Green Technology and Sustainable Technologies
2 Credits
Anaerobic Digestion

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Outline

- **Introduction to Anaerobic Digestion Process**
- **Feedstock Source**
- **Reasons for utilisation of anaerobic processes for waste treatment**
- **Stages of the AD Process**
- **What factors are effecting for optimal digestion?**
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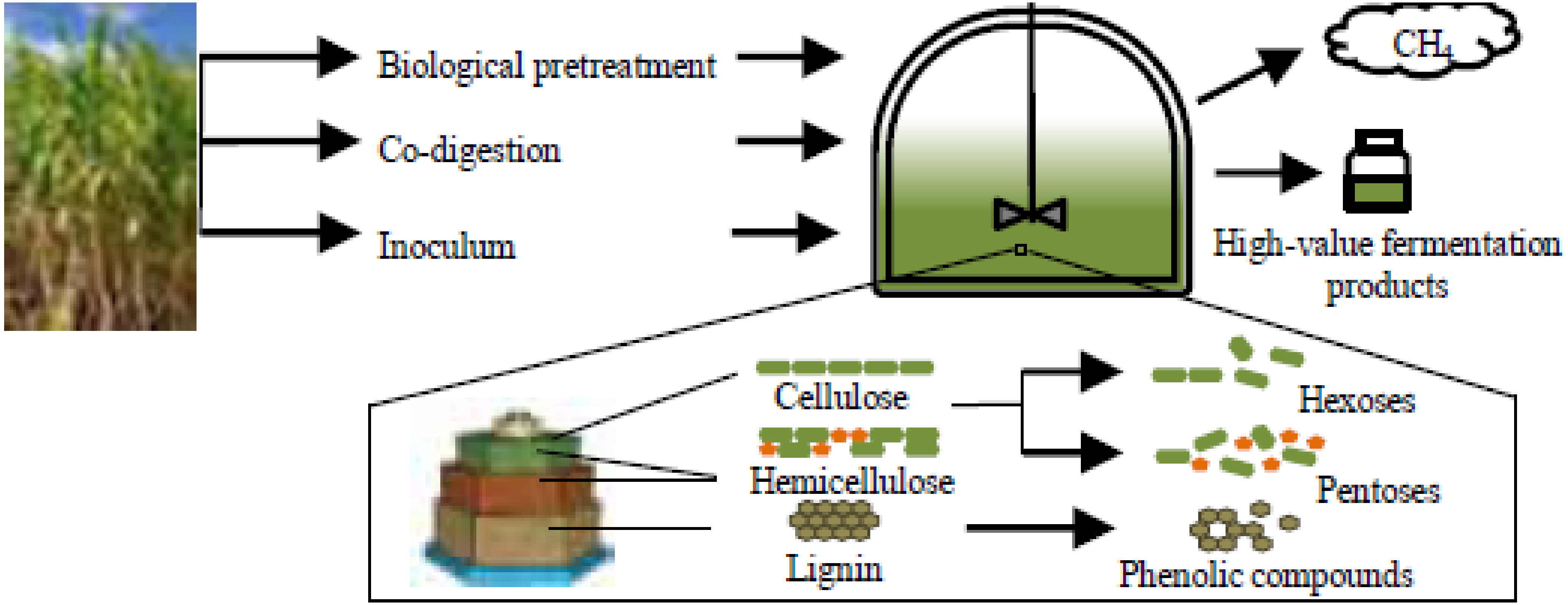
- **Outputs: Biogas and Digestate**
- **Benefits of anaerobic digestion**
- **Factors influencing AD applications**

Introduction to Anaerobic Digestion Process

- Anaerobic digestion occurs naturally wherever high concentrations of wet organic matter accumulate in the absence of dissolved oxygen.

  eg: decay of plant material in wetlands,

  the digestion of food by cattle
- **Anaerobic digestion (AD)** is the natural process that breaks down organic matter in the absence of oxygen to release a gas known as biogas, leaving an organic residue called digestate.
- In the anaerobic digestion process, micro-organisms convert complex organic matter to biogas, which consists of methane (CH_4) and carbon dioxide (CO_2) that can be collected and used as a fuel (biogas).
- Some organic matter remains even after the digestion step, and this is called digestate or digester residue or digested organic matter
- The stabilized solid residue, which averages 40 - 60% by weight of the feedstock, can be used as soil conditioner material.



Anaerobic digestion (Shrestha et al., 2017)

History of Anaerobic Digestion

- The use of wastewater and renewable resources for energy supply was known to the Sumerians, who practiced anaerobic cleansing of waste in 3000 BC.
- The first biogas production was done in the seventeenth century by Robert Boyle and Stephen Hale who identified and noted that flammable gasses released by disturbing the sediment of streams and lakes.
- And in 1808, Sir Humphry Davy determined that methane was present in the gasses produced by the cattle manure.
- First anaerobic digester was built by Leper Colony in Bombay, India in 1859.
- In 1868, Béchamp discovered that a mixed population of microorganisms is required to convert ethanol into methane (Deublein and Steinhauser, 2008).
- In the early 1990s, both commercial and pilot anaerobic digestion plants were designed and built, so that the anaerobic digestion of organic waste became known at world level (Karagiannidis and Perkoulidis, 2009).
- Nowadays thousands of biogas plants operate in Europe as well as in other parts of the world (Al Seadi *et al*., 2008).

- Closed reactors to control the anaerobic process and to collect all of the biogas fuel produced.
- The yield of biogas depends on the composition of the waste feedstock and the conditions within the reactor.
- For example, operating in certain temperature ranges can increase the rate of anaerobic digestion.
- The modern anaerobic digestion treatment processes are engineered to control the reaction conditions to optimize digestion rate and fuel production.

- Animal manure has been successfully used, as a feedstock for many years, however the organic fraction of MSW has a different composition and experience of anaerobic digestion of MSW alone, is more recent and less extensive.
- AD offers a more sustainable waste management option, recovering resources and diverting them from landfill disposal, and uses less space than landfills

Feedstock Source

Feed stocks are normally biodegradable wastes, but energy crops can also be used. Common sources include:

- ✓Municipal, commercial and industrial food wastes
- ✓Agricultural wastes (e.g., slurries, poultry litter and manure)
- ✓Wastewater and sludges from industrial waste treatment (e.g. Sewage sludge, Blackwater (Any waste from toilets or urinals)
- ✓Food/beverage processing waste(e.g. breweries, slaughter houses, dairy)
- ✓Energy crops (e.g., maize, grass and silage)

Mass balance

- Some organic materials such as lignin are resistant to the activities of both groups of bacteria. In an ideal process, the mass balance could be obtained by:

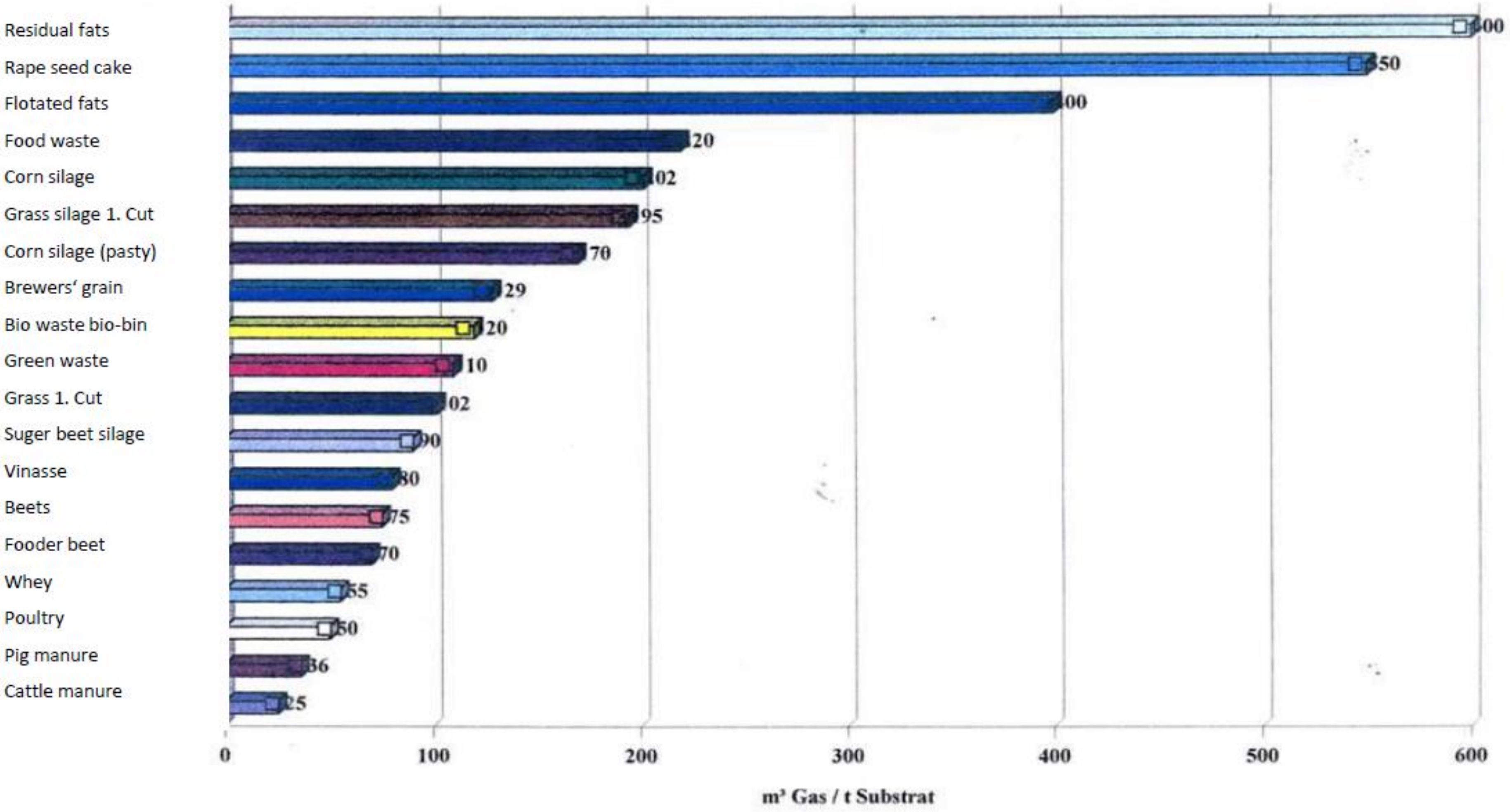
$C_a\,H_b\,O_c\,N_d$ ---------> $n\,C_w\,H_xO_yN_z + m\,CH_4 + s\,CO_2 + r\,H_2O + (d\text{-}nz)\,NH_3$

Where, $s = a - nw - m$ and $r = c - ny - 2s$

- The residual organic matter $C_w\,H_xO_yN_z$ is often similar in composition and characteristics to composted material.
- Adjustment of the high pH is required for use in agriculture.

Biogas yields of organic matters (Alwis, 2001)

Types of organic matter digested	Biogas yield (m^3/kg COD destroyed)	Methane in gas %
Carbohydrates	0.79	50
Proteins	0.96	53
Fat/Lipids	1.43	71
Acetic acid	0.75	50
Sewage sludge	0.85	70



Gas Yields of Different Feedstocks (Gould, 2011)

Typical Biogas Yields

Feedstock	Biogas Yield (m^3/tonne)
Mixed food waste	75 - 200
Cattle slurry	15 - 25
Pig slurry	15 - 25
Poultry litter	30 - 100
Grass silage	160 - 200
Maize silage	200 - 220
Maize grain	560
Crude glycerine	580 - 1000
Fats	up to 1200

Global Methane Initiative

Biogas producing rate of some feedstocks

Materials and their main components	Yield of Biogas m^3/kg TS	Methane content (%)
Animal barnyard manure	0.260 ~ 0.280	50 ~ 60
Pig manure	0.561	
Horse droppings	0.200 ~ 0.300	
Green grass	0.630	70
Flax straw	0.359	
Wheat straw	0.432	59
Leaves	0.210 ~ 0.294	58
Sludge	0.640	50
Brewery liquid waste	0.300 ~ 0.600	58
Carbohydrate	0.750	49
Liquid	1.440	72
Protein	0.980	50

- Feedstocks are converted to biogas and digested material, which reduces their volume. The volume reduction and gas production is dependent on the specific feedstock and process.
- Co-digestion can significantly increase biogas production and possibly volatile solids reduction depending on the type of organic feedstock added and other factors (Parry, 2014).
- Economic feasibility of co-digestion is strongly dependent upon
  - waste characteristics, regional energy costs, and biosolids residual management costs.
  - Most waste streams (perhaps with the exception of FOG) require a tipping fee paid to the digester owner to achieve economic feasibility.
  - Facilities considering co-digestion should consider utilizing existing process capacity prior to exploring construction of additional capacity for co-digestion (Parry, 2014).

- In most developing countries, biodegradable waste content is high.
- Moisture contents of these wastes are ideal for anaerobic digestion.
- MSW are heterogeneous and unsorted wastes consist of inert and toxic compounds that render inhibitory conditions for optimum anaerobic processes.
- So, source separation is essential

Co-digesting MSW with Other Wastes

- Simultaneous anaerobic digestion of multiple organic wastes in one digester
  - Can increase methane production
  - Common to co-digest agricultural waste with food waste and energy crops
  - Possible to co-digest wastes in water treatment plants
  - Feedstocks must be compatible

Feedstock Pre-treatment Requirements

- Anaerobic digestion systems may be enhanced by using pre-treatment of the feedstocks or by using different modifications or configurations of anaerobic digestion.
- Pretreatment methods include thermal, mechanical, chemical, biological, ultrasonic, and combinations of these methods.
- These pretreatments make the feedstock more accessible to anaerobic microorganisms.
- No single pretreatment technology is suitable for all anaerobic digestion systems and feedstocks.

Feedstock Pre-treatment Requirements

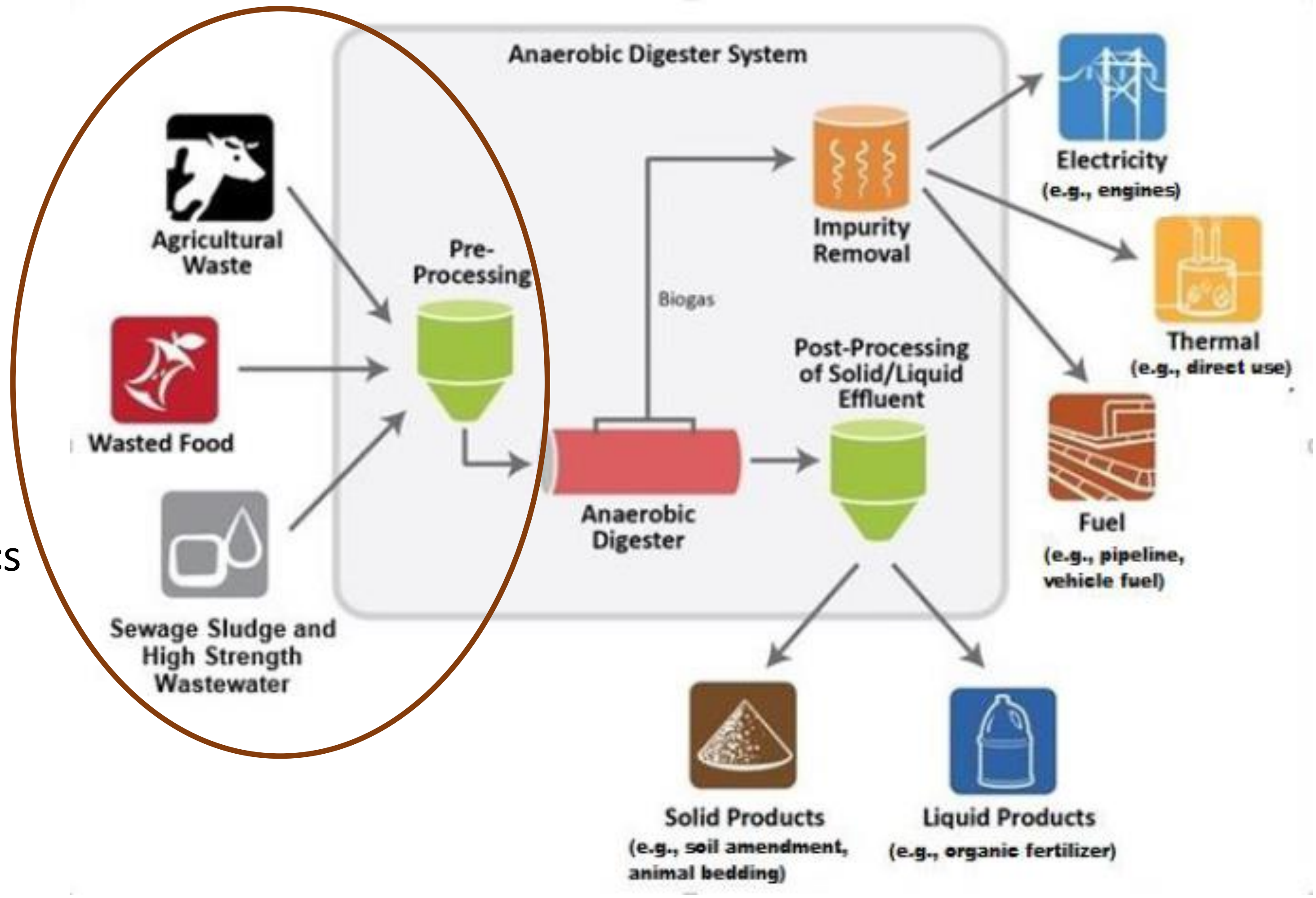
i. Separated food waste : De-packaging may be required depending on contamination levels.

ii. Manures / slurries: Minimal pre-treatment required, usually used with other feedstock.

iii. Commercial & industrial wastes: De-packaging is required to remove plastics and metals. Often highly contaminated so screening is also required.

iv. Effluents: require minimal pre-treatment.

v. Energy crops: Screening to remove stones, cutting or shredded. Silage is usually pre-shredded



Anaerobic System Components (Costa et al., 2015)

- An understanding of the basic principles will provide the basis to comprehend existing reactor configurations as well for developing new anaerobic reactors and supporting technologies for these countries.
- The anaerobic reactions are very slow and considerable research efforts have been made to increase the rate of reaction and gas productions.

Reasons for Utilisation of Anaerobic Processes for Waste Treatment

i. Higher loading rates that are possible than aerobic treatment,
ii. Useful end products such as digested sludge and /or combustible gases,
iii. Stabilisation of organic matter,
iv. Alteration of water-binding characteristics to permit rapid sludge deterring,
v. Solids reduction for easier handling, and
vi. Low microbial growth which will decrease the possible need for supplemental nutrients with nutritionally unbalanced wastes.

Stages of the AD Process

1. Hydrolysis

Breakdown of complex insoluble organic matter into simple sugars, fatty acids and amino acids

2. Acidogenesis

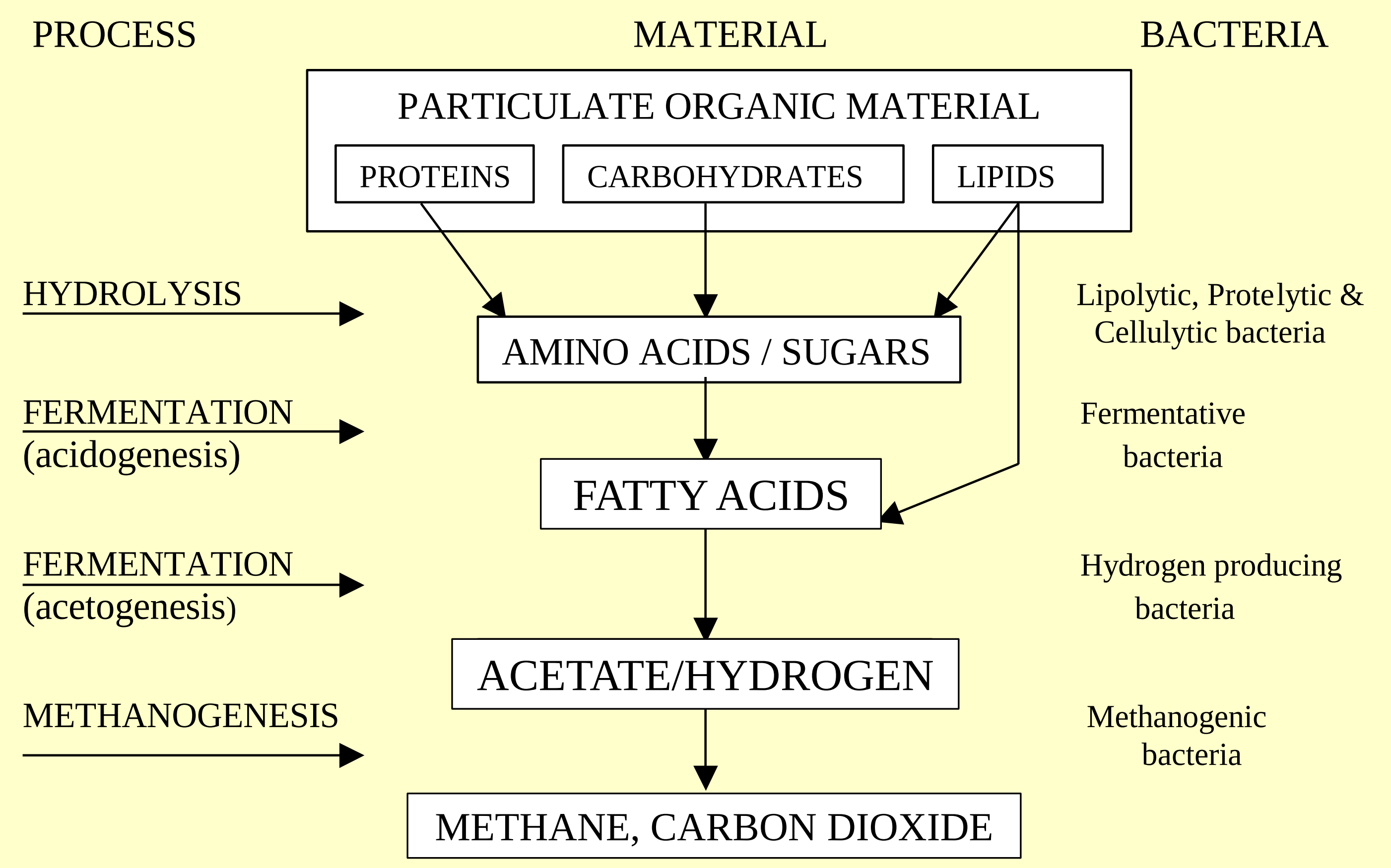
Further breakdown of simple sugars, fatty acids and amino acids into alcohols & volatile fatty acids (VFAs)

3. Acetogenesis

Conversion of VFAs and alcohols into acetic acid, CO_2 and hydrogen

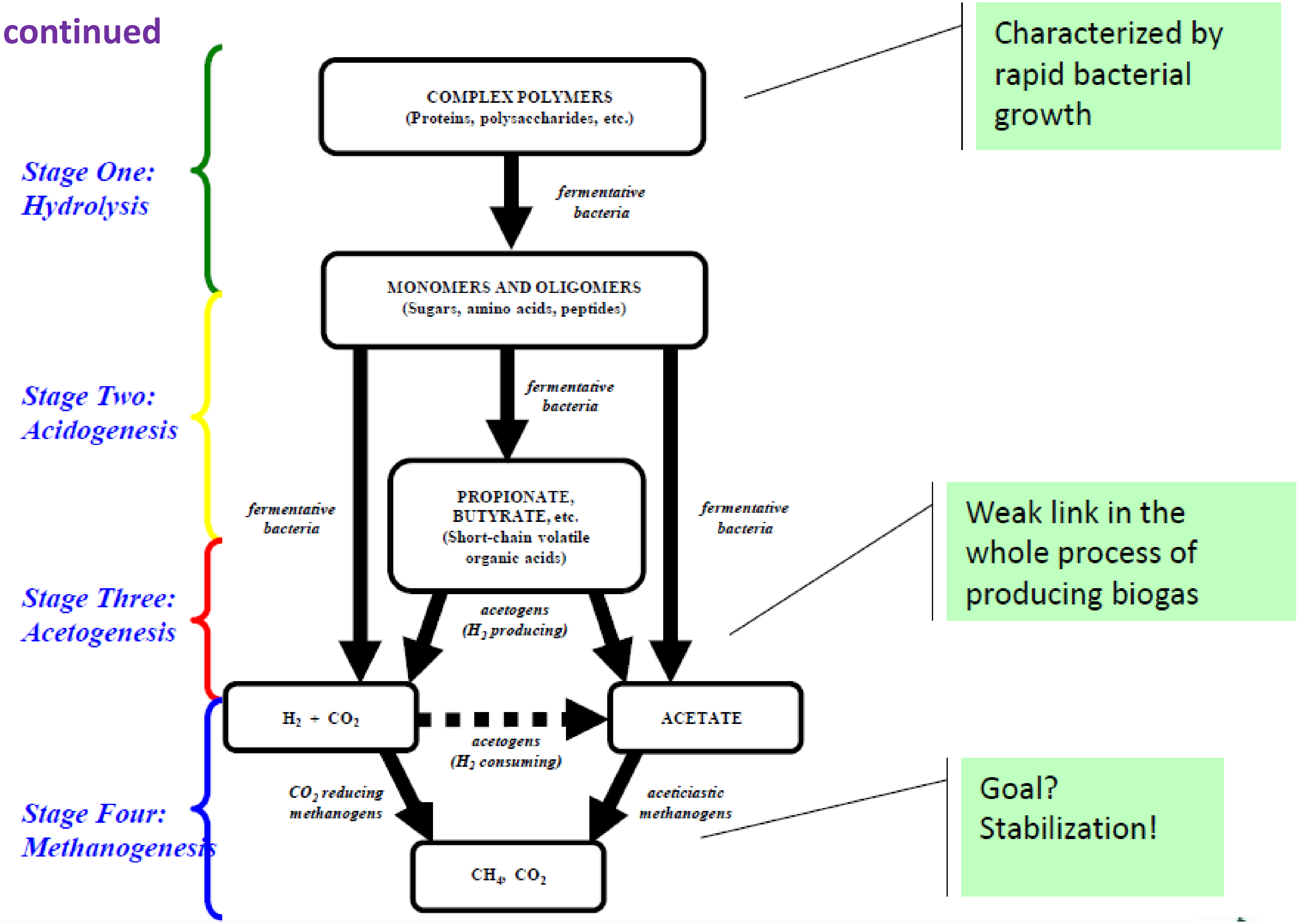
4. Methano-genesis

Finally, the acetic acid and hydrogen is converted into methane and carbon dioxide by methanogenic bacteria



Anaerobic fermentation of organic solids

Stages of the AD Process continued



Source: Syed Hashsham, PhD, lecture notes, Michigan State University (Gould, 2011)

Hydrolysis/Liquefaction

- Involves the breakdown of insoluble, complex organic matter into simple, soluble molecules.
- Cellulose is depolymerised into sugars, alcohols, peptides, amino acids and fatty acids with the help of an enzyme released by the bacteria.
- The first fermentative or hydrolytic groups of organisms are able to attack polymeric molecules though they appear as solid material.
- These microorganisms have elaborate hydrolytic enzymes, which hydrolyze polymeric substrates into low molecular weight material or even monomers.
- For example, proteins to amino acids, polysaccharides to oligo-and mono-saccharides, and lipids to free fatty acids.
- Though diverse substrate specificity exists, many of these bacteria have a wide substrate range and short generation time.

Cont. Hydrolysis/Liquefaction

- They, in competition with major fast growing fermentative bacteria, the other predominant ones, though unable to utilize polymeric material are able to take up smaller soluble molecules for their metabolisms and growth.
- As a result, short chain fatty acids (VFA), i.e., with two to five (or more) carbon atoms, are produced.
- The primary acids produced are acetic acids, followed by propionic and butyric acid, and small quantities of formic, valeric, isovaleric and caproic acids.

- Ammonia, sulphate, iso- acids and certain aromatic compounds are also produced from amino acids.
- As many organic acids are produced during this step, it is often called aciogenesis.
- The acidogenic population is by far the largest of the tropic groups of bacteria in anaerobic digestion.
- Another important aspect of hydrolytic fermentation is that many of these bacteria, in the presence of autotrophic methanogens and sulphate-reducing bacteria, produce hydrogen for the disposal of excess electrons generated during energy yielding oxidation of organic material (Figure 2).

- In some processes this initial step is catalyzed by the use of an acid or alkali.
- In some industrial processes a hydrolysis process is added at the beginning stage to substantially degrade the hydrocarbon content of the solid waste before it is added to the digester.
- This provides a higher methane yield and gives a shorter digestion time. It also reduces the thick fibrous scum that can form on top of the digesting mixture and generally makes it less viscous and easier to process. .

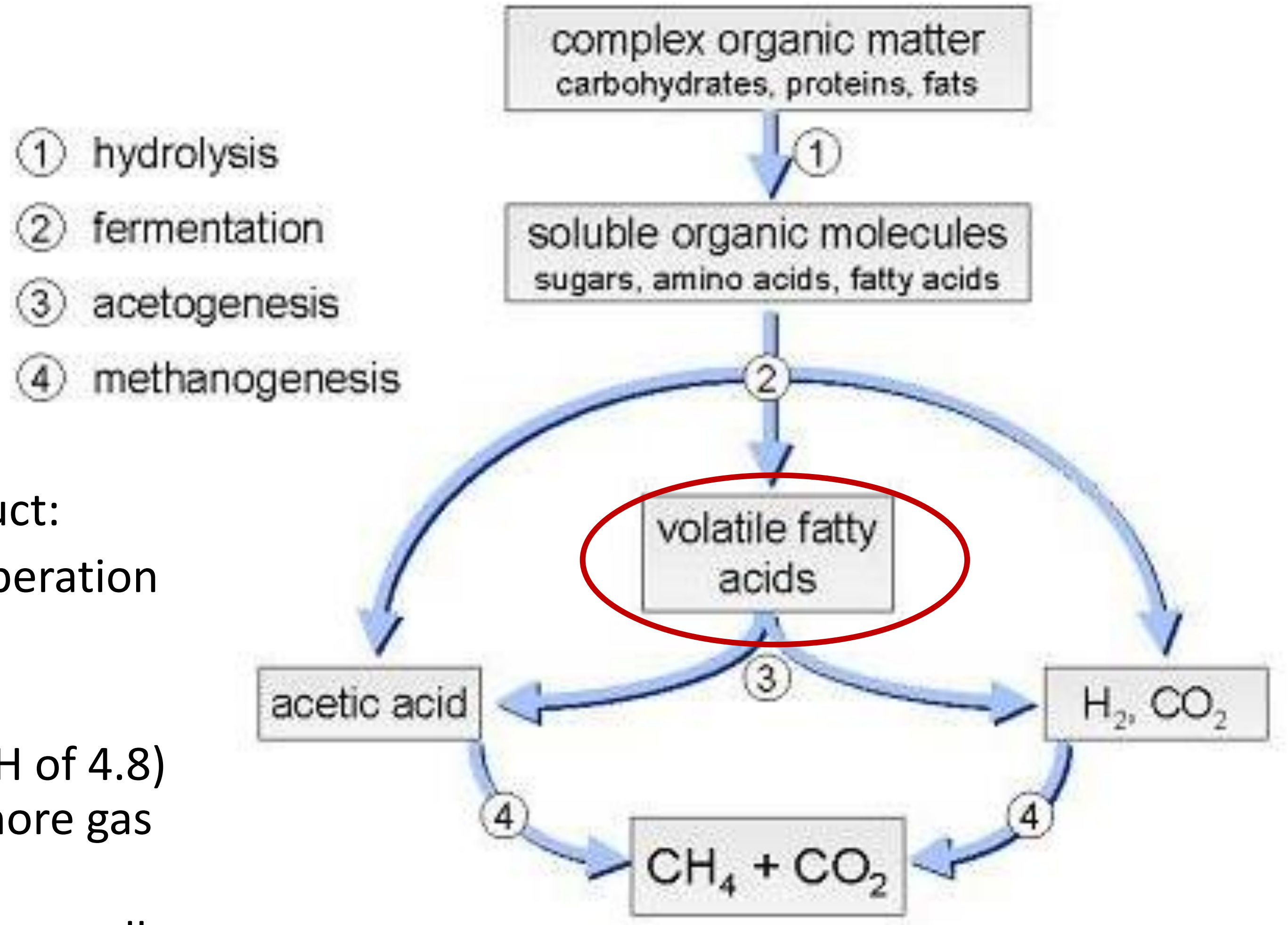
Acetogenesis/Fermentation

- Acetogenic bacteria obtain their energy from the oxidation of organic acids, alcohols and VFAs with more than two carbon atoms,
- for example, caproate, butyrate and propionate.
- Individual species of acetogenic bacteria are usually very specialized and ferment only a limited number of simple compounds to acetate, formate, bicarbonate and hydrogen.

Acetogenesis/Fermentation

- The chemical free energy change is positive for most of these acetogenic reactions under standard conditions.
- The acetogenic bacteria suffer from a thermodynamic product inhibiting by hydrogen.
- Hence, growth rate of the slowest growing trophic groups of anaerobic digestion is totally dependent upon the simultaneous removal of the reduced end products such as acetate and hydrogen.

Stages of the AD Process continued



Volatile fatty acids (VFAs) are an intermediate product:

- They should not accumulate under normal operation
- VFAs (e.g. acetic acid) accumulate if step 4 is inhibited
  - In that case, pH value will drop (e.g. to pH of 4.8) and the digestion process will stop (no more gas production)
  - This is also called a "sour" digester, and is usually very smelly (a well operating digester produces almost no odours)

The chemical reactions that occur during anaerobic digestion (Costa et al., 2015)

Buffer capacity

- If these volatile acids produced at a faster rate than they are utilised, adverse conditions would prevail as long as the buffer capacity of the system can neutralise the excess acids.
- The buffer capacity of the system can be expressed as the alkalinity of the system.
- With a fixed detention time, the alkalinity in an anaerobic unit will be in proportion to the organic loading to the unit.
- By noting the alkalinity in digesters, it is not difficult to understand why variations of acid concentration change due to intermittent loading.
- Anaerobic units which are lightly loaded not only may have inadequate alkalinity to buffer volatile acid variations, but they also will have a low population of methane bacteria to readily metabolise in any large increase in volatile acids.

- Acid forming bacteria thrive over a wide range of environmental conditions.
- Whereas, the methane bacteria are quite sensitive to some of the conditions.
- Therefore, the methane forming stage control the rate of reaction.
- Whenever, the growth rate of methane bacteria is inhibited by adverse environmental conditions, organic acids will accumulate to reduce the pH to a level where almost all bacterial activity comes to a halt.
- The growth of methane bacteria in sludge from domestic wastewater normally is inhibited at pH values less than 6.5 and by organic acid concentration above 2,000 mg/l.
- In other wastes, growth has been observed at organic acid concentration up to 10,000 mg/l.

Methanogenesis

- The acetic acid and hydrogen produced in step 2 are broken down by the acetoclastic methanogenic bacteria forming methane and hydrogen carbonate.
- Hydrogentrophic methanogenic bacteria then reduce the hydrogen carbonate to form methane. Many products, by-products and intermediate products are produced in the process of digestion before the final product of methane is produced.

Examples of some of the reactions that occur during the methanogensis:

- CH_3COOH --------------→ $CH_4 + CO_2$
  Acetic acid → Methane + Carbon Dioxide
- $2CH_3CH_2OH + CO_2$ --------------→ $CH_4 + 2CH_3COOH$
  Ethanol+ Carbon Dioxide → Methane + Acetic acid
- $CO_2 + 4H_2$ --------------→ $CH_4 + 2H_2O$
  Carbon Dioxide + Hydrogen → Methane + Water

Biogas Content

- The gas produced contains methane, carbon dioxide, some inert gases and sulfur compounds.
- Methane, carbon dioxide, and ammonia are the chief gaseous products of the process, amounting to 95-98%.
- The remaining volume consists of hydrogen sulphide and hydrogen.
- Typically 100-200 m^3 of gas is produced per tonne of organic MSW that is digested. Typical Biogas composition:
- Methane 55-70% by vol.
- Carbon dioxide 30-45% by vol.
- Hydrogen Sulphide 200-4000 ppm by vol.
- Energy Content 20-25 MJ/m^3

Biogas Composition

Compound	Range
Methane	50 – 75%
Carbon dioxide	25 – 50%
Nitrogen	0 – 10%
Hydrogen	1 – 5 %
Oxygen	0.1 – 2%
Water vapour	0 – 10 %
Hydrogen sulphide	10 – 30,000 ppm
Ammonia	0.01 – 2.5 mg/m^3

General features of biogas (Riuji, 2009)

Parameter	Value
Energy content	6.0-6.5kW/m^3
Fuel equivalent	0.60-0.65L oil/m^3 biogas
Explosion limits	6-12% biogas in air
Ignition Temperature	650-750 ^0C
Theoretical air demand	5.7m^3 air/m^3 burning gas
Critical pressure	75-89 bar
Critical temperature	-82.5^oC
Normal density	1.2 kg/m^3
Molar mass	16.043 g/mol

The Chemical composition of the biogas released from digester

Component	Household waste	Wastewater treatment plants sludge	Agricultural wastes	Waste of agri-food industry
CH_4 % Vol	50-60	60-75	60-75	68
CO_2 % Vol	38-34	33-19	33-19	26
N_2 % Vol	5-0	1-0	1-0	-
O_2 % Vol	1-0	<0.5	<0.5	
H_2O % Vol	6 (à 40 °C)	6 (à 40 °C)	6 (à 40 °C)	6 (à 40 °C)
Total % Vol	100	100	100	100
H_2S	100-900	1000-4000	3000-10000	400
NH_3	-	-	50-100	-
Aromatic	0-200	-	-	-
Organ chlorinated or organo-fluorated mg/m^3	100-800	-	-	-

Methane (CH_4)

- At room temperature and standard pressure,

  methane is a colorless,

  odorless gas
- Has a boiling point of −162°C at a pressure of one atmosphere
- Flammable only over a narrow range of concentrations (5–15%) in air
- Calorific value of 10 kWh/Nm^3 or 35,900 kJ/Nm^3
  - Hence, biogas with 65% methane has a calorific value 6.5 kWh/m^3 (23,300 kJ/m^3)

(Flammability or Inflammability is the ease with which a substance will ignite, causing fire or combustion. Materials that will ignite at temperatures commonly encountered are considered flammable)

Optimum operational range of the AD process(Khanal, 2008 and Deublein and Steinhauser (2011)

Parameters	Mixed-culture	Hydrolysis/acidogenesis	Methanogenesis
pH	6.8–7.4	5.2–6.3	6.7–7.5
Temperature (°C)	Mesophilic: 35 Thermophilic: 55	25–35	Mesophilic: 32–42 Thermophilic: 50–58
Solids retention time (SRT) (days)	High-rate: 15–30 Low-rate: 30–60		
Total VFAs (mg/L as acetic acid)	50–250		
Acetic acid (mg/L)	<1000		
Propionic acid (mg/L)	<250		
Oxidation reduction potential (ORP) (mV)	−200 to −350	+400 to −300	<−250
Alkalinity (ALK) (mg/L as $CaCO_3$)	1500–3000		
VFA/ALK ratio	0.1–0.2		
Carbon to nitrogen (C/N) ratio		10–45	20–30
Carbon to nitrogen to phosphorus (C:N:P) ratio	350:7:1	100:5:1	120:5:1
NH_4^+-N (mg/L)	50–1,000	⩽1,500	
H_2 (mg/L)	<100		

What factors are effecting for optimal digestion?

i. Microbial population
ii. Availability and accessibility of food (volatile solid content)
iii. Operation strategy (Loading the digester, operational stretegy)
iv. Microbial contact with food (mixing)
v. Environmental factors (temperature, pH)

Each of these factors can be monitored and controlled by the operator.

Micro-organisms in Anaerobic Digestion

- These three different types of microorganism's growth rate, pH, nutritional requirements differ from each other.
- The optimum pH of acidogenic bacteria is 5.2 to 6.5 and the specific growth rate is over two days.
- Some of the products of acidogenic bacteria namely acetate and hydrogen can be metabolized by mathanogenic bacteria.
- Mathanogenic bacteria cannot metabolize propionate and butyrate.

Micro-organisms in Anaerobic Digestion

- Therefore, propionate and butyrate are further degraded to acetate and hydrogen by acetogenic bacteria.
- Their growth rate is very slow, with a minimum doubling time of 3.6 days.
- The optimum pH of these microorganisms is 6 to 7.
- Methanogens are among the most fastidious of anaerobes.

Micro-organisms in Anaerobic Digestion

- They require vitamins, unusual trace elements as Co, Ni, and fatty acids as acetate or specific cofactors (coenzyme M), unique to methanogenic microorganisms.
- There are two methanogenic precursors.
- They are acetate and $H_2 – CO_2$.
- Approximately 70% of the digester methane come from acetate and other 30% come from carbon dioxide reduction to methane.

Micro-organisms in Anaerobic Digestion

- Methanogenic bacteria grow more slowly than acetogenic bacteria.
- Acid forming bacteria and methanogenic microorganism differ not only in terms of their nutritional and pH requirements, but also with respect to their physiology, growth and nutrient uptake kinetics and in their particular ability to withstand environmental changers.
- Anaerobic microorganisms are very sensitive to changers in their environment even small changers could cause the entire reactor that is methanogens die and acid producers synthesis acid and decrease pH.

- Changes in temperature also essential factor for microorganisms.
- Most anaerobic microorganisms function in the mesophilic (26-43^{0}C) and thermophilic (45-65^{0}C) temperature ranges.
- Therefore, digesters have to be heated and kept at constant temperature.
- Nutrient concentration and degree of mixing are a few of the many changers that affect normal operation of anaerobic bacteria.

- A constant supply of fresh influent ensures nutrient availability and good mixing makes the process more efficient overall by providing greater contact of microorganisms and sludge.
- Organic loading rate and hydraulic retention times also have great affect to the growth of microorganisms.
- High organic loading rate and short hydraulic retention time are more favorable to acid forming bacteria while it preclude the establishment of the acetogenic bacteria.

- When consider above factors acid forming bacteria and methane forming bacteria involve in anaerobic digestion process.
- But the problem is conditions that are favorable to the growth of acid forming bacteria may be inhibitory to methane forming bacteria.
- Therefore it is very important that their operating conditions may be selectively determined in order to maximize not only acid forming bacteria but also methane forming bacterial growth to achieve optimum digestion.

Solids Content

- Wet digestion <20% solids

  Add biosolids, recycled process water or some other liquid
- Dry Digestion > 20% solids

  Still may be adding some liquid

Organic loading rate

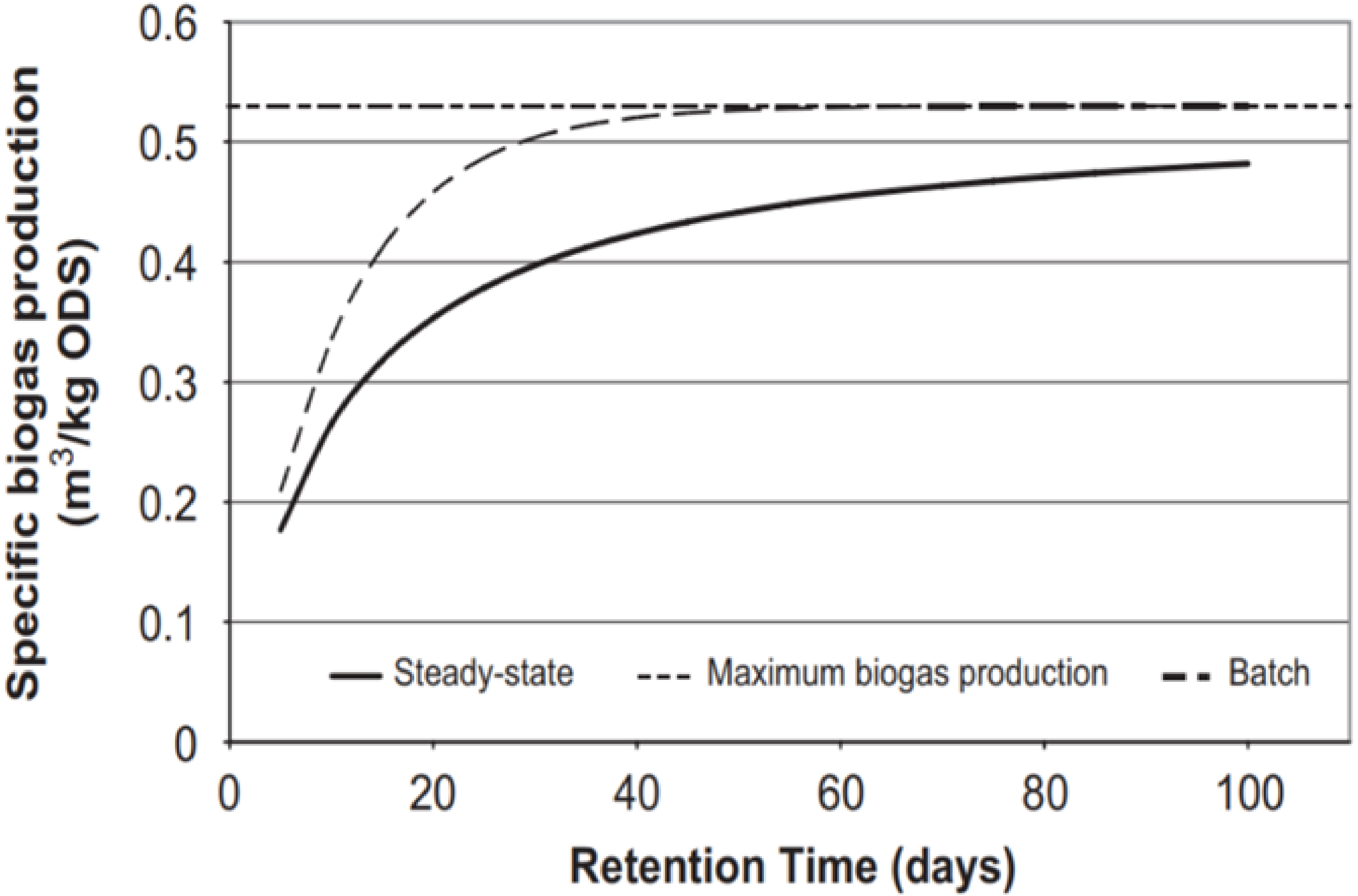
- Organic loading rate is the mass of organic matter loaded per day per for a given cross sectional area of the reactor.
- Feeding the system above its sustainable OLR results in low biogas yield due to accumulation of inhibiting substances such as fatty acids in the digester slurry.
- In such a case, the feeding rate to the system must be reduced. Many plants have reported system failures due to overloading.
- Vandevivere (1999) reports OLR is twice in high solids in comparison to low solids.

C/N Ratio

- Optimum C/N ratios in anaerobic digesters are 20–30.
- A high C/N ratio is an indication of rapid consumption of nitrogen by methanogens and results in lower gas production.
- A lower C/N ratio causes ammonia accumulation and pH values exceeding 8.5, which is toxic to methanogenic bacteria.
- Optimum C/N ratios of the digester materials can be achieved by mixing materials of high and low C/N ratios, such as organic solid waste mixed with sewage or animal manure.
- The recommended C: N: P ratio for the anaerobic digestion is 100:5:0.5.

Hydraulic Retention Time

- The required retention time for completion of the AD reactions varies with differing technologies, process temperature, and waste composition.
- The retention time for wastes treated in mesophilic digester range from 10 to 40 days.
- Lower retention times are required in digesters operated in the thermophilc range.
- A high solids reactor operating in the thermophilic range has a retention time of 14 days (Personal Communication with M. Lakos, May 2001).
- Specific biogas production with hydraulic retention time is illustrated in Figure 2.1 (Lise Appels, 2008).



Specific biogas production with hydraulic retention time (Lise Appels, 2008)

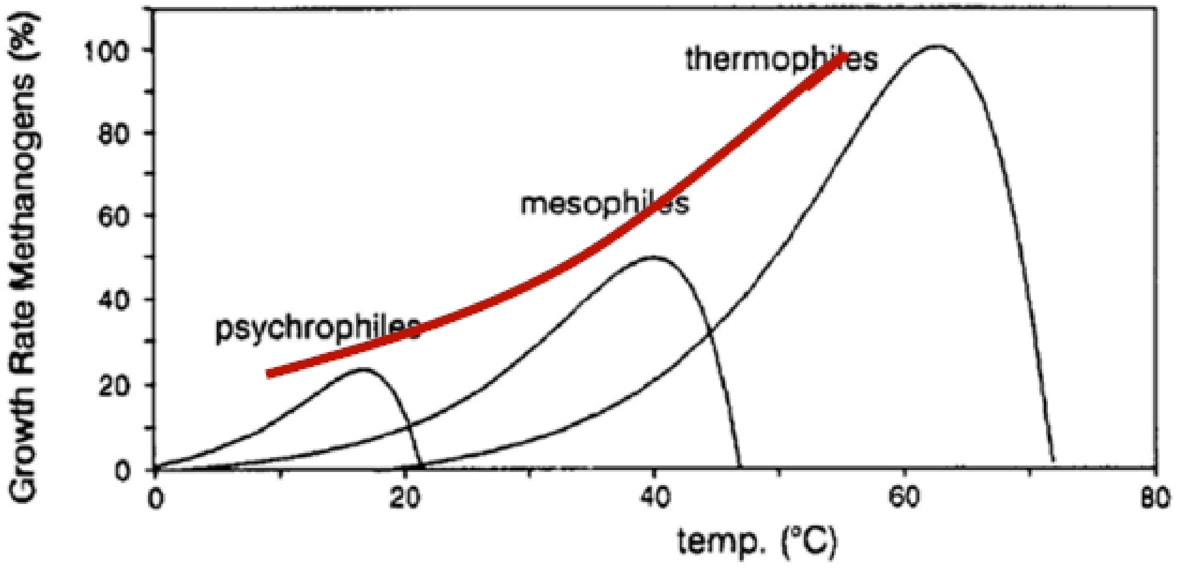
Dilution

- A key parameter in the successful operation is controlling the high performance of the reactor.
- Water or slurry can be added to dilute of the raw materials.
- Solid to liquid ratio changes with different systems.
- Average ratios are 10-25% but some systems may change this range up to 30% (Thiyanathan, 2010).

Mixing

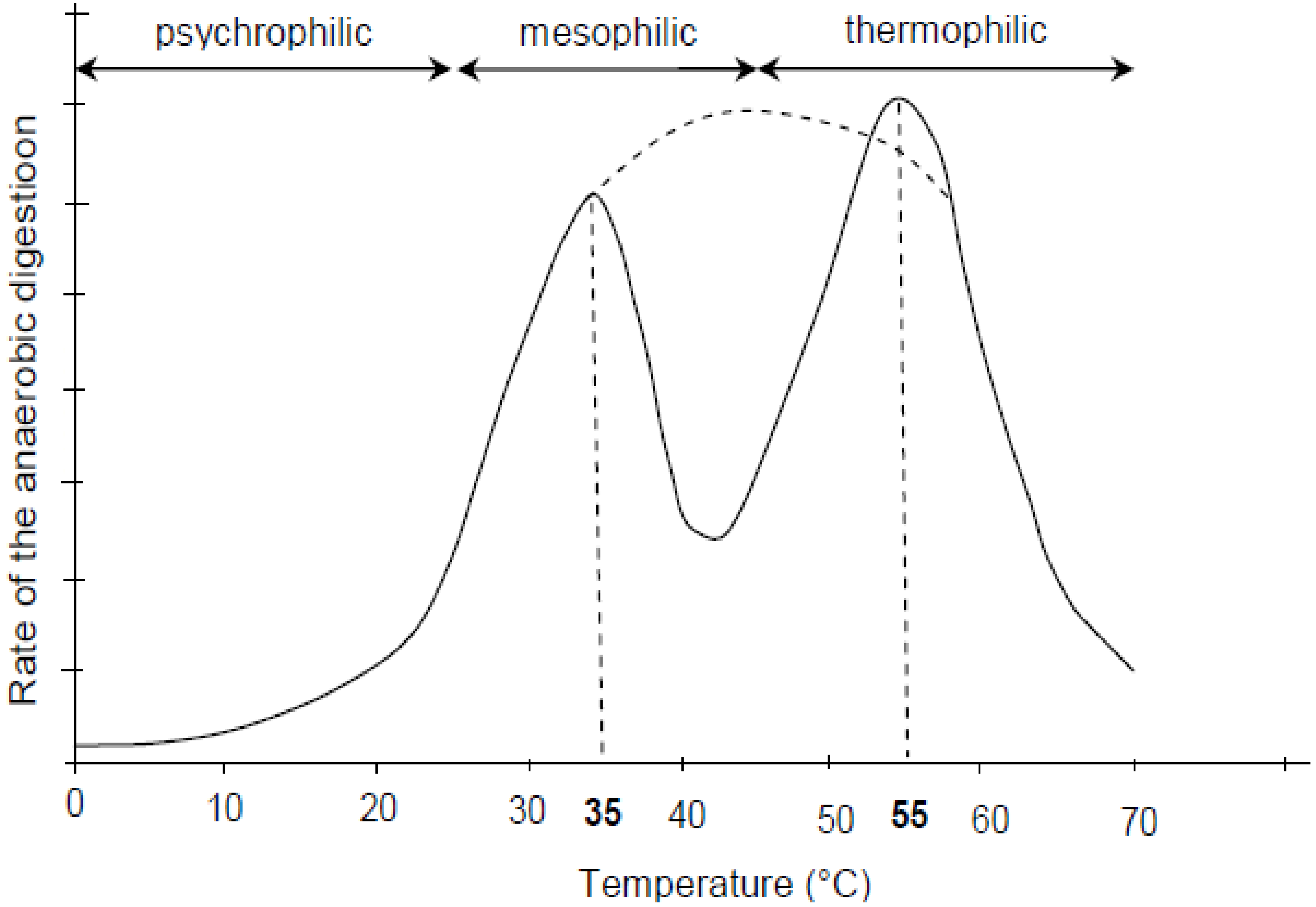
- The purpose of mixing in a digester is to blend the fresh material with digestate containing microbes.
- Furthermore, mixing prevents scum formation and avoids temperature gradients within the digester.
- However excessive mixing can disrupt the microbes so slow mixing is preferred.
- The kind of mixing equipment and amount of mixing varies with the type of reactor and the solids content in the digester.

Digestion process temperature



Variations of growth rate of methanogens with temperature

- ✓ Like all biological processes, anaerobic digestion is temperature dependent
- ✓ (higher conversion rates at higher temperatures) → digesters are typically heated / insulated or below ground)
- ✓ The anaerobic digestion processes occur at optimum manner in tropical countries due to high annual temperatures.
- ✓ Temperature stability during operation is very critical for optimum results, since different digestion stages have different optimum temperature ranges.
- ✓ For example, most of the acidogens grow and perform well under mesophilic temperatures, whereas the methanogens prefer higher temperatures (Adekunle & Okolie, 2015)



Influence of temperature on the rate of anaerobic digestion process (Damásio, 2009)

- Psychrophilic 5 - 25 ^{o}C (typically ambient temperature) used for low technology treatment without heating
- Mesophilic 30 - 45 ^{o}C (typically 30 – 37 ^{o}C)
  - ✓Used in many process applications for household waste, and commercial food wastes, and animal slurry with a high content of ammonia.
  - ✓Stable process
  - ✓Retention time 15-30 days
  - ✓Most popular option in developed countries

- Thermophilic 50 – 60 ^{o}C used for high yielding processes, often with more advanced process technology and where sanitation is required
  - Faster
  - Uses more energy (from the biogas)
  - Pathogen reduction
  - Suitable for a wider range of feedstocks
  - Retention time of 12-14 days
  - More complex & less stable
  - More expensive due to higher energy input requirement

- Different temperatures for each stage

TPAD = temperature-phased anaerobic digester

pH value

- Anaerobic bacteria, specially the methanogens, are sensitive to the acid concentration within the digester and their growth can be inhibited by acidic conditions.
- It has been determined (RISE-AT, 1998) that an optimum pH value for AD lies between 5.5 and 8.5.
- During digestion, the two processes of acidification and methanogenesis require different pH levels for optimal process control.
- The retention time of digestate affects the pH value and in a batch reactor acetogenesis occurs at a rapid pace.
- Acetogenesis can lead to accumulation of large amounts of organic acids resulting in pH below 5.
- Excessive generation of acid can inhibit methanogens, due to their sensitivity to acid conditions.
- Reduction in pH can be controlled by the addition of lime or recycled filtrate obtained during residue treatment.
- In fact, the use of recycled filtrate can even eliminate the lime requirement.
- As digestion reaches the methanogenesis stage, the concentration of ammonia increases and the pH value can increase to above 8.
- Once methane production is stabilized, the pH level stays between 7.2 and 8.2(Verma, 2002).

Nutrients and Trace metals

- All microbial processes including anaerobic process requires macro (N, P and S) and micro (trace metals) nutrients in sufficient concentration to support biomass synthesis.
- In addition to N and P, anaerobic microorganisms especially methanogens have specific requirements of trace metals such as Ni, Co, Fe, Mo, Se etc.
- The nutrients and trace metals requirements for anaerobic process are much lower as only 4 - 10% of the COD removed is converted biomass.

Toxicity

- Heavy metals, mineral ions, and detergents are some of toxic compounds that inhibit the anaerobic microorganism’s growth in the digester.
- Also, some of minerals act as the stimulant to the bacteria growth such as, small quantity of sodium, potassium, calcium, magnesium, ammonium, and Sulphur.
- But those minerals can be toxic when the concentration is high. Heavy metals are very important for microorganism growth.
- The amount of heavy metal content is determined by the reaction of the microorganisms such as high concentration of heavy metals act as the toxic compounds also low concentration of heavy metal essential for microorganism’s growth.

Essential conditions for efficient anaerobic treatment

- Avoid excessive air/O_2 exposure
- No toxic/inhibitory compounds present in the influent
- Maintain pH between 6.8 –7.2
- Sufficient alkalinity present
- Low volatile fatty acids (VFAs)
- Temperature around mesophilic range (30-38 ^{o}C)
- SRT/HRT >>1 (use high rate anaerobic reactors)

- Anaerobic digestion (AD) is a mature technology that relies upon a synergistic effort of a diverse group of microbial communities for metabolizing diverse organic substrates.
- AD is highly sensitive to process disturbances, and thus it is advantageous to use online monitoring and process control techniques to efficiently operate AD process.
- A range of electrochemical, chromatographic and spectroscopic devices can be deployed for on-line monitoring and control of the AD process.
- While complexity of the control strategy ranges from a feedback control to advanced control systems, there are some debates on implementation of advanced instrumentations or advanced control strategies.
- Centralized AD plants could be the answer for the applications of progressive automatic control field.

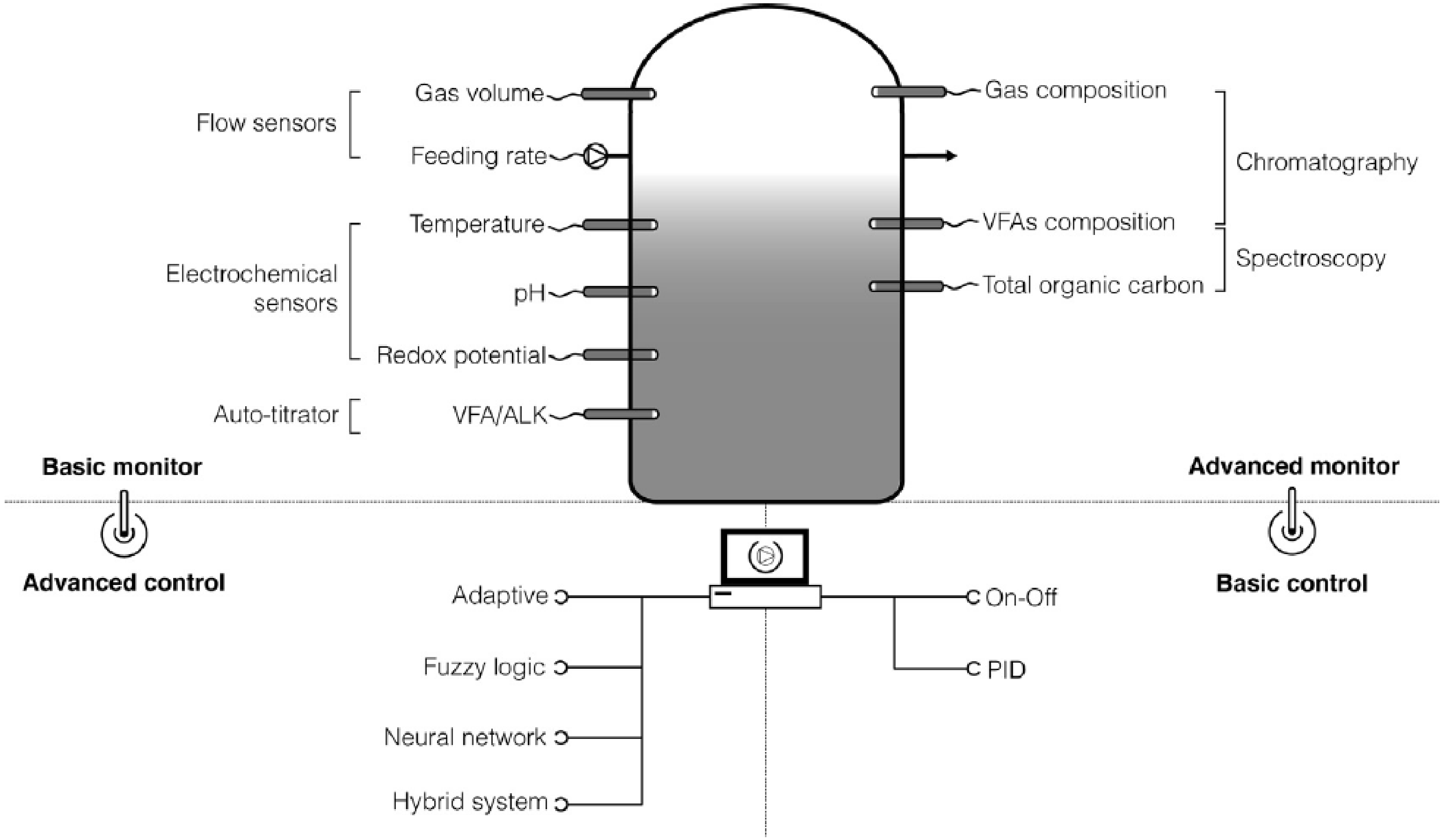
Process Monitoring (vital)

What should you monitor?

- ✓pH
- ✓Carbon : Nitrogen
- ✓Methane (CH_4)
- ✓Volatile Fatty Acids
- ✓Alkalinity
- ✓Ammonia concentration
- ✓Trace elements
- ✓Retention time

Measuring techniques of parameters in anaerobic digestion
(Nguyen et al., 2015)

Parameters	Techniques					
	Physical sensors	Electrochemical sensors	Gas chromatography	Liquid chromatography	Spectroscopy	Titration
pH		+				+
Alkalinity	+	+			+	+
Total VFAs			+	+	+	+
Individual VFAs			+	+	+	
Biogas volume	+					
Biogas composition		+	+	+	+	
NH_4^+–N		+	+	+	+	+
Chemical oxygen demand (COD)					+	+
Total organic content (TOC)				+	+	+
H_2S		+	+	+	+	+
H_2		+	+			



Monitoring techniques and control strategies in the AD system
(Nguyen et al., 2015)

Automatic AD process control system

- Automatic AD process control system enables quick process stabilization with less operation and maintenance inconveniences.
- The ultimate objective of automatic control is to allow AD processes stably operate at their maximum capacity. The system consists of two constituents, monitoring and control.
- First, the process parameters that are sensitive to process disturbances, such as pH, biogas/methane production rate, ammonia, VFAs composition, and total VFAs to alkalinity (VFA/ALK) ratio are closely monitored.
- Next, the monitoring data is sent to control system to regulate/control these parameters around desired ranges.
- Diverse process control systems have been studied and tested in AD systems.
- The control strategy could be as simple as a feedback on/off control, or as complicated as adaptive, fuzzy logic, neural network control, or their combinations (Pind et al., 2003b; Batstone et al., 2004; Drosg, 2013).
- Advanced control system could be equipped with basic monitoring techniques; on the other hand, simple control strategies could be compensated by advanced monitoring equipment (Nguyen et al., 2015)