

Lecture 10

SECONDARY TREATMENT (2)

Course: Water Reuse
 Dr. Alireza Bazargan
info@environ.ir

Phosphorous removal

- Phosphorus can lead to unwanted aquatic growth (eutrophication) or biofouling in industrial applications.
- For decentralized applications, phosphorus removal is accomplished typically by filtration through reactive media or chemical precipitation. Biological phosphorus removal (BPR) is not suitable for small applications because it adds complexity
- BPR can be applied for large plants and can be accomplished by configuring an anaerobic zone ahead of the aerobic or anoxic zone.

Dr. Alireza Bazargan info@environ.ir

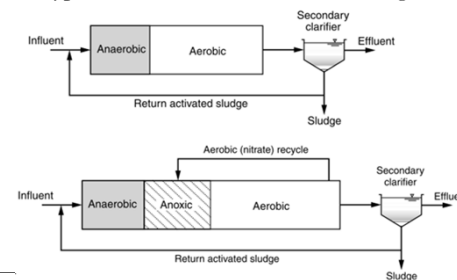
Biological phosphorus (P) removal

- Certain P accumulating bacteria can be used as part of the activated sludge process. After the P uptake has occurred, these organisms must be removed or wasted from the process to accomplish P removal.
- Barnard (1975) named any process with an anaerobic/aerobic sequence to promote BPR: *Phoredox*
- Some of the process names that have evolved to designate specific process configurations include A/O (anaerobic/aerobic only) and A²O (anaerobic/anoxic/aerobic).

Dr. Alireza Bazargan info@environ.ir

Biological phosphorus (P) removal

- The main difference between the Phoredox (A/O) process and the A²O process is that nitrification does not occur in the A/O process. The A²O process is one of the basic types used for nitrate removal along with BPR.

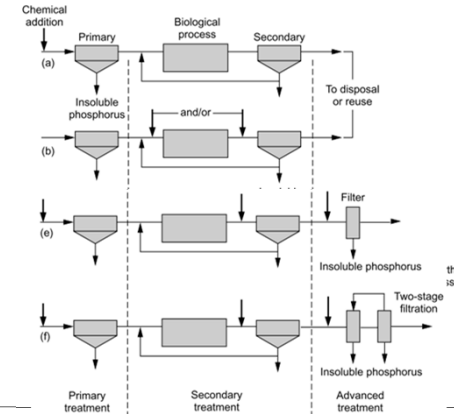


Phosphorus (P) removal by chemicals

- The removal of P from wastewater involves the incorporation of P into the TSS and the subsequent removal of those solids.
- P removal is brought about by the addition of salts of the multivalent metal ions that form precipitates of sparingly soluble phosphates.
- The multivalent metal ions that are used most commonly are calcium [Ca(II)], aluminum [Al(III)], and iron [Fe(III)]. Polymers have been used effectively in conjunction with alum and lime as flocculent aids.

Dr. Alireza Bazargan info@environ.ir

Phosphorus (P) removal by chemicals



Alternative points of chemical addition for phosphorus removal: (a) before primary sedimentation, (b) before and/or following biological treatment, (c) following secondary treatment, and (d-f) at several locations in a process known as *split treatment*.

Advantages and disadvantages

Advantages and disadvantages of chemical addition with metal salts and lime at various locations of a treatment plant for phosphorus removal^a

Location of chemical addition	Advantages	Disadvantages
Addition of metal salts		
Prior to primary sedimentation	Increases BOD and TSS removal; lowest degree of metal leakage	Least efficient use of metal; polymer may be required for flocculation; sludge more difficult to dewater than primary sludge
Prior to secondary sedimentation	Lowest cost; lower chemical dosage than prior to primary sedimentation; less effect on pH than lime; available mixing in activated sludge aeration system is utilized; improves stability of activated sludge; polymer may not be required	Overdose of metal can cause pH toxicity; increases TDS in reclaimed water
Post secondary treatment with clarification	Low phosphorus content in effluent; most efficient metal use	Additional flocculation and sedimentation step required thus increasing capital cost; highest metal leakage; increases TDS in reclaimed water
Post secondary treatment with filtration (single or two stage)	Lowest phosphorus content in effluent	Length of filter run may be reduced with single-stage filtration; two-stage filtration more costly
Multiple locations	Provides greatest flexibility in optimizing phosphorus removal	More complicated chemical distribution and control system

Advantages and disadvantages

Advantages and disadvantages of chemical addition with metal salts and lime at various locations of a treatment plant for phosphorus removal^a

Location of chemical addition	Advantages	Disadvantages
Addition of lime		
Prior to primary sedimentation	Increased BOD and TSS removal thereby reducing load in aeration tanks; lime recovery demonstrated	Because excessively high pH interferes with the biological process, lime addition is limited to a pH of about 9.0; soluble phosphorus level is 2 to 3 mg/L
Prior to secondary sedimentation	Lower chemical dosage than prior to primary sedimentation; biological system breaks down complex phosphates to more readily precipitated orthophosphate form	Inert solids added to mixed liquor, reducing the percentage of volatile solids; high pH or returned solids may affect biological treatment performance
Post secondary treatment with clarification	Low phosphorus content in effluent; lime recovery demonstrated	Additional flocculation and sedimentation step required; with high pH or low alkalinity in treated wastewater, recarbonation is required
Post secondary treatment with filtration (single or two-stage)	Lowest phosphorus content in effluent	Length of filter run may be reduced with single-stage filtration; two-stage filtration is more costly; solids settling may be more difficult instage first-settling

Membrane bioreactors (MBR)

- Membrane bioreactors combine biological treatment with an integrated membrane system to provide enhanced organics and suspended solids removal.
- By coupling a biological reactor with a membrane system (MF or UF), conventional treatment operations can be eliminated such as gravity sedimentation and media filtration that might be used to produce an equivalent effluent.
- MBR membranes are either hollow fiber or fixed plate. They can be either pressure driven or vacuum driven.

Dr. Alireza Bazargan info@environ.ir

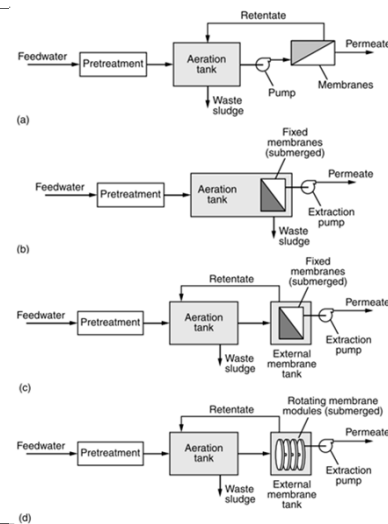
Why MBR?

- The main advantages of MBR are:
 - They operate with higher SS concentrations and the reactor hydraulic retention times are shorter, so the reactor size is smaller = can be located closer to the point of reuse
 - higher quality product water can be obtained (0.04 to 0.4 μm pores, means low TSS, turbidity, and bacteria);
 - Longer solids retention (2-3 times higher than conventional processes), result in less sludge production, more stable operation, and less chance for process upsets
 - systems are simpler to operate

Dr. Alireza Bazargan info@environ.ir

MBR types

General types of membrane bioreactors:
 (a) with external pressure-driven membrane,
 (b) integrated submerged,
 (c) with external submerged, and
 (d) with external submerged rotating membrane.

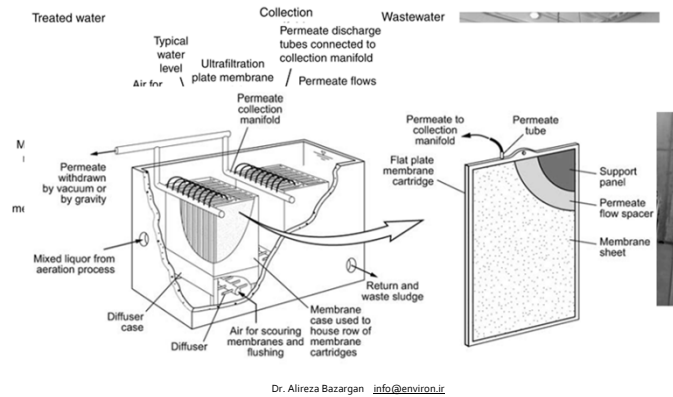


MBR disadvantages

- (1) high capital costs;
- (2) a potential high recurring cost of periodic membrane replacement;
- (3) higher energy costs due to membrane scouring as compared to conventional suspended-growth processes;
- (4) potential membrane fouling that affects the ability to treat design flows;

Dr. Alireza Bazargan info@environ.ir

Membrane types



Comparison

Conventional activated sludge		
BOD	mg/L	5-25
TSS	mg/L	5-25
Turbidity	NTU	5-15 ^c
Activated sludge with BNR		
BOD	mg/L	5-15
TSS	mg/L	5-20
Turbidity	NTU	2-8
Membrane bioreactor		
BOD	mg/L	<3
TSS	mg/L	≤1
Turbidity	NTU	≤1

^cTurbidity values of less than 2 NTU have been observed in plants with deep clarifiers (e.g., sidewater depths of 5.5 to 6 m). Corresponding BOD and TSS values are in the range from 3 to 6 mg/L.

Dr. Alireza Bazargan info@environ.ir

Wastewater characterization for design

Summary of equations used commonly in wastewater characterization^a

Equation	Eq. No.	Definition of terms
$nbVSS = [1 - (bpCOD/pCOD)] VSS$	(7-1)	bcOD = biodegradable COD, mg/L
$bpCOD = \frac{(bCOD/BOD)(BOD - sBOD)}{COD - sCOD}$	(7-2)	bpCOD = biodegradable particulate COD, mg/L
$pCOD = COD - sCOD$		iTSS = inert TSS, mg/L
$COD = bcOD + nbCOD$	(7-3)	nbCOD = nonbiodegradable COD, mg/L
$bCOD = -1.6(BOD)$	(7-4)	nbpCOD = nonbiodegradable particulate COD, mg/L
$nbCOD = nbsCOD + npbCOD$	(7-5)	nbsCOD = nonbiodegradable soluble COD, mg/L
$bCOD = sbCOD + rbCOD$	(7-6)	nbVSS = nonbiodegradable VSS, mg/L
$iTSS = TSS - VSS$	(7-7)	pCOD = particulate COD, mg/L
		rbCOD = readily biodegradable COD, mg/L
		sBOD = soluble BOD, mg/L
		sCOD = soluble COD, mg/L
		sbCOD = slowly biodegradable COD, mg/L

^aAdapted from Tchobanoglous et al. (2003).

Dr. Alireza Bazargan info@environ.ir

Performance effects

Wastewater constituents that affect the performance of membrane bioreactors

Type of constituent	Specific constituent	Effect on MBR
Physical	High concentration of TSS (>30 mg/L), hair, fibrous material, and other inert solids	Buildup on membrane surfaces that may cause reduced membrane efficiency, physical damage to membranes, and ability to maintain membrane cleaning. May decrease permeate quality.
	Temperature variations	Affects water viscosity and flux rate.
Chemical	High alkalinity	Membrane fouling that may require acid cleaning to remove chemical foulants.
	Soluble iron	Membrane fouling causing diminished performance and more frequent cleaning.
	Oil and grease	Membrane fouling causing diminished performance and more frequent cleaning.
Biological	Surfactants	Foaming that requires cleanup.
	Oxidants, e.g., ozone and chlorine	Attacks certain types of membrane material.
	Dissolved and colloidal organic matter	Membrane fouling causing diminished performance and more frequent cleaning.
	Extracellular polymeric substances (EPS)	Clogs membrane pores resulting in diminished membrane performance and more frequent cleaning; also affects viscosity of sludge.

Suspended growth equations

Equation	Eq. No.	Definition of terms
$k_T = k_{20}\theta^{T-20}$	(7-8)	DO = dissolved oxygen concentration, ML ⁻³
$r_{sw} = -\frac{kXS}{K_s + S}$	(7-9)	F/M = food-to-microorganism ratio
$\mu_m = kY$	(7-10)	f_d = fraction of cell mass remaining
$r_{su} = -\frac{\mu_m XS}{Y(K_s + S)}$	(7-11)	k = maximum rate of substrate utilization, T ⁻¹ k_d = endogenous decay coefficient, T ⁻¹ k_{dn} = endogenous decay coefficient for nitrifying organisms, T ⁻¹
$r_g = Y\frac{kXS}{K_s + S} - k_d X$	(7-12)	k_T = reaction rate coefficient at temperature (T) k_{20} = reaction rate coefficient at 20°C K_n = half-velocity constant for nitrification, ML ⁻³ K_o = half-saturation coefficient for DO, ML ⁻³ K_o' = oxygen inhibition coefficient, ML ⁻³ K_a = half-velocity constant, ML ⁻³
$\mu = \frac{r_g}{X}$	(7-13)	K_{a,NO_3} = half-velocity constant for denitrification, ML ⁻³
$SRT = \frac{VX}{(Q - Q_w)X_w + Q_w X_R}$	(7-14)	L_{org} = volumetric organic loading rate, ML ⁻³ T ⁻¹ μ = specific growth rate, T ⁻¹
$SRT = \frac{1}{\mu}$	(7-15)	μ_m = maximum specific growth rate, T ⁻¹

Dr. Alireza Bazargan info@environ.ir

Suspended growth equations

Equation	Eq. No.	Definition of terms
$\frac{1}{SRT} = -\frac{YkS}{K_s + S} - k_d$	(7-16)	μ_n = specific growth rate for nitrification, T ⁻¹ μ_{nm} = maximum specific growth rate of nitrifying bacteria, T ⁻¹
$S = \frac{K_s[1 + (k_d)SRT]}{SRT(Yk - k_d) - 1}$	(7-17)	N = NH ₄ -N concentration, ML ⁻³ NO_3 = nitrate nitrogen concentration, ML ⁻³ η = ratio of substrate utilization rate with nitrate versus oxygen as the electron acceptor
$X = \left(\frac{SRT}{\tau}\right)\left(\frac{Y(S_o - S)}{1 + (k_d)SRT}\right)$	(7-18)	P_X = solids, M
$(X_{vss})(V) = (P_{X,vss})SRT$	(7-19)	Q = flow rate, L ³ T ⁻¹
$(X_{TSS})(V) = (P_{X,TSS})SRT$	(7-20)	Q_w = waste sludge flow rate L ³ T ⁻¹
$R_o = Q(S_o - S) - 1.42 P_{X, bio}$	(7-21)	R_o = oxygen, MT ⁻¹ r_g = net biomass production rate, ML ⁻³ T ⁻¹ r_{su} = soluble substrate utilization rate, ML ⁻³ T ⁻¹
$F/M = \frac{QS_o}{VX}$	(7-22)	S = concentration of growth limiting substrate in solution, ML ⁻³ S_o = influent concentration, ML ⁻³
$L_{org} = \frac{Q(S_o)}{V}$	(7-23)	SRT = solids retention time, T TSS = total suspended solids, M τ = hydraulic retention time (V/Q), T θ = temperature activity coefficient V = volume, L ³
$\mu_n = \left(\frac{\mu_{nm}N}{K_n + N}\right)\left(\frac{DO}{K_o + DO}\right) - k_{dn}$	(7-24)	

Suspended growth equations

Equation	Eq. No.	Definition of terms
$r_{su} = \left(\frac{kXS}{K_s + S}\right)\left(\frac{NO_3}{K_{s,NO_3} + NO_3}\right)\left(\frac{K_o}{K_o + DO}\right)\eta$	(7-25)	VSS = volatile suspended solids, M X = biomass concentration, ML ⁻³ X_o = concentration of biomass in the effluent, ML ⁻³ X_R = concentration of biomass in the return line from clarifier, ML ⁻³ X_{vss} = volatile solids mass in reactor, ML ⁻³ X_{TSS} = total solids mass in reactor, ML ⁻³ Y = biomass yield, M of cell formed per M of substrate consumed Y_n = g biomass produced/g NH ₄ -N utilized

^aAdapted from Tchobanoglous et al. (2003).

Note: Expressions for units are M = mass, L = length, and T = time.

Dr. Alireza Bazargan info@environ.ir

Activated sludge design values for heterotrophic bacteria

Coefficient	Unit	Range	Typical value
μ_m	g VSS/g VSS·d	3.0–13.2	6.0
K_s	g bCOD/m ³	5.0–40.0	20.0
Y	g VSS/g bCOD	0.30–0.50	0.40
k_d	g VSS/g VSS·d	0.06–0.20	0.12
f_d	Unitless	0.08–0.20	0.15
θ values			
μ_m	Unitless	1.03–1.08	1.07
k_d	Unitless	1.03–1.08	1.04
K_s	Unitless	1.00	1.00

Activated sludge design coefficients for heterotrophic bacteria at 20°C^a

Dr. Alireza Bazargan info@environ.ir

Activated sludge design values for nitrification kinetics

Coefficient	Unit	Range	Typical value
μ_{nm}	g VSS/g VSS · d	0.50–0.90	0.85
K_n	g $\text{NH}_4\text{-N}/\text{m}^3$	0.5–1.0	0.70
Y_n	g VSS/g $\text{NH}_4\text{-N}$	0.10–0.15	0.12
k_{dn}	g VSS/g VSS · d	0.05–0.17	0.17
θ values			
θ_n	unitless	1.06–1.123	1.072
K_n	unitless	1.03–1.123	1.053
k_{dn}	unitless	1.02–1.08	1.029

Activated sludge design nitrification kinetic coefficients at 20°C^a

Dr. Alireza Bazargan info@environ.ir

Biosolids production

- Determination of the solids production is important for two reasons: (1) for process control and (2) for the design of subsequent solids processing facilities
- There are two methods for biosolid determination.
- The first method is based on an estimate of an observed solids yield from published data from similar facilities;
- The second is based on the actual activated sludge process design in which wastewater characterization is done and the various sources of solids are considered and accounted for.

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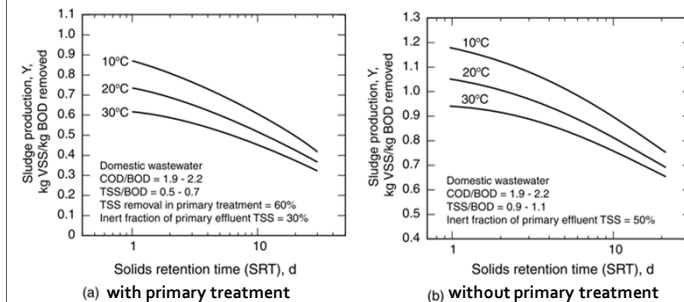
Biosolids determination from similar facilities' data

$$P_{X,VSS} = Y_{obs}(Q)(S_o - S)(1 \text{ kg}/10^3 \text{ g})$$

- $P_{X,VSS}$ = net waste activated sludge produced each day, kg VSS/d
 Y_{obs} = observed yield, g VSS/g substrate removed
 Q = influent flow, m³/d
 S_o = influent substrate concentration, g/m³ (mg/L)
 S = effluent substrate concentration, g/m³ (mg/L)

The observed yield decreases as the SRT is increased due to biomass loss by increased endogenous respiration. The yield is lower with increasing temperature as a result of a higher endogenous respiration rate at higher temperature. The yield is higher when no primary treatment is used as more settleable organic matter and nonbiodegradable VSS (nbVSS) remains in the influent wastewater.

Biosolids determination from similar facilities' data



The temperature correction value θ for endogenous respiration in the reaction rate equation, Eq. (7-8), is 1.04 between 20 and 30°C, and 1.12 between 10 and 20°C