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Introduction to the Science of Anaerobic Digestion

ABC – West Coast Operator Training Course

February 26, 27, 28 2019

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Agenda The Science of Anaerobic Digestion

- Storytime!
- The Process of Anaerobic Digestion
- The Estimation of Biogas Production?
- Types of Anaerobic Digestion
- What comes out of a digester?
- General Terms and the 5 Factors

Steps of Anaerobic Digestion

- Four Stage Process
  - Hydrolysis - Complex organics to simple organics
  - Acidogenisis - Hydrolysis products into short chain VFAs
  - Acetagenisis - Simple organics and VFAs to acetate, CO_2, H_2
  - Methanogenisis - CO_2 and acetate to methane
- Notes:
  - No one microbe can degrade all substrates
  - No substrate can be degraded by all microbes
- Therefore
  - A large number of microbes
  - A large diversity of microbes
  - Are needed to degrade
    - A large quantity of substrates
    - A variety of substrates

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Microbes Needed for Methanogenesis

- Hydrolytic bacteria
  - Amylase-producing
  - Lipase-producing
  - Protease-producing
- Fermentative bacteria
- Acetogenic (acetate-forming) bacteria
- Sulfate-reducing bacteria (SRB)
- Methanogens (archaea)
  - Acetotrophic
  - Hydrogenotrophic
  - Methylotrophic
- To increase diversity and number of microbes
  - Increase and vary the substrates to be degraded
  - Bioaugment

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Hydrolysis of Insoluble cBOD:
Insoluble: Starches, Lipids, Proteins

↓

Soluble: Sugars, Fatty Acids, Amines

↓

Fermentation of Sugars, Fatty Acids, Amines

↓

Acids and Alcohols

Fermentation of Sugars, Fatty Acids, Amines

↓

Acids and Alcohols

↓

Acetogenesis

↓

Methanogenesis (Methane Production)

Digester Temperature Considerations

- Mesophilic (25 to 38 ºC)
  - Moderate loading rate
  - Cleaner biogas
  - Higher yield of microorganisms
  - Larger experience base
- Thermophilic (50 to 57 ºC)
  - Higher loading rate
  - Better virus kill
  - Smaller reactor volume
  - Higher O&M costs
  - Slower yield of microorganisms
  - Fewer installed applications
- TPAD (Temperature Phased AD) – Combination of above
  - Mesophilic systems can also include a short heat treatment / pasteurization phase.

Biogas Generation

- 5.6 cubic ft of methane produced per lb of organic material converted (based on BOD destruction)
- Utilizing BMP accounts for the fact that not all VS is created equally
- Biogas is 50-70% CH_4, 50-30% CO_2
- Dry Heating Value - 500 to 700 BTU/CF

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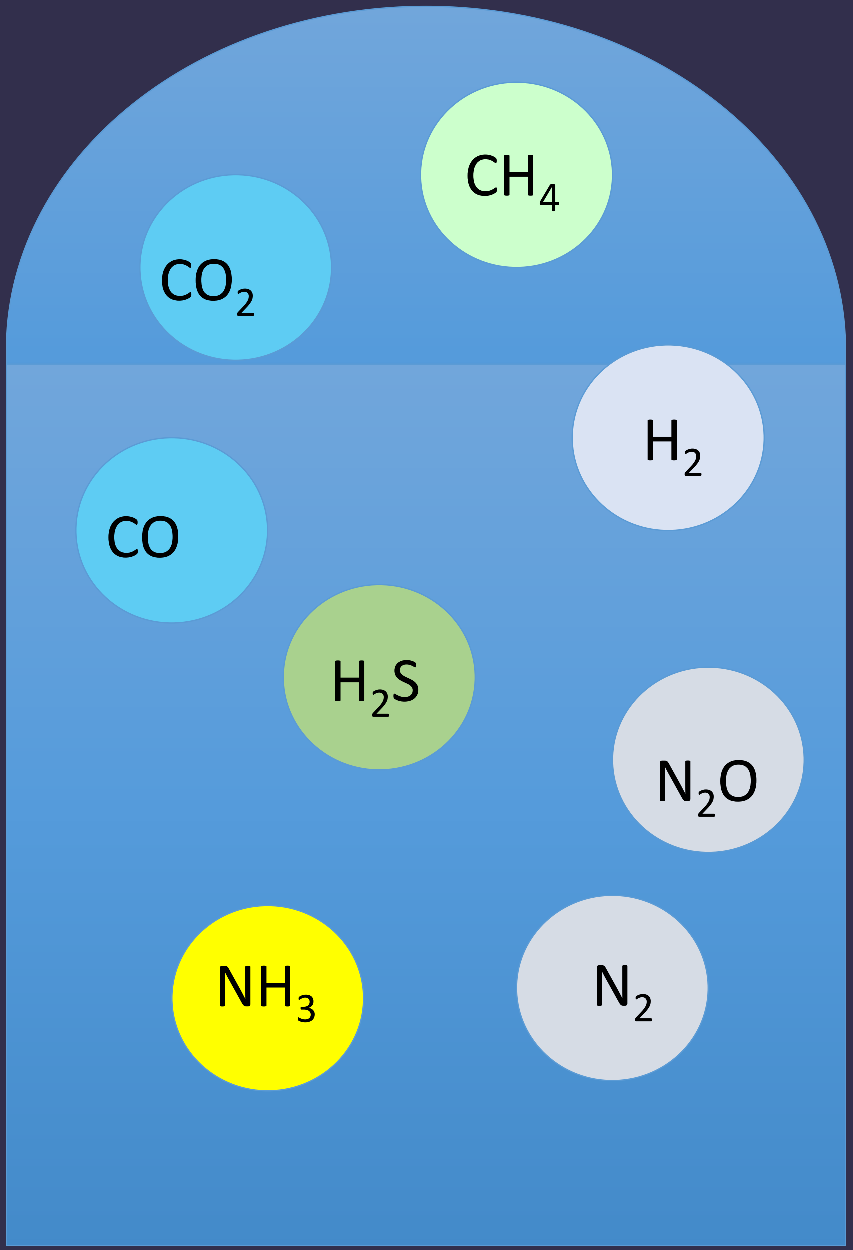
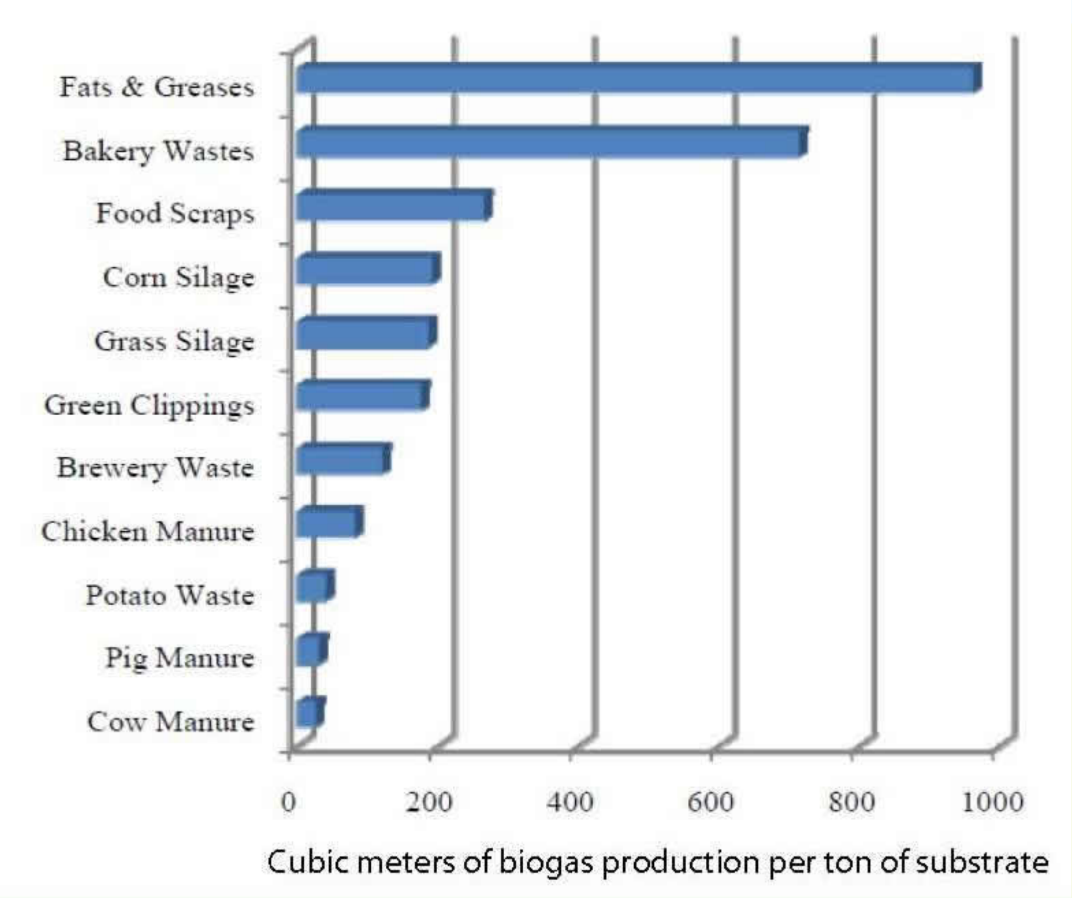

CH_4
CO_2
H_2
CO
H_2S
N_2O
NH_3
N_2

What wastes are BEST for making biogas?



35x manure
25x manure
10x manure

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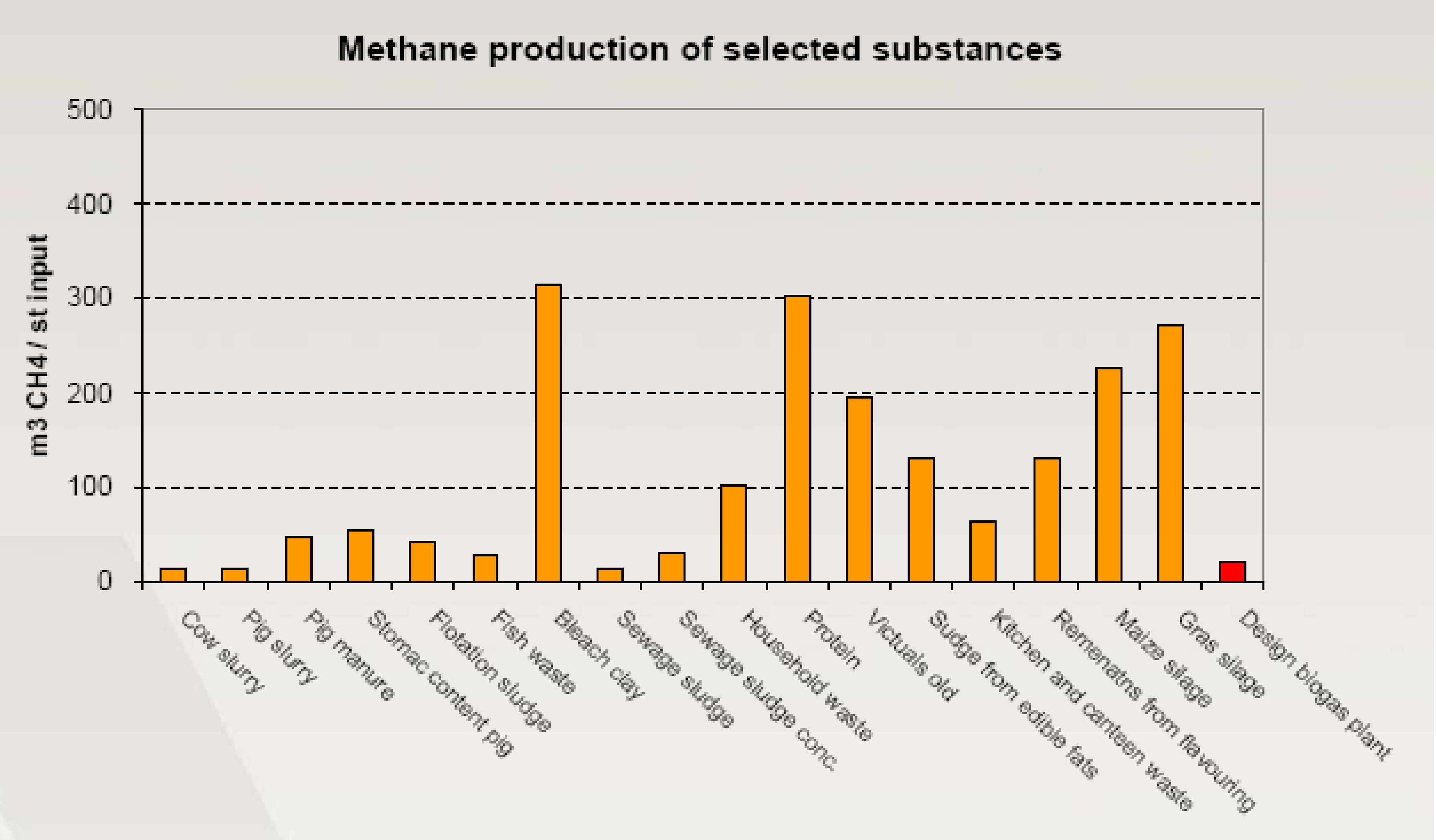
CH_4 Production Capacity



Typical BMP Graph

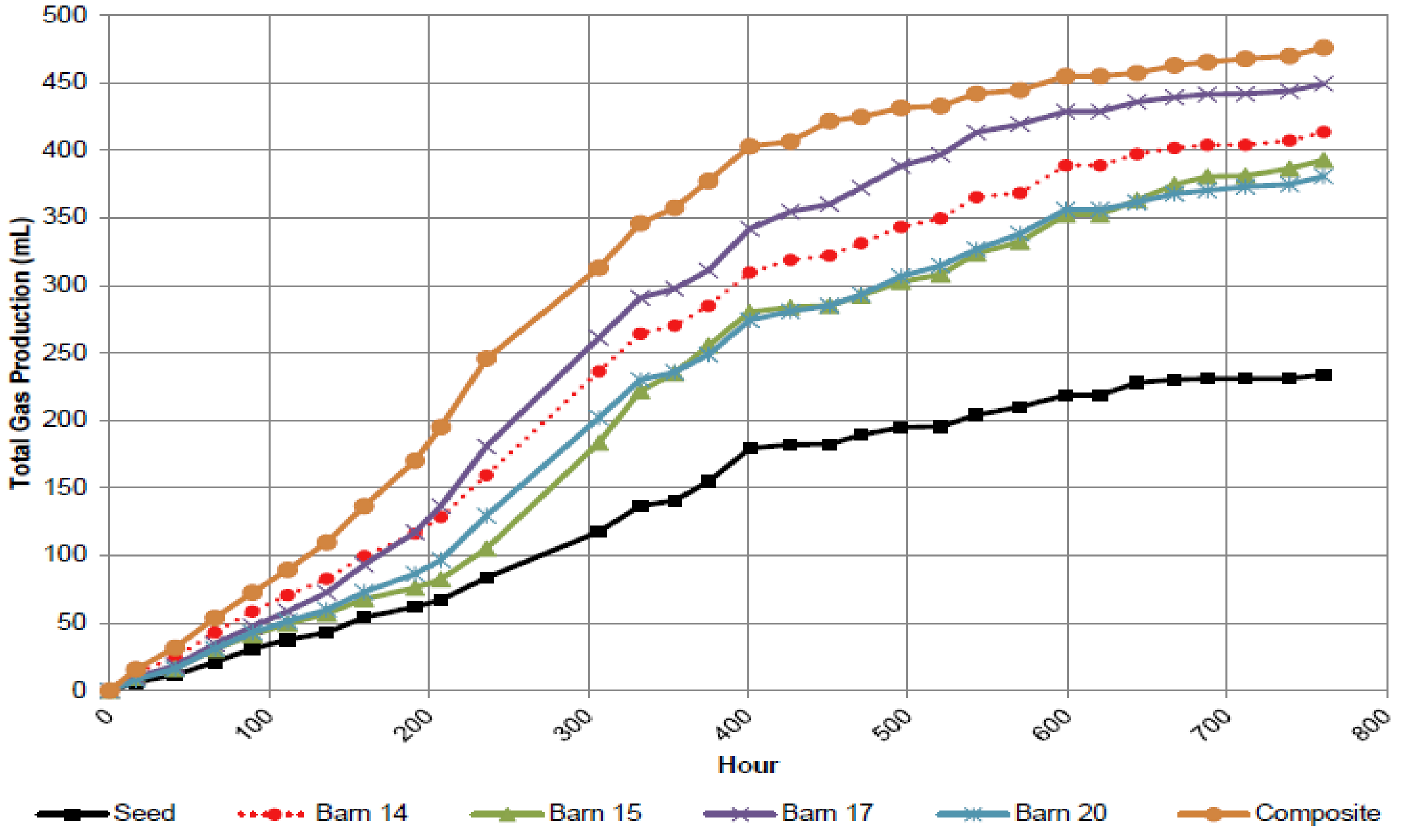


Figure 1. Cumulative Biogas Volume (Average of Triplicates)
*Gas volumes are corrected for change in temperature. Gas is counted at 22 C and corrected to STP (0 C, 1 atm).

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Biogas Analysis BMP Summary

Flask	Initial VS (mg/L)	Normalized VS (mg)	Total Gas Produced (mL) [2]	*Normalized Gas Produced (mL)	Average Methane (%)	Max Methane (%)	*Biogas / Initial VS (L/kg) [1]
Seed 1	5,040		226		49	57	
Seed 2	5,127		236		53	62	
Seed 3	6,152		241		55	66	
Barn 14 (1)	10,168	709	394	160	65	73	238±11
Barn 14 (2)	10,330	734	415	181	65	70	
Barn 14 (3)	10,885	817	431	197	65	70	
Barn 15 (1)	9,617	627	381	147	59	68	248±32
Barn 15 (2)	9,607	625	374	140	61	73	
Barn 15 (3)	9,873	665	423	189	61	68	
Barn 17 (1)	8,938	525	448	214	62	69	392±24
Barn 17 (2)	9,085	547	455	221	61	68	
Barn 17 (2)	9,307	580	446	212	62	70	
Barn 20 (1)	9,418	597	390	156	62	71	237±35
Barn 20 (2)	9,922	672	367	133	63	72	
Barn 20 (3)	9,462	603	386	152	61	72	
Composite (1)	9,560	618	460	226	65	70	398±28
Composite (2)	9,327	583	477	243	64	69	
Composite (3)	9,615	626	492	258	63	69	

± Standard Deviation
*Normalized to seed control samples
[1] Average/Standard deviation of triplicate samples
[2] Biogas is counted in a lab maintained @ 22°C. Biogas is corrected to STP (0°C, 1 atm) and assumed to be saturated.

AD Technologies

AD Technologies

1. **Covered Lagoon**
2. UASB (Upflow Blanket)
3. Fixed Growth (Fixed Film)
4. **CSTR (Total mix Tank)**
5. **Plug Flow**
6. **Dry (Hauls or Rooms)**

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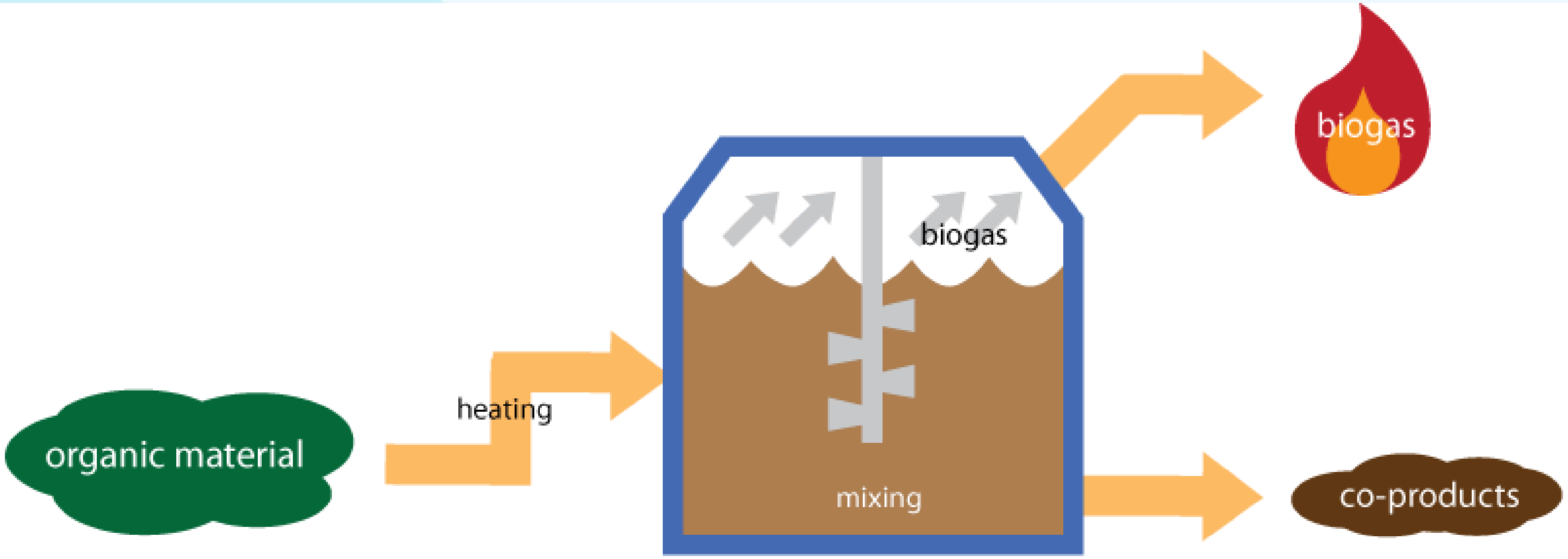
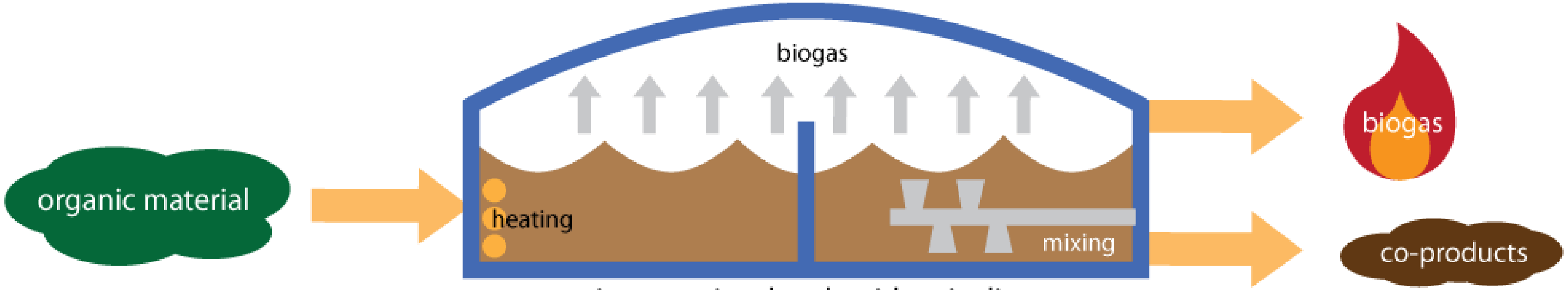
AD Technologies (wet)

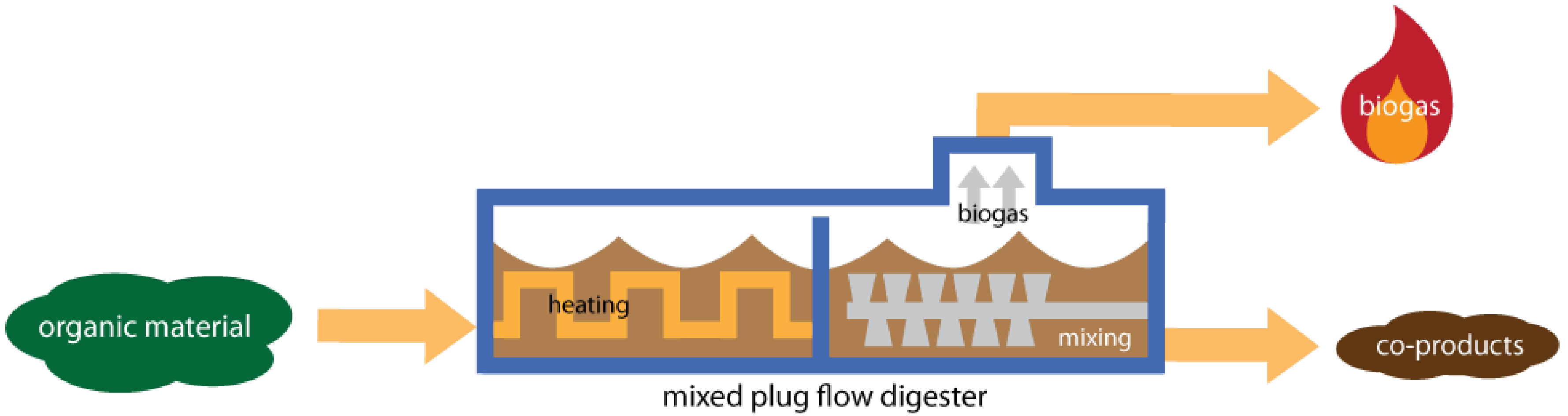


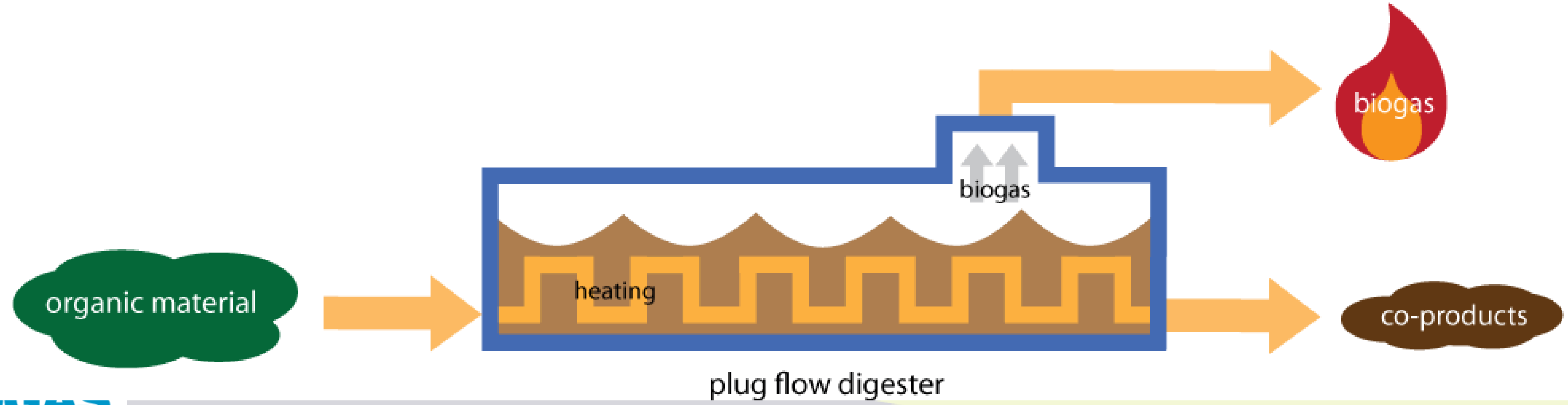
continuous stirred tank - top mixed digester



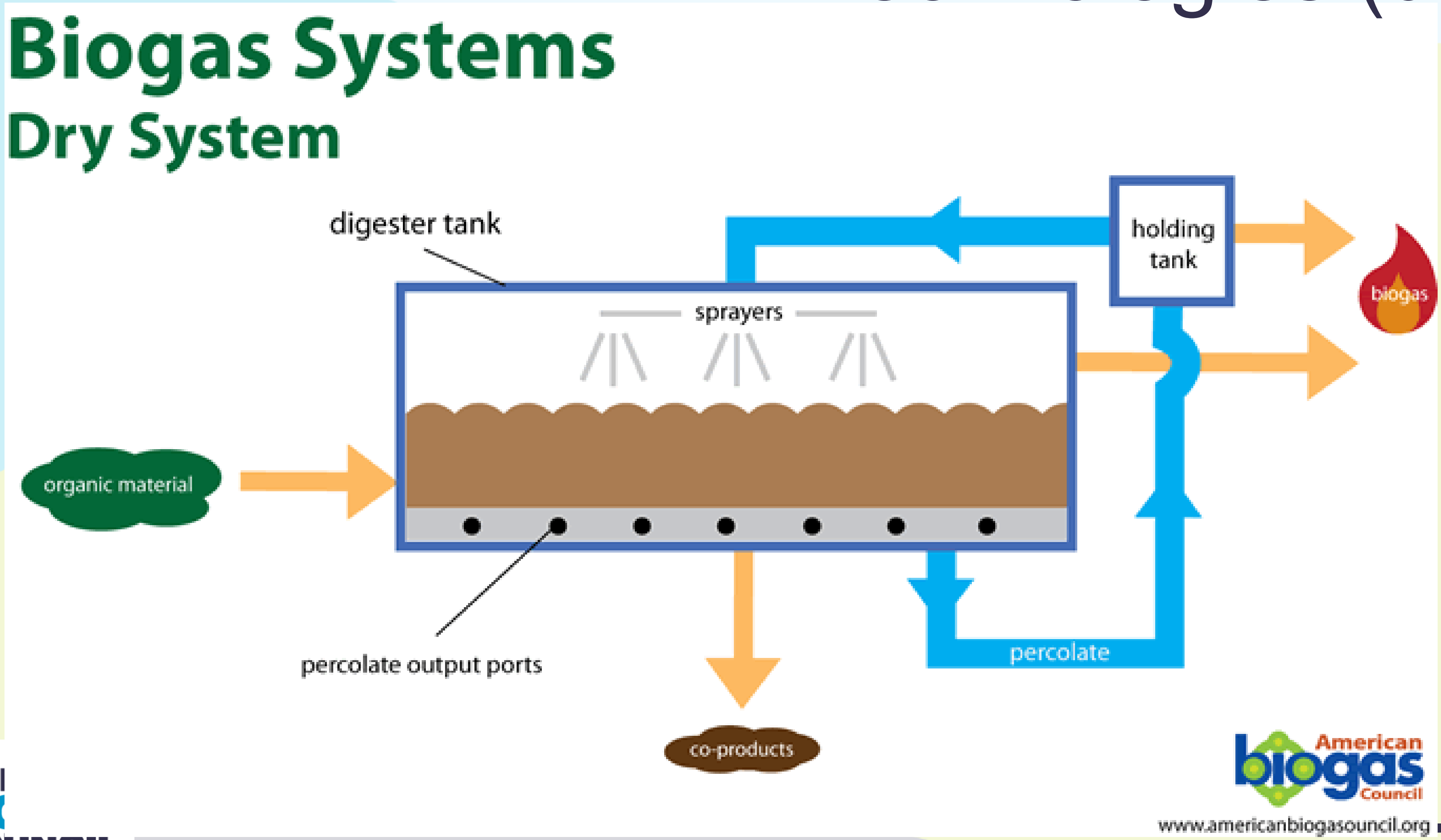
continuous stirred tank - side mix digester

AD Technologies (wet)



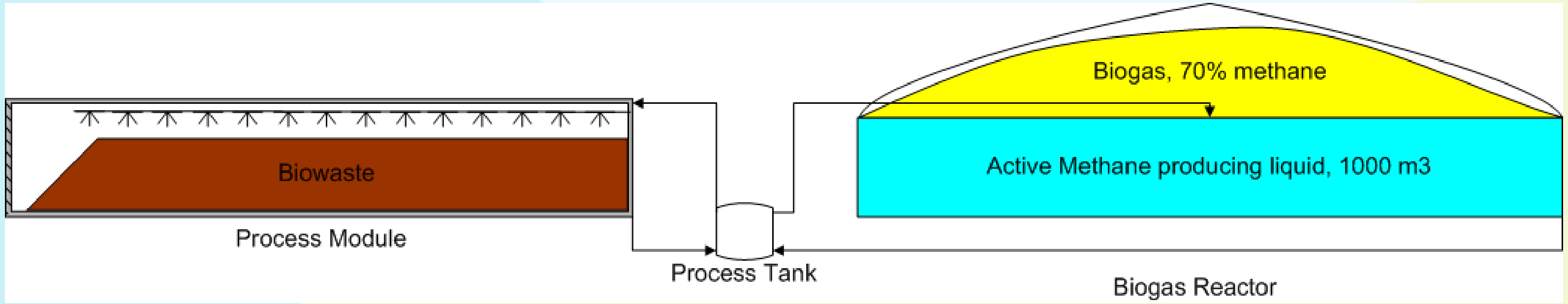


AD Technologies (dry)



Dry AD | Process

- 3-step integrated high solids anaerobic digestion and in-vessel compost technology



1. Process module is filled. Doors sealed. The biogas production process starts
2. Ceiling nozzles spray percolate (liquid) from a nearby tank into the biomass
   - Percolate, which contains methane producing microbes is continuously recirculated through the biomass and into the reactor tank for biogas generation
3. After the conclusion of the methane production period, the biomass (the "digestate") is composted within the same module
   - Digestate is never exposed to environment
   - Air is drawn into the modules creating ideal aerobic conditions
   - The digestate is converted into a high quality compost and soil amendment

Image used with permission from Turning Earth, LLC and Solum A/S

Material Management

Typical Influent

- **Dairy**

TS	8.6%
TSS	6.6%
TDS	2.1%
Organic N	3.9%
Inorganic N	11.9%
TN	0.5%
TP	0.1%
Ortho-P	1.6%
Suspended P	1.0%
TK	16.2%

- **Municipal**

TS	2.4%
TSS	2.4%
TDS	0.0%
Organic N	0.1%
Inorganic N	0.2%
TN	0.3%
TP	0.2%
Ortho-P	0.1%
Suspended P	0.1%
TK	0.0%

- **Industrial**

TS	10%
TSS	1.1%
TDS	1.1%
Organic N	0.0%
Inorganic N	0.0%
TN	0.1%
TP	0.1%
Ortho-P	0.0%
Suspended P	0.0%
TK	0.0%

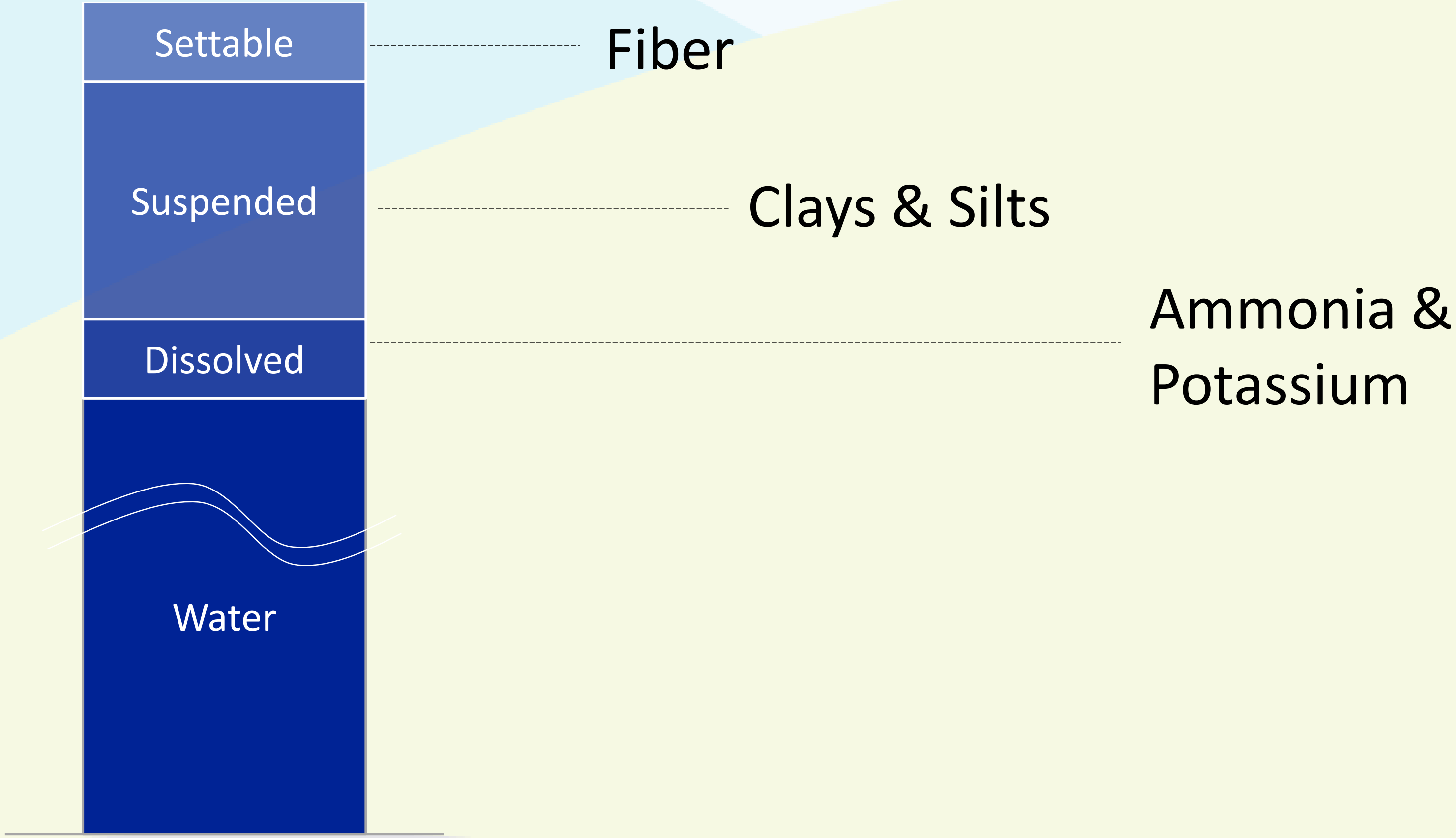
What is Missing or New?

TS
TSS
TDS
Organic N
Inorganic N
Ortho-P
Suspended P
TK

TS
TSS
NH_3
Inorganic N
$CaPO_4$
TK

Digestate Composition

Composition of Digestate



Settable Solids Separation

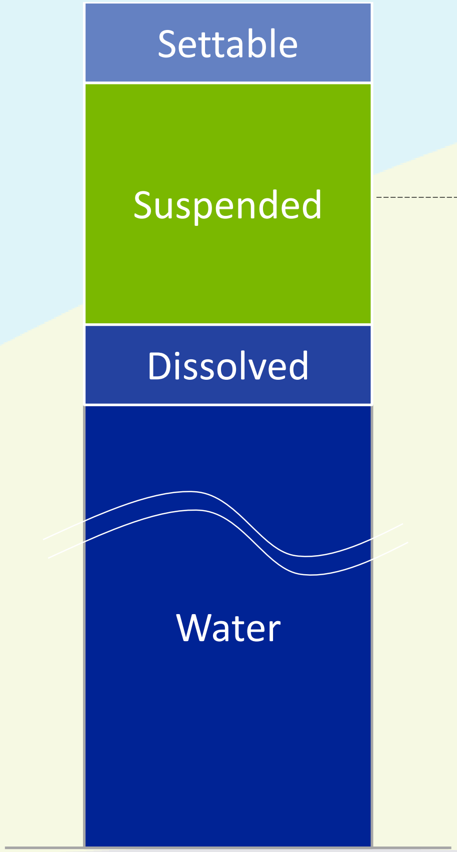
Composition of Digestate

Settable Solids

- Screen Press
- Static Screen
- Rotary Screens

Suspended Solids Separation

Composition of Digestate



Suspended Solids

- DAF
- Polymer Assisted
- Horizontal Decanters

Dissolved Solids Separation

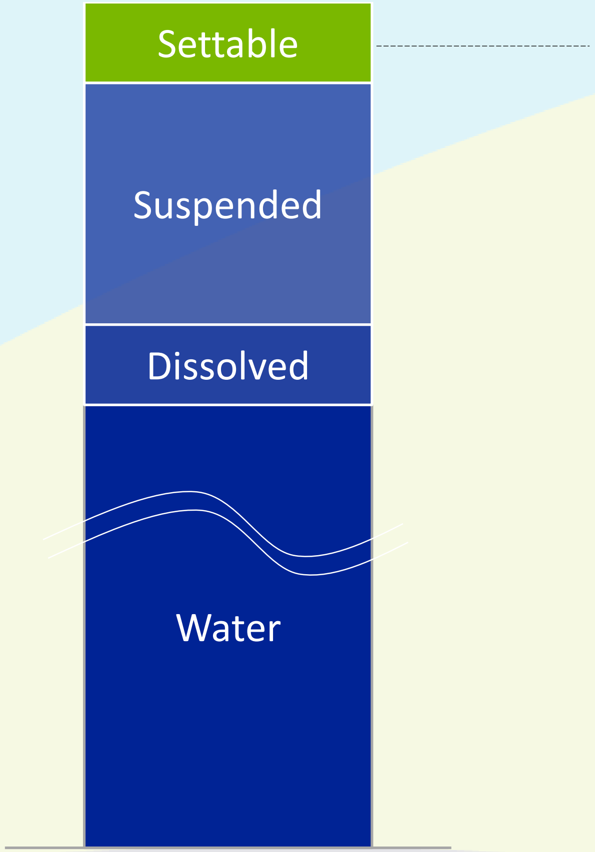
Composition of Digestate

Dissolved Solids

- Struvite
- Evaporator
- Reverse Osmosis
- Microfilter

Settable Solids Products

Composition of Digestate

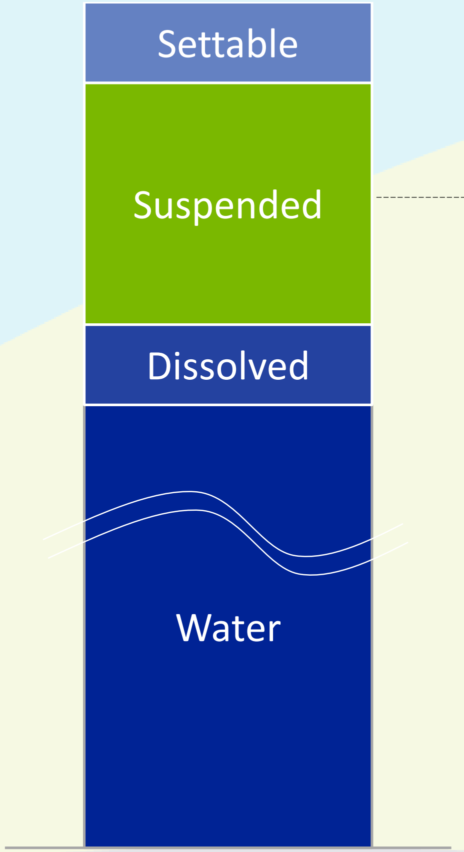


Settable Solids

- Compost
- Bedding
- Soil Amendment
- Other Things. …

Suspended Solids Products

Composition of Digestate

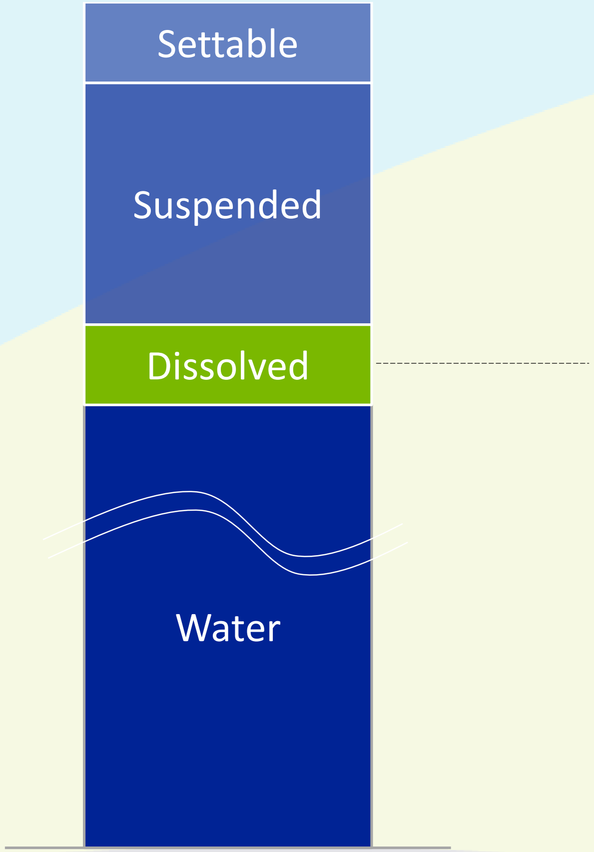


Suspended Solids

- Add to Compost
- Pelletize
- Drying

Dissolved Solids Products

Composition of Digestate



Dissolved Solids

- Ammonia Sulfite Crystals
- Recovered Potassium & Phosphorous

Operator Philosophy

The Conundrum

The anaerobic digestion system is designed to operate with little maintenance and minimal biological problems.

Conversely, digesters are complex living organisms that require knowledgeable, trained, and motivated operators if they are to operate successfully.

Ref: Dr. Dana Kirk, PE, PHD, ADREC and Michelle, Crook, PE MDA

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“Data” terms for AD operators

- **Total solids (TS)** – solid concentration of biomass
- **Volatile solids (VS)** – organic fraction of total solids
- **Fixed solids (FS)** – inorganic fraction of total solids
- **Alkalinity** – ability of a solution to neutralize acids
- **Volatile fatty acids (VFA)** – organic acids created during the fermentation process
- **Chemical oxygen demand (COD)** – measure of organic concentration of water
- **Hydraulic retention time (HRT)** – theoretical liquid storage duration
- **Solid retention time (SRT)**– theoretical solids holding period

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The key to good operation and control of a digester is …

- B A L A N C E!
  - The rate of acid formation and methane production must be approximately equal – otherwise, the reaction will be out of balance.
  - Never shock system; a change in any parameter more than 10% in one day. This is important for:
    - Maintaining the proper balance between the acid-forming and the methane-producing microorganisms requires maintaining definite ranges and ratios of solids loading, alkalinity, VFA's, temperature, pH and mixing.
    - When the methanogens fail to keep pace with the fermenting bacteria, the digester goes acidic and is referred to as being "sour".

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What factors are necessary for optimal digestion?

- Five factors affect digestion:
  - Microbial population
  - Availability and accessibility of food
  - Loading the digester
  - Microbial contact with food (mixing)
  - Environmental factors
- Each of these factors can be monitored and controlled by the operator.

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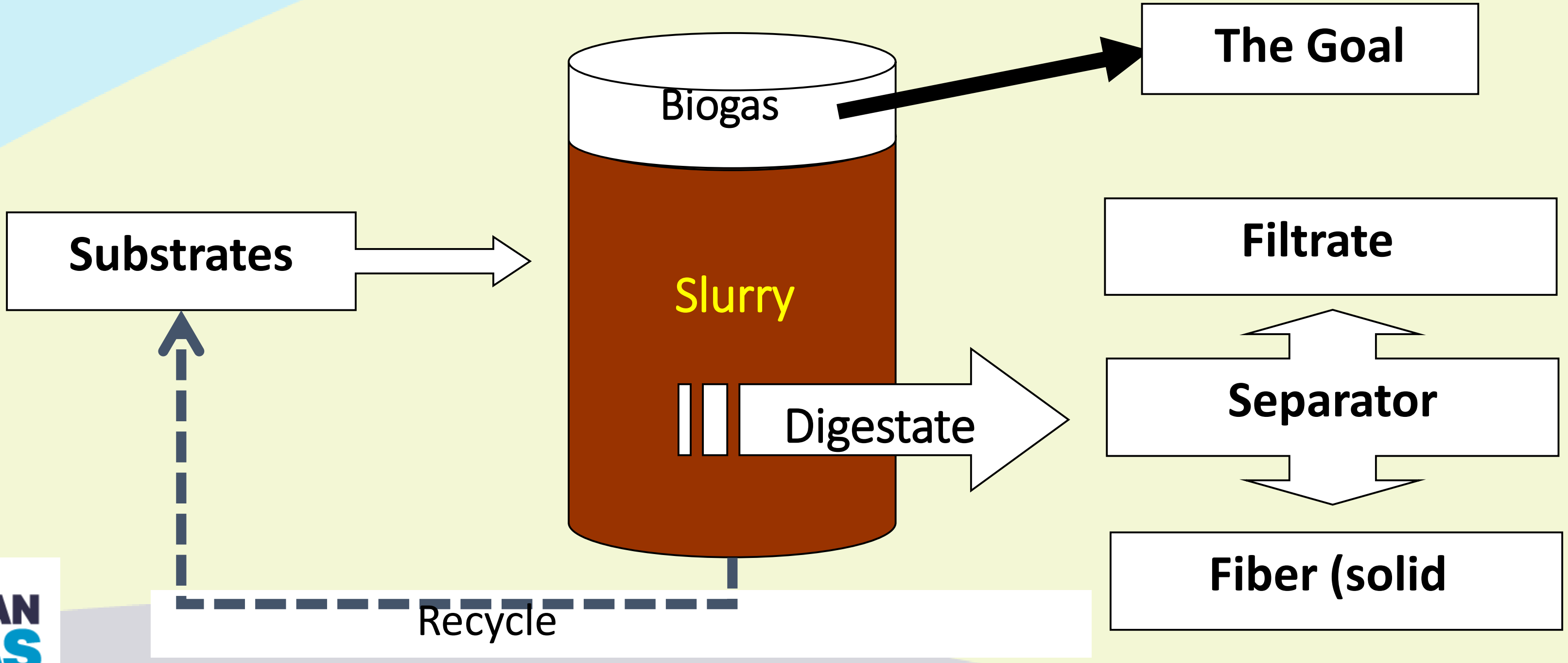
1st Factor – Microbial Population

- The key is to maintain adequate quantities of fermenting bacteria and methanogens.
- Feed <7% fresh material each day or recycle a portion of the liquid digestate (i.e. seed feedstock), "Friendly Bacteria with Knowledge"



2nd Factor – Microbial Food

$$Volatile\,Solids \xrightarrow{\text{fermenting bacteria}} Organic\,Acids + Hydrogen$$

- A list of organic acids are as follows:
  - **Volatile Acids:** Formic acid, n-Valeric acid, *Acetic acid*, Isovaleric acid, *Propionic acid*, Caproic acid, *n-Butyric acid*, Heptanoic acid, Isobutyric acid, Octanoic acid
  - **Non-Volatile Acids:** Lactic acid, Pyruvic acid, and Succinic acid
- Digesters should receive feedstocks high in volatile solids for maximum biogas production.
- Feedstocks vary in their potential to produce biogas.
- Fats, which are high in volatile solids, generate the greatest biogas while manures, by comparison, generate the lowest.

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3rd Factor – Digester Loading

- Loading the digester refers to the amount and type of feedstocks added to the digester. Feedstocks are introduced at such a rate as to maintain microorganism populations. Feeding must be monitored and controlled by the operator.
- The operator must consider the:
  - Energy concentration and chemical composition of in the incoming feedstocks.
  - Amount of volatile solids in the feedstock, which tells how much of the material can be used as food by the fermenting bacteria and indirectly the amount of grit (i.e. material that will not contribute to biogas production)
  - Ratio of volatile solids per unit to digester volume, which is used as a loading factor (i.e. **mass of VS per gallon of digester capacity**).
  - Hydraulic loading (hydraulic retention time) which is related to microbial growth and washout.
- Remember: the quantity and characteristics of the feedstocks will affect the efficiency of the digestion process.

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Factor #3 – Digester Loading

- Frequent, regular loadings (feedings) is recommended
  - Continuous
  - Intermittent
- AD loading can be based on volume or solids
  - Volumetric loading
    - Maintain design HRT
    - AD systems have fixed volume, feedstock volumes typically vary
    - Reducing HRT may impact biogas production and treatment
  - Solids loading (organic loading rate)
    - Typically based on VS, COD is an alternate
    - Relationship between mass of VS and the system volume
    - Normal range 0.03 to 0.30 lb VS/ft^3/d
- Avoid excess water whenever possible
  - Heating issues
  - Reduce retention time
  - Impact on alkalinity

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Factor #3 – Digester Loading

- Important digester loading data
  - System volume
  - Daily flow rate
  - TS, VS & COD
- Performance values (tracking)
  - Organic loading rate
  - HRT

4th Factor – Contact (Mixing)

- Stabilization cannot occur unless microorganisms are brought into contact with the food. The goals of mixing are to:
  - Expose the microorganisms to the maximum amount of food
  - Reduce the volume occupied by settled inorganic material, such as grit, and the floating organic material (scum blanket)
  - Prevent the formation of a floating crust layer which can slow the percolation of biogas out of the slurry

- The benefits of mixing are:
  - Speeding up the breakdown of the volatile solids
  - Increasing the amount of gas production

- Mixing is accomplished in two ways:
  - Gas evolution
    - As gas rises to the surface it effectively causes mixing
  - By mechanical means
    - Different mixing devices and mechanical impellers
    - The amount and frequency of mixing are controlled by the operator

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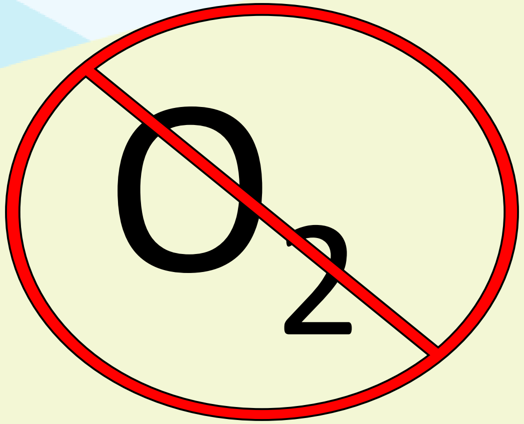
5th Factor – Environmental Factors

- Anaerobic conditions
- Temperature
  - Mesophilic
  - Thermophilic
- Digester robustness
  - Temperature swings
  - Chemicals
  - Added water



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5^{th} Factor – Environmental Factors

- Buffers
  - Process stability largely depends on a digester's ability to resist a change in pH
  - Buffering capacity is measured as alkalinity
  - When the pH suddenly starts to change, it means that:
    - The natural alkaline buffer in the digester has been reduced
    - Acids are being made faster than can be buffered
    - Methanogens cannot convert acids into methane fast enough

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5th Factor – Environmental Factors

- Buffers (cont.)
  - Volatile acids and alkalinity are measured to indicate the progress of digestion and to control the digester
    - Volatile acids (VFA) to total alkalinity (TA) ratio (VA:TA)
    - A ratio between 0.1 and 0.4 means that there is between 10 and 2.5 times more alkalinity than volatile acids (meaning the digester will be well buffered to keep the pH from changing)
    - For manure digesters, recent research seems to indicate the highest ratio is 2.0

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Monitoring Parameters & Acceptable Ranges

- TS – 1 to 20%
- VS – 0.03 to 0.30 lb VS/ft^3/d
- COD – 0.03 to 0.75 lb COD/ft^3/d
- pH – 6.4 to 8.2
- VFA – 50 to 300 mg/L as acetic
- Alkalinity – 3,000 to 5,000 mg/L as $CaCO_3$
- Ammonia – 1,500 to 3,000 mg/L

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Metcalf and Eddy, Inc. 1991. Wastewater Engineering: Treatment, Disposal and Reuse. 3rd Ed.

Acceptable Operational Conditions

Parameter	Value/Range of Values
SRT	10 to 15 days
pH	7.0 to 7.2
Alkalinity	1500 to 3000 mg/L as $CaCO_3$
Gas composition, % CH_4	65-70
Gas composition, % CO_2	30 to 35
Temperature, Mesophilic	30 to 35 ^{o}C
Temperature, Thermophilic	50 to 56 ^{o}C
Volatile acids-to-alkalinity	0.1 to 0.2
Volatile acids as Acetate	Optimum:50 to 500 mg/L Marginal: 500 to 2000 mg/L
ORP: Hydrogenotrophic	< - 175 mV
ORP: Acetotrophic	< - 300 mV

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In closing…

- Establish a monitoring program that fits the system management and provides sufficient information to operate the system
- Review data on regular intervals
- Graph and Trend Data
- Examine changing conditions
- Maintain data collection tools; you will need it at the most inopportune time
- Live the 10% Rule
- Put your self in the shoes of the bugs

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THANK YOU

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References and Acknowledgements

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