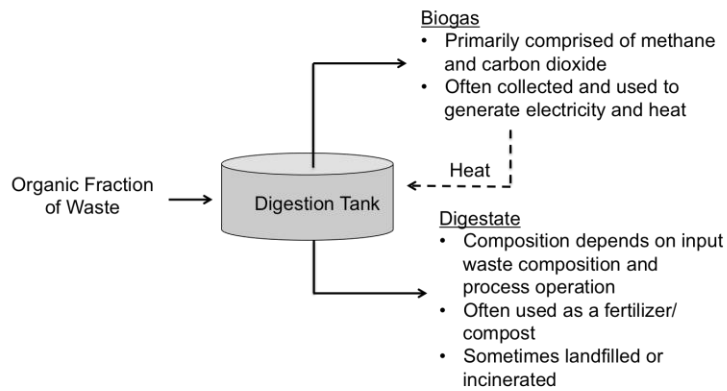
Critical Thinking Questions - Anaerobic Digestion Solutions

I. Introduction to Anaerobic Digestion

1. Anaerobic digestion is the biological conversion of organics that occurs in the absence of oxygen and results in the production of methane and carbon dioxide.

2. Candidate wastes for this process: food wastes (residential, commercial, industrial), yard trimmings. These wastes are organic and readily degradable (non-cellulosic).

3.



4. Potential reasons for conducting AD: diversion from landfills; generation of biogas; meet state diversion goals; improve sustainability associated with the waste management system. Student answers will vary for the remainder of this problem.

5. Answers to this question may vary. Inclusion of the following factors/issues:

Factor/Issue	Importance/Impact on the Process
Waste composition and mass	Appropriate sizing and design of the facility
Collection and/or separation of the waste components being anaerobically digested	Collection system may need to be designed/modified. Feasibility and economic factors associated with this are important.
Ability to use generated biogas	Biogas is a source of revenue. Need to understand if infrastructure for its use needs to be constructed /designed or modified.
Economics associated with using the biogas	Potential revenue from the process
Type of AD system being used	Dictates design of the digestion system
Digestate use or disposal	This is an important output of the process. Need to know what this stream will be used for or if it will be sent to a local landfill, etc.

6. Answers will vary.

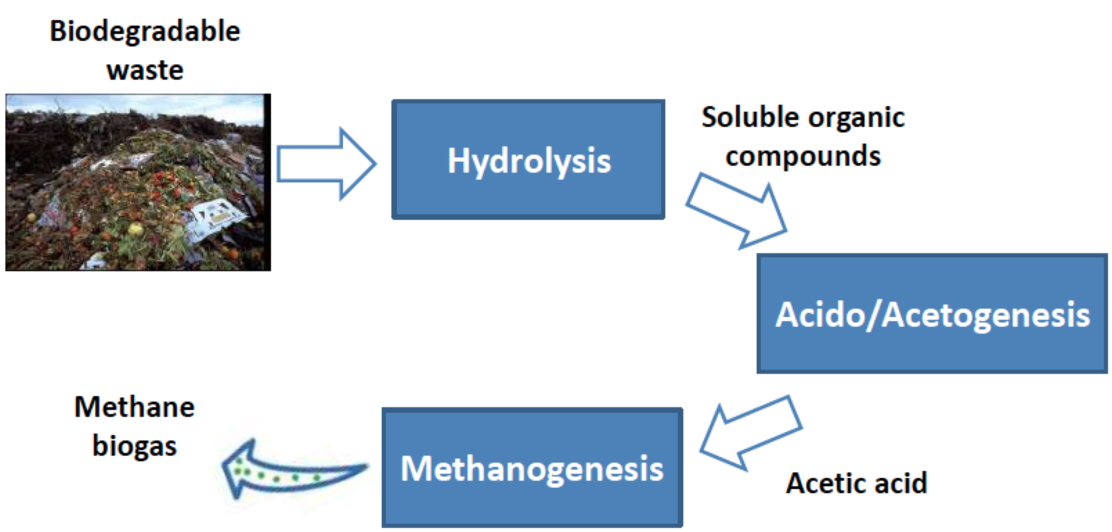
II. History of Current State of Anaerobic Digestion in the U.S. and Europe

1. In Europe, AD is being conducted routinely, mostly due to high landfill tipping rates and policies requiring waste diversion from landfills. As of 2015, 244 AD plants were in operation. Of these facilities, 89% are stand alone, while 11% are co-digestion facilities. In the US, AD has not been used as routinely. This practice is just becoming more prevalent. As of 2016, only 29 stand-alone and 129 co-digestion AD facilities exist in the US.

III. Overview of Anaerobic Digestion Processes

1.
   a. Temperature: Temperature is an important parameter. Temperature must be suitable for the microbial process occurring. Generally, processes are either mesophilic (68-112°F) or thermophilic (113-176°F). Lower temperatures during the process are known to decrease microbial growth, substrate utilization rates, and biogas production. Lower temperatures may also result in an exhaustion of cell energy, a leakage of intracellular substances or complete lysis. High temperatures lower biogas yield due to the production of volatile gases such as ammonia, which suppresses methanogenic activities.
   b. Nutrients: These are required for microbial processes to be sustained. Lack of nutrients will ultimately result in microbial processes ceasing.
   c. Toxic compounds: Presence of these compounds may disrupt the microbial processes.

2.



3.

Term	Definition
Hydrolysis	Conversion of solid waste organics to simple sugars and amino acids. This is the rate-limiting step of the digestion of refractory materials such as fruit peels. Wood debris and green wastes.
Anaerobic	In the absence of oxygen
Aerobic	In the presence of oxygen
Autotroph	Microorganism that uses inorganic carbon as a carbon source
Chemotroph	Obtain energy from the oxidation of electron donors
Phototroph	Uses light as an energy source to carry out cellular metabolic processes
Heterotroph	Uses organic carbon as the carbon source
Fermentation	Occurs under anaerobic conditions during which organic molecules serve as both electron donors and electron acceptors
Methanogenesis	Generation of methane
Mesophilic	Temperature range: 68-112^{o}F
Thermophilic	Temperature range: 113-176^{o}F

IV. Anaerobic Digestion Biogas Production

1.

Step 1:

Use the following table to determine the chemical formula of the food waste.

Component	C	H	O	N	S	Ash
Food Waste	48	6.4	37.6	2.6	0.4	5
Paper	43.5	6	44	0.3	0.2	6
Cardboard	44	5.9	44.6	0.3	0.2	5
Plastics	60	7.2	22.8	0	0	10
Textiles	55	6.6	31.2	4.6	0.15	2.5
Rubber	78	10	0	2	0	10
Leather	60	8	11.6	10	0.4	10
Yard Wastes	47.8	6	38	3.4	0.3	4.5
Wood	49.5	6	42.7	0.2	0.1	1.5
Inorganic	0.5	0.1	0.4	0.1	0	98.9

Molecular Weight = 1,781 g/mole

Step 2:

Recognize that stoichiometry can be used to calculate moles of CH4 generated/mole food waste, which can then be converted to m3 CH4/tonne of food waste

Stoichiometric Relationship:

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right) H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right) CH_4 + \left(\frac{4a-b+2c+3d}{8}\right) CO_2 + dNH_3$$

- Moles of CH_4/mole food waste = $\left(\frac{4a+b-2c-3d}{8}\right)$
- Plugging in values = $\left(\frac{(4\times22)+173-(2\times83)-(3\times1)}{8}\right)$ = 11.5 moles CH_4/mole food waste
- Convert moles food waste to mass food waste:

$$\frac{11.5\ moles\ CH_4}{1\ mole\ food\ waste\ \times\left(\frac{1{,}781\ g\ food\ waste}{mole\ food\ waste}\right)} = 0.0065\ \frac{moles\ CH_4}{g\ food\ waste}$$

- Convert this to m^3 CH_4/tonne of food waste:

Note the following conversions:
1 tonne = 1,000,000g = 1 Mg
At STP, 22.4 L/mole of Gas
1 m^3 = 1000 L

$$= 0.0065\frac{moles\ CH_4}{g\ food\ waste}\times\frac{1{,}000{,}000\ g}{tonne}\times\frac{22.4\ L}{mole\ gas}\times\frac{1\ m^3}{1000\ L}$$

$$= 144.6\ \frac{m^3 CH_4}{tonne\ food\ waste}$$

Step 3:

Already calculated the volume of CH_4/tonne food waste. Now calculate the volume of CO_2/tonne of food waste.

- Moles of CO_2/mole food waste = $\left(\frac{\boldsymbol{4a-b+2c+3d}}{\boldsymbol{8}}\right)$
- Plugging in values: $\left(\frac{(4 \times 22)-173+(2 \times 83)+(3 \times 1)}{8}\right) = 10.5\ moles\ \frac{CO_2}{moles}\ food$
- Convert moles food waste to mass food waste:

$$\frac{10.5\ moles\ CH_4}{1\ mole\ food\ waste\ \times \left(\frac{1{,}781\ g\ food\ waste}{mole\ food\ waste}\right)} = 0.0059\ moles\ \frac{CO_2}{g\ food\ waste}$$

- Convert this to m^3 CO_2/tonne of food waste:

Note the following conversions:
1 tonne = 1,000,000g = 1 Mg
At STP, 22.4 L/mole of Gas
1 m^3 = 1000 L

$$= 0.0059\ \frac{moles\ CO_2}{g\ food\ waste} \times \frac{1{,}000{,}000\ g}{tonne} \times \frac{22.4\ L}{mole\ gas} \times \frac{1\ m^3 CO_2}{1000\ L}$$

$$= 132.1\ \frac{m^3 CO_2}{tonne\ food\ waste}$$

- Add the CO_2 and CH_4 volumes:

$$\frac{144.6\ m^3 CH_4}{tonne\ food\ waste} + \frac{132.1\ m^3 CO_2}{tonne\ food\ waste} = \frac{276.7\ m^3\ gas}{tonne\ food\ waste}$$

- Multiply by the mass of food waste

$$276.7\ m^3\ \frac{gas}{tonne\ food\ waste} \times 1\ tonne\ food\ waste = 276.7\ m^3 biogas$$

Determination of the electricity generated from the AD of organics.

Step 1:

- Only the methane fraction of the biogas can be used to generate electricity. Calculate the total volume of methane:

$$\frac{144.6\ m^3 CH_4}{tonne\ food\ waste} \times 1\ tonne\ food\ waste = 144.6\ m^3\ CH_4$$

Step 2:

- Gas collection efficiencies are generally high during AD. There may be some small losses, generally ranging from 0-10% (ref 1). Therefore, collection efficiencies range from 90-100%.
- Conversion efficiencies of CH4 to electricity may range from:

20 – 40% (based on ref 2)

- Conversions/relationships to know:

Energy Content of Methane = 55.5 kJ/kg

1 kWh = $\mathbf{3.6 \times 10^6\ J}$

Density of methane = 0.656kg/m^3

Step 3:

- Determine the fraction of methane available for conversion to electricity (assume a collection efficiency of 98%):

$$=144.6\ m^3\ CH_4 \times 0.98$$
$$= 141.7\ m^3 CH_4$$

- Determine the electricity that can be generated, accounting for the conversion efficiency (assume a conversion efficiency of 20%):

$$= 141.7\ m^3 CH_4 \times 0.2 \times \frac{55\ kJ}{kg\ CH_4} \times \frac{0.656\ kg}{m^3} \times \frac{1\ kWh}{3.6 \times 10^6\ J} \times \frac{1000\ J}{kJ}$$

= 0.28 kWh

2.

Table 1. Waste Composition

Component	Wet Weight, g	%MC
Food Waste	0	70
Paper	100	6
Cardboard	0	5
Plastics	0	0
Textiles	0	0
Rubber	0	0
Leather	0	0
Yard Wastes	0	0
Wood	0	0
Inorganic	0	0

Table 2. Chemical Composition of Waste Components

Component	C	H	O	N	S	Ash
Food Waste	48	6.4	37.6	2.6	0.4	5
Paper	43.5	6	44	0.3	0.2	6
Cardboard	44	5.9	44.6	0.3	0.2	5
Plastics	60	7.2	22.8	0	0	10
Textiles	55	6.6	31.2	4.6	0.15	2.5
Rubber	78	10	0	2	0	10
Leather	60	8	11.6	10	0.4	10
Yard Wastes	47.8	6	38	3.4	0.3	4.5
Wood	49.5	6	42.7	0.2	0.1	1.5
Inorganic	0.5	0.1	0.4	0.1	0	98.9

Solution:

Step 1: Calculate weight of each element

Component	Wet Weight, g	%MC	Dry Weight, g	C	H	O	N	S	ASH
Food Waste	0	70	0	0.00	0.00	0.00	0.00	0.00	0.00
Paper	100	6	94	40.89	5.64	41.36	0.28	0.19	5.64
Cardboard	0	5	0	0.00	0.00	0.00	0.00	0.00	0.00
Plastics	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Textiles	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Rubber	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Leather	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Yard Wastes	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
Wood	0	0	0	0.00	0.00	0.00	0.00	0.00	0.00
TOTALS:	100		94	40.89	5.64	41.36	0.28	0.19	5.64

Step 2: Calculate the weight of H and O in water

- How much water is in the waste?
  - 6 g (Wet waste – Dry waste)
- Calculate the weight of H and O in the waste
  - H: 0.667 g H --- (weight of Moisture/MW H_2O) x 2
  - O: 5.333 g O --- (weight of Moisture/MW of H_2O) x 16

Step 3: Add the H and O to the composition found in the table above:

Element	g, w/o water	g, w/ water
C	40.89	40.89
H	5.64	6.31
O	41.36	46.69
N	0.28	0.28
S	0.19	0.19
ASH	5.64	5.64

Step 4: Determine the molar composition of the elements, neglect ash

Element	Atomic Wt	Moles, w/o water	Moles, w water
C	12.01	3.405	3.405
H	1.01	5.584	6.244
O	16	2.585	2.918
N	14.01	0.020	0.020
S	32.07	0.006	0.006

Step 5: Normalize mole rations

	N=1		S=1	
Element	Mole Ratio w/o Water	w/ water	Mole Ratio w/o Water	w/ water
C	169.1	169.1	580.8	580.8
H	277.4	310.2	952.6	1065.2
O	128.4	145.0	441.0	497.8
N	1.0	1.0	3.4	3.4
S			1.0	1.0

Use the chemical composition to determine the volume of CH_4 produced from paper

From chemical formula, we know the following:

a = 169.0
b = 310.0
c = 145.0
d = 1.0

Molecular weight = 4676.8 g/mole

- Use the anaerobic degradation equation:

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3$$

moles of CH_4 generated/moles MSW =
86.6
moles of CH_4 generated/g MSW =
0.01852228
Assuming STP, m^3 CO_2/g MSW =
0.000415

moles of CO_2 generated/moles MSW =
82.4
moles of CO_2 generated/g MSW =
0.0176
Assuming STP, m^3 CO_2/g MSW =
0.000395

Total Volume of gas (m^3)/g MSW =
0.000809

Mass of MSW:
1000.00 g

Assuming 100% biodegradation:

0.809 m^3 of biogas

3.

1 Mg/week of an organic waste stream with composition listed below

Waste Component	Composition of waste (%, by weight)
Food Waste	80
Paper	10
Cardboard	10

*assume 90% of organics biodegrade

Find:

a) Methane potential of this waste (m^3/tonne waste)
b) Volume (m^3) of biogas generated from one year worth of waste
c) Electricity (kWh) generated from one year worth of waste

Solution:

1) Determining the Chemical Composition of Solid Waste

Table 1. Waste Composition		
Component	Wet Weight (g)	% MC
Food Waste	80	6
Paper	10	6
Cardboard	10	6
Plastics	0	0
Textiles	0	0
Rubber	0	0
Leather	0	0
Yard Wastes	0	0
Wood	0	0
Inorganics	0	0

Table 2. Chemical Composition of Waste Components						
Component	C	H	O	N	S	Ash
Food Waste	48	6.4	37.6	2.6	0.4	5
Paper	43.5	6	44	0.3	0.2	6
Cardboard	44	5.9	44.6	0.3	0.2	5
Plastics	60	7.2	22.8	0	0	10
Textiles	55	6.6	31.2	4.6	0.2	2.5
Rubber	78	10	0	2	0	10
Leather	60	8	11.6	10	0.4	10
Yard Wastes	47.8	6	38	3.4	0.3	4.5
Wood	49.5	6	42.7	0.2	0.1	1.5
Inorganic	0.5	0.1	0.4	0.1	0	98.9

Step 1: Calculate the weight of each element

Component	Wet Weight (g)	%MC	Dry Weight (g)	C	H	O	N	H	Ash
Food Waste	80	70	24	11.52	1.54	9.02	0.62	0.10	1.20
Paper	10	6	9.4	4.09	0.56	4.14	0.03	0.02	0.56
Cardboard	10	5	9.5	4.18	0.56	4.24	0.03	0.02	0.48
Plastics	0	0	0	0	0	0	0	0	0
Textiles	0	0	0	0	0	0	0	0	0
Rubber	0	0	0	0	0	0	0	0	0
Leather	0	0	0	0	0	0	0	0	0
Yard Waste	0	0	0	0	0	0	0	0	0
Wood	0	0	0	0	0	0	0	0	0
Totals:	100		42.9	19.79	2.66	17.40	0.68	0.13	2.27

Step 2: Calculate the weight of H and O in water:

a) How much water is in this waste? 57.1g (wet waste – dry waste)
b) Calculate the weight of H and O in the waste
   H: 6.344 g H – (Weight of Moisture/MW H_2O) x 2
   O: 50.75 g O – (Weight of Moisture/MW H_2O) x 16

Step 3: Add H and O to the composition found in table above

Element	g w/o waster	g w/ water
C	19.79	19.79
H	2.66	9.00
O	17.40	68.15
N	0.68	0.68
S	0.13	0.13
ASH	2.24	2.24

Step 4: determine the molar composition of the elements. Neglect ash

Element	Atomic Weight	Moles w/o water	Moles w/ water
C	12.01	16.48	1.648
H	1.01	2.634	8.916
O	16	1.087	4.260
N	14.01	0.049	0.049
S	32.07	0.004	0.004

Step 5: Normalize mole ratios

	N=1		S=1	
Element	Mole Ratio w/o water	Mole Ratio w/ water	Mole ratio w/o water	Mole Ratio w/ water
C	33.9	33.9	394.9	394.9
H	54.2	183.5	631.4	2137.0
O	22.4	87.7	260.6	1021.0
N	1.0	1.0	11.6	11.6
S			1.0	1.0

Use the chemical composition to determine the methane potential and volume

- From the chemical formula, we know the following:

  a= 34.0
  b= 184.0
  c= 88.0
  d= 1.0

  Molecular Weight= 2016.2 g/mole

- Use the anaerobic degradation equation:

$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3$$

Moles of CH4 generated/Moles MSW	= 17.6	Moles CO_2 generated/moles MSW	= 16.4
Moles CH_4 generated/g MSW	= 0.00874	Moles CO_2 generated/g MSW	= 0.00812
Assuming STP, m^3 CH_4/g MSW	=0.000196	Assuming STP, m^3 CO_2/g MSW	= 0.000182

Part a) Methane Potential = 195.8 m^3/tonne of waste

Total Mass Generated=	1.00	Mg/week
7 days/week and 365 days/year	52.14	Mg/year

90% of waste biodegrades

Part b)

Biodegradable Mass =	46.928	Mg/year
	46928571.43	g/year
Assuming STP, m^3 CO_2 =	17726.9	m^3 of biogas

Part c)
Gas Collection Efficiency = 95%
Conversion Efficiency to electricity = 20%

kWh Generated = 17.498

4.
Given:
- 1,000 Mg/year of waste to their landfill
- They are considering diverting a fraction of their currently landfilled food waste to a newly constructed AD unit
- The fraction of this waste stream that is food is 20%

Find:
Construct a graph that illustrates how the fraction of diverted food correlates with energy production (kWh/year)

Solution:
Determining the chemical composition of Solid Waste

Table 1. Waste Composition

Component	Wet Weight (g)	%MC
Food Waste	1	70
Paper	0	6
Cardboard	0	5
Plastics	0	0
Textiles	0	0
Rubber	0	0
Leather	0	0
Yard Wastes	0	0
Wood	0	0
Inorganic	0	0

Table 2. Chemical Composition of Waste Components

Component	C	H	O	N	S	Ash
Food Waste	48	6.4	37.6	2.6	0.4	5
Paper	43.5	6	44	0.3	0.2	6
Cardboard	44	5.9	44.6	0.3	0.2	5
Plastics	60	7.2	22.8	0	0	10
Textiles	55	6.6	31.2	4.6	0.2	2.5
Rubber	78	10	0	2	0	10
Leather	60	8	11.6	10	0.4	10
Yard Waste	47.8	6	38	3.4	0.3	4.5
Wood	49.5	6	42.7	0.2	0.1	1.5

Inorganic	0.5	0.1	0.4	0.1	0	98.9

Step 1: Calculate the weight of each element

Component	Wet Weight (g)	%MC	Dry Weight (g)	C	H	O	N	S	Ash
Food Waste	1	70	0.3	0.14	0.02	0.11	0.01	0.00	0.02
Paper	0	6	0	0	0	0	0	0	0
Cardboard	0	5	0	0	0	0	0	0	0
Plastics	0	0	0	0	0	0	0	0	0
Textiles	0	0	0	0	0	0	0	0	0
Rubber	0	0	0	0	0	0	0	0	0
Leather	0	0	0	0	0	0	0	0	0
Yard Wastes	0	0	0	0	0	0	0	0	0
Wood	0	0	0	0	0	0	0	0	0
Totals:	1		0.3	0.14	0.02	0.11	0.01	0.00	0.02

Step 2: Calculate the weight of H and O in water

a) How much water is in this waste? 0.7 g (wet weight – dry weight)

b) Calculate the weight of H and O in the waste

H: 0.0778 g H – (Wt of moist/MW H_2O) x 2

O: 0.6222 g O – (Wt of moist/MW H_2O) x 16

Step 3: Add H and O to the composition found in above table

Element	(g) w/o water	(g) w/ water
C	0.14	0.14
H	0.02	0.10
O	0.11	0.74
N	0.01	0.01
S	0.00	0.00
ASH	0.02	0.02

Step 4: Determine the molar composition of the elements. Neglect ash

Element	Atomic Weight	Moles, w/o water	Moles, w/ water
C	12.01	0.012	0.012
H	1.01	0.019	0.096
O	16.00	0.007	0.046
N	14.01	0.001	0.001
S	32.07	0.000	0.000

Step 5: Normalize mole ratios

	N=1		S=1	
Element	Mole Ratio w/o Water	w/ water	Mole Ratio w/o water	w/water
C	21.5	21.5	320.4	320.4
H	34.1	172.5	508.0	2566.1
O	12.7	82.5	188.4	1227.7
N	1.0	1.0	14.9	14.9
S			1.0	1.0

Use the chemical composition to determine the volume of CH_4 produced

From Chemical formula, we know the following:

a= 22.0
b= 172.0
c= 83.0
d= 1.0

Molecular Weight= 1780.0 g/mole

Use anaerobic respiration equation:

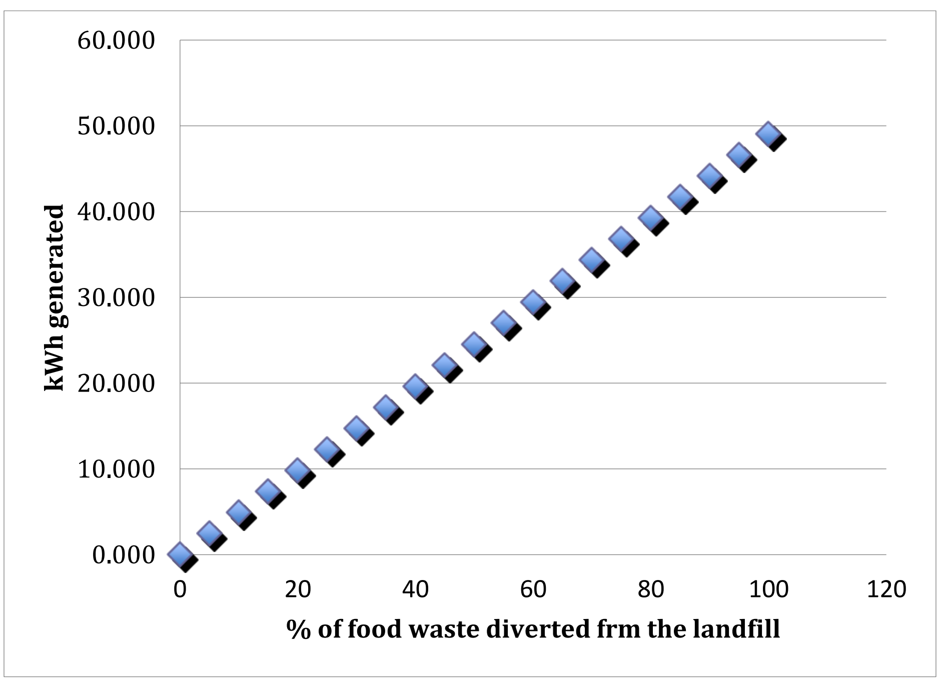
$$C_aH_bO_cN_d + \left(\frac{4a-b-2c+3d}{4}\right)H_2O \rightarrow \left(\frac{4a+b-2c-3d}{8}\right)CH_4 + \left(\frac{4a-b+2c+3d}{8}\right)CO_2 + dNH_3$$

Moles CH_4 generated/moles MSW= 11.4
Moles CH_4 generated/g MSW= 0.00639
Assuming STP, m^3 CH_4/g MSW= 0.000143

Step 3: Construct the graph

Total Mass of food waste generated each year = 200 Mg
Assume:
Fraction of food waste that biodegrades completely = 90%
Gas collection efficiency = 95%
Conversion efficiency to electricity = 20%

% of Waste Diverted	Mass of Waste Diverted (Mg)	Mass of Diverted Waste that Biodegradres (Mg)	kWh Generated
0	0	0	0.000
5	10	9	2.453
10	20	18	4.907
15	30	27	7.360
20	40	36	9.813
25	50	45	12.267
30	60	54	14.720
35	70	63	17.173
40	80	72	19.626
45	90	81	22.080
50	100	90	24.533
55	110	99	26.986
60	120	108	29.440
65	130	117	31.893
70	140	126	34.346
75	150	135	36.800
80	160	144	39.253
85	170	153	41.706
90	180	162	44.160
95	190	171	46.613
100	200	180	49.066



V. Types of Anaerobic Digestion Systems

1.

Term	Definition
Low-solids AD	These systems are generally wet AD systems in which the MSW is diluted and contain < 15% total solids.
High-solids AD	These systems are generally dry AD systems that contain > 20% total solids
Dry AD	No additional liquid is added to the digestion process
Wet AD	Additional moisture (e.g., wastewater, fresh water) is added to the digestion process
Single stage AD	Digestion occurs in one reactor
Mulit-stage AD	Digestion occurs in steps: 1. hydrolysis/fermentation and 2. methanogenesis
Organic loading rate	Mass of volatile solids added per volume-day
Process Water	Water from the digestion process
Batch reactor	Non-continuous process in which materials are placed into a reactor as a single mass or batch. Upon completion of the digestion process, the digested mass is removed. A new batch is then added.
Continuous reactor	Flow of feedstock into the digester occurs continuously.

2. Answers will vary.