Techno-economic and Life-Cycle Analysis of a Commercial AD System

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October 20, 2022

Outline

1. MSU South Campus Anaerobic Digester (MSU SCAD)
2. Organic wastes for the SCAD
3. Long-term operational data
4. Techno-economic analysis of the digestion operation
5. Life cycle impact analysis of the digestion operation
6. Summary

1. MSU South Campus Anaerobic Digester (SCAD)

Why did the MSU build a demonstration digester

- Utilize food wastes from dining halls and animal wastes on campus
- Generate renewable electricity
- Control odor
- Mitigate climate change – lowering greenhouse gas emissions
- Carry out research, education, and extension activities at the large scale

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

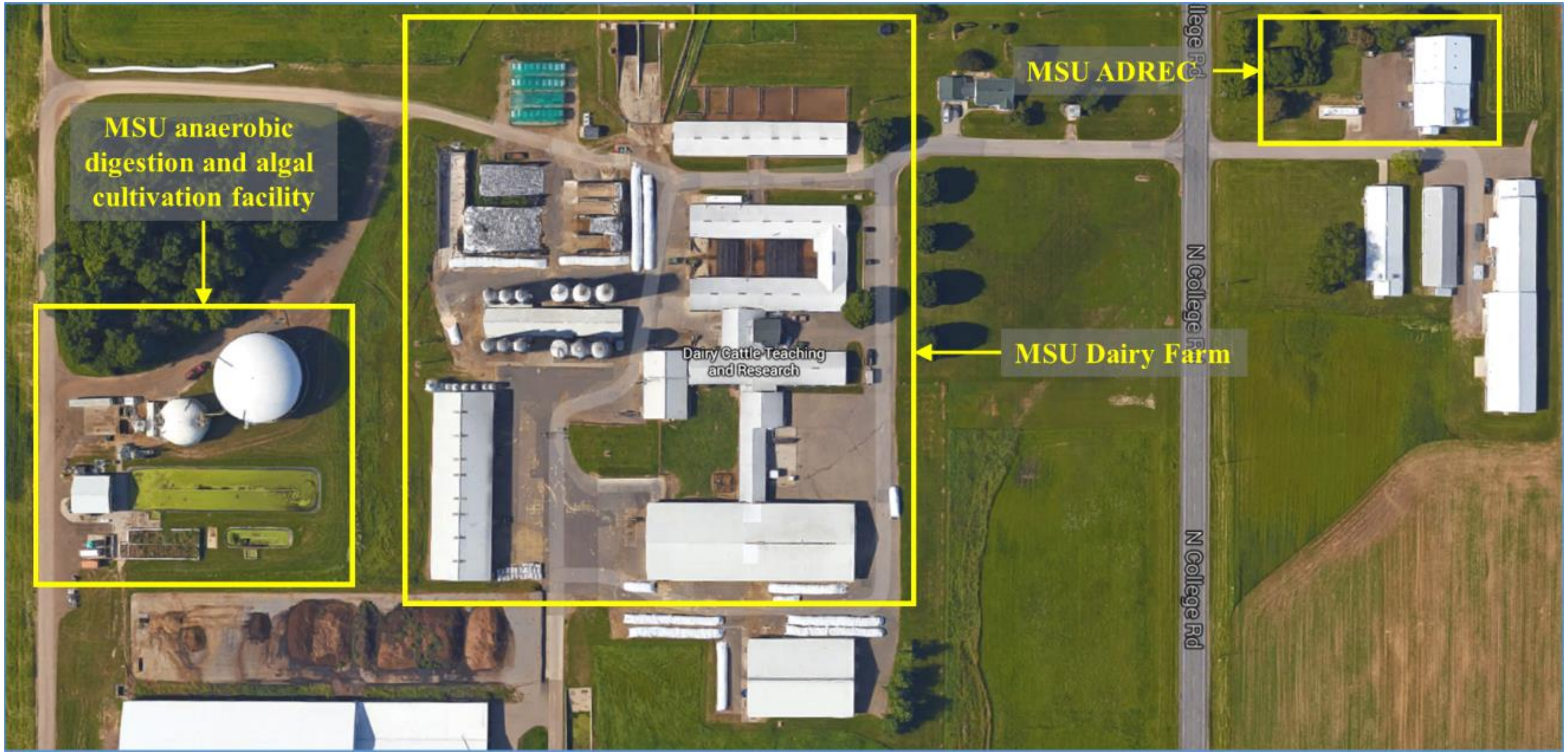
Renewable electricity from a solar-bio-power unit

GHG emission
http://www.huffingtonpost.com/2013/07/25/carbon-emissions-developing-countries_n_3651513.html

Animal manure
www.wikipedia.com

1. MSU South Campus Anaerobic Digester (SCAD)

Where is the MSU SCAD



Located next to the MSU Dairy Cattle Teaching and Research Center, 4075 College Rd, Lansing, 48910

1. MSU South Campus Anaerobic Digester (SCAD)

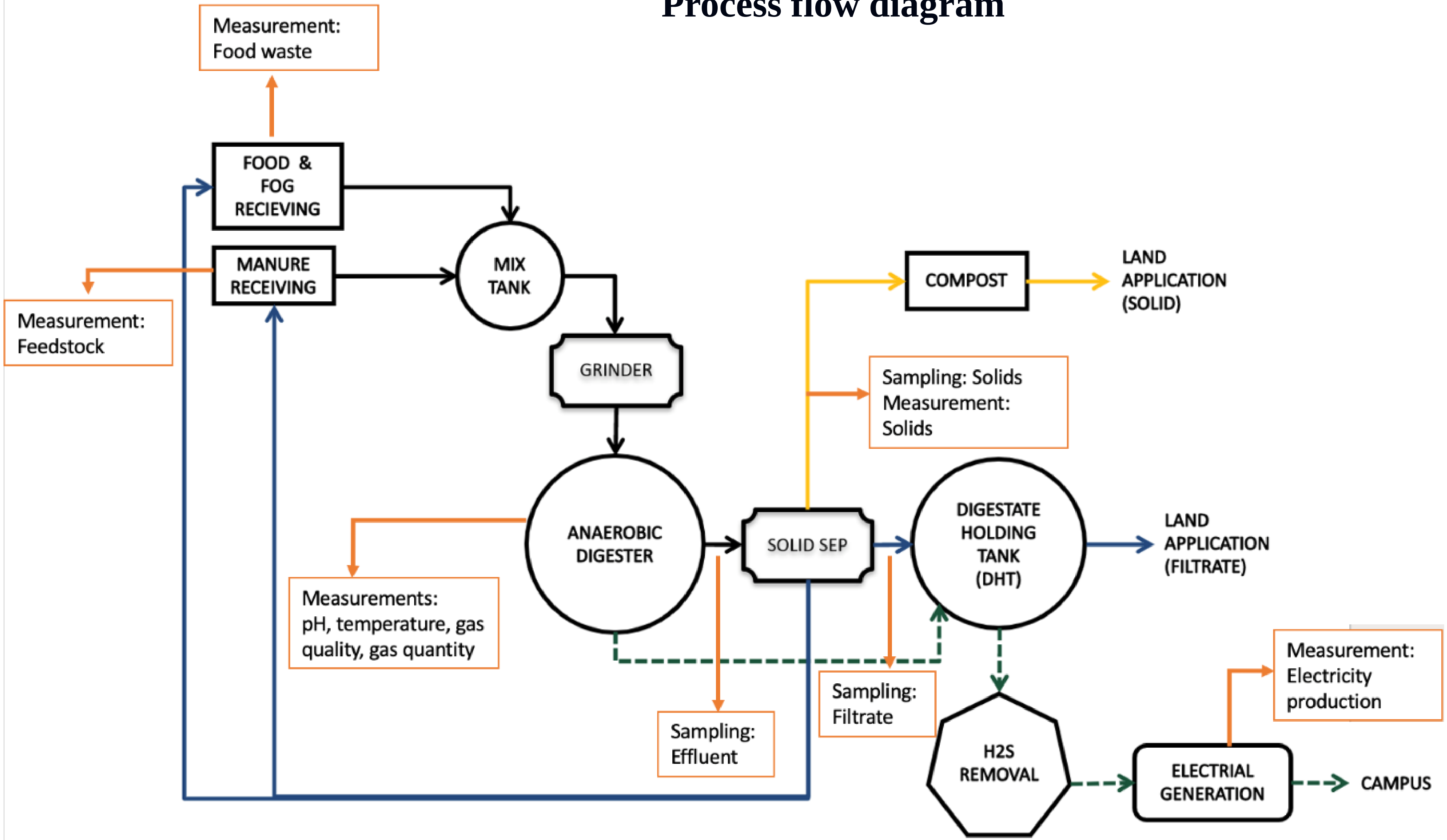
Configuration of the MSU SCAD

- Digester tank
  - 400,000 gallons
  - The tank with a diameter of 52 ft and a height of 26 ft plus cover
- Digestate storage tank
  - 2.1 million gallons
  - The tank with a diameter of 101 ft and a height of 42 ft plus cover
- CHP unit
  - 400 kW electrical production & 450 kW of thermal energy recovery
  - Offset power at 8 to 10 south campus facilities
  - Thermal energy used to sustain the process, heat support building and separator area
- Digestate treatment
  - Separated solids to compost
  - Separated liquid to storage and land application

MSU SCAD

1. MSU South Campus Anaerobic Digester (SCAD)

Process flow diagram



2. Organic wastes for the SCAD

Organic wastes in manure pit and food waste pit for the SCAD

Organic wastes fed to different pits

No	Manure Pit	Food Pit
1	Digestate (recycle)	Filtrate (recycle)
2	Filtrate (recycle)	Cart Food Wastes (Pre and post-consumer)
3	ANS Other (i.e., eggs)	Fat, Oil, and Grease (FOG)
4	Beef Manure	Other
5	Dairy Gutter Manure (Dairy G)	Pineapple (P.A.) and other Fruits
6	Dairy Freestall Manure (Parlor)	Pulp
7	Poultry Manure	SLS Solids (Coarse digestate fiber)
8	SLS Solids	Waste Forage
9	Swine Manure	
10	Waste Forage	

Food wastes (Pre-consumer)

Food wastes (Post-consumer)

Fruit & Vegetable

FOG

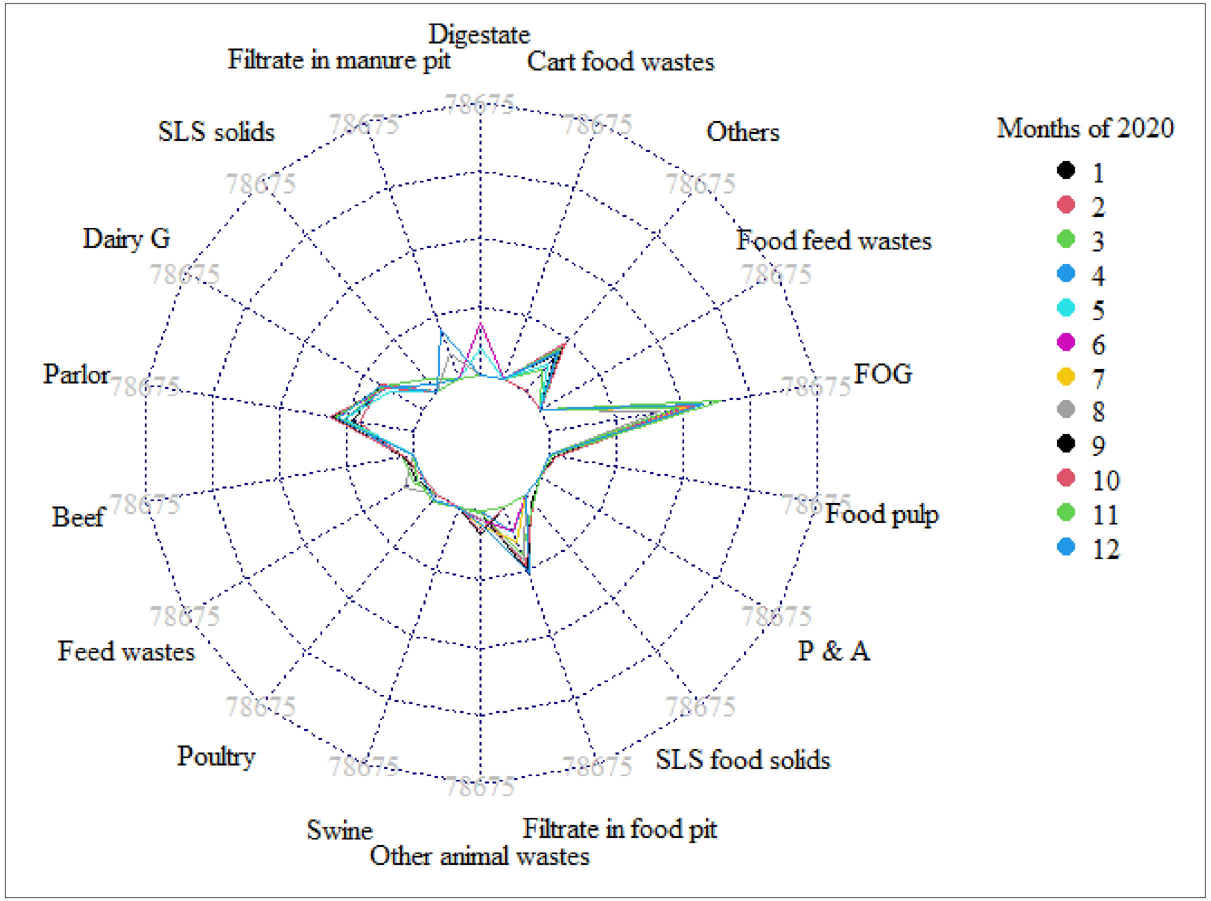
2. Organic wastes for the SCAD

Organic wastes in manure pit and food waste pit for the SCAD

Wastes in manure and food pits

Year	Manure Pit (Metric ton/year)	Food Pit (Metric ton/year)	Total (Metric ton/year)	Food Pit (%)
2014	14,763	8,533	23,297	37%
2015	13,805	12,800	26,605	48%
2016	11,059	11,726	22,785	51%
2017	11,109	9,129	20,238	45%
2018	10,859	8,605	19,464	44%
2019	11,353	10,539	21,893	48%
2020	10,332	14,531	24,863	58%
Max	14,763	14,531	26,605	58%
Min	10,332	8,533	19,464	37%
Mean	11,802	10,637	22,618	47%
Average	**11,897**	**10,838**	**22,735**	**47%**
St. Dev	1,683	2,294	2,499	7%

Monthly feeding amounts of different waste streams (2022)



2. Organic wastes for the SCAD

Characterization of the organic wastes fed to the SCAD

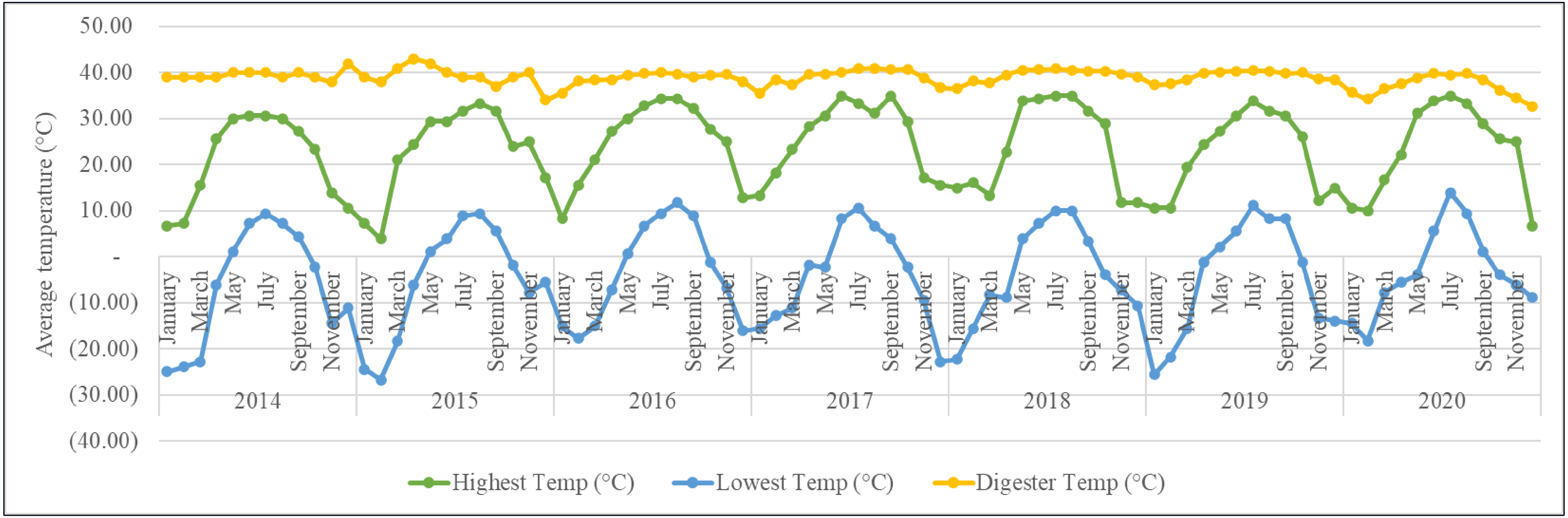
Characterization of the organic wastes

Feedstock	TS (mg/L)	VS (mg/L)	pH	EC (mS/cm)	SCOD (mg/L)	TN (mg/L)	TP (mg/L)	NH3 (mg/L)
Parlor Manure	63,844±20,998	52,742±18,966	7.01±0.30	13.72±1.37	25,900	2,190±214	1,210	932
Beef	462,152±109,098	393,620±100,761	8.64±0.06	1.89±0.76	-	-	-	-
Dairy Gutter	162,268	142,940	8.23	7.74	-	5,050	1,386	1,085
FOG	120,191±172,277	105,384±142,739	5.50±1.51	12.17±38.04	109,380± 167,383	15,250	300	253.75
Food Other	219,447±286,460	193,795±265,043	5.41±1.45	8.52±6.03	-	9,139±10,502	1,032±1,360	195±363
Pineapple	127,389±14,312	114,749±5,820	3.91±0.04	2.26±0.62	-	595	109	62.70
Pulp	275,459	262,105	4.36	1.49	-	-	-	-

3. Long-term Operational Data

Digester temperature (2014-2020)

Profile of monthly digester temperature



MICHIGAN STATE UNIVERSITY

BAE Department of Biosystems and Agricultural Engineering

3. Long-term Operational Data

Hydraulic retention time (HRT) (2018-2020)

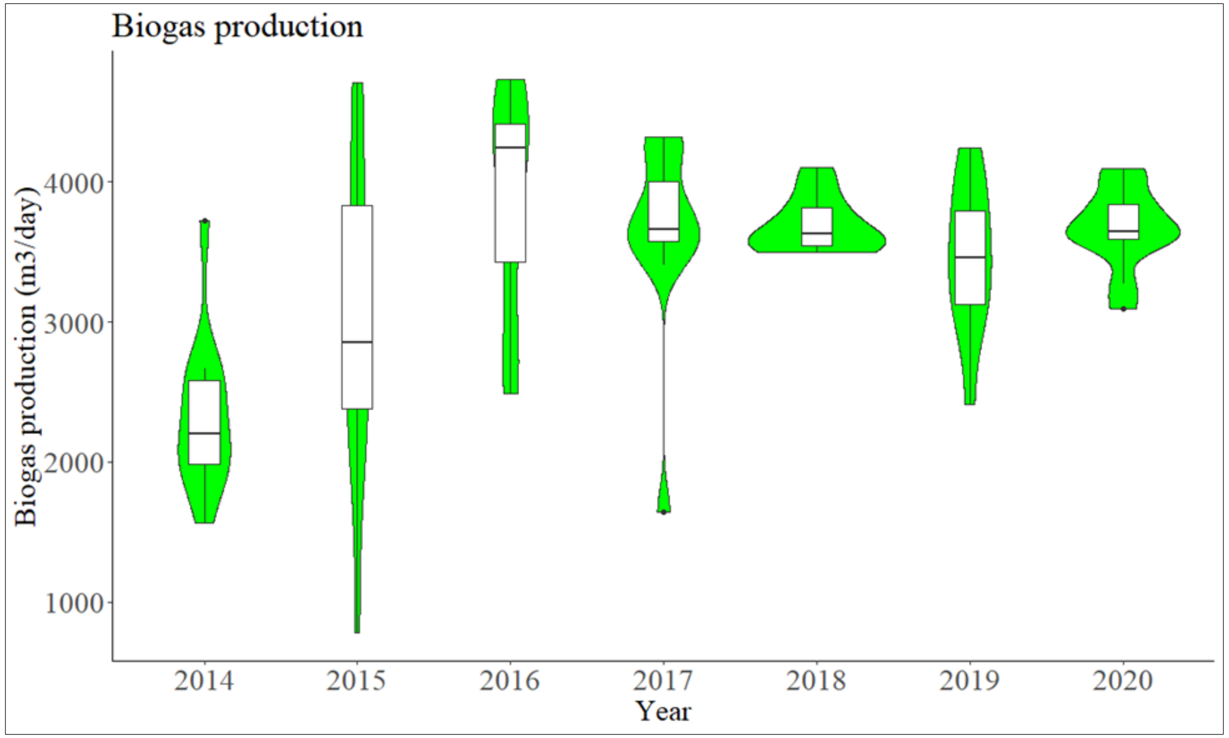
Comparison of HRT in 2018-2020: daily, 7 days average, and 30 average

Month	HRT								
	Day								
	2018			2019			2020		
	Daily	7 Days AVG	30 Days AVG	Daily	7 Days AVG	30 Days AVG	Daily	7 Days AVG	30 Days AVG
January	24	24	24	29	21	21	20	20	20
February	28	25	25	71	42	29	19	19	19
March	23	23	23	26	25	30	30	24	22
April	21	26	24	27	26	25	28	24	23
May	20	28	25	18	19	21	20	22	22
June	24	29	28	20	22	19	27	28	25
July	20	28	29	28	25	24	28	21	24
August	25	34	30	35	26	25	18	16	7
September	18	27	31	20	24	20	25	19	19
October	20	28	26	35	21	20	18	16	16
November	21	24	25	40	31	27	27	26	21
December	18	22	22	26	25	25	67	26	26
Average	21.7	26.5	25.9	31.2	25.69	23.8	27.3	21.8	20.3
St. Dev	2.8	3.1	2.7	13.6	5.9	3.5	12.6	3.8	4.8

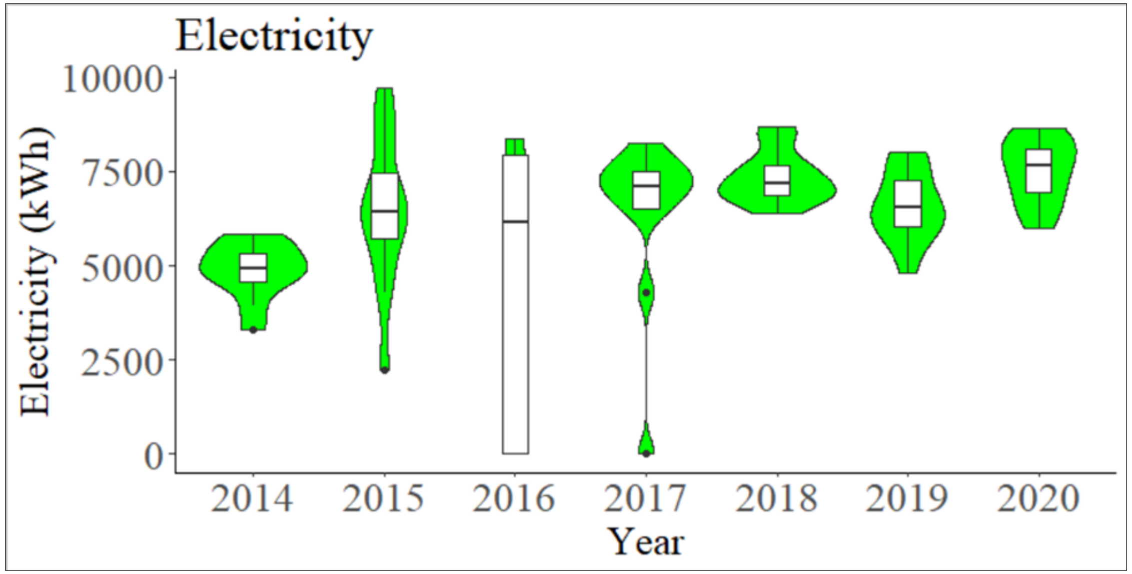
3. Long-term Operational Data

Biogas production and methane content (2014-2020)

Distribution of daily biogas production



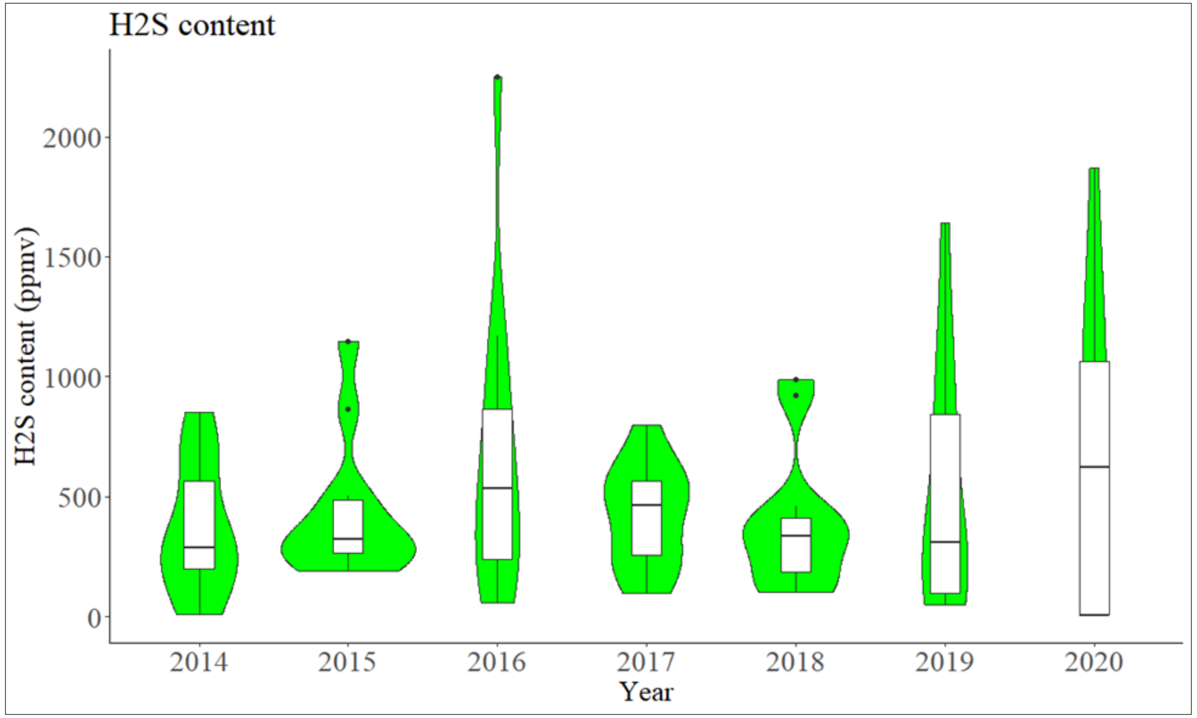
Distribution of daily electricity production



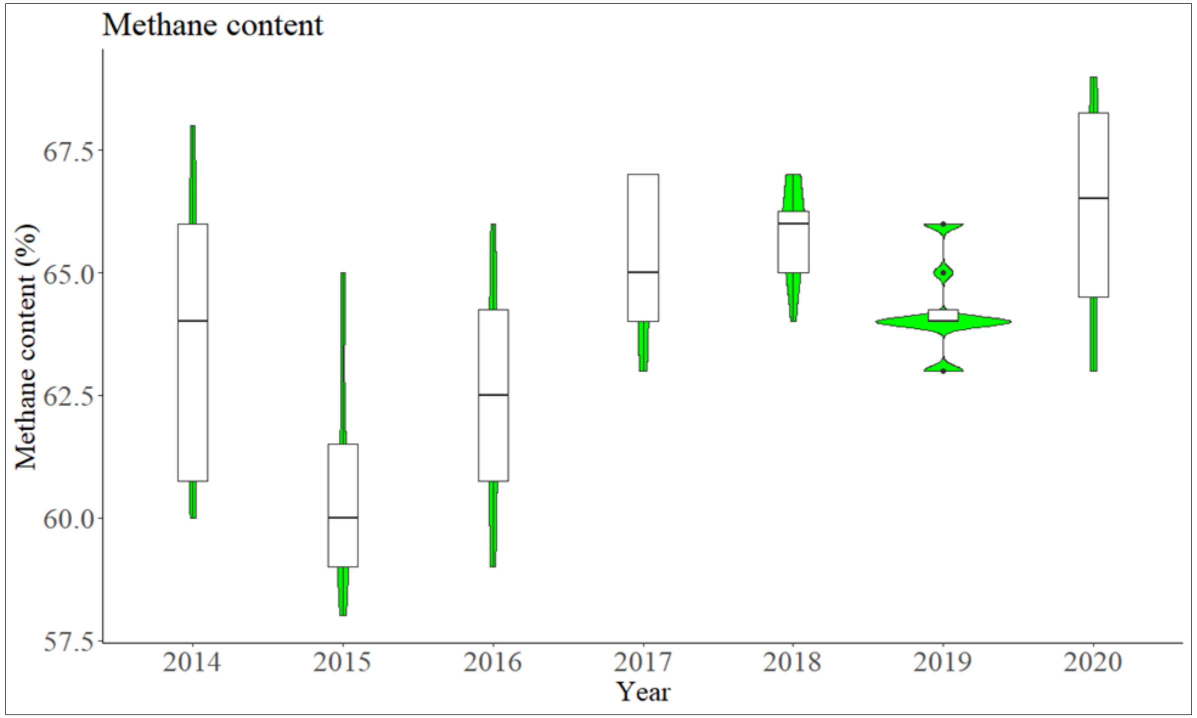
3. Long-term Operational Data

Biogas production and methane content (2014-2020)

Distribution of H2S content in biogas



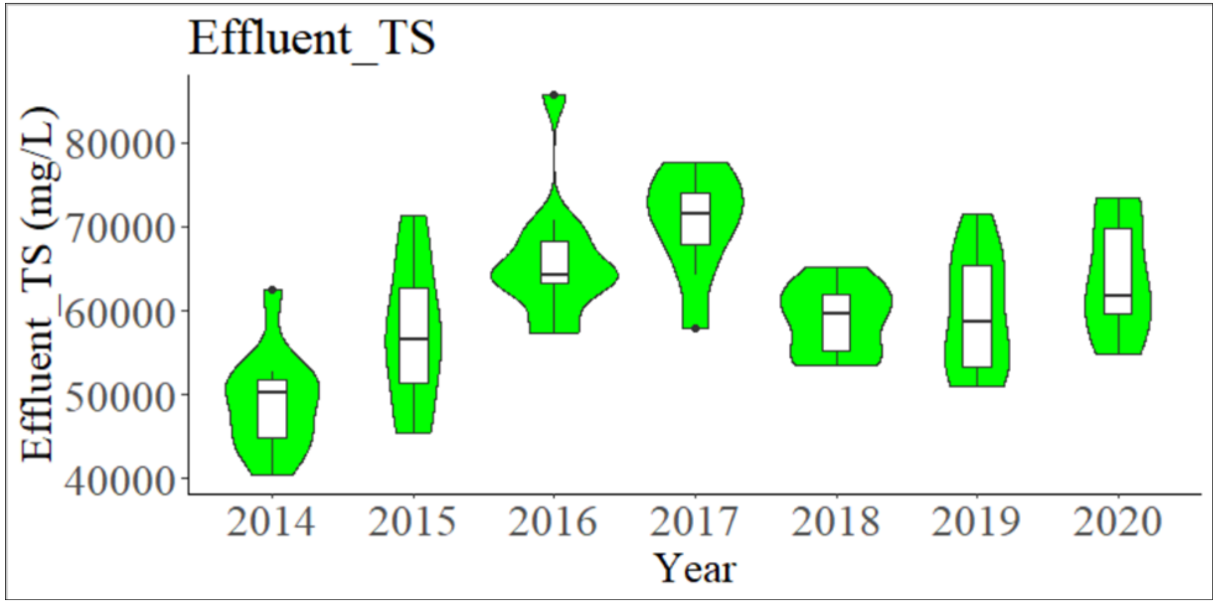
Distribution of methane content in biogas



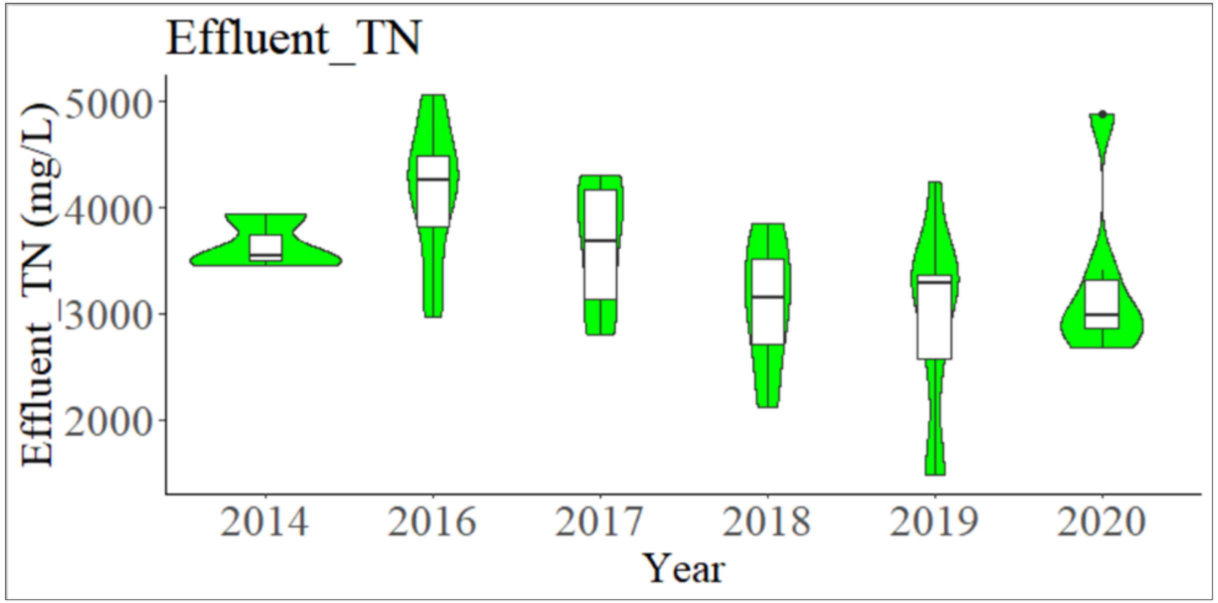
3. Long-term Operational Data

Characteristics of digestate (2014-2020)

Distribution of TS in the digestate



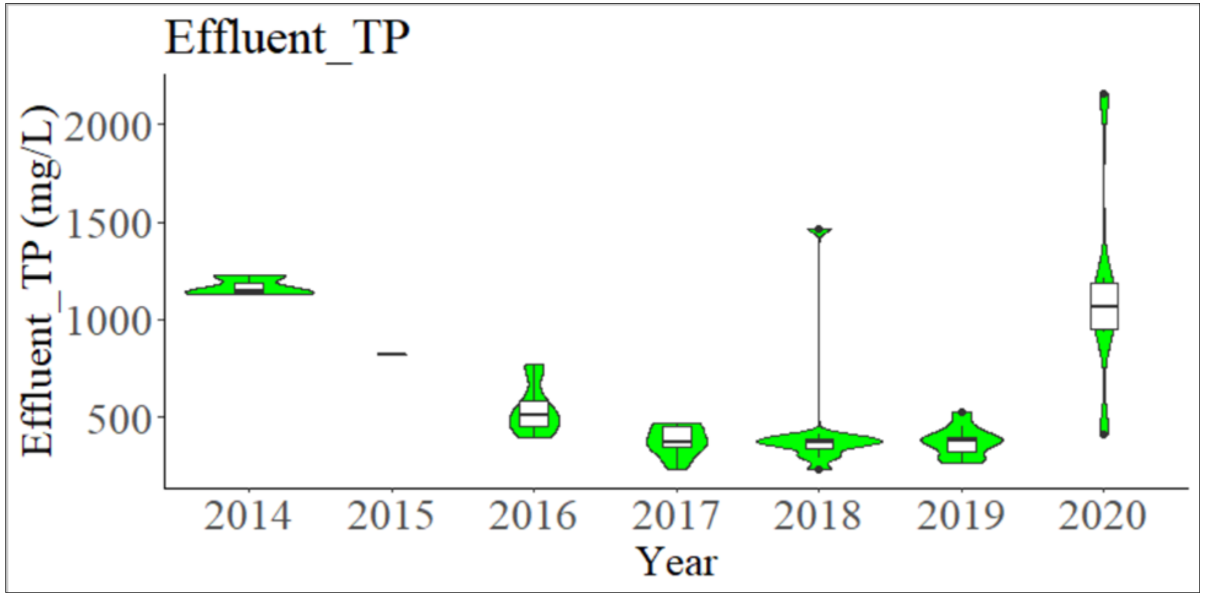
Distribution of TN in the digestate



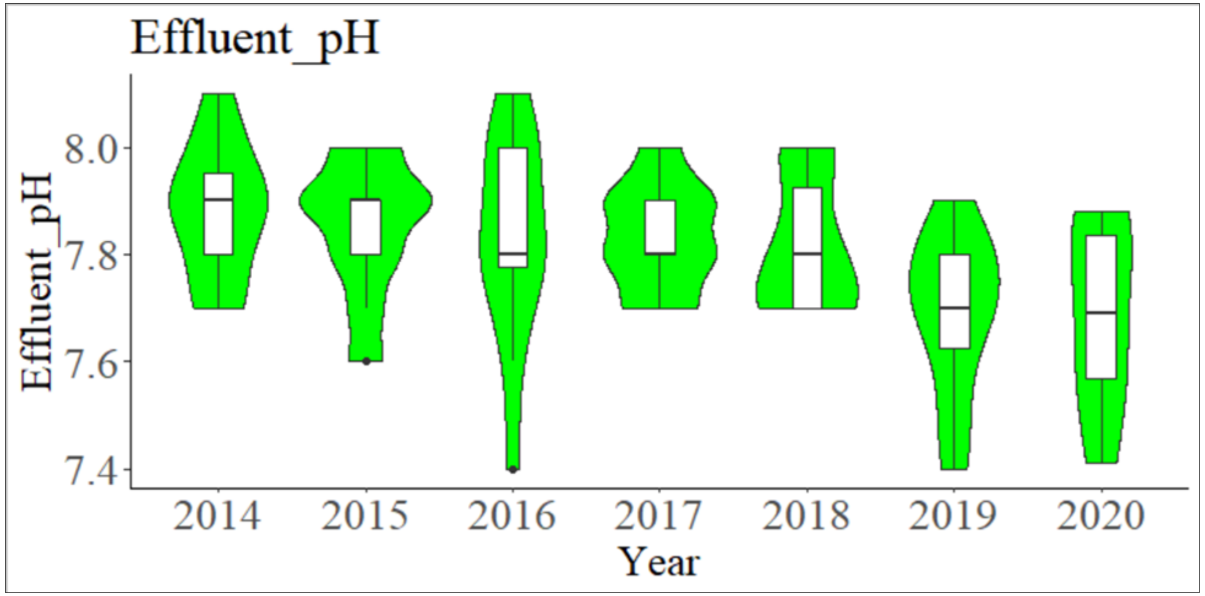
3. Long-term Operational Data

Characteristics of digestate (2014-2020)

Distribution of TP in the digestate



Distribution of pH in the digestate



3. Long-term Operational Data

TS and VS reduction (2014-2020)

TS reduction

Year	TS (mg/L)				Reduction %
	Influent	n	Effluent	n	
2014	93,359±12,280	12	49,085±5,709	11	47
2015	107,615±4,216	4	57,082±8,282	10	47
2016	104,673±20,115	7	65,928±7,110	12	37
2017	107,881±17,283	3	70,359±5,929	9	35
2018	113,498	1	58,913±3,944	12	48
2019	-		59,702±6,768	10	-
2020	-		64,138±6,668	7	-
Max	**113,498**		**70,359**		**48**
Min	**93,359**		**49,085**		**35**
Mean	**105,186**		**60,398**		**42**
Average	**105,405**		**60,744**		**43**
St. Dev	**6,666**		**6,377**		**6**

VS reduction

Year	VS (mg/L)				Reduction %
	Influent	n	Effluent	n	
2014	80,623±10,397	12	38,018±4,767	11	53
2015	93,101±3,727	4	43,803±7,684	10	53
2016	90,718±17,274	7	52,485±6,158	12	42
2017	96,555±16,237	3	58,056±4,682	9	40
2018	103,020	1	47,524±3,339	12	54
2019	-		47,354±6,291	10	-
2020	-		51,626±5,843	7	-
Max	**103,020**		**58,056**		**54**
Min	**80,623**		**38,018**		**40**
Mean	**92,504**		**48,029**		**48**
Average	**92,803**		**48,209**		**48**
St. Dev	**7,366**		**5,989**		**6**

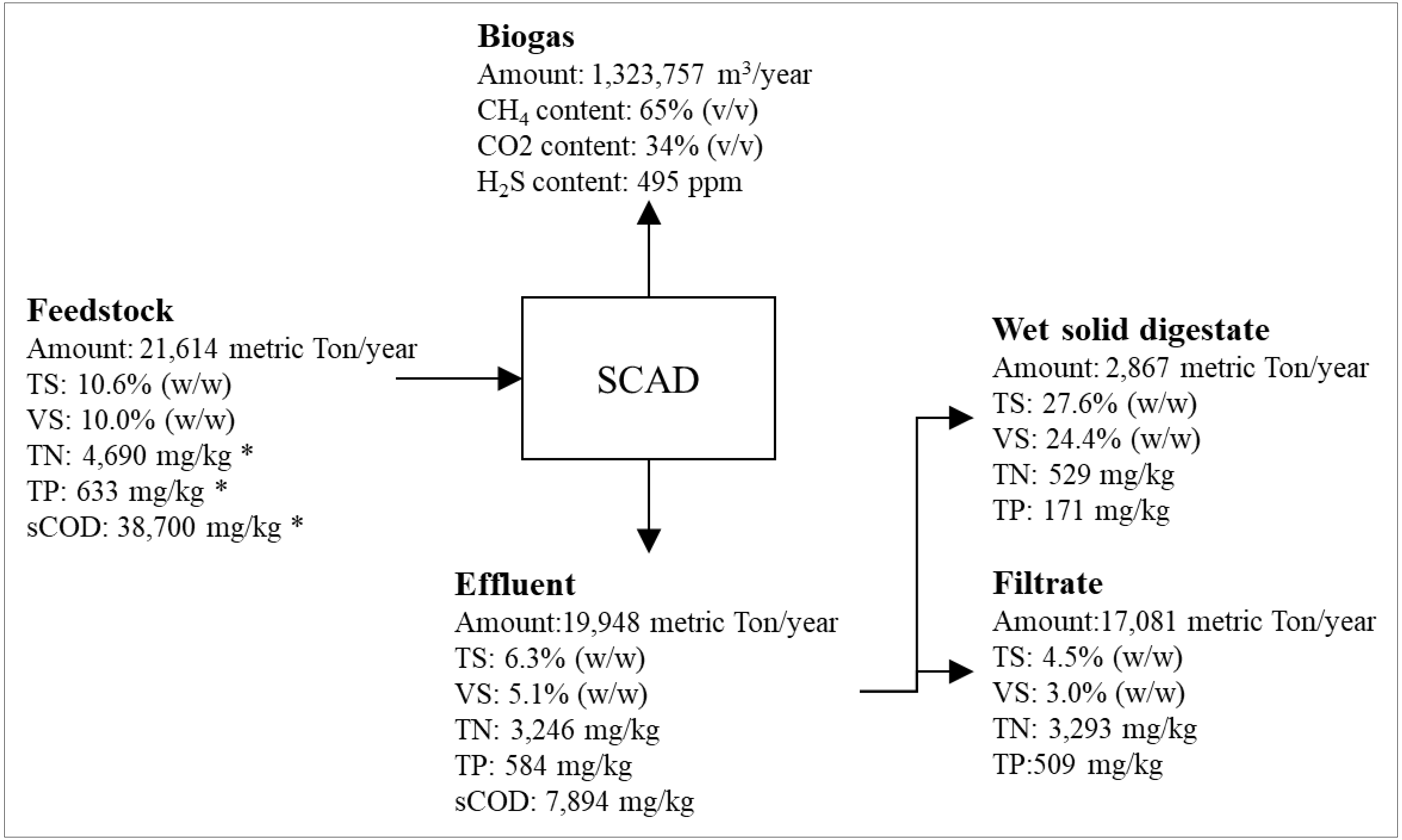
3. Long-term Operational Data

Summary of the SCAD performance (2014-2020)

Year	Input			Output			
	Total Manure Pit Metric Ton	Total Food Pit Metric Ton	Total Feedstock Metric Ton	Total Biogas SCM	Total Electricity kWh	Effluent Total Metric Ton	Wet Fiber Total Metric Ton
2014	14,763	8,533	23,297	846,232	1,727,073	11,273	3,920
2015	13,805	12,800	26,605	1,103,695	2,118,966	14,100	4,858
2016	11,059	11,726	22,785	1,418,746	1,470,356	14,007	3,583
2017	11,109	9,129	20,238	1,326,335	2,169,693	12,751	2,779
2018	10,859	8,605	19,464	1,348,024	2,680,954	14,857	1,884
2019	11,353	10,539	21,893	1,280,438	2,333,449	15,762	2,758
2020	10,332	14,531	24,863	1,340,179	2,664,665	17,745	3,082
Total	**83,281**	**75,864**	**159,145**	**8,663,649**	**15,165,156**	**100,495**	**22,864**
Average	**11,897**	**10,838**	**22,735**	**1,237,664**	**2,680,954**	**14,356**	**3,266**
St. Deviation	**1,683**	**2,294**	**2,499**	**198,468**	**1,470,356**	**2,081**	**958**

4. Techno-economic Analysis

Mass balance of the digestion system *



*: The calculation is based on the data from 2018 - 2020

4. Techno-economic Analysis

Energy balance of the digestion system [a]

	SCAD
Energy input	
Heat input (W_{heat}, kWh-e/year) [b]	-742,090
Electricity input ($W_{electricity}$, kWh-e/year) [c]	-170,320
Energy output	
Energy output as heat (E_{heat}, kWh-e/year) [d]	5,584,551
Energy output as electricity ($E_{electricity}$, kWh-e/year) [e]	2,462,190
Net energy output	
Net heat output (kWh-e/year) [f]	4,842,461
Net electricity output (kWh-e/year) [g]	2,291,870

a. Negative numbers mean energy inputs, and positive numbers mean energy outputs.

b. Eq. 1 was used to calculate the heat input.

c. Eq. 2 was used to calculate the electricity input.

d. The annual biogas production of 1,323,757 m^3 with 65% (v/v) of methane was used to calculate the energy content of the biogas. The low heating value of methane is 35.8 MJ/m^3 methane. The thermal conversion efficiency of the CHP unit is 65%.

e. The electricity output is the metered number of the digestion operation.

f. The net heat output = $E_{heat} – W_{heat}$

g. The net electricity output = $E_{electricity} - W_{electricity}$

4. Techno-economic Analysis

Economic performance of the digestion system [a]

Capital expenditure (CapEX)	Cost	Reference
Feedstock Receiving	$727,927	Data
Digester	$1,442,140	Data
CHP	$778,651	Data
Bond	$38,143	Data
Interconnection	$300,000	Data
Site improvements & excavation	$300,000	Data
Total CapEX	**$3,586,861**	

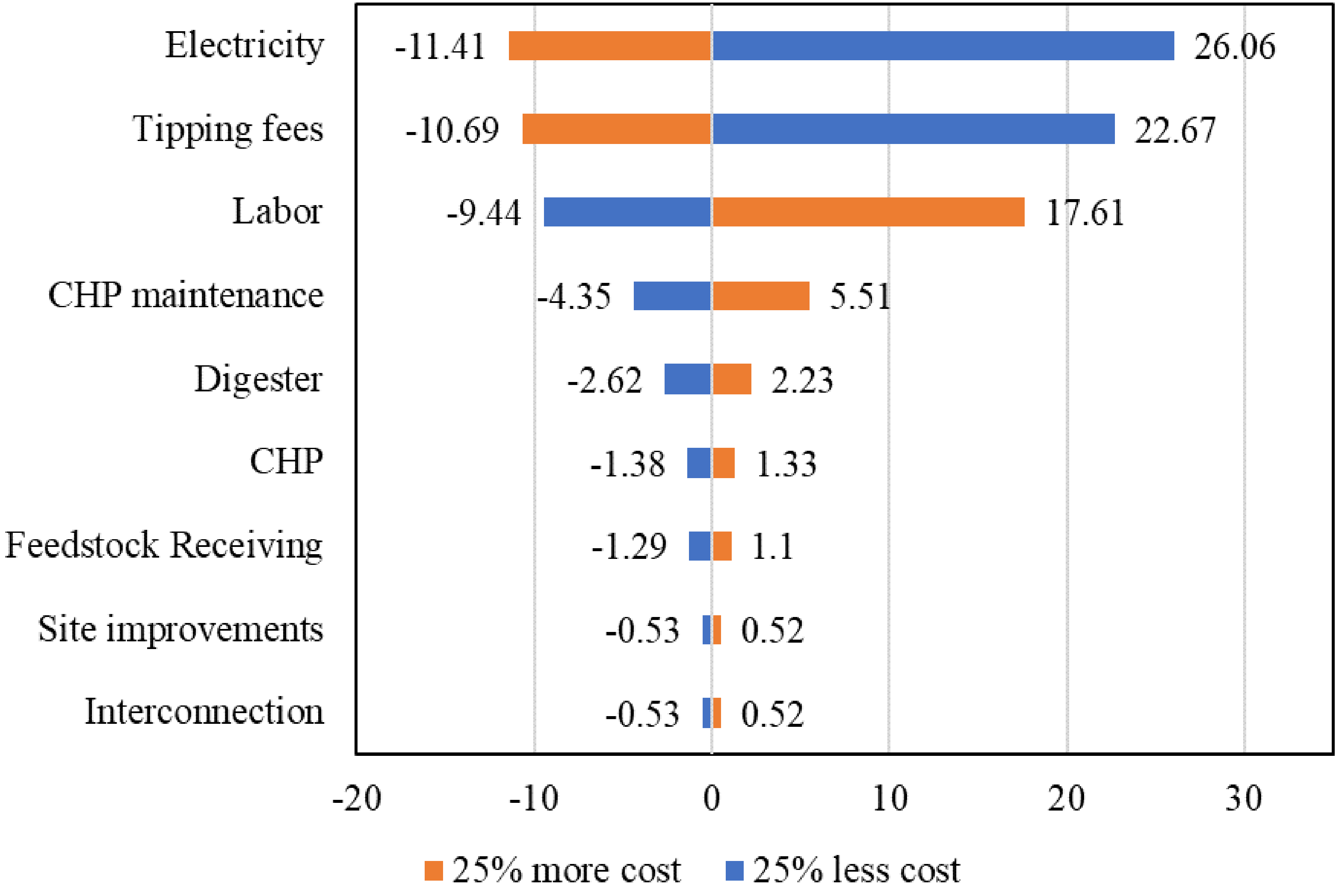
Revenue (per year)	Cost	Reference
Electricity [b]	$237,746	Data
Tipping	$217,854	Data
Total revenue (per year)	**$455,600**	
Total net revenue (per year) [c]	**$157,444**	
Payback time (Years) [d]	**21.5**	

OpEX (per year)	Cost	Reference
AD Repairs	$28,373	Data
ADMIN Fee	$2,948	Data
Bio Analysis	$2,827	Data
CHPS	$74,226	Data
Labor	$123,616	Data
Laundry	$378	Data
Maintenance and Repair	$6,482	Data
MISC	$4,064	Data
Motor Pool / Vehicle	$1,165	Data
Supplies	$396	Data
Telephone	$772	Data
Transport (DHT)	$52,910	Data
Total OpEX (per year)	**$298,156**	

a. The OpEX and revenue are the operational data from 2019-2020.
b. The average electricity price is $0.10/kWh.
c. The net revenue = Total revenue – Total OpEx
d. The 5-year average local inflation of 3.2% in the U.S. is used as the inflation rate. The depreciation period is set at 20 years. The depreciation is just on CapEx. The annual depreciation rates from MARCRS (Modified Accelerated Cost Recovery System) are: 0.100, 0.188, 0.144, 0.115, 0.092, 0.074, 0.066, 0.066, 0.065, 0.065, and 0.033 (after 10 years).

4. Techno-economic Analysis

Sensitivity analysis on the payback period of the digestion system



- Nine variables – feedstock receiving, digester, CHP, interconnections, site improvements, CHP maintenance, labor, electricity, and tipping fees – were taken into consideration for the economic sensitivity.

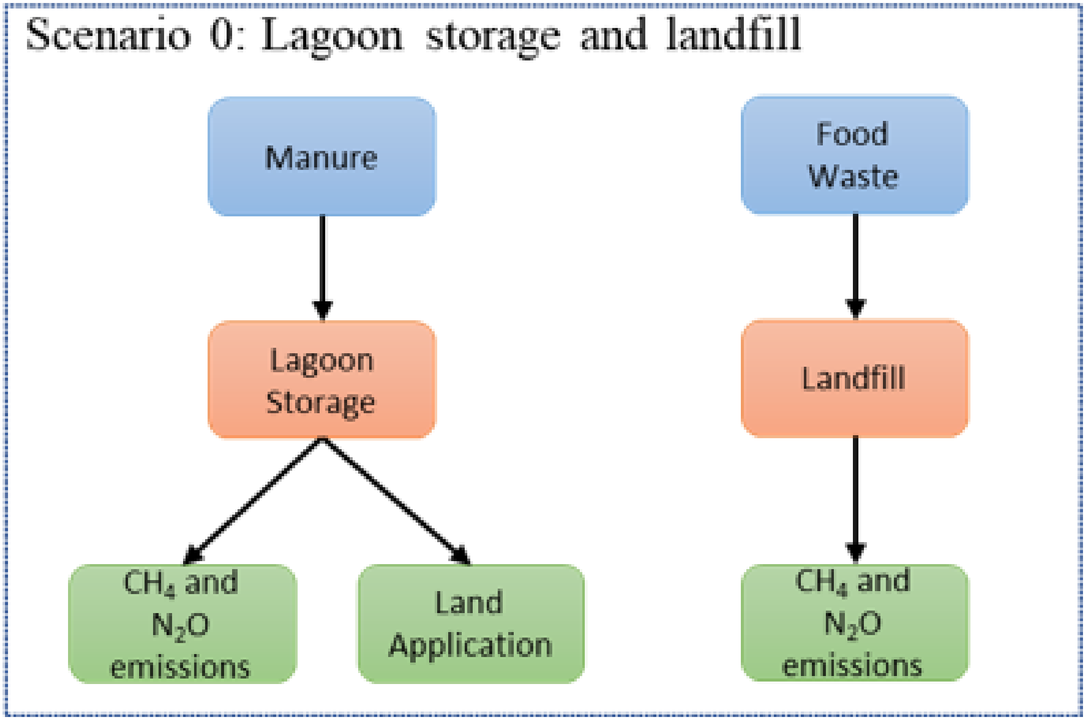
- The analysis was done by modifying each variable by ± 25% while keeping the other variables constant for the baseline scenario.

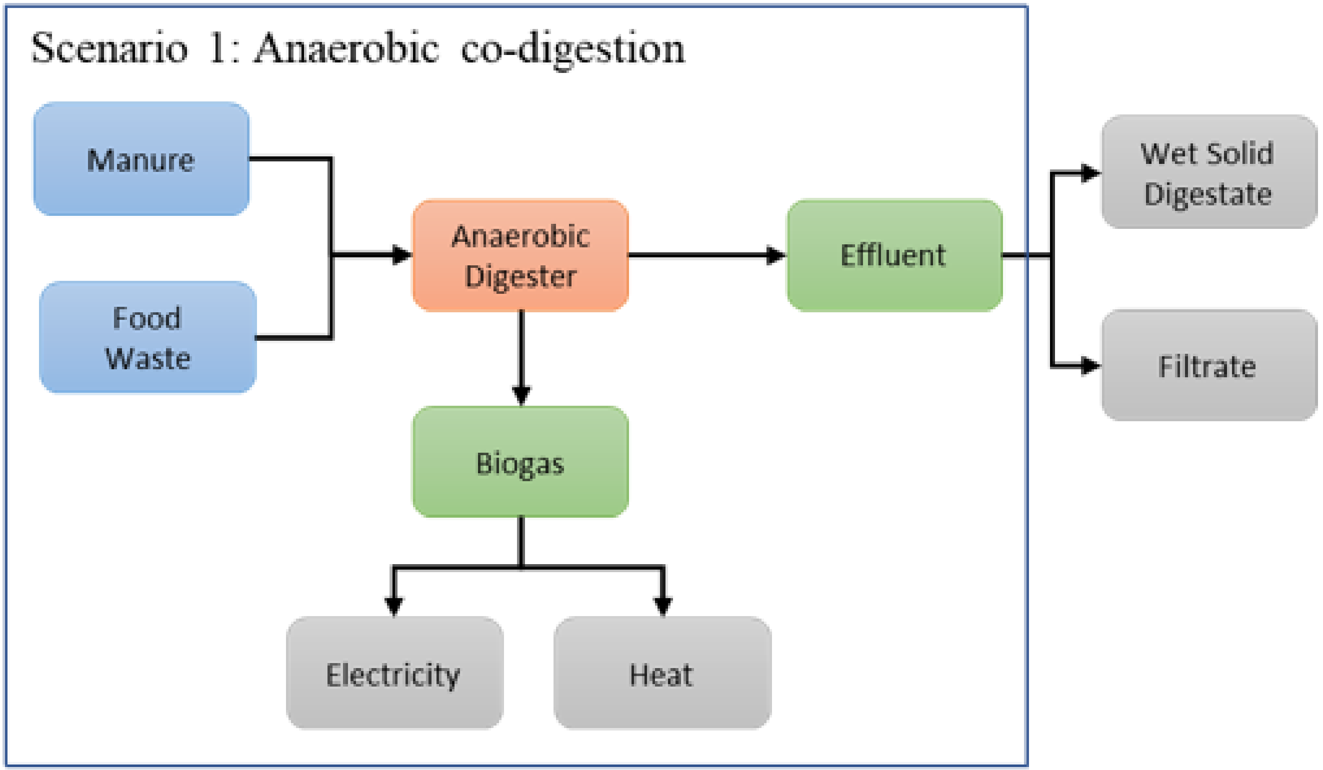
- The electricity revenue and tipping fees are the main factor to the economic performance of the commercial digesters. The payback period is reduced to 10 and 11 years, respectively, with 25% increase on electricity cost and tipping fees.

5. Life Cycle Impact Analysis

Scenarios and boundaries for life cycle impact assessment

- Scenario 1: Co-digestion system of manure and food wastes
- Scenario 0: Lagoon storage and landfill application of manure and food waste





5. Life Cycle Impact Analysis

Inventory for the life cycle impact assessment [a]

	Value	Unit	Source	DQI
Raw materials				
Manure wastes	10,913	Metric ton/year	Data	1, 1, 2, 2, 1, 1
Total solids of manure wastes	11.4	%	Data	1, 1, 2, 2, 1, 1
Volatile solids of manure wastes	10.0	%	Data	1, 1, 2, 2, 1, 1
TN of manure wastes	4,143	mg/kg	Data	1, 1, 2, 2, 1, 1
TP of manure wastes	413	mg/kg	Data	1, 1, 2, 2, 1, 1
sCOD of manure wastes	59,446	mg/kg	Data	1, 1, 2, 2, 1, 1
Food wastes	10,701	Metric ton/year	Data	1, 1, 2, 2, 1, 1
Total solids of food wastes	10.1	%	Data	1, 1, 2, 2, 1, 1
Volatile solids of food wastes	9.3	%	Data	1, 1, 2, 2, 1, 1
TN of food wastes	5,318	mg/kg	Data	1, 1, 2, 2, 1, 1
TP of food wastes	449	mg/kg	Data	1, 1, 2, 2, 1, 1
sCOD of food wastes	17,525	mg/kg	Data	1, 1, 2, 2, 1, 1

	Value	Unit	Source	DQI
Anaerobic digestion and energy production inventory				
Biogas production	1,323,757	m^3/year	Data	1, 1, 2, 2, 1, 1
CH_4 content in biogas	65	% v/v	Data	1, 1, 2, 2, 1, 1
CO_2 content in biogas	34	% v/v	Data	1, 1, 2, 2, 1, 1
Electricity production from biogas	2,462,190	kWh-e/year	Data	1, 1, 2, 2, 1, 1
Heat production from biogas	5,584,551	kWh-e/year	Data	1, 1, 2, 2, 1, 1
Effluent	19,948	Metric ton/year	Data	1, 1, 2, 2, 1, 1
TS of effluent	6.3	% (w/w)	Data	1, 1, 2, 2, 1, 1
TN of effluent	3,246	mg/kg	Data	1, 1, 2, 2, 1, 1
TP of effluent	584	mg/kg	Data	1, 1, 2, 2, 1, 1
sCOD of effluent	7,894	mg/kg	Data	1, 1, 2, 2, 1, 1
N_2O emission from the effluent	0.005	g N_2O/g TN	Ref.	2, 1, 1, 4, 1, 2
GWP of N_2O	298	g CO_2-e/g N_2O	Ref.	2, 1, 1, 4, 1, 2
CH_4 emission from effluent	3.08×10^{-4}	Metric ton CO_2-e/metric ton TS	Ref.	2, 1, 1, 4, 2, 2
Water eutrophication potential (WEP) of TN	0.9864	g N-e/kg TN	Ref.	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of TP	7.29	g N-e/kg TP	Ref.	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of COD	0.05	G N-e/kg COD	Ref.	2, 1, 1, 4, 1, 2

5. Life Cycle Impact Analysis

Inventory for the life cycle impact assessment [a] (cont'd)

	Value	Unit	Source	DQI
Animal wastes lagoon storage and land application inventory				
CH_4 emission	0.127	Metric ton CH_4/metric ton VS	(Owen & Silver, 2015)	2, 1, 1, 3, 2, 2
N_2O emission	0.005	g N_2O/g TN in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of TN	0.9864	g N-e/kg TN in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of TP	7.29	g N-e/kg TP in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of COD	0.05	g N-e/kg COD in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2

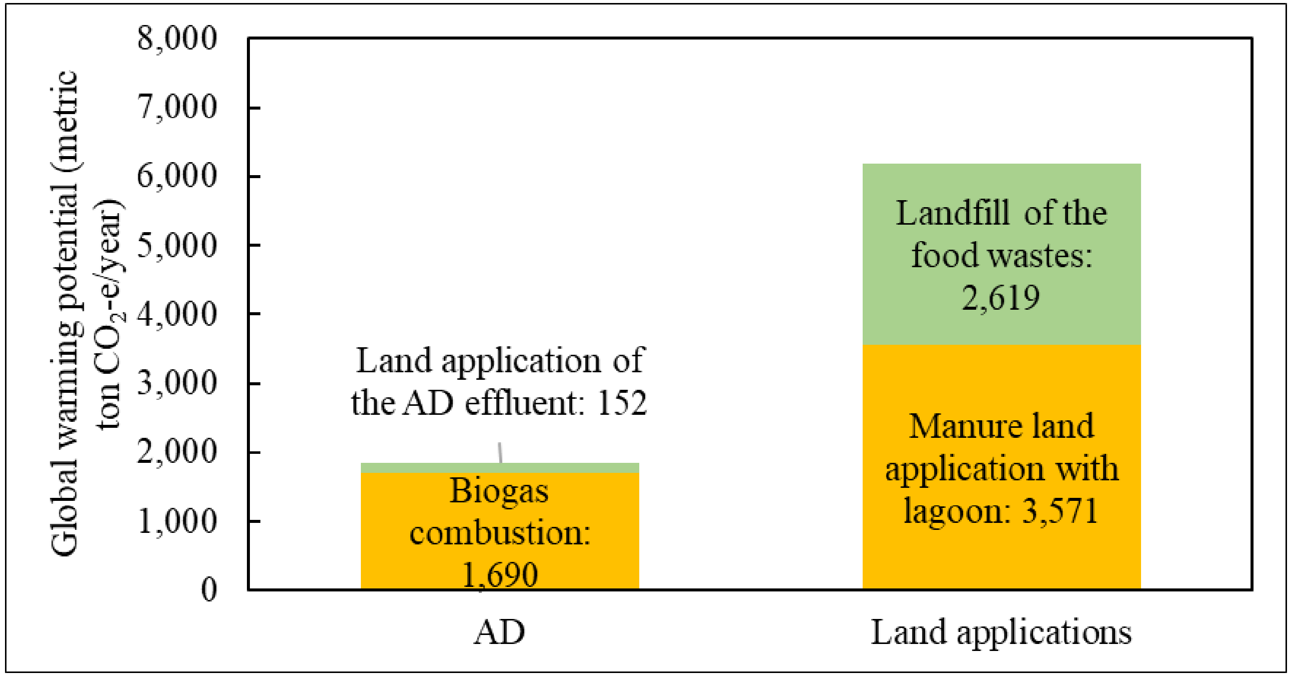
	Value	Unit	Source	DQI
Food wastes landfill inventory with landfill gas (LFG) combustion				
CH_4 emission, food wastes landfill	2.3	Metric ton CO_2-e/ton TS food waste	(Environmental Protection Agency, 2020)[b]	2, 1, 1, 1, 2, 2
N_2O emission	0.005	g N_2O/g TN in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of TN	0.9864	g N-e/kg TN in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of TP	7.29	g N-e/kg TP in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of COD	0.05	G N-e/kg COD in the waste	(RTI International, 2010)	2, 1, 1, 4, 1, 2
Water eutrophication potential (WEP) of COD	0.05	G N-e/kg COD	Ref.	2, 1, 1, 4, 1, 2

a. CO_2 from manure wastes and food wastes is not counted in the calculation of greenhouse gas emissions because the CO_2 is considered of biogenic origin and therefore is assumed to be offset by CO_2 capture by regrowth of the plants.
b. The moisture content of the typical food wastes in the reference is set at 70%.

5. Life Cycle Impact Analysis

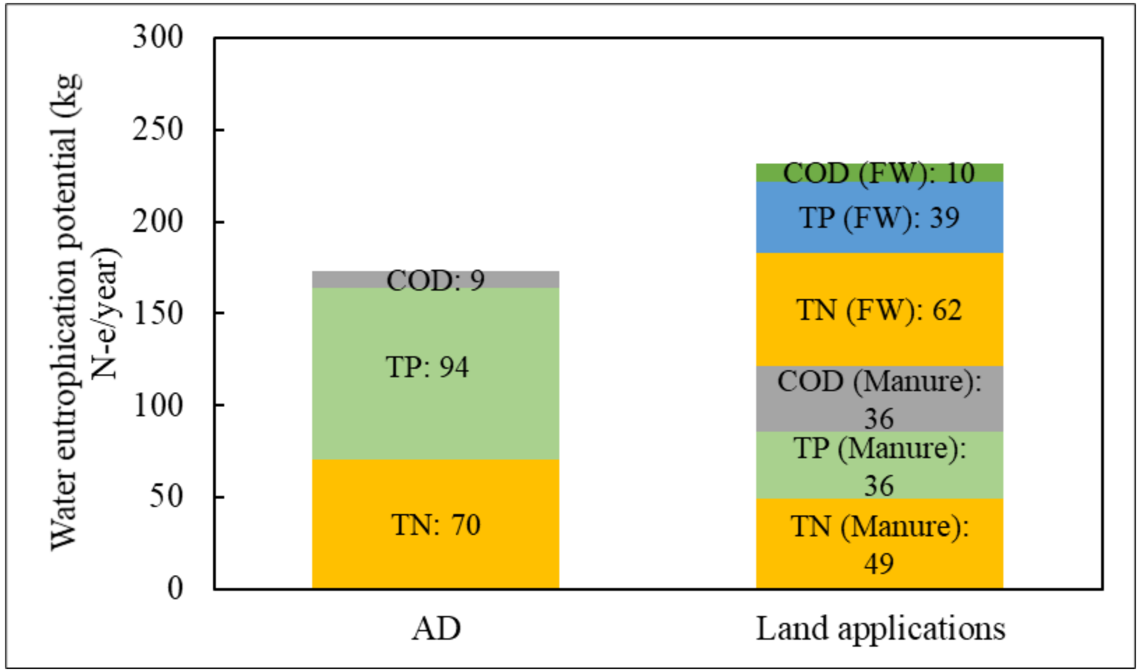
The life cycle impact assessment

Global warming potential (GWP)



1,842 ton CO_2-e/year	6,190 ton CO_2-e/year

Water eutrophication potential (WEP)



173 kg N-e/year	232 kg N-e/year

- The SCAD reduces GWP up to 70%.
- The SCAD reduces WEP up to 25%.

6. Summary

- With understanding characteristics of different feedstock, anaerobic co-digestion can handle multiple waste streams to enhance digestion performance (biogas production).
- Dairy manure is a significant component to stabilize the digestion performance.
- Increasing the value of biogas (e.g., renewable natural gas) is a key factor to improve the economic performance of the digestion, and reduce the payback time.
- The life cycle impact analysis elucidated that the anaerobic digestion can significantly reduce GWP and WEP. **The liquid digestate needs to be further treated to reduce the WEP of anaerobic digestion.**

MICHIGAN STATE UNIVERSITY

Thank You!

BAE Department of Biosystems and Agricultural Engineering

MSU Anaerobic Digestion Research and Education Center (MSU ADREC)


Main building of ADREC


High-bay area


Wet labs


Hot room


The pilot solar-bio-power system in Costa Rica


A plug-flow digester (1,000 m^3)


The container waste utilization unit

Pilot membrane reactor and ultrafiltration unit

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