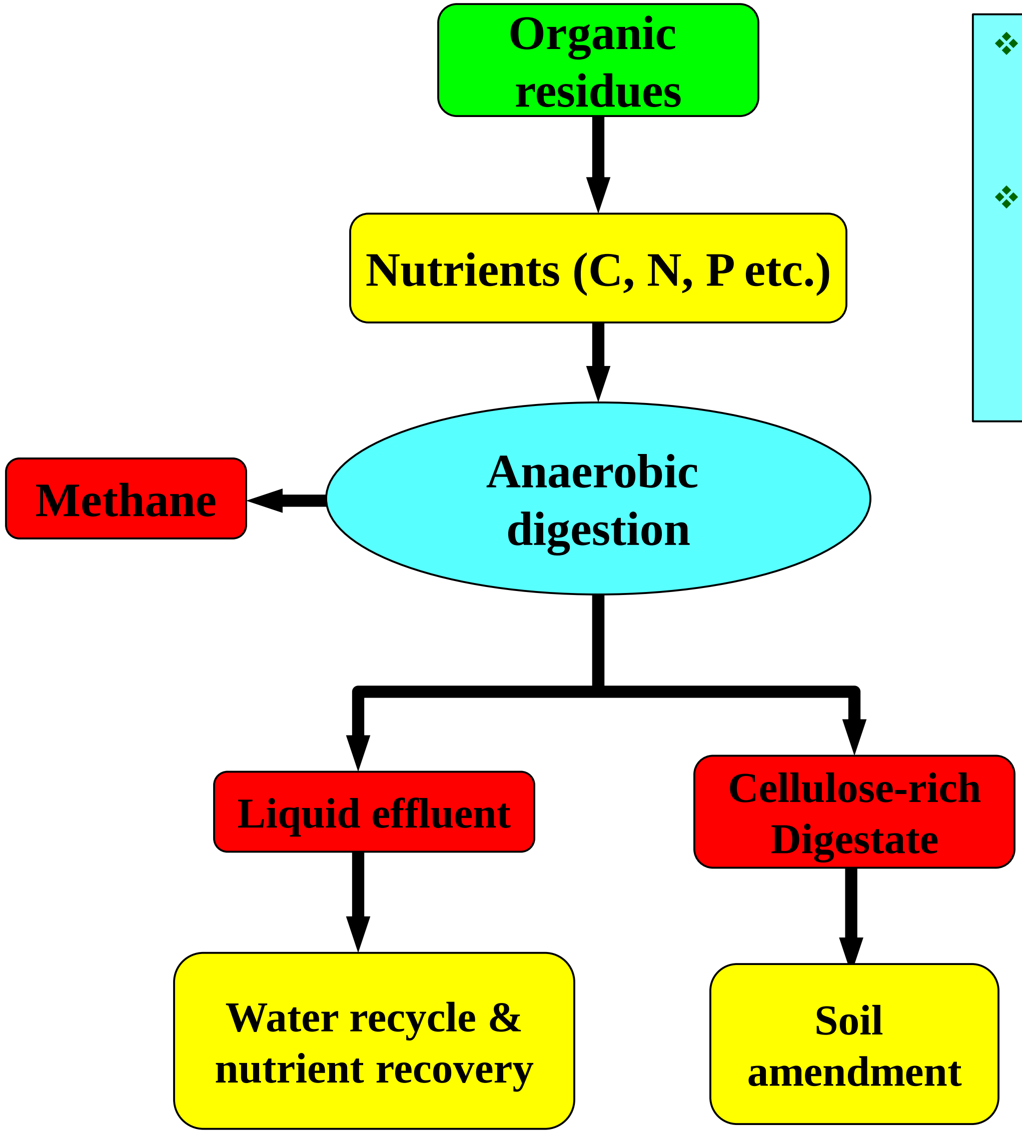


- High-efficiency anaerobic digestion
- Solar-biopower generation
- Water reclamation and nutrient recovery

*: Solid black lines are mass flow; red frames are unit operations; dash blue lines are energy flow.

4. Integrated organic wastes utilization

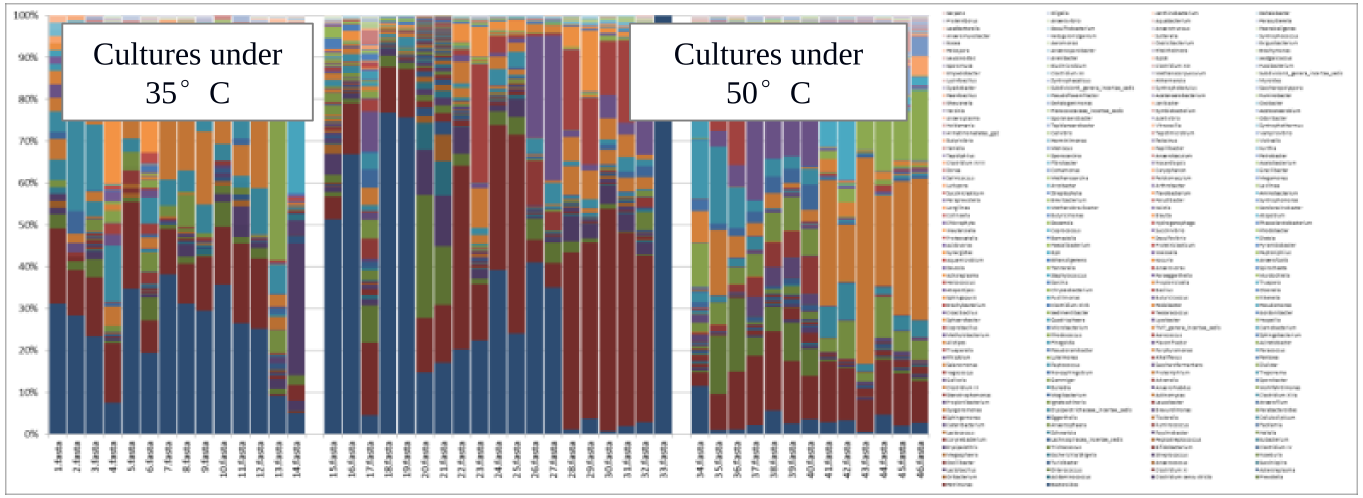
Anaerobic digestion – improving the digestion efficiency



- **Primers for metagenomics analysis:** Universal primers 341 F (5’-CCTACGGGNBGCASCAG-3’) and 805 R (3’-GACTACNVGGGTATCTAATCC-5’)
- **Data processing:** Fastq data from Illumina sequencing are analyzed using BION, a open-source package for microbial community analysis form the Danish Genomic Institute, Aarhus, Denmark

Illumina MiSeq 2000

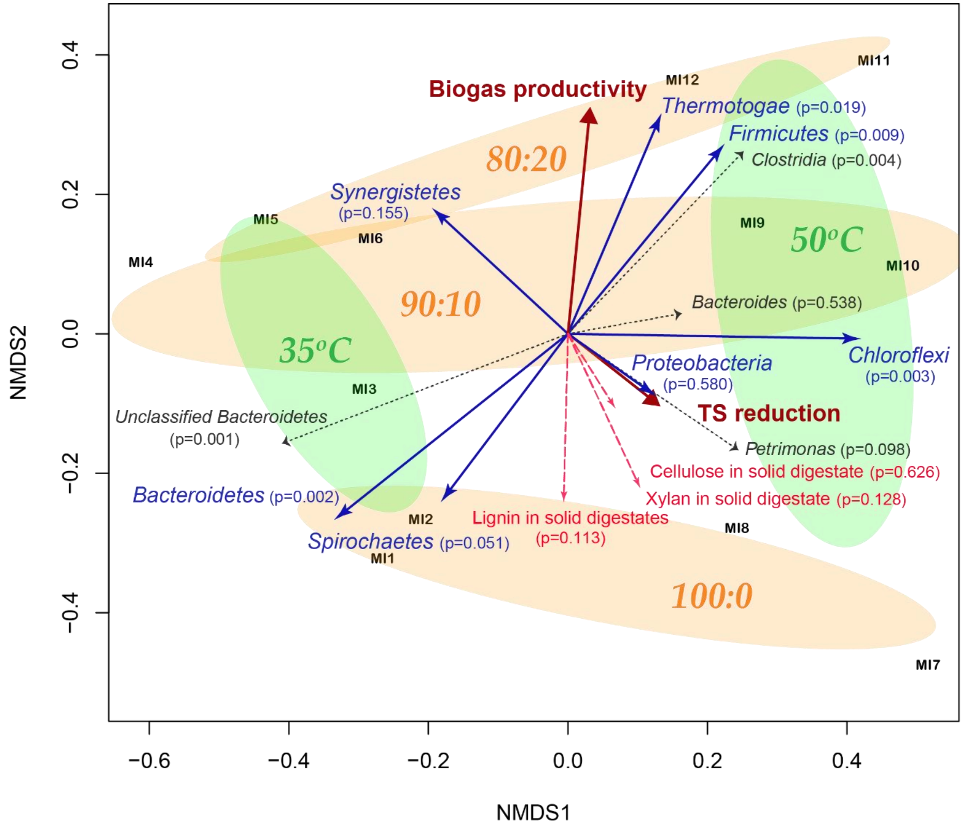
Abundances of microbial community



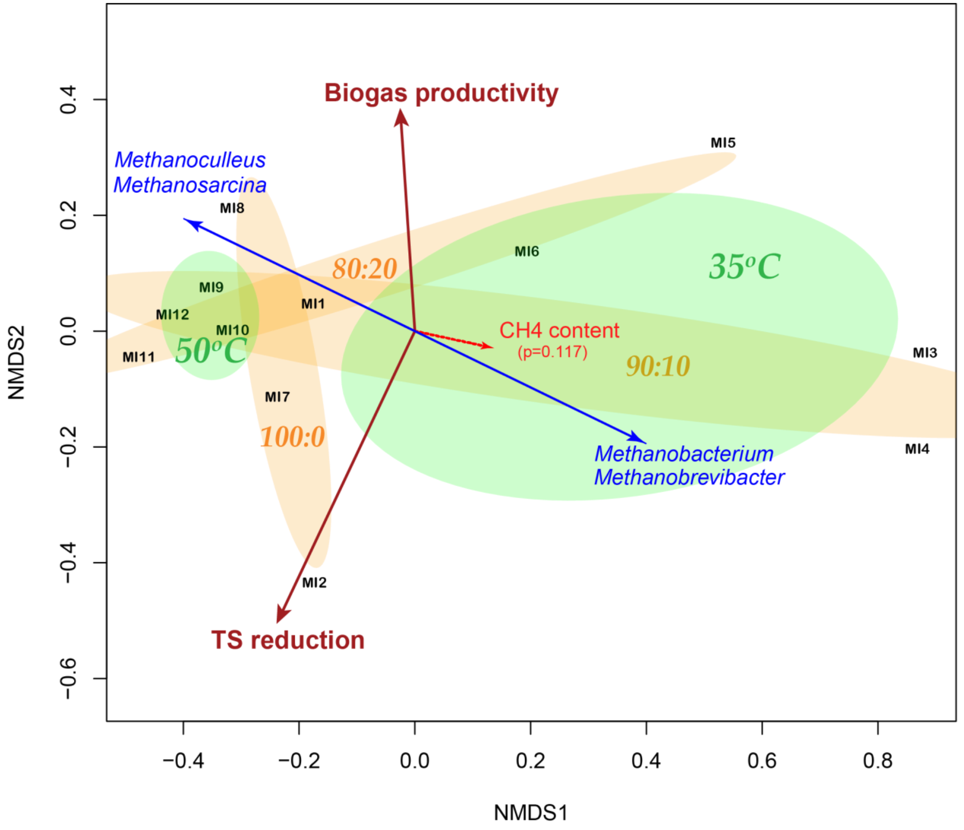
4. Integrated organic wastes utilization

Anaerobic digestion - Relationship between microbial communities and digestion performance

Non-metric Multi-dimensional Scaling (NMDS) analysis of microbial community*



Interaction between **Bacteria** and digestion performance



Interaction between **Archaea** and digestion performance

The blue solid arrows demonstrate dominant phyla; the blue dashed arrows demonstrate dominant classes or genera; the ellipses demonstrate the dispersion of each factor using standard error of the weighted average scores.

Anaerobic digestion - Digestion performance on biogas and solid digestate production

Biogas production

Parameter	Co-digestion of manure and lignocellulosic biomass
CH_4 yield (g CH_4 /kg feed)	86 ~ 100
Volume production (L biogas/ kg feed)	150 ~ 200
Methane composition (%)	60 ~ 65

- Co-digestion of manure and crop residues/energy crop can increase methane production.
- **Anaerobic digestion can homogenize the feedstocks to generate solid digestate that is a good feedstock for composting of soil amendment production.**
- Fiber size is smaller and bulk density is higher than other cellulosic materials (less truck loads for transportation).
- Solid digestate is available year-around.

Characteristics of raw feedstocks*

	DM	CS	SW
Total solids (TS, %)	13.50	91.19	92.66
Volatile solids (% TS)	87.29	94.17	95.56
Carbon (% TS)	43.51	46.61	44.99
Nitrogen (% TS)	2.45	0.51	0.56
Cellulose (% TS)	23.53	36.27	34.67
Xylan (% TS)	14.22	19.99	21.33
Lignin (% TS)	26.27	19.75	21.27

Characteristics of solid digestate from different feedstock combination *

Characteristic	DM = 100	DM:CS = 80:20	DM:CS = 60:40	DM:SG = 80:20	DM:SG = 60:40
Total solids (%)	11.54	11.55	10.49	11.10	11.00
Volatile solids (%TS)	84.11	86.37	87.11	86.98	86.75
Carbon (%TS)	50.75	50.00	50.05	49.50	50.05
Nitrogen (%TS)	1.84	1.62	1.17	1.31	1.02
Cellulose (%TS)	**24.86**	**26.63**	**28.30**	**27.22**	**26.17**
Xylan (%TS)	**14.42**	**14.31**	**15.89**	**15.38**	**15.73**
Lignin (%TS)	37.31	37.06	34.29	35.26	33.82

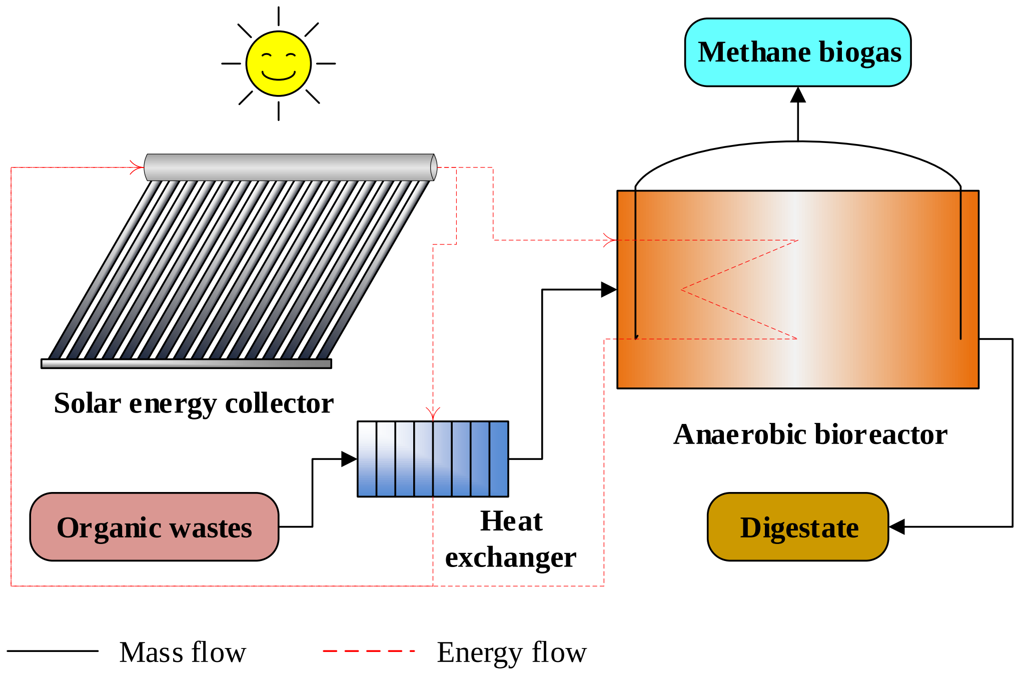
*: DM represents dairy manure; CS represents corn stover; SG represents switchgrass.

4. Integrated organic wastes utilization

Solar-biopower generation – Use biogas to store solar energy

- **Overcome the disadvantages of individual technologies**
  - Unsteady energy flow for solar power generation
  - Low efficiency of mesophilic anaerobic digestion
  - Higher energy requirement of thermophilic aerobic digestion
  - Negative energy balance for small operations

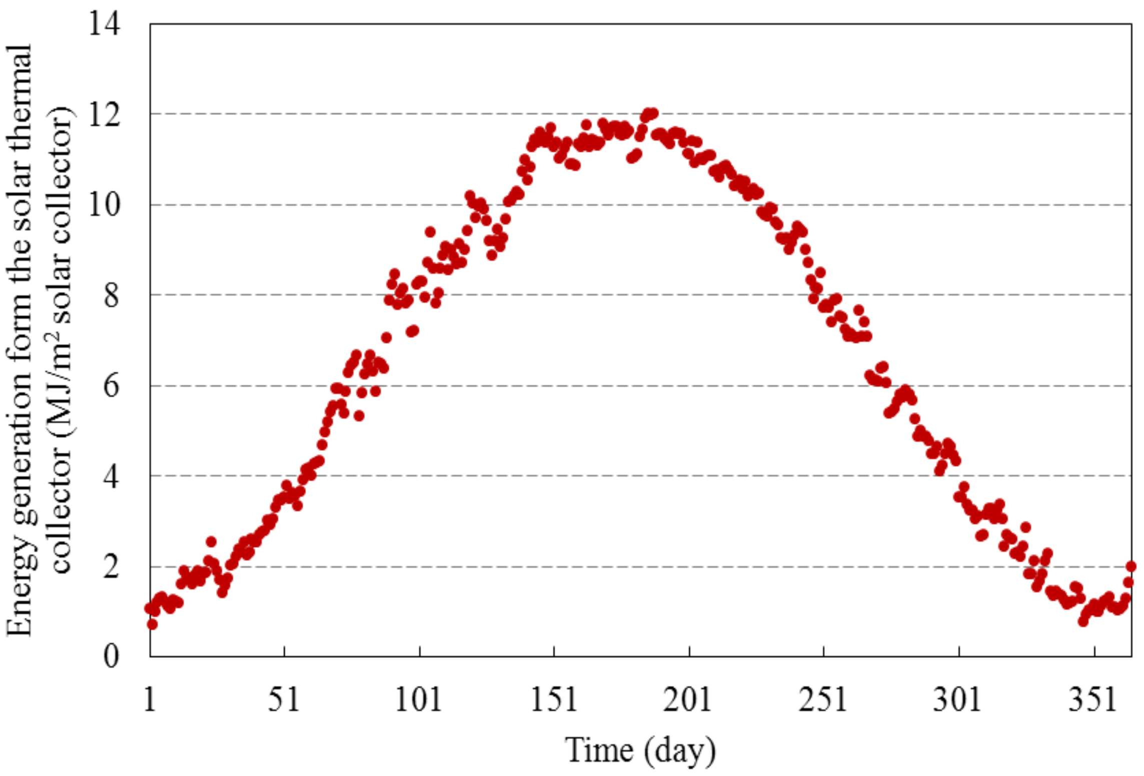
- **Provide sufficient and stable energy for small-medium sized farms**
  - Solar energy utilization
  - Improved efficiency of anaerobic digestion
  - Biogas as a novel biochemical storage for solar energy



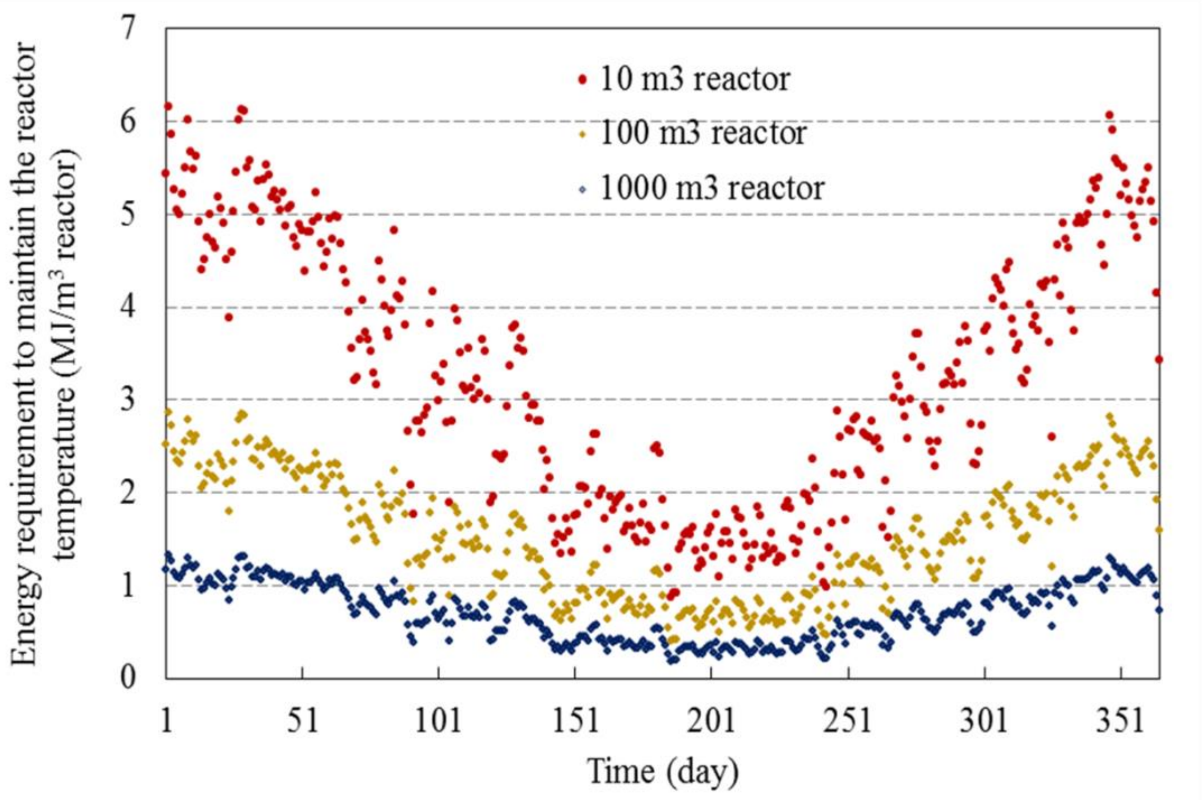
Solar-biopower generation – Biogas as a chemical storage of solar energy

Solar-biopower generation – Use biogas to store solar energy

Energy collection from the solar collector



Energy collection from the solar collector



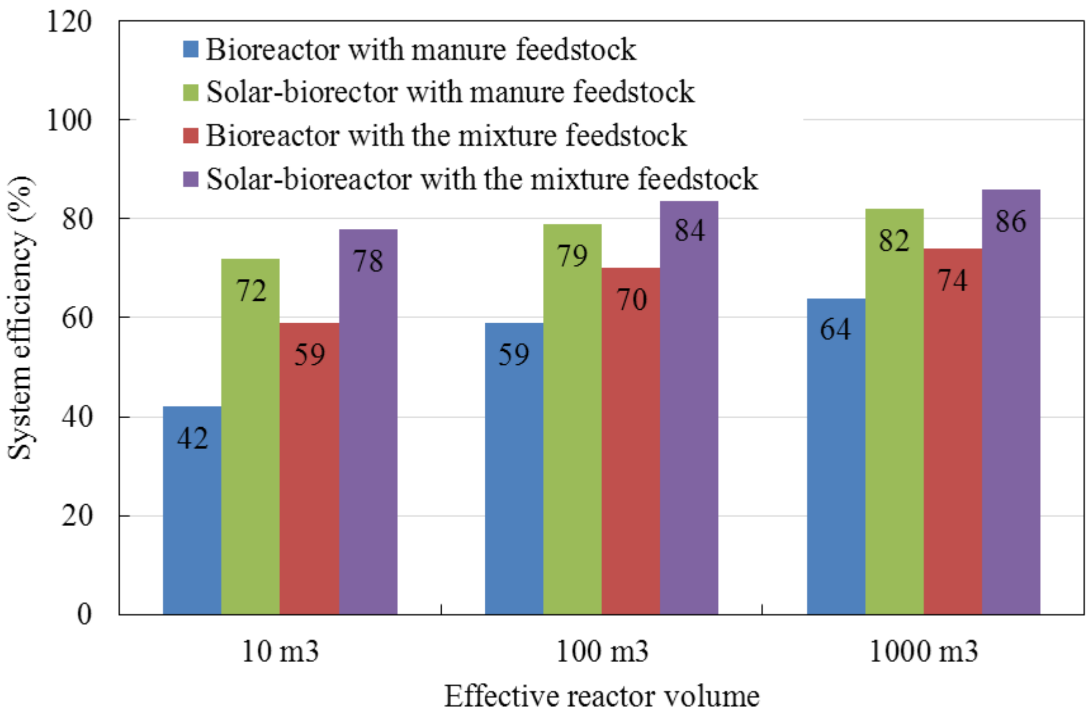
Energy requirement for maintaining the digester temperature

4. Integrated organic wastes utilization

Solar-biopower generation – Using biogas to store solar energy

The optimal configuration of solar-biopower system

Parameter	Effective reactor volume		
	10 m^3	100 m^3	1000 m^3
Solar collector area (m^2/m^3 reactor)	0.72	0.46	0.40
Annual solar storage efficiency (%)	78	84	86
Annual solar-bioreactor system efficiency (%)	78	84	86
Total methane (m^3/m^3 reactor/year)	130	130	130
Total methane energy (MJ/m^3 reactor/year)	4924	4924	4924
Methane storing solar energy (m^3/m^3 reactor/year)	33	24	21
Solar energy stored in methane gas (MJ/m^3 reactor/year)	1268	903	806
System net energy output (MJ/m^3 reactor/year)	3795	4113	4231



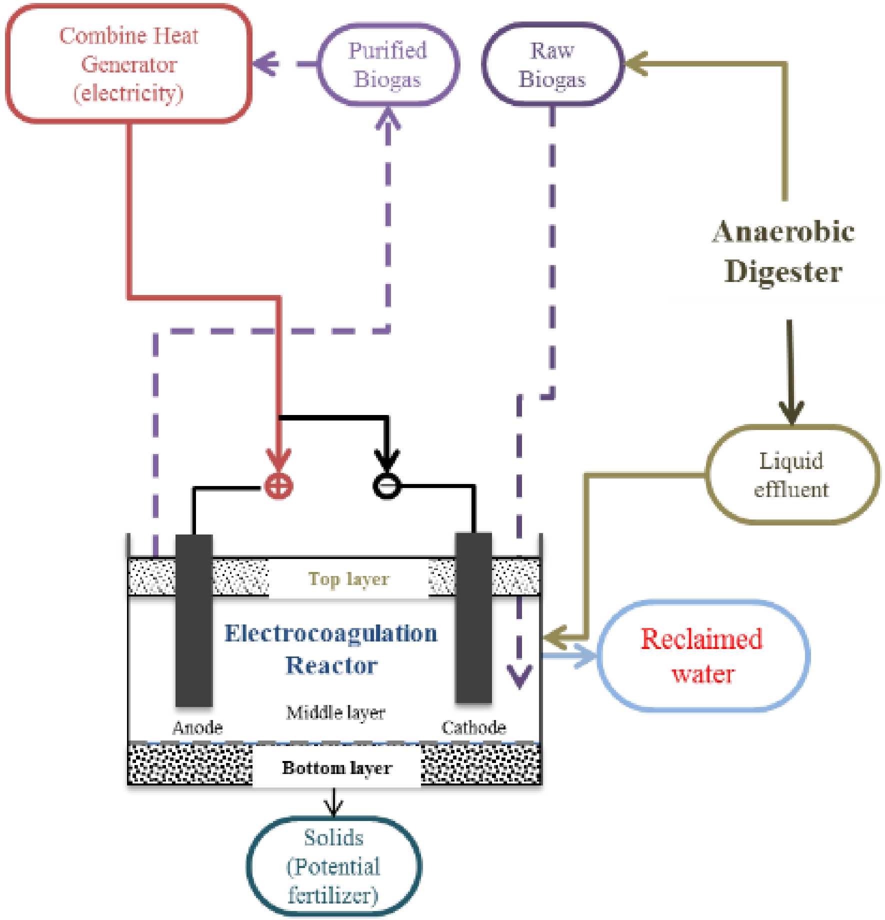
Comparison of system efficiencies between bioreactors with and without solar unit at different sizes

- The solar storage and system efficiencies of manure digestion system were 72%, 79% and 82% for 10 m^3, 100 m^3 and 1000 m^3 reactors respectively, while better corresponding efficiencies of 78%, 84% and 86% were achieved for co-digestion system due to higher biogas yield.

4. Integrated organic wastes utilization

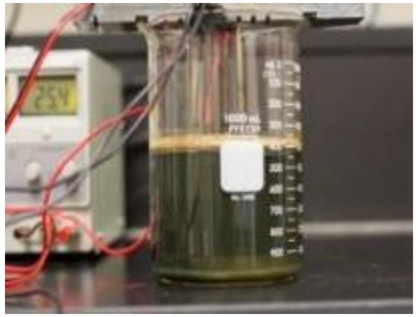
Water reclamation and nutrient recovery - Electro-coagulation and membrane filtration of liquid digestate

Flowchart of EC process



The new EC design has a dual function of biogas clean-up and liquid effluent treatment.

Experimental setup for EC and membrane studies


500 mL EC unit without biogas pumping


3 L EC unit with biogas pumping

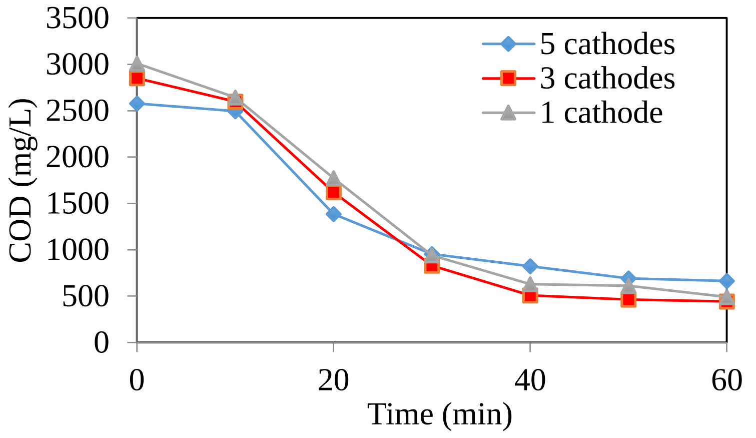

Lab-scale HP 4750 filtration unit

Modified membranes for the study

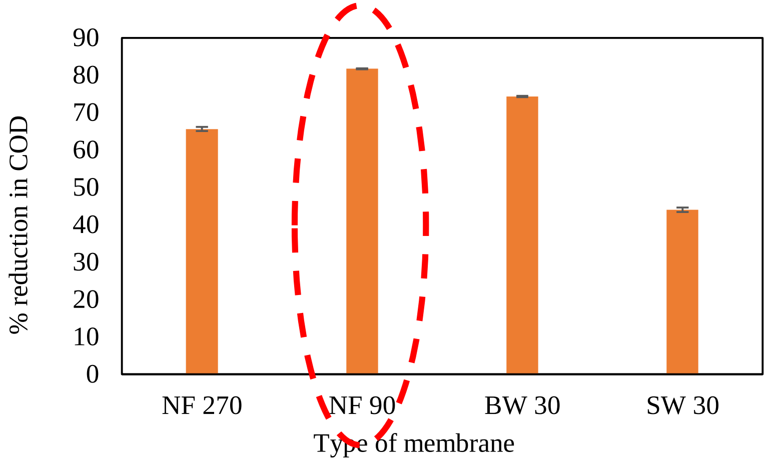
Membrane type	Supporting electrolyte concentration	Operating pressure (bar)
NF 270 modified with $(PDAC/SPS)_{15}$ *	0.5 M	10
NF 90 modified with $(PDAC/SPS)_{5}$	1M for topmost SPS layer; 0.5 for all other layers	15
SW 30 (RO membrane)	-	15
BW 30 (RO membrane)	-	15

*: poly(diallyldimethylammonium) chloride (PDAC)/poly(styrene sulfonate) (SPS)

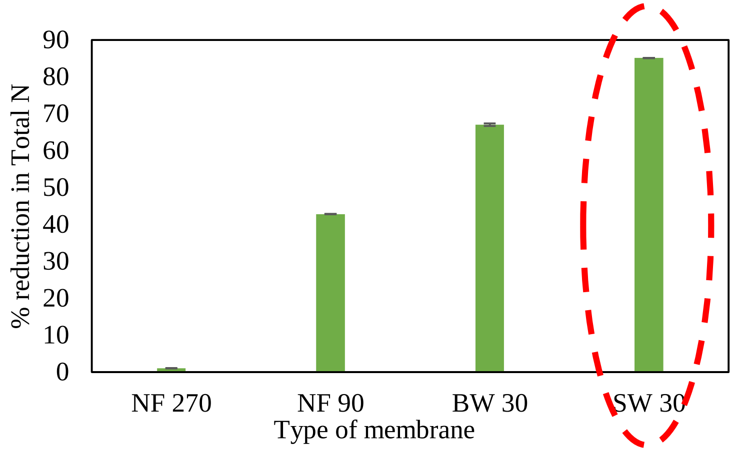
Water reclamation and nutrient recovery - Electro-coagulation and membrane filtration of liquid digestate



COD removal of the EC process

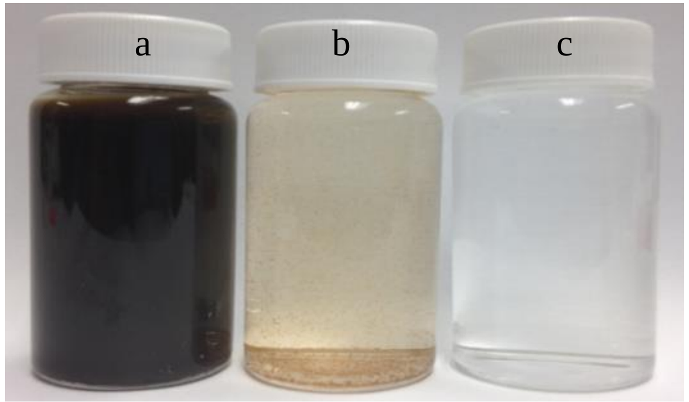


COD removal of the modified nano-membranes



TN removal of the modified nano-membranes

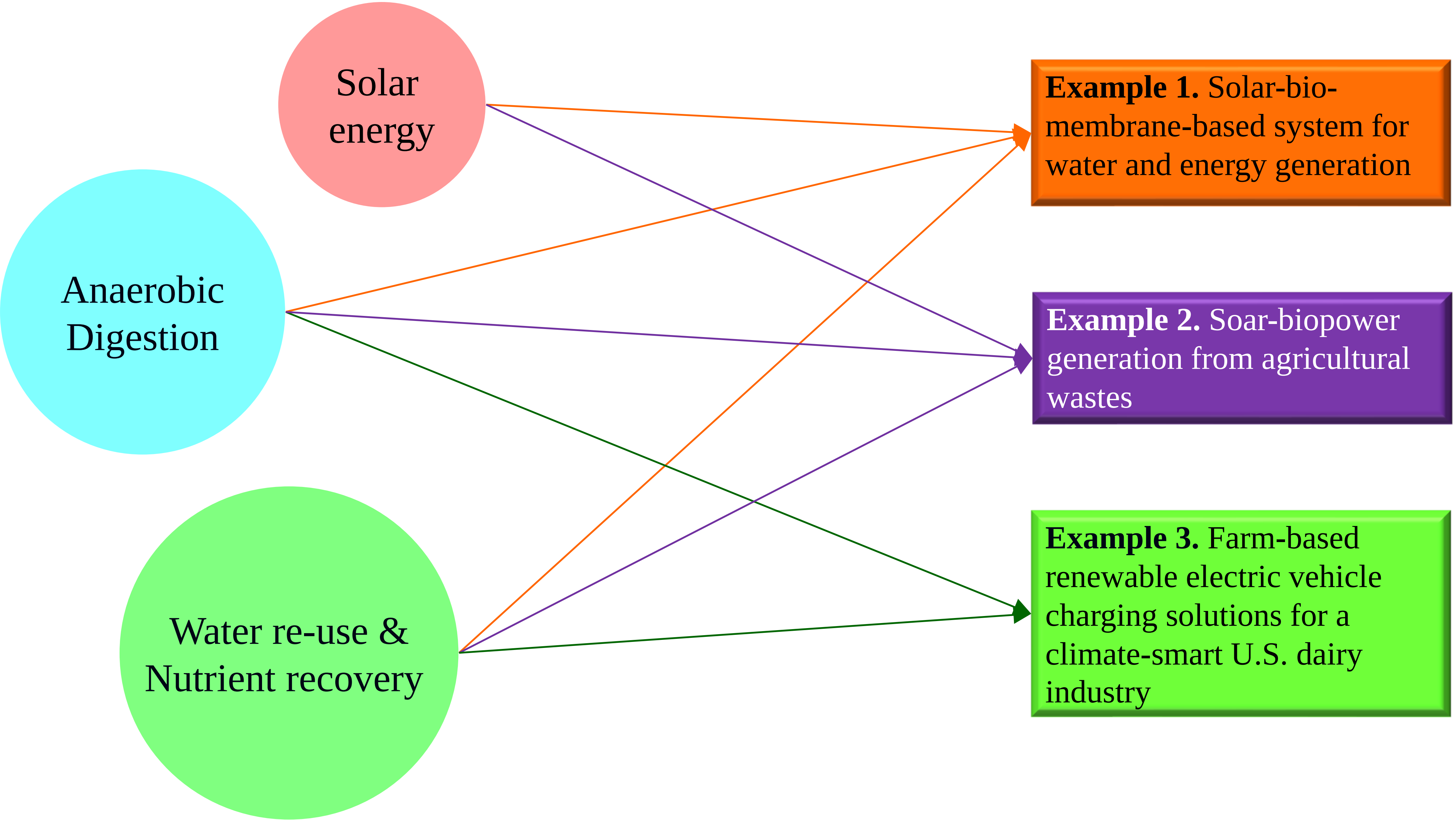
- Overall 90% of COD, >99% of TP removal was achieved by EC.
- Biogas pumping reduced 36% energy consumption of EC.
- H_2S in biogas was completely removed.
- The EC sludge is rich in phosphorus and iron, and is a good semi-solid fertilizer.
- The combination of NF 90 and SW 30 membranes is suitable for the reduction in COD, Total N and Total P.
- The final clean water contains 3 mg/L COD, 1.5 mg/L TN, 0.34 mg/L TP, and 1 NTU.



Water reclamation performance

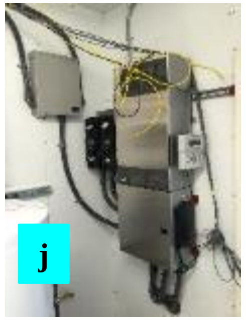
a. The AD effluent, b. after the EC treatment, c. after the nano-filtration

5. Case studies



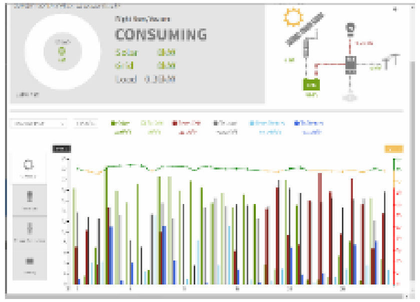
Example 1. Solar-bio-nano-based system for water and energy generation

The solar-bio-nano-based system

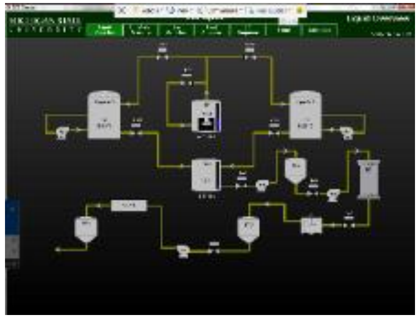


a. The pilot system
b. Inside the container
c. Solar thermal collector
d. Feeding unit
e. Digesters
f. EC unit
g. Centrifuge
h. Filtration unit
i. Biogas storage
j. Power controller
k. Control unit
l. Battery
m. Stirling engine

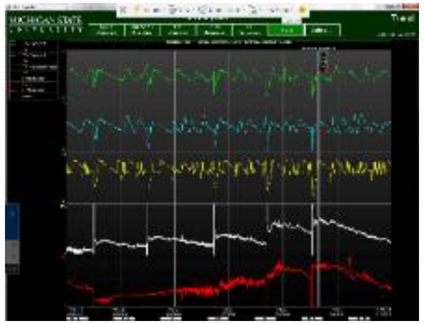
Control and data interface



Power control unit



System interface

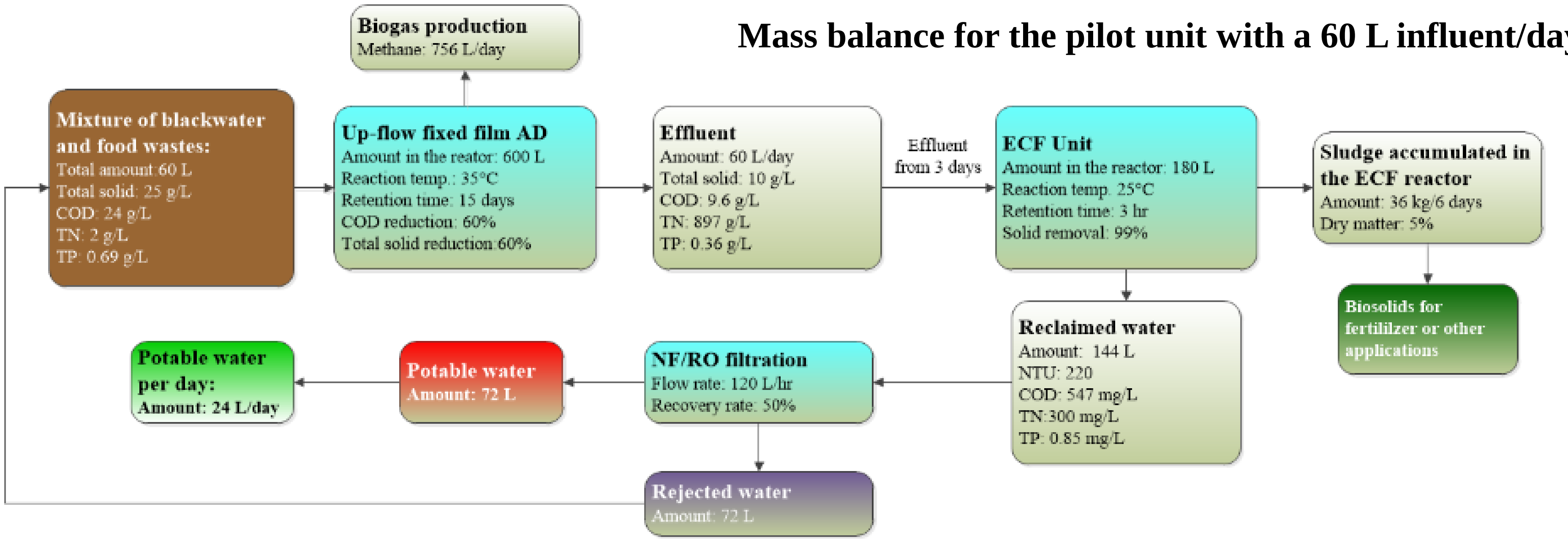


Data trend

Example 1. Solar-bio-nano-based system for water and energy generation

Mass and energy balance of the pilot unit

Mass balance for the pilot unit with a 60 L influent/day [a, b]



a: All numbers are from the experimental results on the pilot unit.
b: The methane content in biogas is 70%.

Energy balance for the pilot unit with a feed rate of 60 L influent/day [a, b]

Energy generated		Energy consumed				Net energy output (kwh-e/day)
Solar energy (kwh-e/day)	Biogas engine (kwh-e/day)	AD energy (kwh-e/day) [b]	ECF electricity (kwh-e/day)	Pump for filtration (kwh-e/day)	Other uses (kwh-e/day) [c]	
11.8	5.3	-12	-0.3	-0.3	-0.5	3.9

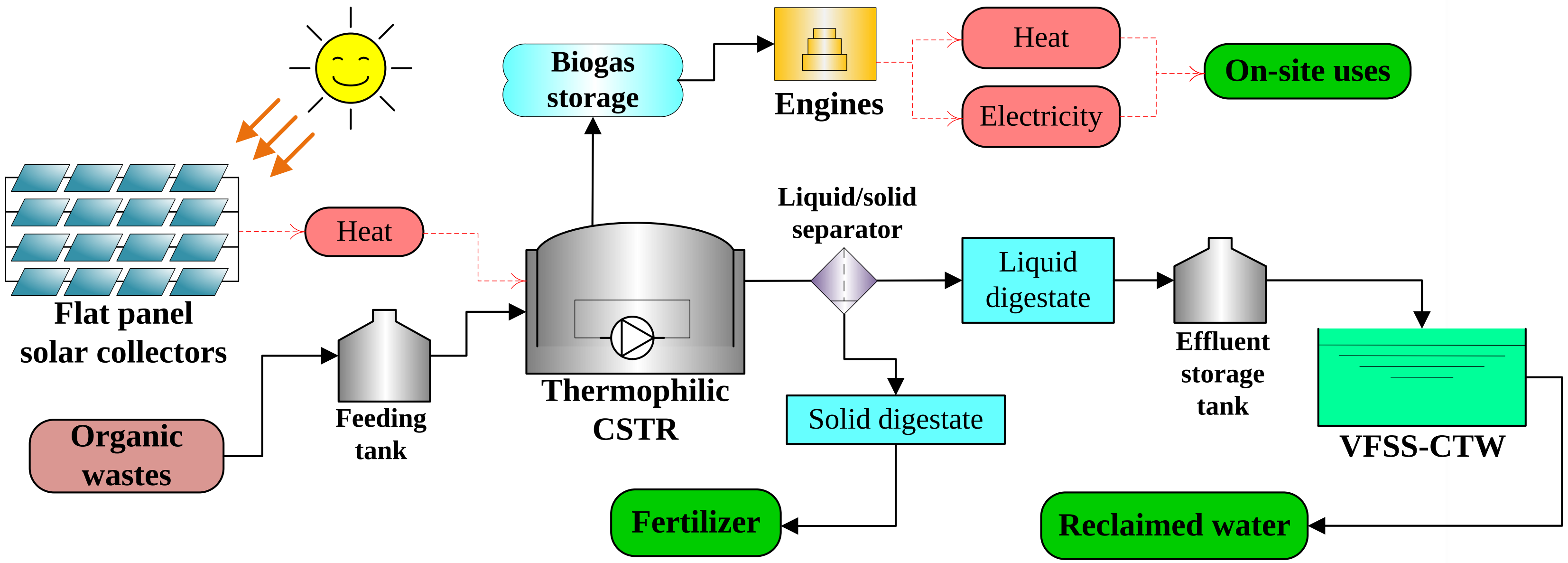
a: The positive numbers are energy generated. The negative numbers are energy consumed.
b: AD energy includes grinding, heating, and pumping.
c: Other uses include control panel and water pumps

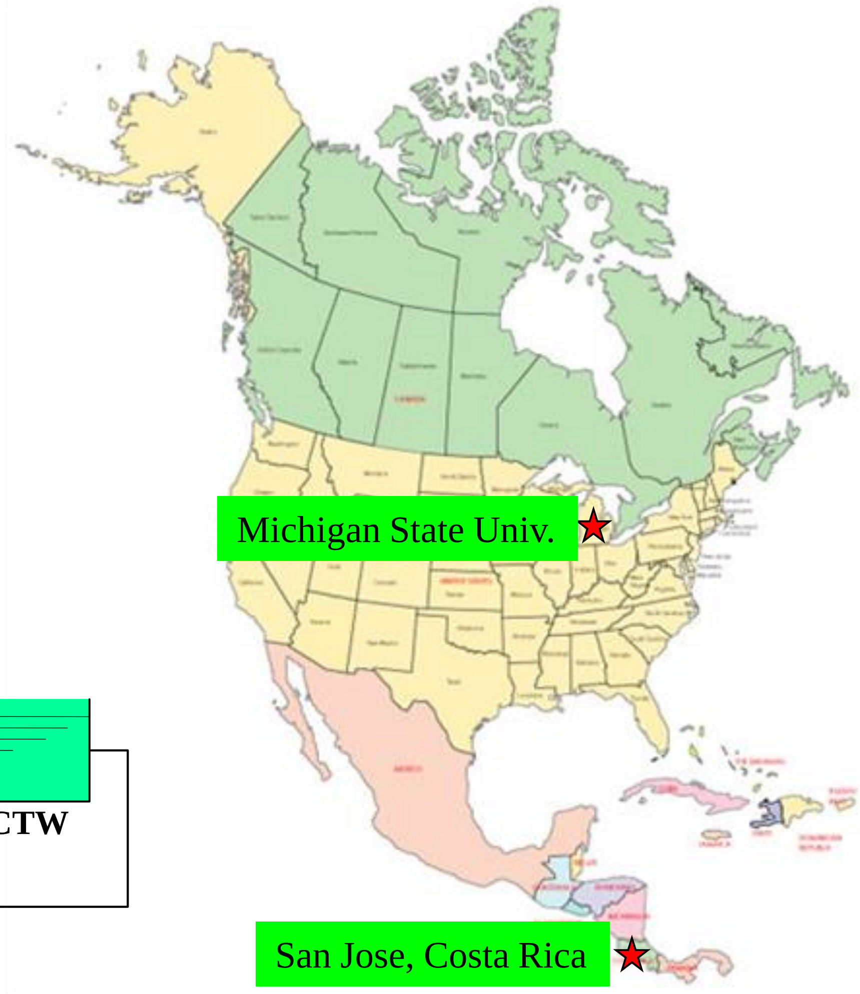
Example 2. A solar-bio-power generation from agricultural wastes

A demonstration-scale solar-biopower generation system (1 m^3 per day):

- Sixteen 2x1 m flat-plate solar collector with support
- One 22 m^3 anaerobic digester with a 50 m^3 gas bag
- Two 16 kW combined heating and power unit
- Four 144 m^2 wetland/sandfilter cells

Flowchart



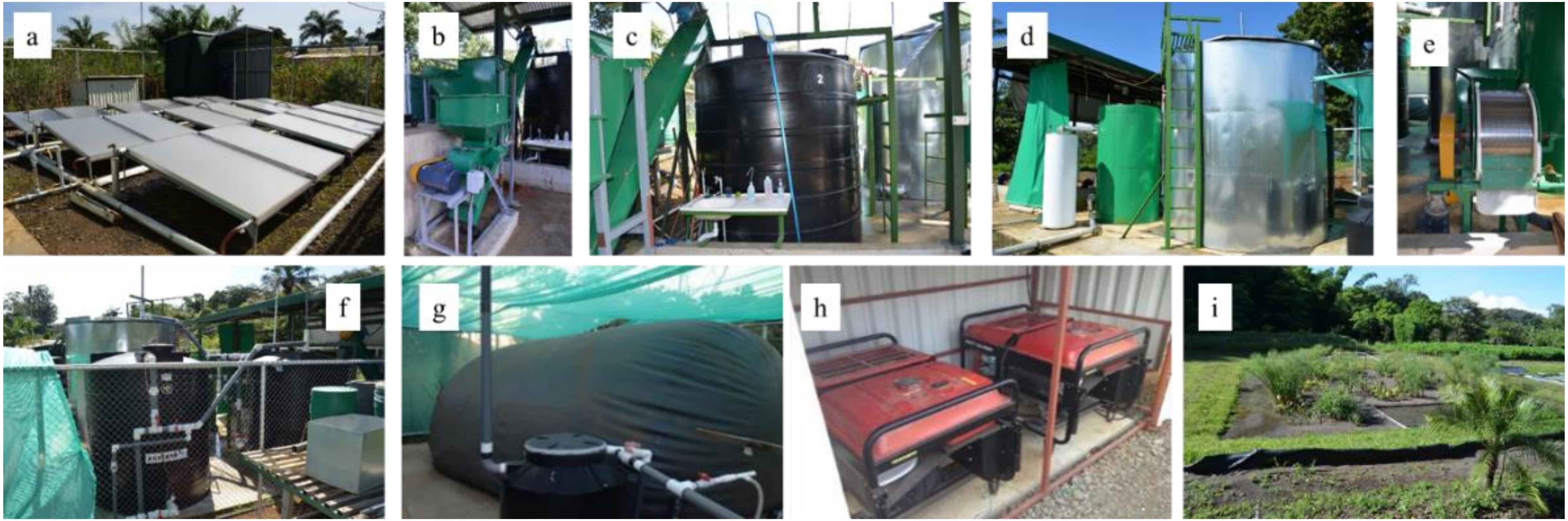


*: The system is located at Fabio Agricultural Station, Alajuela, Costa Rica

5. Case studies

Example 2. A solar-bio-power generation from agricultural wastes

The system



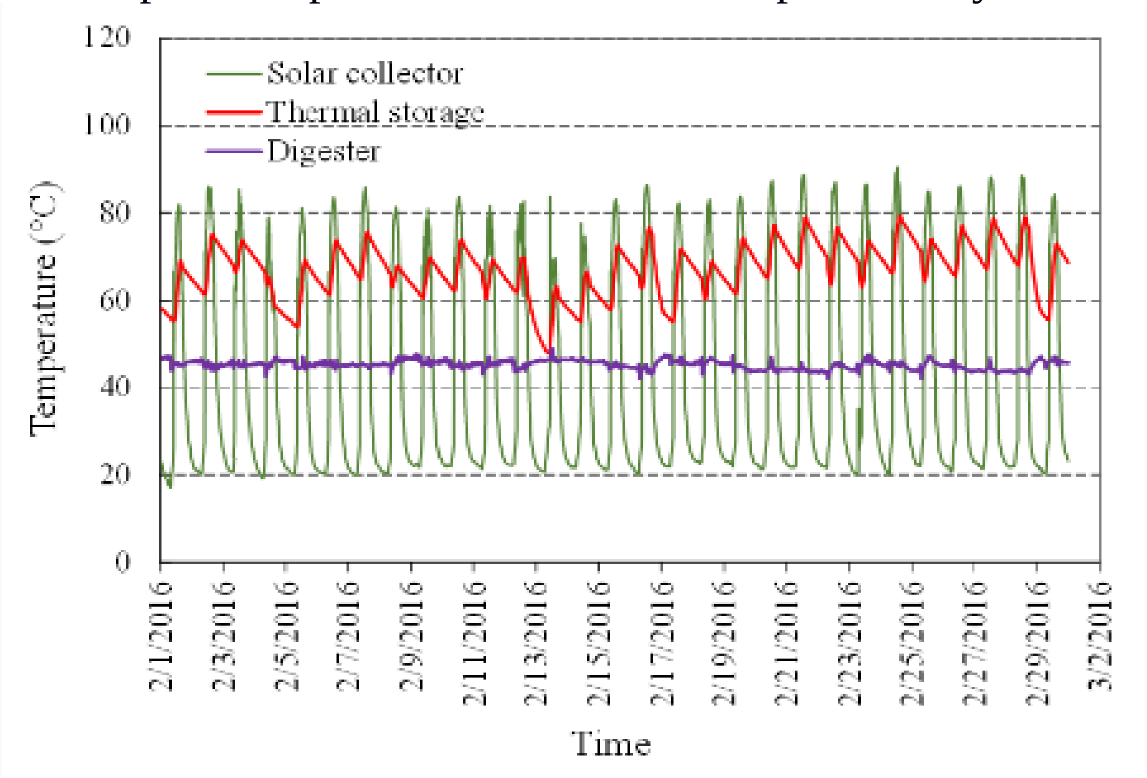
a. Solar thermal collectors, b. Grinder, c. Feeding tank, d. CSTR and hot water tank, e. Liquid and solid separator, f. Liquid effluent tank, g. Biogas bag, h. Engines, i. Vertical flow subsurface constructive wetland

Example 2. A solar-bio-power generation from agricultural wastes

System performance

- Treated 900 kg per day of mixed manure and food wastes
- Generated 550 kg per day reclaimed water
- Produced 28 kg per day semi-solid digestate as a fertilizer

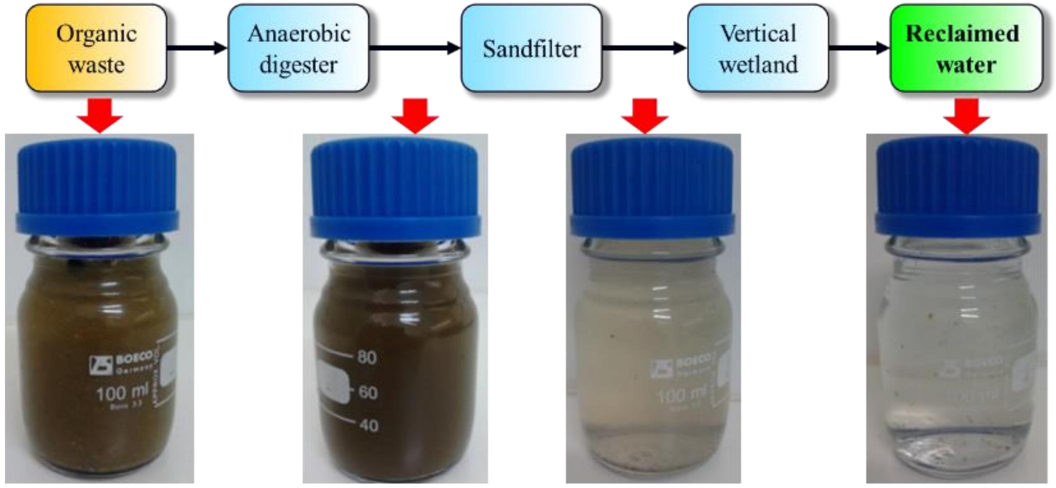
Temperature profiles of the solar-bio-powered system



Energy balance of the solar-bio-powered system

System	Solar-bio-powered system	Without solar thermal collector
Heat input (MJ/day)	0.00	-126.00
Electricity input (MJ/day)	-43.36	-43.36
Energy output (MJ/day)	306.00	306.00
Net energy (MJ/day)	262.64	136.64

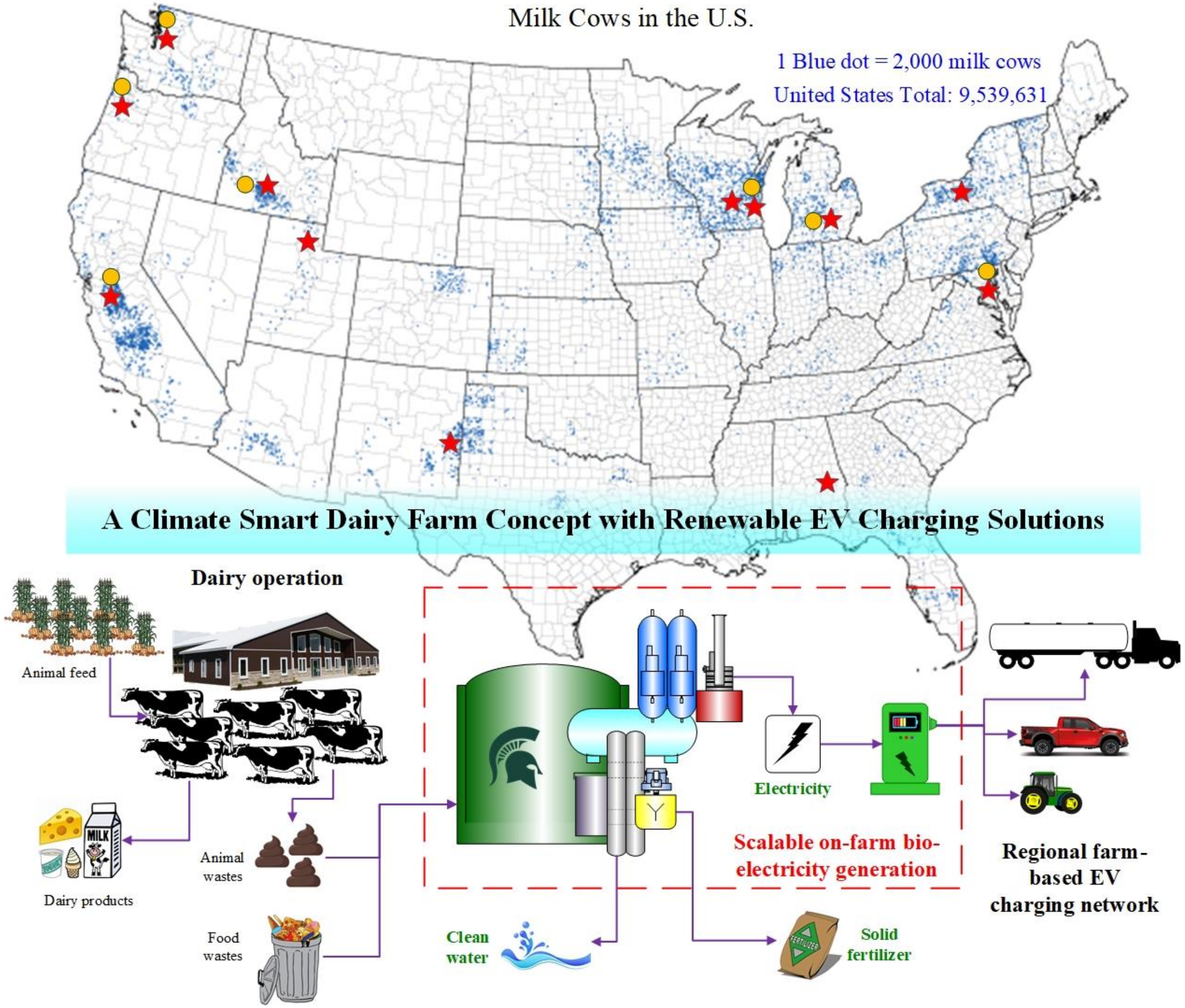
Water reclamation



Original waste stream | The effluent from solar-bioreactor | The water from the 1st cell of post-treatment | The water from the 2nd cell of post-treatment

5. Case studies

Example 3. Farm-based renewable electric vehicle charging solutions for a climate-smart U.S. dairy industry



- Dairy manure contains approximately 45% of the gross carbon in forage feeds.
- The GHG released from the manure accounts for roughly 1/3 of the global warming potential in the entire dairy supply chain.
- Anaerobic digestion on the manure and food waste can generate 59 TWh of biogas electricity per year.
- The U.S. dairy industry has the electricity potential to satisfy the demand of 9.6 million electric pickup trucks (16% of all pickup trucks in operation in the U.S.)

Conclusions

- Applying system approach is a way to develop sustainable waste management practices for small- and medium-sized farms.
- Anaerobic digestion can play dual roles of generating bioenergy/solid fertilizer and pretreating organic wastes for nutrient and water reclamation.
- The combined electrocoagulation and membrane technology can effectively reclaim water form high-strength wastewater streams like anaerobic digestate.
- Farms can tailor the system to satisfy their wastes management needs and maximize the benefits of their wastes utilization.

Acknowledgment

My Colleagues

Dr. Susie Liu, Biosystems & Agricultural Engineering, Michigan State University;
Dr. Dana Kirk, Biosystems & Agricultural Engineering, Michigan State University;
Dr. Ajit Srivastava, Biosytems & Agricultural Engineering, Michigan State University;
Dr. Dawn Reinhold, Biosystems & Agricultural Engineering, Michigan State University;
Dr. Ilsoon Lee, Chemical Engineering and Material Science, Michigan State University;
The research team at University of Costa Rica, Costa Rica;

Financial Supports

The U.S. Department of Energy;
The U.S. Department of Defense;
The U.S. Department of State;
The U.S. Department of Transportation;
The U.S. Department of Agriculture;
Private companies;
Michigan State Public Service Commission;
Michigan State Animal Agriculture Initiative;
Michigan State AgBioResearch;
Michigan State University Vice President Office for Research and Graduate Study

Thank You!

MSU Anaerobic Digestion Research and Education Center (MSU ADREC)

Main building

High-bay area

Wet labs

Hot room

CSTR system
(2000 m^3, 0.5 MW)

Plug flow system
(1000 m^3)

Algal race-way system
(1,600 m^2 pond)

Solar panels

Homepage: http://www.egr.msu.edu/bae/adrec/