Introduction to Anaerobic Digestion

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Applicability

- Natural Examples
  - Flooded soils (e.g., marshes)
  - Rumen
  - Termite gut
- Waste Treatment
  - Anaerobic digestion of sewage sludge (common, long experience)
  - Septic tanks
  - Sanitary landfills (including reactor landfills)
  - Industrial wastewater treatment (limited to date)
  - Solid waste (limited to date in USA)
- Basic processes same (specific factors and results may differ)

Definitions of Terms

- Aerobic, Oxic - Oxygen (O_2) present
- Anaerobic, Anoxic - O_2 absent
  - In environmental field, sometimes distinguish:
    - anoxic - nitrate (NO_3^-) present
    - anaerobic - nitrate absent

Need for Energy

- Organisms need energy (as well as nutrients)
- Much of life is a struggle for energy
  - light (phototrophs)
  - chemical energy (chemotrophs) - stored in bonds
- Chemotrophs obtain energy by oxidation
  - breaking bonds, removing electrons
  - must “dump” electrons someplace

Energy Yielding Metabolism

- Respiration: inorganic terminal electron acceptor
  - Aerobic: oxygen
  - Anaerobic: nitrate, iron II, manganese IV, sulfate, carbon dioxide, many others
- Fermentation: organic terminal electron acceptor
  - electrons moved to another organic molecule or to another part of same molecule

Aerobic Respiration

- <u>Not</u> Anaerobic Digestion
- Requires Oxygen
  - yields the most energy
  - favored if O_2 is present
- O_2 atmosphere (21%) normal to us, but:
  - “new” - only ~2.5 billion years
  - toxic waste product of oxygenic photosynthesis
  - produced by bluegreens, later algae and plants

Anoxic Conditions

- Not Anaerobic Digestion
- If O_2 absent but NO_3^- present
  - many aerobic microorganisms able to use NO_3^-
  - almost as much energy available (~80%)
  - product is N_2 gas - no smell!
  - known as "denitrification" (N lost from system)
- If Iron III present
  - now learning - many microorganisms can use it
  - converted to Fe II

Aerobic (and "Anoxic") Degradation

- Aerobic and anoxic conditions:
  - often one microorganism can completely degrade an organic compound
  - produces CO_2 and H_2O
  - called mineralization (convert compound entirely to inorganic forms)

Anaerobic Metabolism

- Oxygen absent
- Yields much less energy
- If O_2 present:
  - competition with aerobes (aerobes "win")
  - some switch to aerobic (facultative anaerobes)
  - inhibition of enzymes
  - toxicity - lethal to strict anaerobes

Anaerobic Life

- Originally all life was anaerobic
- Many microbes still are
- Three "Domains" of life
  - Archaea[1] (microorganisms)
  - Bacteria[1] (microorganisms)
  - Eukarya (*e.g.*, fungi[2], protozoa[3], algae, plants, animals[4])

[1]many anaerobes; [2]some anaerobes; [3]some anaerobes (rumen, termite gut, digestion?); [4]some anaerobic metabolism (e.g., lactic acid buildup in muscles)

Anaerobic Conditions

- Sludge
  - lots of organic material (e.g., 1% solids = 10,000 mg/L)
  - dissolved oxygen only a few mg/L
  - nitrate-N may be ~25 mg/L if nitrification plant
  - iron III < 1 mg/L
  - all these quickly used up
  - results in true anaerobic conditions
- Solid Waste
  - organic concentrations higher
  - <u>if wet</u>, low oxygen
  - probably low nitrate, iron III
  - quickly goes anaerobic

Anaerobic Consortia

- Consortium
  - 2 (or more) groups of microbes work together
  - degrade compounds that neither can completely degrade alone
- Under anaerobic conditions:
  - usually microorganisms more specialized
  - only carry out a few steps
  - complete mineralization requires sequential activity of several groups of microbes

Steps in Anaerobic Digestion

- Hydrolysis (liquefaction)
- Acidogenesis (acid formation)
- Mineralization

Hydrolysis

- Polymers/complex molecules broken down to subunits
  - proteins → amino acids
  - cellulose and starch → sugars
  - lipids (fats, oil, grease) → fatty acids
- Wide variety of microbes, some facultative
- Usually does not provide energy

Acidogenesis

- Mainly fermentations
  - provides relatively little energy
  - produces small (many 2-4 carbon), simple (organic acids, alcohols) organic compounds
  - a main product is acetic acid:

    CH_3-COOH
  - no net BOD reduction (measure of waste strength)

Anaerobic Mineralization

- Converts simple organics to inorganics
- Main products may include
  - carbon dioxide - CO_2
  - hydrogen - H_2
  - hydrogen sulfide - H_2S (sulfate reduction)
  - methane - CH_4 (methanogenesis)
- BOD reduction mainly from removal of the H_2, H_2S, and/or CH_4

Sulfate Reduction

- If sulfate (SO_4^{2-}) present
  - can be reduced to sulfide
  - provides more energy than methanogenesis (so sulfate reducers have advantage)
  - usually only 20-100 mg/L in sewage, mostly from drinking water (so runs out)
  - much more in sea water, some industrial wastes
  - solid waste? (gypsum?)

Sulfate Reduction (cont.)

- Produces:
  - black color - FeS (ferrous sulfide)
  - rotten egg odor - H_2S (hydrogen sulfide)
- Not desirable for anaerobic digestion
  - odor
  - toxicity (to process and people)
  - usually only small amounts formed, and trapped as FeS
  - problem with high sulfate wastes

Sulfate Reducing Microorganisms

- Once thought only one group, *Desulfovibrio*
- Actually - very diverse, many types
  - Bacteria & Archaea
  - many only utilize simple fermentation products (H_2, organic acids)
  - some can utilize a wider variety of, and more complex, compounds
- Outcompete methanogens if sulfate present

Methanogenesis

- Methane production
- Very few reactions
  - anaerobic respiration: CO_2 reduction

    $$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$$

  - use of methanol, formic acid, acetic acid; e.g.:

    $$CH_3COOH \rightarrow CH_4 + CO_2$$

- Gas often ~2/3 methane, ~1/3 carbon dioxide

Methanogens

- Narrow group of microbes
  - one group within Archaea (not bacteria)
  - inhibited by mildly acidic pH
- Previously thought were bacteria
- Previously thought one could utilize ethanol
  - called *Methanobacillus omelianskii*
  - turned out to be a consortium
    - a bacteria that converted ethanol to acetic acid
    - an archaea that converted acetic acid to methane

Advantages of Anaerobic Treatment/Digestion

- Produce methane
  - value as fuel
  - several potential uses
    - heating of reactor
    - space heating (offices, labs, indoor work areas)
    - drive engine (*e.g.*, for aerators at treatment plants)*
    - generate electricity*
    - fuel for vehicles**

* Could use waste heat for reactor and space heating

** Especially appropriate for landfills.

Advantages (cont.)

- Do not need to supply oxygen
  - energy/cost savings, especially for high strength wastes
  - no oxygen limitation - hard to transfer enough oxygen for high strength wastes
- Some compounds treatable anaerobically but not aerobically
  - PHBV biodegradable plastic
  - polychlorinated biphenyls (PCBs)

Advantages (cont.)

- Little biomass produced
  - most of energy goes into methane, not microbes
  - low nutrient (N and P) requirements
- Can have very concentrated waste, since no need to transfer oxygen to it

Disadvantages

- Instability
  - wide variety of microbes producing acids
  - narrow group of methanogens destroying acids
  - methanogens are sensitive to low pH
  - if pH drops:
    - methanogens slow down
    - acid accumulates
    - pH drops
    - methanogens slow down more
  - digester goes "sour"
  - can be from toxics, but usually overloading

Disadvantages (cont.)

- Slow growth of anaerobes
  - start up and recovery are slow
  - need to heat to get reasonable rates
    - usually ~35 C (~95 F)
    - uses ~1/2 of methane for heating with sludge (expect better for solid waste)
    - some are thermophilic - run at ~50 C (~130 F)
- Some wastes not treatable anaerobically
  - some oils, polycaprolactone plastic

Disadvantages (cont.)

- Odors
  - H_2S, sour (acetic acid)
- Incomplete treatment
  - solids are solubilized
  - concentrated BOD in supernatant/leachate
- Solubilizes nutrients - N and P
  - may be a problem for facilities with nutrient limitation regulations
  - high ammonia in leachate

Questions/Comments

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