Lecture 24 - Sludge Stabilization

Process of treating solids to make them stable - i.e. not subject to further degradation, not putrescible

Process reduces odor and pathogens

Alternative processes:

Anaerobic digestion (most common)
Aerobic digestion
Composting
Alkaline stabilization (addition of lime)
Combustion (incineration)

Anaerobic digestion

Basic principles were covered in Lecture 16 on stabilization ponds

Review of overall process (Fig 15.1 from WEF, pg 2.) as four steps:

1. Hydrolysis breaks down complex organics
2. Acidogenesis (fermentation) forms volatile fatty acids and acetogenesis breaks down complex fatty acids to acetic acid (CH_3COOH)
3. Methogenesis converts acetic acid to CO_2 and CH_4

Overall process stabilizes (i.e. destroys) about 40 to 65% of VSS depending on character of sludge - lower percentage when organics are complex and more difficult to degrade

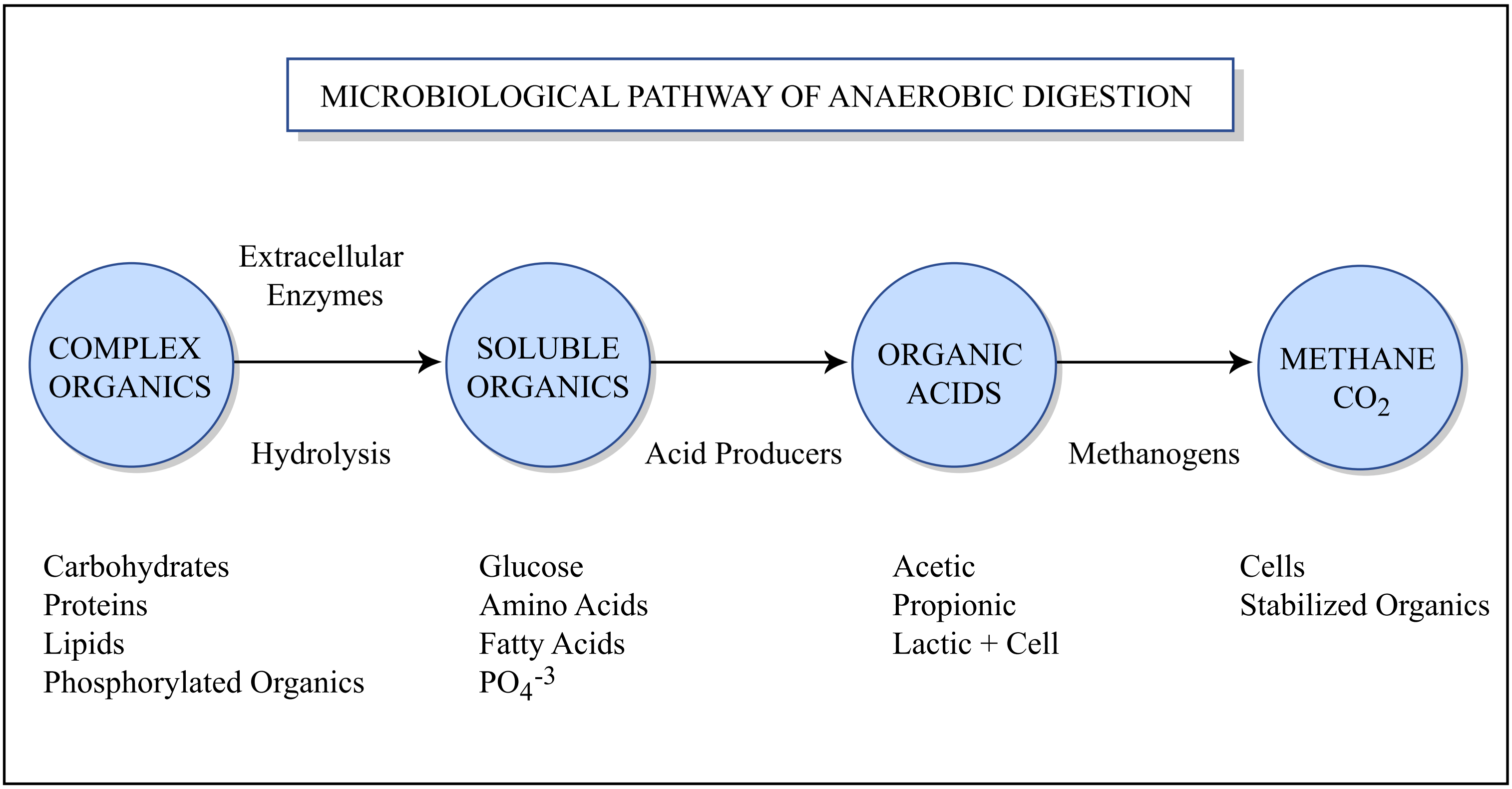


Figure by MIT OCW.

Adapted from: WEF. "Wastewater Treatment Plant Design. Water Environment Federation." Alexandria, Virginia, 2003.

Generalized reaction

$$\text{Organic matter} + \text{Combined oxygen} \xrightarrow{\text{Anaerobes}} \text{New cells} + \text{Energy for cells} + CH_2 + CO_2 + \text{Other end products}$$

Combined oxygen: CO_3^{2-}, SO_4^{2-}, NO_3^-, PO_4^{3-}

Other end products: H_2S, H_2, N_2

Organic matter: carbohydrates, proteins, fats, oils

Specific reaction for glucose (a carbohydrate and simple sugar)

$$C_6H_{12}O_6 + 2H_2O \rightarrow \underbrace{2CH_3COOH}_{\text{acetic acid}} + 4H_2 + 2CO_2$$

$$CH_3COOH \rightarrow CH_4 + CO_2$$

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

Breakdown pathways:

1. Carbohydrates → Simple sugar → Alcohols Aldehydes → Organic acids

Carbohydrates contain C, O, H with O:H = 1:2 (as in H_2O)

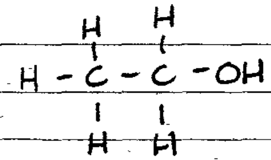
Sugars carbohydrate with carbonyl group

as aldehyde group $R-\overset{H}{\overset{|}{C}}=O$

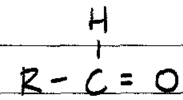
as keto group $R-\overset{O}{\overset{\|}{C}}-R'$

Alcohols - contain OH group R-OH

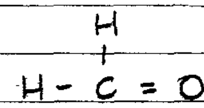
ethyl alcohol



Aldehydes - contain carbonyl group

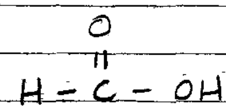


formaldehyde



Organic acids - contain carboxyl group R-COOH

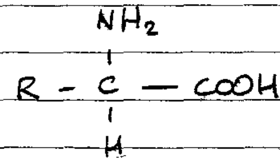
formic acid



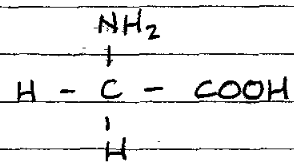
2. Proteins → Amino acids → Organic acids + NH_3

Protein - large complex molecules of C, H, O, N
and possibly P, S

Amino acids - contain amino group



Glycine



3. Fats and oils → Organic acids

Organic acids that result from breakdown are volatile acids - low MW acids that can be distilled at atmospheric pressure

Figure 32.1 from Clair N. Sawyer, Perry L. McCarty, and Gene F. Parkin, 2003. Chemistry for Environmental Engineering and Science, Fifth Edition. McGraw-Hill.
on page 6 shows pathways of COD conversion

Methanogenic bacteria needed to mediate reactions are ubiquitous in nature, but at low concentrations. Generally necessary to "seed" anaerobic reactors to get them started.

Other anaerobes start more quickly and can produce volatile acids faster than methanogenic bacteria can keep up with them.

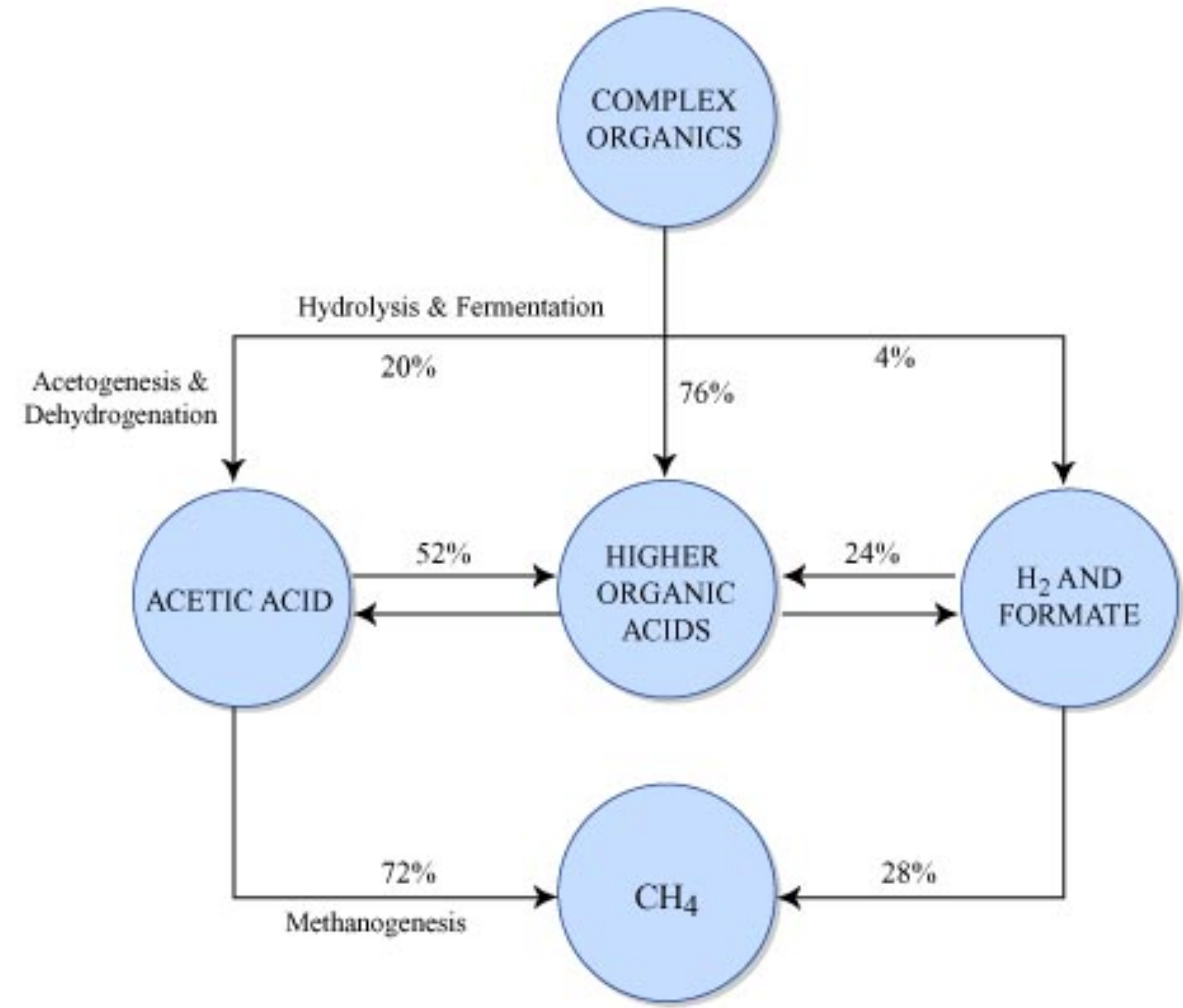
Methanogenic bacteria are inhibited at $pH < 6.5$
Fermentative and acidogenic bacteria at $pH < 5$

Between pH 6.5 and pH 5, acids are produced with essentially no breakdown
Volatile acids concentrations can go to 2000 - 6000 mg/L
Sludge gets "pickled"

Methanogens are the prima donnas of anaerobic digestion: very sensitive to changes in temp. and pH

Acidogens are more robust, and keep producing volatile acids when methogens are not necessarily processing them

Key to successful digestion is keeping acidogens and methanogens in balance - monitor pH to keep track of system state



Stages in the methane fermentation of complex wastes. Percentages represent conversion of waste COD by various routes.

Figure by MIT OCW.

Adapted from: Sawyer, C. N., P. L. McCarty, and G. F. Parkin. *Chemistry for Environmental Engineering and Science*. 5th ed. Boston, MA: McGraw-Hill, 2003.

Alkalinity of sludge buffers changes to pH to some extent

$$R-COOH + HCO_3^- \rightarrow R-COO^- + H_2O + CO_2$$

$R-COOH$: org. acid; HCO_3^-: bicarbonate alkalinity

Organic acid neutralized with only slow change in pH but with loss of [Alk]

When [Alk] < 1000 mg/L as $CaCO_3$ pH starts to change rapidly

[Alk] is generated as a by-product of CO_2 generation

$$CO_2 + H_2O \rightleftharpoons H_2CO_3^* \rightleftharpoons H^+ + HCO_3^-$$

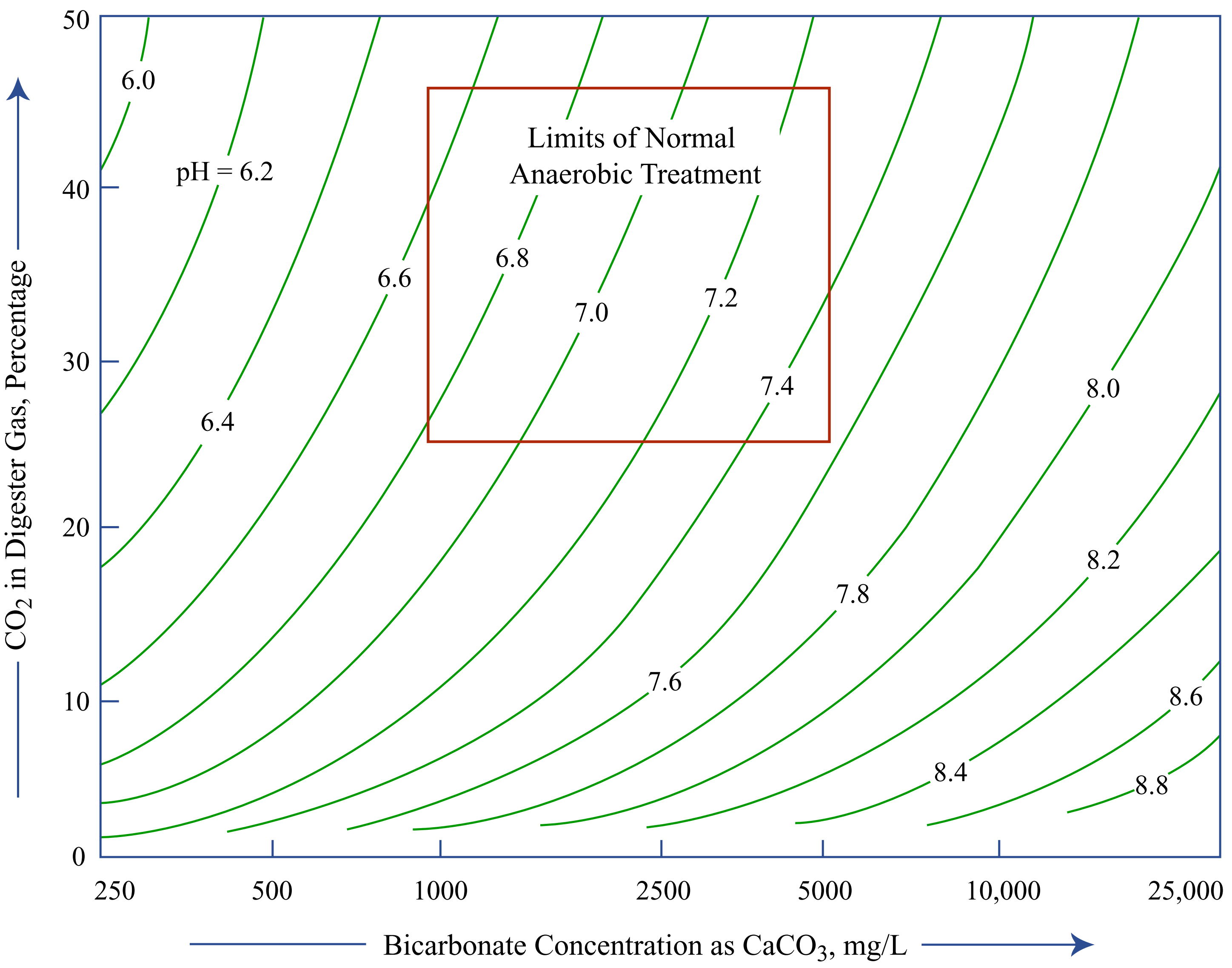
Successful operating range for CO_2, [Alk] and pH are shown in Fig 32.2 from Sawyer et al., 2003, on pg 8

[Alk] can also be managed by adding chemicals, e.g. sodium bicarbonate $NaHCO_3$ (alka seltzer) or lime

Key to successful digester operation is chemical monitoring, especially pH and volatile acids conc.

Volatile acids are reported "as acetic acid" – i.e. molar conc of other acids is converted to mg/L assuming 1 mole = 60 g acetic acid (MW of acetic acid is 60)

Different acid concentrations measured with chromatography



Relationship between pH, bicarbonate concentration, and carbon dioxide concentration at 35°C and 1 atm.

Figure by MIT OCW.

Adapted from: Sawyer, C. N., P. L. McCarty, and G. F. Parkin. *Chemistry for Environmental Engineering and Science*. 5th ed. Boston, MA: McGraw-Hill, 2003.

Operating conditions for anaerobic digestion

	Optimal	Usual range
Temp.	35C (98F)	29-35C (85-98F)
pH	7-7.2	6.7-7.4
Alk		1000-5000 mg/L as $CaCO_3$
Vol acids		50-250 mg/L at acetic acid (2000 mg/L max)

Gas composition 55-75% methane
25-45% CO_2

Solids reduction 50-75% VSS
35-50% TSS

Gas production 0.75-1.1 m^3 per kg VSS destroyed

Inhibitory compounds

High ion concentrations
Some metals
Ammonia, sulfide gas

$\Big\}$ can be toxic to bacteria

See Table 15.1 from WEF, 2004 on pg 10

Some chemicals (e.g. sulfide) are difficult to avoid altogether
Iron salts (ferrous chloride $FeCl_2$ or ferrous sulfate $FeSO_4$)

$$FeCl_2 + H_2S \rightarrow FeS\downarrow + 2HCl$$

$$FeSO_4 + H_2S \rightarrow FeS\downarrow + H_2SO_4$$

SUBSTANCE	MODERATELY INHIBITORY CONCENTRATION, mg/L	STRONGLY INHIBITORY CONCENTRATION, mg/L
Na^+	3500 - 5500	8000
K^+	2500 - 4500	12000
Ca^{++}	2500 - 4500	8000
Mg^{++}	1000 - 1500	3000
Ammonia-nitrogen (pH dependent)	1500 - 3000	3000
Sulfide (un-ionized gas)	200	200
Copper (Cu)	—	0.5 (soluble) 50-70 (total)
Chromium VI (Cr)	—	3.0 (soluble) 200-250 (total)
Chromium III	—	180-420 (total)
Nickel (Ni)	—	2.0 (soluble) 30.0 (total)
Zinc (Zn)	—	1.0 (soluble)

Toxic and Inhibitory Concentrations of Selected Inorganic Materials in Anaerobic Digestion

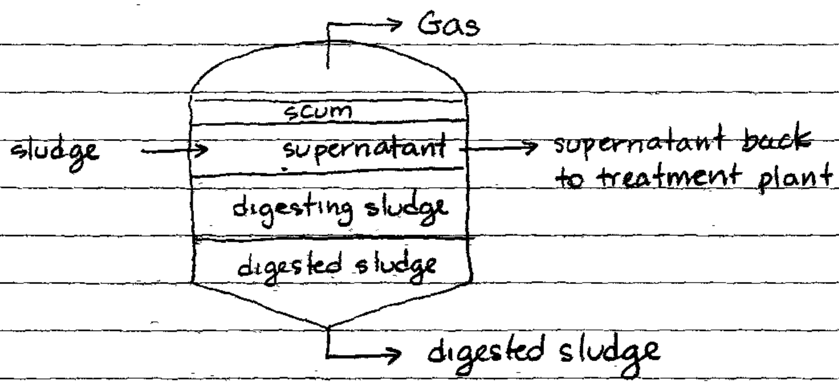
Figure by MIT OCW.

Adapted from: WEF. Wastewater Treatment Plant Design. Water Environment Federation, Alexandria, Virginia, 2003.

Digester design

Low-rate digestors

Oldest design
Cylindrical tank with roof (often a floating cover)
No mixing - contents stratify in digester



See Figure 15.2 from WEF, 2004 pg 12

Low loading rates, large tank sizes
detention times = 30 to 60 days

Used only for small plants

High rate digesters

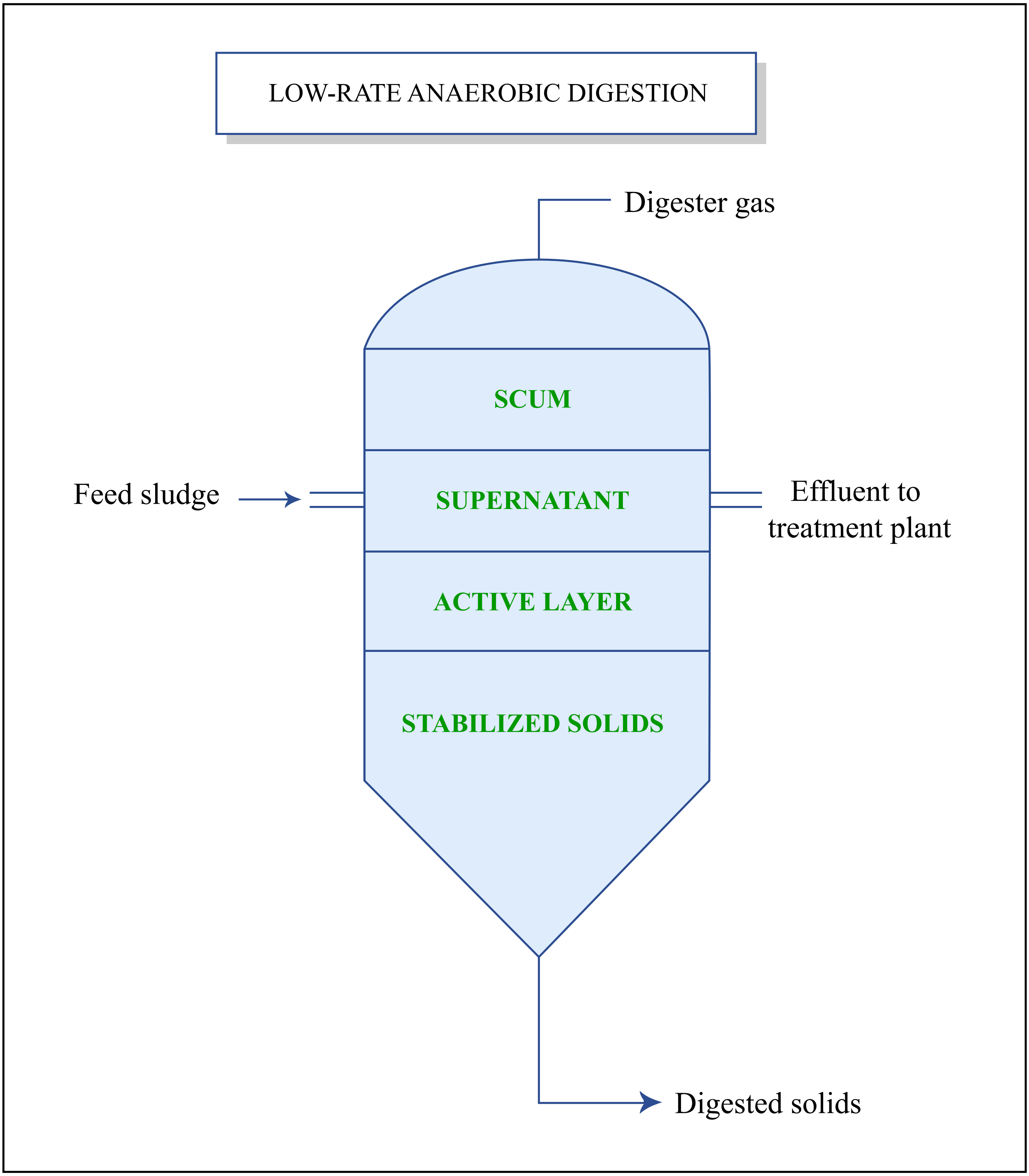
Supplemental heating and mixing
Sludge is pre-thickened

Mixing systems vary - see Figure 19.9 from Reynolds and Richards, 1995 pg 13

In common use

One variation is egg-shaped digester - see Fig. 15.9 and 15.10 from WEF, 2004 pg 14

Steep top and bottom reduce scum and grit buildup
Shape creates easier mixing



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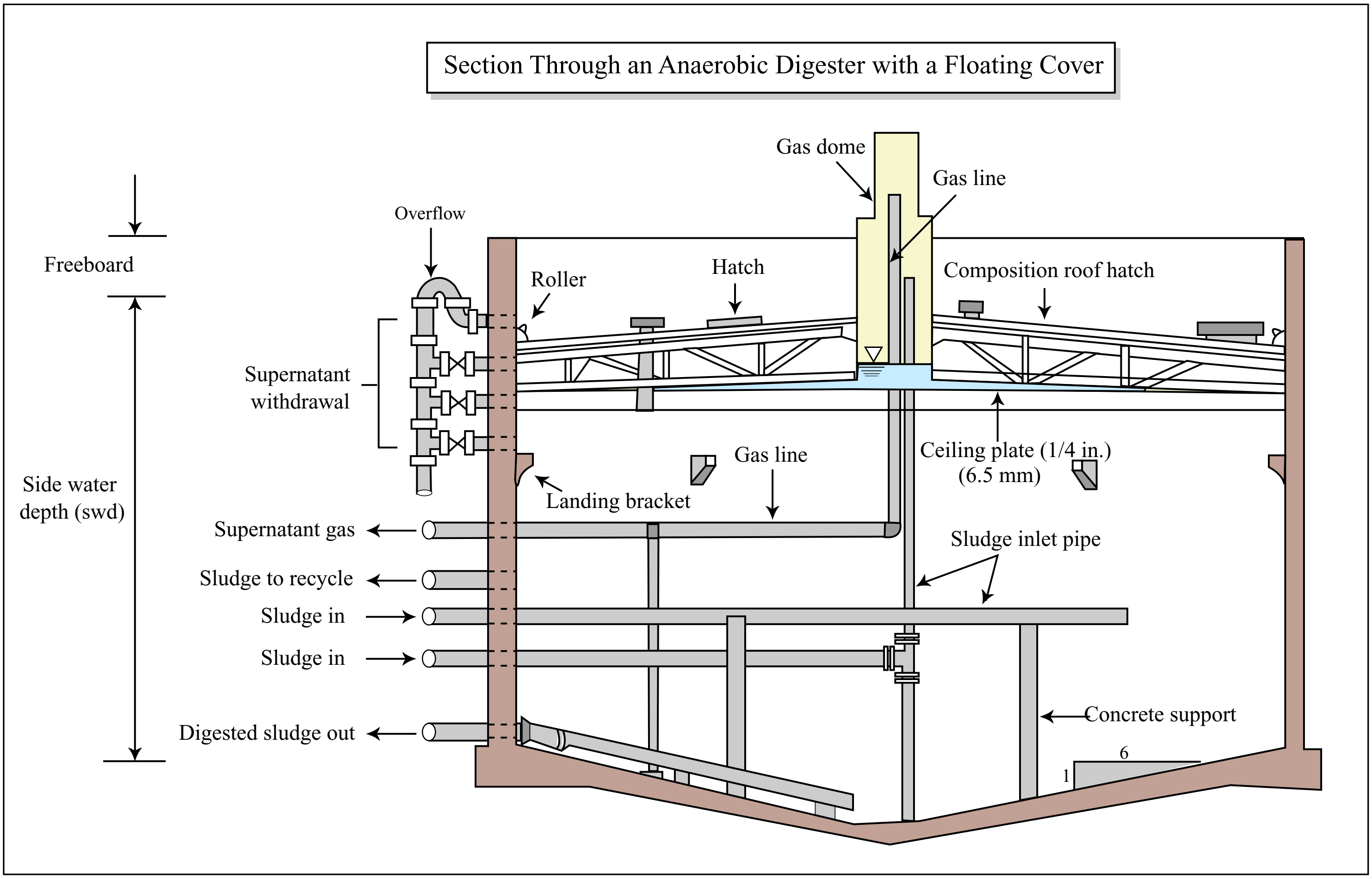

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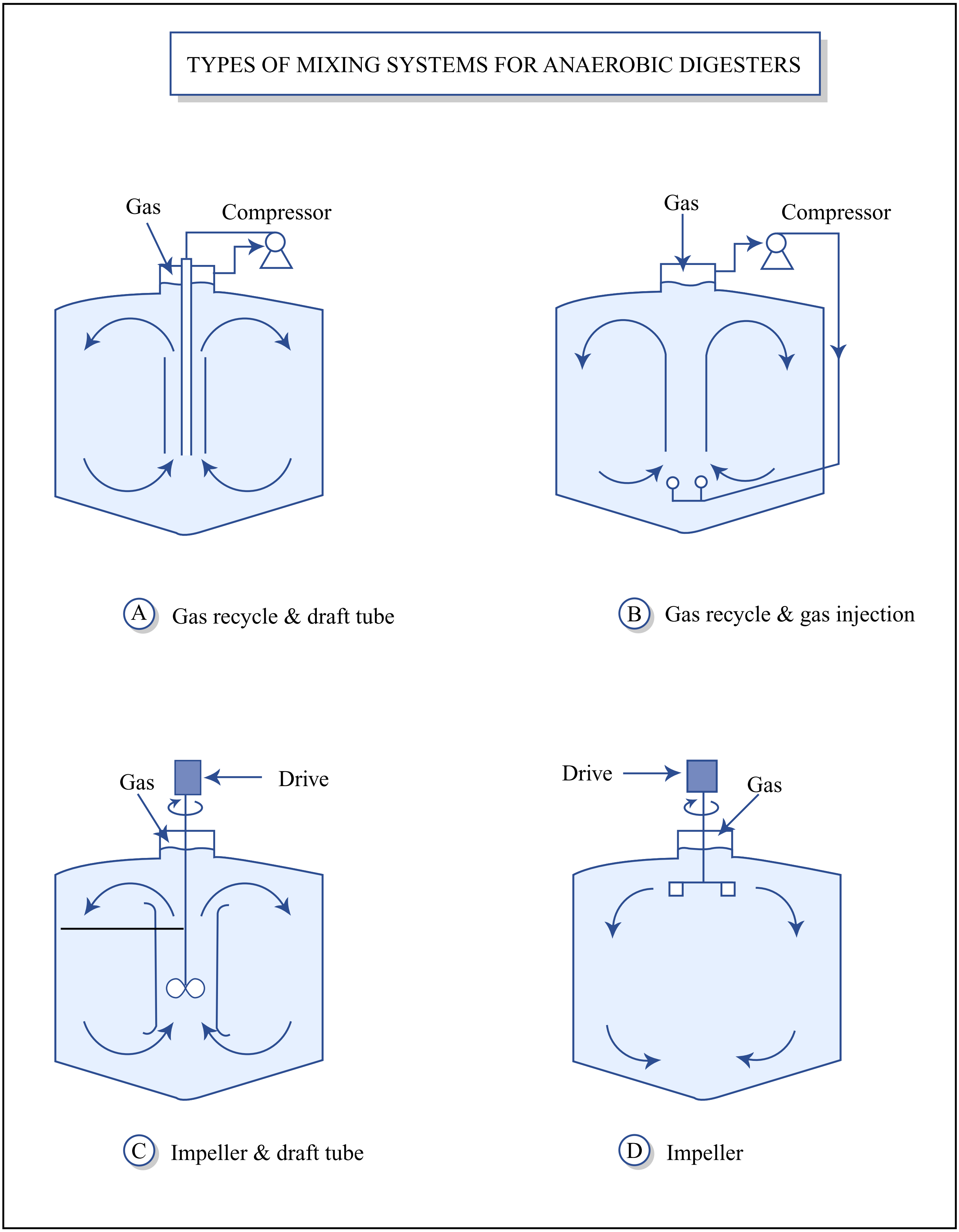
Adapted from: Reynolds, T. D., and P. A. Richards. *Unit Operations and Processes in Environmental Engineering*. 2nd ed. Boston, MA: PWS Publishing Company, 1996, p. 582.



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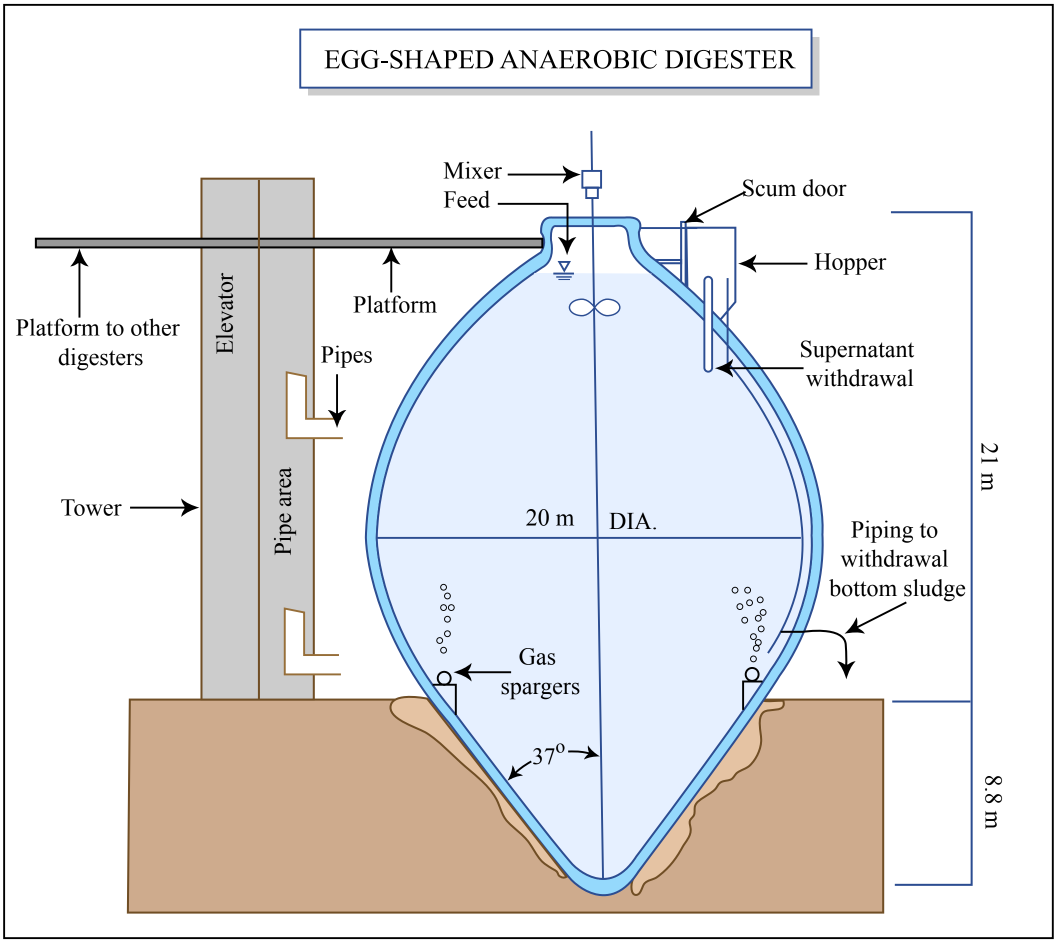

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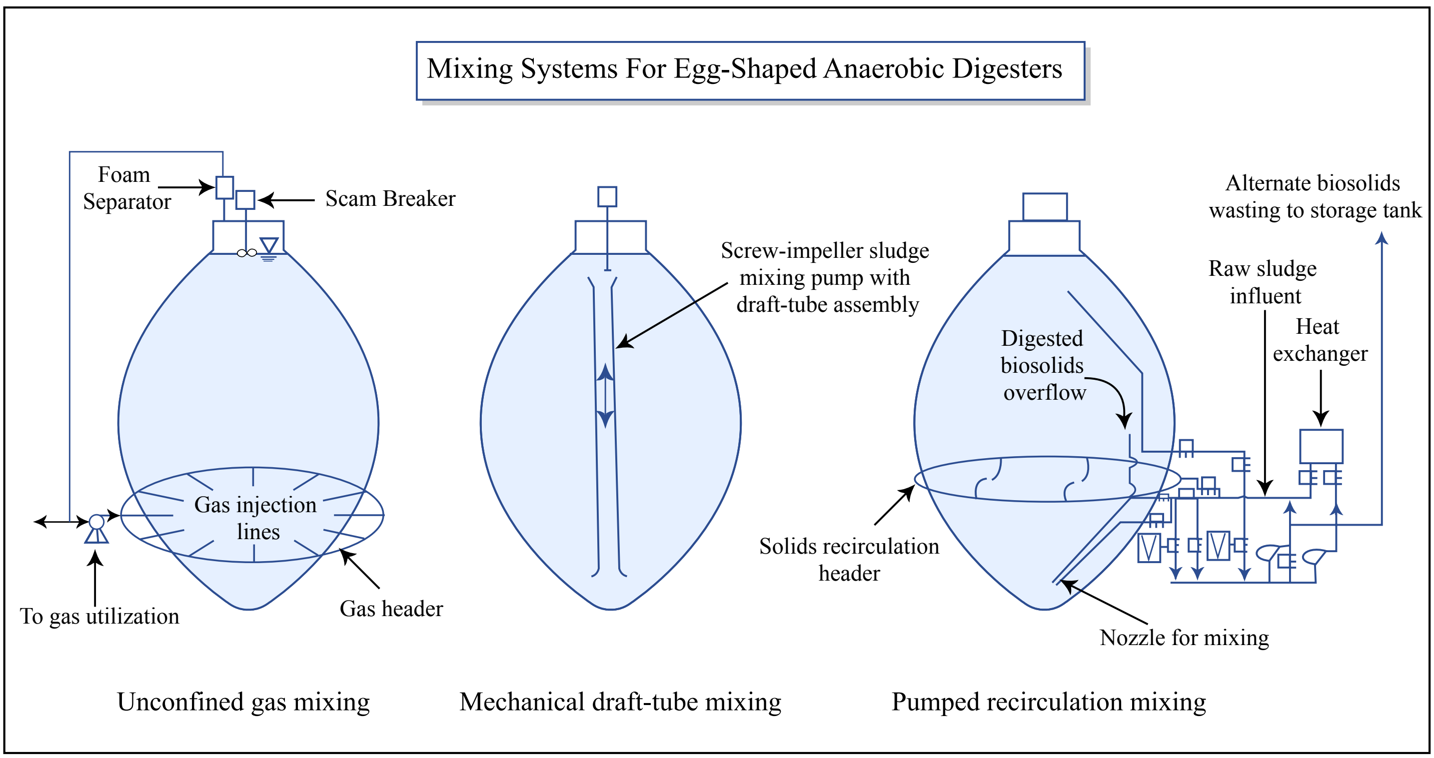

Figure by MIT OCW.

Adapted from: WEF. Wastewater Treatment Plant Design. Water Environment Federation, Alexandria, Virginia, 2003.

Design

Minimum solids retention time

$$\theta_{min} = \frac{YKS}{K_s + S} - K_d$$

θ_{min} = minimum retention time [T]

Y = yield coeff [M VSS / M COD]

≅ 0.04 g VSS/g COD (typical value)

K = max specific substrate use rate [M COD/M VSS · T]

= 6.67 (1.035^{T-35}) g COD/g VSS · d

T = temperature (°C)

K_s = half-saturation const

= 1.8 (1.112^{T-35}) g COD/L

S = conc of biodegradable substate (function of treatment plant) [M COD/L^3]

K_d = endogenous decay coeff [T^{-1}]

≅ 0.03 (1.035^{T-35}) day^{-1}

θ_{min} = 4 days at 35-40 C

11 days at 18 C

Design θ is 2.5 times θ_{min}

Typical loading rates

1.9 - 2.5 $kg\ VSS / m^3 \cdot d$

3.2 $kg\ VSS / m^3 \cdot d$ is maximum to avoid accumulation of toxics, washout of methanogens

Gas production $\approx$ 0.8 to 1.1 m^3 / kg VSS destroyed

VSS destruction $V_d = 13.7 \ln \theta + 18.9$

V_d in %
θ in days

Aerobic digestion

Similar to Activated Sludge process

Advantages compared to anaerobic digestion
- Fewer operational problems
- Less monitoring and maintenance
- Lower capital costs

Disadvantages
- Higher energy needed for aeration and mixing
- Does not generate methane as useful by-product
- Lower solids content, higher volume sludge
- Sludge has poorer properties for mechanical dewatering

Aerobic digesters tend to be used at smaller plants

Aerobic digestion operates similarly to AST

Solids retention time = 40 days at 20 C, 60 days at 15 C

VS loading ≃ 1.6 - 4.8 kg VS / m^3·d
(higher than anaerobic digester)

Cells are in endogenous respiration conditions - cell material is consumed by digestion process

Reduction in VSS is 38-50% (about 2/3 of anaerobic)

Oxygen conc is kept low ~1 mg/L - this prevents nitrification and consequent pH change

Chemical reactions:

Biomass destruction

$$C_5H_7NO_2 + 5O_2 \rightarrow 4CO_2 + H_2O + NH_4HCO_3$$

Nitrification

$$NH_4^+ + 2O_2 \rightarrow NO_3 + 2H^+ + H_2O$$

Other options for sludge

Open-air drying beds
Sludge dried in open air on coarse sand
Problems with odor, poor performance in wet weather, large land area required, labor for removal of dried cake

Composting
Mixed with dry organic amendment - sawdust, straw, dried manure
Placed in windrows and turned to aerate

Pressure filtration
Used to dewater digested sludge
Similar to gravity belt thickener but with additional step for pressure filtration
Requires polymer addition to enhance water separation over gravity belt portion of filter
See illustration - Figure 11-56 from M.J. Hammer and M.J. Hammer, Jr., 2004. Water and wastewater technology, Fifth edition. Pearson Prentice Hall. on pg. 19

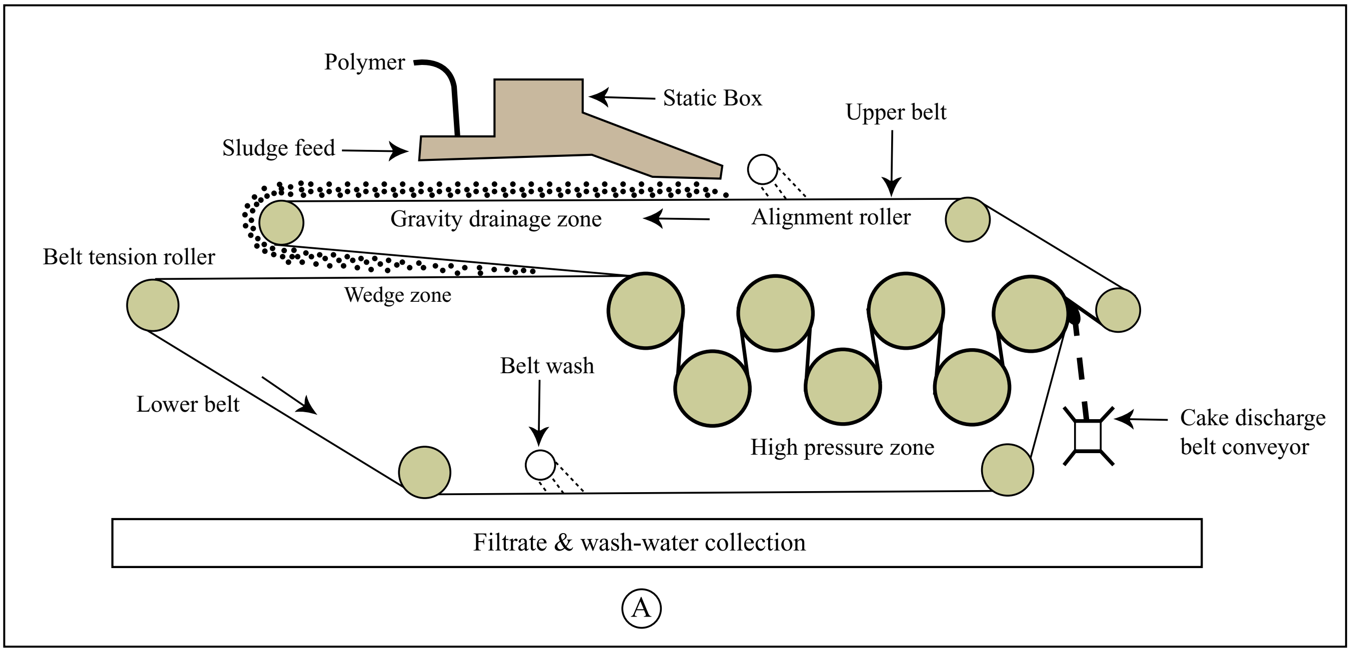

Figure by MIT OCW.

Adapted from: Hammer, M. J., and M. J. Hammer, Jr. *Water and Wastewater Technology*. 5th ed. Upper Saddle River, NJ: Prentice-Hall, Inc., 2004. Figure 11-56.