# Chapter 2
# Fundamentals of Biological WW treatment

**Definition of biological treatment:-**

It is the type of wastewater treatment in which a variety of microorganisms, principally bacteria, ore used to remove dissolved and particulate matter.

## 2.1 Objectives of biological WW treatment:

1. Transform (i.e convert) dissolved and particulate organic biodegradable compounds into acceptable end products.
2. Capture and incorporate suspended and non settleable colloidal solids into a biological floc or biofilm that can be removed by settling.
3. Transform or remove nutrients, such as nitrogen and phosphorus

## 2.2 Role of microorganism in WW treatment:-

### A- Classification of microorganisms:-

- **By kingdoms: "five kingdoms":-**
  - Animals ----- Rotifers
  - Plants ----- some algae
  - Fungi ----- mushrooms, yeasts
  - Protista ----- Amoebas, some algae

- **By energy and carbon source:-**

**- Heterotrophic microorganisms:-**

Microorganisms that use organic matter as a source of carbon.

**- Autotrophic microorganisms:-**

Microorganisms that use $CO_2$ as a carbon source.

**-Phototrophic microorganisms:-**

Microorganisms that rely only on the sun for energy.

**-Chemotropic microorganisms:-**

Microorganisms that extract energy from chemical reactions (oxidation / reduction reactions).

- **By their relation to oxygen:-**

**-Obligate aerobes:-**

Microorganisms that can not survive in the presence of oxygen. They are also called anaerobic.

**-Facultative anaerobes:-**
Microorganisms that can survive in the presence and absence of oxygen. A group of facultative anaerobes called denitrifies under anoxic conditions use the oxygen in nitrates (N3O- )and nitrites (N2O- ) to survive.
**•By their proffered temperature:-**
Each species of bacteria reproduces best within a limited range of temperatures.
**-Psychophiles:-**
Bacteria that grows best below 20oC.
**-Mesophiles:-**
Bacteria that grows best below 25oC – 40oC.
**-Thermophiles:-**
Bacteria that grows best below 45oC – 60oC.
**-Stenothermophiles:-**
Bacteria that grows best below 60oC.

*** Note:-**
when we classify a microorganism we mention its carbon source, energy source, relation with oxygen and some time, temperature.

**Example:-**

**Algae:-** aerobic photoautotrophs

**Fungi:-** obligate anaerobes nonphotosynthetic heterotrophic

**Protozoa:-** aerobic chemoheterotrophic

Relation with $O_2$ | Energy source | Carbon source

**B. Role of microorganisms in WWT:-**

Microorganisms are used mainly for the removal of organic matter, nitrogen, and phosphorus

**1. Biological organic matter removal:-**

**a. Aerobic biological oxidation (using aerobic bacteria)**

<u>first step</u>: oxidation and synthesis

$COHNS + O_2 + \text{nutrients} \rightarrow CO_2 + NH_3 + C_5H_7NO_2 + \text{other end products.}$

<u>Second step</u>:- Endogenous decay or respiration

$C_5H_7NO_2 + O_2 \rightarrow 5CO_2 + 2H_2O + NH_3 + \text{energy}$

**b. Anaerobic Fermentation**

Examples:-

(Methanol) $4CH_3OH \rightarrow 3CH_4 + CO_2 + 2H_2O$ {removal of methanol}

(Methylamine) $4\,(CH_3)_3N + H_2O \rightarrow 9CH_4 + 3CO_2 + 6H_2O + 4NH_3$ (removal of methylamine)

**Note:-**

Notice that anaerobic fermentation of organic matter always results in the production of methane.

## 2. Biological nitrogen removal:-

Nitrogen in the form of ammonia ($NH_3$) and organic nitrogen is removed biologically by two step process, the first step in called nitrification, the second step is called denitrification.

### a. Nitrification:-

In this process ammonia is first converted to $N_2O^-$ by a bacteria called nitrosomonas, then $N_2O^-$ is converted to $N_3O^-$ by a bacteria called nitrobacter.

$2NH_4^+ + 3O_2 \rightarrow 2NO_2^- + 4H^+ + 2H_2O$

$2\ NO_2^- + O_2 \rightarrow 2NO_3^-$

*** Note:-**

These bacteria are autotrophic (i.e do not need organic matter as a carbon source)

### b. Denitrification:-

In this process, $NO_3^-$ is converted to nitrogen gas $N_2$ by denitrifying bacteria. This bacteria is heterotrophic, since it needs organic matter as a carbon source. Organic matter needed for denitrifying bacteria can be taken from raw wastewater, or by adding other organic materials such as methanol and ethanol.

(Methanol): $5\ CH_3OH + 6\ NO_3^- \rightarrow 3\ N_2 + 5CO_2 + 7H_2O + 6OH^-$

### 3. Biological phosphorus removal:-

Phosphorus is removed from WW using special type of bacteria that is able to store phosphates in their cells under aerobic conditions and able to release phosphate under anaerobic conditions.

This fact is utilized, and this type of bacteria is allowed to grow in aerobic tanks to store "P" then this baeteria is separated and taken to anaerobic tanks were they release "P", then the same baeteria is recycled to aerobic tank and so on.

## 2.3 Types of biological process for WWT:-

The principal biological processes used for WWT can be divided into two main categories:

- Suspended growth processes.
- Attached growth processes.

### A. Suspended growth process

### a. Definition:-

It is a biological treatment process in which microorganisms are maintained in suspension while converting organic matter or other constituents in the wastewater to gases and cell tissue.

**b. Examples on this process:-**

- Conventional activated sludge system.
- Oxidation ditches.
- Sequencing batch reactor (SBR).
- Aerated lagoons.
- Up flow sludge blanket reactors

**B Attached growth process**

**a. Definition**

It is a biological treatment process in which microorganisms responsible for the conversion of organic matter or other constituents in wastewater to gases and cell tissue are attached to some inert material such as rocks, sand, or specially designed ceramic or plastic materials. Attached growth treatment processes are also called fixed film process.

**b. Examples on this process:**

- Trickling filters.
- Rotating biological contactors (RBC).
- Packed – bed reactors.
- Fluidized bed biofilm reactors

**Note:-**

Biological treatment systems are also classified as Natural or Technology systems.

**2.4 bacterial growth kinetics (Monod equation)**:-

It is important to understand the way by which the bacterial growth can be quantified. The most famous equation used to describe the rate of bacterial growth is the Monod equation:

$$\mu = \mu_m \frac{S}{K_s + S} \qquad \text{................ (1)}$$

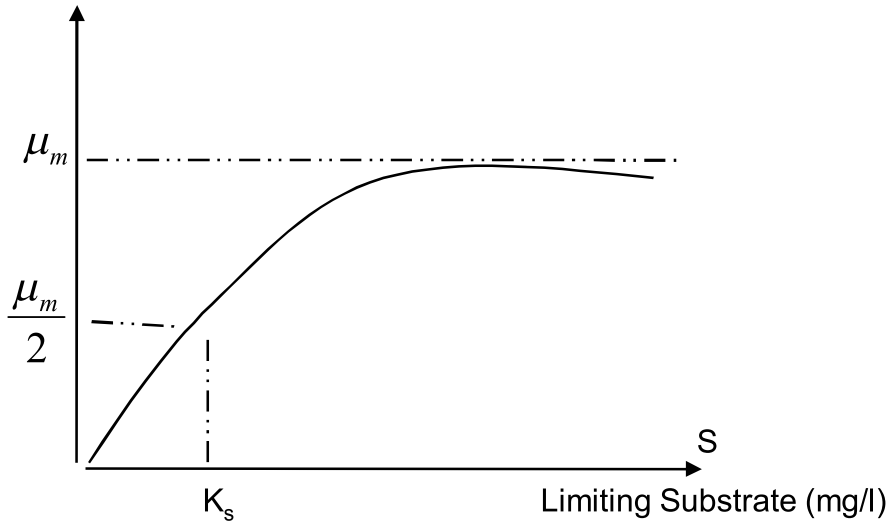
**Where,**

$\mu_m$ = maximum growth rate, $T^{-1}$

S = concentration of the limiting substrate, mg/L

Ks = half saturation constant, mg/L

The above equation is a hyperbolic function as shown on the figure below:




it was also found that the rate of change of biomass (microorganisms) concentration is governed by the following expression:-

$$\frac{dx}{dt} = \mu x \qquad \text{…………….} \ (2)$$

**where**,

$\frac{dx}{dt}$ = biomass growth rate, mg/L.t (it is also called rgrowth or rg)

$\mu$ = growth rate constant, t-1

X = concentration of biomass, mg/L

Supstitute from (1) into (2):

$$\frac{dx}{dt} = \frac{\mu_m Sx}{K_s + S} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(3)} \qquad \left( \frac{dx}{dt} = r_g \right)$$

equation (3) accounts for growth only. To account for death or decay of biomass another term is subtracted as follows:-

$$\frac{dx}{dt} = \frac{\mu_m Sx}{K_s + S} - \text{Kd X} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(4)}$$

where Kd = endogenous decay rate constant, t-1

* The rate of substrate utilization by the biomass is expressed using the following relation:-

$$\frac{-ds}{dt} = \frac{1}{Y}\frac{dx}{dt} \quad \ldots\ldots\ldots\ldots\ldots\ldots \text{(5)}$$

where, Y= biomass yield, $\frac{\text{g biomass produced}}{\text{gS consumed}}$

Substitute equ. In to equ:-

$$\frac{ds}{dt} = -\frac{1}{Y}\left[\frac{\mu_m SX}{K_s + S} - K_d X\right] \quad \text{................ (6)}$$

Note:-

ds/dt is also given the term: rsu $\rightarrow$ rate of substrate utilization.

$$\text{rsu} = -\frac{1}{Y}\left[\frac{\mu_m SX}{K_s + S} - K_d X\right] \quad \text{................ (7)}$$

if the decay term is neglected, then:-

$$r_{su} = -\frac{\mu_m SX}{Y(K_s + S)} = \frac{ds}{dt} \quad \text{................ (8)}$$

## 2.5 Types of reactors used for wastewater treatment:-

Biological reactions used for the treatment of wastewater are carried out in containers or tanks commonly known as reactors.

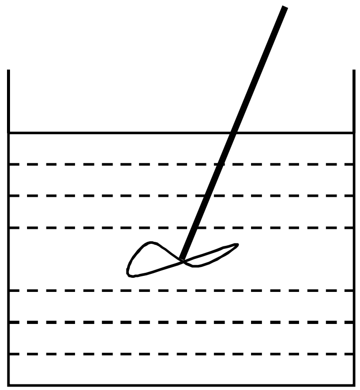
**Types of reactors:-**

The following are the main types of reactors used for WWT:-

**a. Batch reactor:-**

**The characteristics of this reactor are:-**

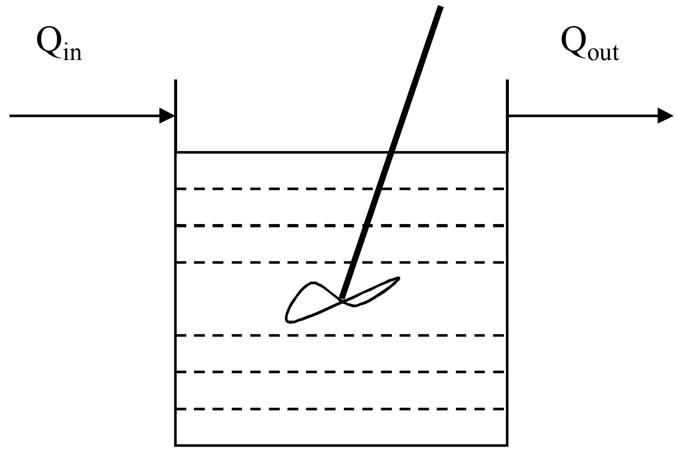
- a batch of WW is added to the reactor and allowed to react.
- During reaction no flow is allowed in or out of the reactor.
- The contents of the reactor are mixed completely, so the concentration of microorganism and pollutants (i.e BOD, TSS, etc) are the same every where



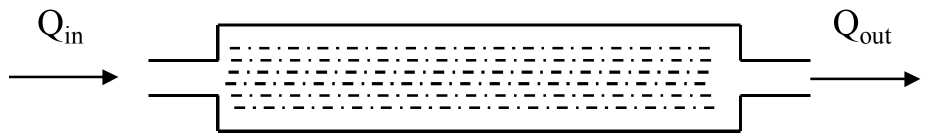
**b. Completely – mixed reactor:-**

**Characteristics of this type of reactors are:-**

- Wastewater flows continuously in and out of the reactor.
- The content of the reactor is completely mixed and the concentration of microorganisms (biomass) and pollutants are the same every where inside the reactor.



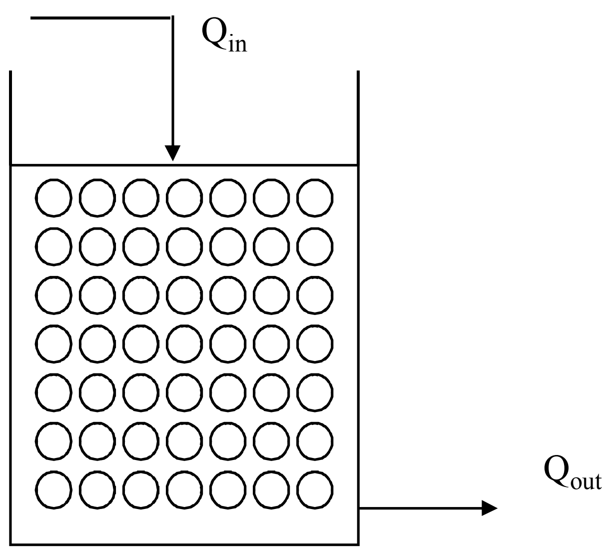
**C. Plug – flow reactor: - (or tubular reactor)**
**Characteristics of this type of reactor are:-**
- Wastewater flows continuously in and out of the reactor.
- No mixing in the reactor, fluid particles pass through the tank and are discharged in the same sequence they inter. The concentration of biomass and pollutants is high at the inlet of the reactor and low at the outlet.



**d. Packed – bed reactor:-**

**Characteristics of this type of reactors are:-**

- a solid media is packed in the reactor to allow the microorganisms to grow on.
- Wastewater flows continuously in and out of the reactor.
- This reactor is used for attached growth treatment systems

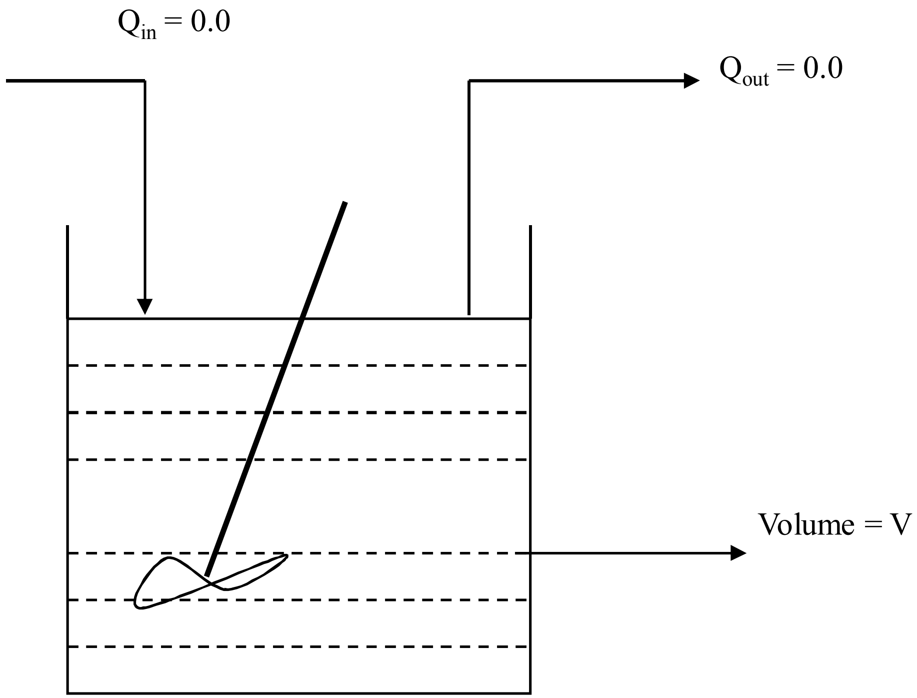


## 2.6 Modeling of biological treatment kinetics:-

In this part, we need to develop mathematical equations to model the biological reactions in the different types of reactors mentioned above:-

### A. Modeling batch reactors:-

To derive an equation to model the biological reaction in this reactor, we apply mass balance analysis on the substrate (i.e the pollutant of concern, such as BOD, N …..):-



Accumulation = inflow mass – outflow mass + generation of mass or substrate

$$\frac{ds}{dt} V = Qin\ So - Qout\ S + rsu\ V$$

For batch reactor Qin = Qout = 0.0

So $\Rightarrow \frac{ds}{dt} = r_{su}$ from eq. (8) $\rightarrow r_{su} = \frac{-\mu_m XS}{y(K_s + S)}$

$\frac{ds}{dt} = \frac{\mu_m XS}{y(K_s + S)}$, by integration:-

$$K_s \ln \frac{S_0}{S_t} + S_0 - S_t = X\left(\frac{\mu_m}{Y}\right)t \qquad \text{................ (9)}$$

**Where:-**

SO = initial substrate concentration at t = 0.0

St = substrate concentration at time t, mg/L

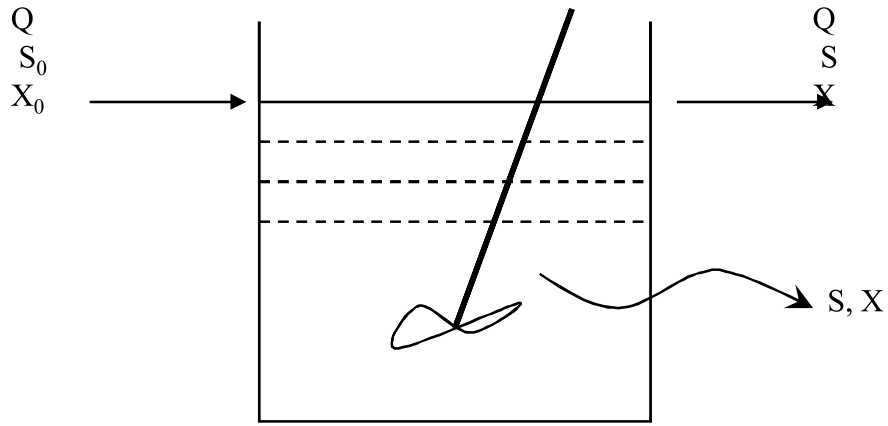
T = time, days.

Equation (9) is used for the design of batch reactors

**B. Modeling completely mixed reactors:-**

**a. <u>completely mixed reactor without solids recycle:-</u>**

**apply mass balance analysis on biomass, and on substrate:-**



* <u>biomass – mass balance:-</u>

$$\frac{dX}{dt} \quad V = QXO - Q\,X + Vrg$$

But $r_g = \dfrac{\mu_m XS}{K_S + S} - K_d X$ (from eq. 4)

Thus $\Rightarrow \dfrac{dx}{dt} \bullet V = QX_0 - QX + V\left(\dfrac{\mu_m XS}{K_s + S} - K_d X\right)$

we assume that Xo = 0.0, and this equation is simplified to:-

$\dfrac{Q}{V} = \dfrac{\mu_m S}{K_s + S} - K_d$ or $\rightarrow$ $\dfrac{1}{\theta} = \dfrac{\mu_m S}{K_s + S} - K_d$ ……………. (10)

**where:-**

Q = flow rate, volume / time.

V = volume of the reactor,

θ = hydranlic detention time = V/Q,

X = concentration of biomass in the reactor, mass/volume.

So = concentration of substrate in the influent mass/volume.

S = concentration of substrate in the tank and in the effluent.

* Substrate mass balance:-

$$\frac{ds}{dt} \bullet \text{V = QSo – QS + Vrus}$$

$$r_{su} = \frac{-\mu_m XS}{y(K_s + S)} \rightarrow \frac{ds}{dt} \bullet V = QS_0 - QS - \frac{V}{Y}\left(\frac{\mu_m XS}{K_S + S}\right)$$

At steady state $\dfrac{ds}{dt}$ = 0.0, thus the above equation becomes:-

$$(S_0 - S) - \frac{V}{QY}\left(\frac{\mu_m XS}{K_S + S}\right) = 0.0, but \frac{V}{Q} = \theta$$

Thus $\Rightarrow (S_0 - S) - \dfrac{\theta}{Y}\left(\dfrac{\mu_m XS}{K_S + S}\right) = 0.0$ ................ (11)

If equation (10) is rearranged in the following form:-

$\dfrac{1}{\mu_m}\left(\dfrac{1}{\theta} + K_d\right) = \dfrac{S}{K_S + S}$ , and this term is substituted in equation(11) $\Rightarrow$

then eq.(11) Becomes:-

$$(S_0 - S) - \frac{\theta}{Y}\left[\mu_m X\left(\frac{1}{\mu_m}\left[\frac{1}{\theta} + K_d\right]\right)\right]$$

Rearranging:-

$X = \dfrac{Y(S_0 - S)}{1 + K_d\theta}$ ................ (12)

Yobs is the observed biomass yield, which is the actual increase rate of biomass. If Kd is assumed to be 0.0, then Yobs = Y. But usually Kd has a Value > 0.0, and Yobs is <Y.

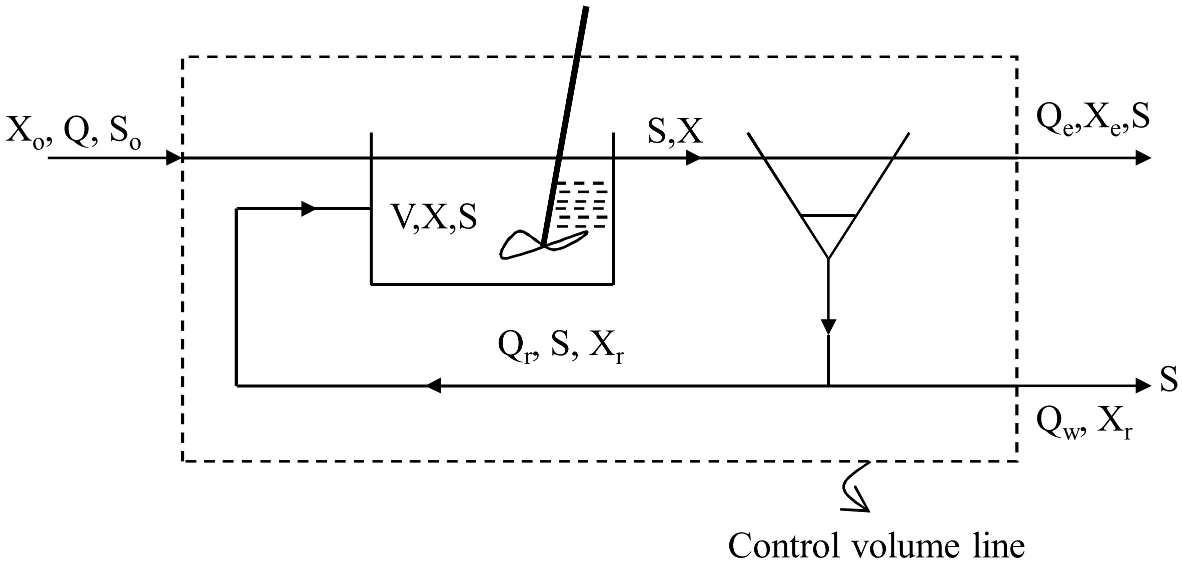
*** Note:-**

There is an important parameter used in relation to bacterial growth defined as:-

$K = \frac{\mu_m}{Y}$ ,Called the maximum substrate utilization rate per unit mass of microorganisms.

**b. Completely mixed reactor with solids recycle:**

This process is called the activated sludge system.



- Biomass – mass balance:-

$$\frac{dx}{dt} \bullet V = QX_0 - \left(Q_w X_r + Q_e X_e\right) + Vr_g$$

$\frac{dx}{dt}$ = rate of change of microorganisms in the reactor,

V = reactor volume,
Q = WW flow rate,
Xo = concentration of microorganisms in the influent,
Qw = Waste flow rate,
Xr = concentration of biomass in the return line,
Qe = effluent flow rate,
Xe = concentration of biomass in effluent,
rg = net rate of microorganisms growth (mass/unit volume time)

Assuming steady state conditions then → $\frac{dx}{dt}$ = 0.0, and assume Xo= 0.0

and substitute for rg from equation (4), the above equation simplifies to:-

$$Q_w X_r + Q_e X_e = V\left[\frac{\mu_m S X}{K_s + S} - K_d X\right]$$

$$\frac{Q_w X_r + Q_e X_e}{VX} = \frac{\mu_m S}{K_s + S} - K_d \quad \text{................ (14)}$$

The left hand side of equation (14) is the inverse of the mean cell residence time:-

$\theta_c = \dfrac{VX}{Q_w X_r + Q_e X_e}$ $\Rightarrow$ so equation (14) becomes:-

$$\frac{1}{\theta_c} = \frac{\mu_m S}{K_s + S} - K_d \quad \text{................ (15)}$$

* Substrate-mass balance:-

$$\frac{ds}{dt}\bullet V = QS_0 - \left(Q_w + Q_e\right) + S + Vr_{su} \quad \text{where?} \quad r_{su} = -\frac{\mu_m SX}{Y(K_s + S)}$$

At steady state $\frac{dS}{dt} = 0.0$

$$QS_0 - V\left[\frac{\mu_m SX}{Y(K_s + S)}\right] = Q_w S + Q_e S \quad \text{where?} \qquad Q_e = Q - Q_w$$

$$QS_0 - V\left[\frac{\mu_m SX}{Y\left(K_s + S\right)}\right] = QS \;\Rightarrow \text{rearrange}$$

$$\frac{Q}{V}\left(S_0 - S\right) = \frac{\mu_m SX}{Y(K_s + S)} \Rightarrow \frac{Q}{V} = \frac{1}{\theta}$$

then ? $$\frac{Y\left(S_0 - S\right)}{X\theta} = \frac{\mu_m S}{K_s + S} \;\ldots\ldots\ldots\ldots\ldots\ldots\; (16)$$

Substitute from (16) into (15) and rearrange:-

$$X = \frac{\theta_c}{\theta} \cdot \frac{Y(S_0 - S)}{(1 + K_d \theta_c)} \quad \ldots\ldots\ldots\ldots\ldots\ldots (17)$$

Equation (17) is used for calculating and designing the steady state biomass concentration in completely mixed reactor with solids recycle.

$\Rightarrow$ rearrange equation (15) and solve for S $\Rightarrow$

$$S = \frac{K_s (1 + K_d \theta_c)}{\theta_c (\mu_m - K_d) - 1} \quad \ldots\ldots\ldots\ldots\ldots\ldots (18)$$

Equation (18) is used to find the steady state substrate concentration in a completely mixed reactor with solids recycle.

* Some parameters of concern:-

$\dfrac{F}{M} = \dfrac{QS_0}{VX} = \dfrac{S_0}{\theta X}$ (Food to microorganism ratio in the reactor)

$U = \dfrac{S_0 - S}{\theta X}$ (specific substrate utilization rate)

$\dfrac{F}{M} = U \dfrac{S_0}{S_0 - S}$ (relation between $\dfrac{F}{M}$ and U)

$\theta_c^{\,m}$ = minimum sludge retention time

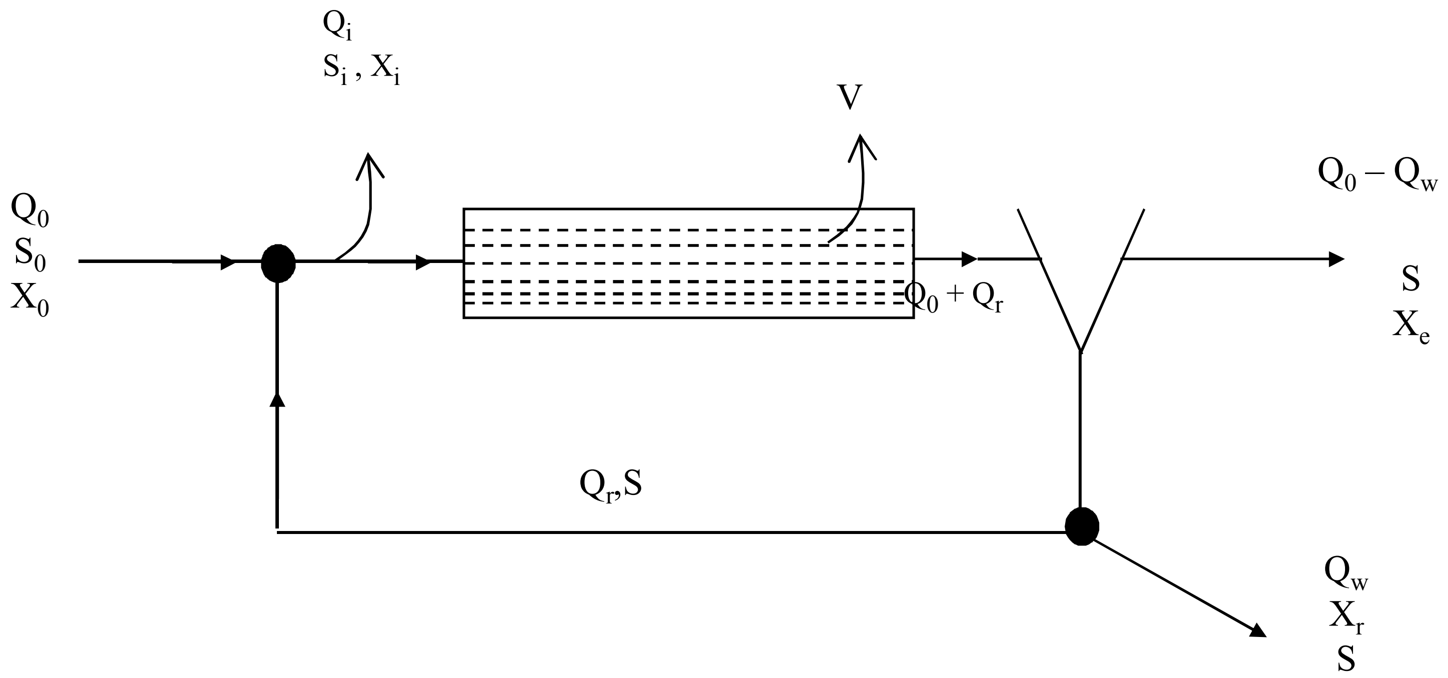
$$\frac{1}{\theta_c^m} = \frac{\mu_m S_0}{K_s + S_0} - K_d \cong \mu_m - K_d$$

$$S.F = \frac{\theta_c}{\theta_c^m}$$ (Safety factor, 2<S.F<20)

$$S_{\min} = K_S \frac{K_d}{\mu_m - K_d}$$ (The minimum substrate that should be maintained in the reactor to support biomass growth)

$P_x = Y_{obs}\, Q\, (S_o - S)$ (biomass production per unit time $= Q_W X_r + Q_e X_e$

## C. Modeling of plug – flow reactor with solids recycle:-




Mass balance analyses similar to that performed for completely mixed reactor with solids recycle is used to derive the design equations of the plug – flow reactor (PFR).

**The resulting design equations are:-**

$$\bar{X} = \frac{\theta_c}{\theta} \frac{Y(S_0 - S)}{1 + K_d \theta_c} \text{ ................ } (19)$$

Where $\bar{X}$ is the average biomass concentration in the PFR. (Note: similar to completely mixed with solid recycle)

$$\frac{1}{\theta_c} = \frac{\mu_m (S_0 - S)}{(S_0 - S) + (1+\alpha) K_s \ln(Si/S)} - K_d \text{ ................ } (20)$$

**Note:** $\mu_m = Yk$

**Where:-**

$si = \dfrac{Q_0 S_0 + Q_r S}{Qi}$ = substrate concentration after mixing the influent wastewater with the recycle flow.

$Q_i = Q_o + Q_r$

$\propto = \dfrac{Q_r}{Q_o}$ (recycle ratio)

**The solids retention times is related to the reactor volume and recycle flow as follows:-**

$$\theta_c = \frac{V \bar{X}}{Q_w X_r + (Q_0 + Q_w) X_e} \ldots\ldots\ldots\ldots\ldots (21)$$

If $X_e$ is neglected compared to $X_r$, equation (21) becomes:-

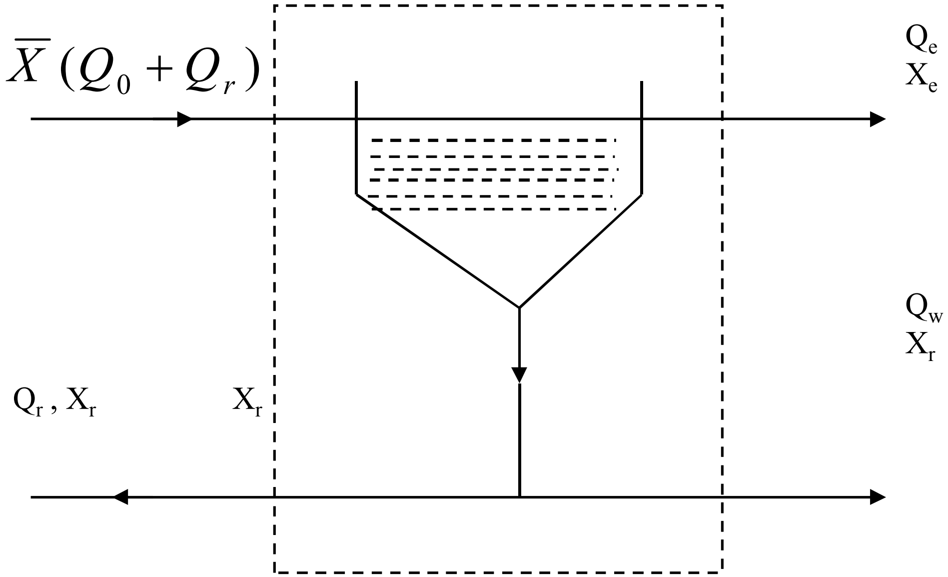
$$\theta_c = \frac{V \bar{X}}{Q_w X_r} \ldots\ldots (22)$$

***Note:-**
equations (21) and (22) apply for complete mixed Reactor with solids recycle (CMR). Equations (19), (20), (21) and (22) are used to design PFRs.

*** Note:-**
The recycle ratio "α " or "R" can be found using mass balance around the final sedimentation tank.

$$Q_r = \frac{Q_0 \bar{X} - Q_w X_r - (Q_0 - Q_w) X_e}{X_r - \bar{X}}$$

$$\alpha = \frac{Q_r}{Q_0} = R$$


$\overline{X}\,(Q_0 + Q_r)$
$Q_e$
$X_e$
$Q_w$
$X_r$
$Q_r$ , $X_r$
$X_r$