หอสมุดกลาง จุฬาลงกรณมหาวิทยาลัย

III THEORETICAL CONSIDERATION

3.1 Activated Sludge

The activated sludge process may be defined as a system in which flocculated biological growths are continuously circulated and contacted with organic waste in the presence of oxygen. The oxygen is usually supplied from air bubbles injected into the sludge-liquid mass under turbulent conditions. The process involves an aeration step followed by a solid-liquid separation step from which the separated sludge is recycled back for admixture with the waste. The aeration step may be considered in three functional phases:

(a) a rapid absorption of waste substrate by the active sludge

(b) progressive oxidation and synthesis of the absorbed organics and organics concurrently removed from solution,

(c) further aeration resulting in oxidation and dispersion of the sludge particles.

Various modifications of the activated sludge process have been developed to achieve economic advantage in construction and operation.

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Factors that must be considered in the design of the activated-sludge process include

(1) loading criteria,

(2) selection of reactor type,

(3) sludge production,

(4) oxygen requirements and transfer,

(5) nutrient requirements,

(6) environmental requirements,

(7) solid-liquid separation, and

(8) effluent characteristics.

3.1.1 Conventional Activated Sludge Process consists of four functional steps:

(a) Primary sedimentation to remove settleable organic and inorganic solids.

(b) Aeration of a mixture of waste and a biological active sludge.

(c) Separation of the biologically active sludge from its associated treated liquor by sedimentation.

(d) Return of settled biological sludge to be admixed with the raw wastes.

The conventional process can operate over a wide range of loading conditions, varying from an active sludge with high synthesis yields to extended aeration in which most of the sludge synthesized in the process is destroyed by oxidation. The loading limitation on the process is that required to effect flocculation and permit settling and separation of the biological floc.

Conventional activated sludge treatment of waste produces over 90 percent BOD reduction.

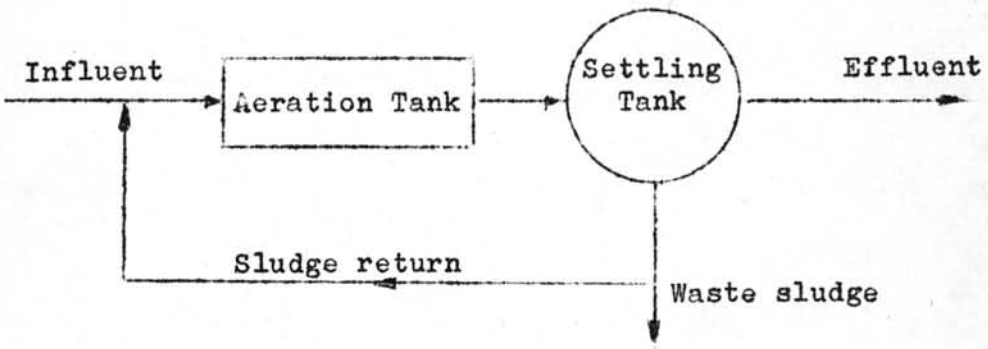


Figure 3.1[6] Conventional Activated Sludge

3.1.2 Contact - Stabilization

The contact-stabilization process was developed to take advantage of the absorptive properties of activated

sludge. In some case, primary settling is eliminated. It has been postulated that BOD removal occurs in two stages in the activated sludge process. The first is the absomptive phase which requires 20 to 40 min. During this phase most of the colloidal, finely suspended, and dissolved organics are absorbed in the activated sludge. The second phase, oxidation, then occurs, and the absorbed organics are metabolically assimilated. In the activated sludge processes mentioned so far, these two phase occur in a single tank. In the contact-stabilization process, the two phases are separated and occur in different tanks.

The settled sewage is mixed with return activated sludge and aerated in a contact tank for 30 to 90 min. During this period, the organics are absorbed by the sludge floc. The sludge is then separated from the treated effluent by sedimentation, and the returned sludge is aerated from 3 to 6 hr in a sludge aeration tank. During this period, the absorbed organics are utilized for energy and production of new cells. A portion of the returned sludge is wasted prior to recycle, to maintain a constant MLVSS concentration in the tanks.

The aeration volume requirements are approximately 50 percent of those of a conventional or tapered-aeration plant. It is thus often possible to double the plant capacity of an existing conventional plant by redesigning it to use contact

stabilization. The redesign may require only changes in plant piping or relatively minor changes in the aeration system.

The contact-stabilization process has been found to work very well on domestic wastes; however, before using it on industrial wastes or mixtures of domestic and industrial wastes, laboratory tests should be performed. Its value in industrial waste treatment is limited largely to waste in which the organic matter is not predominantly soluble.

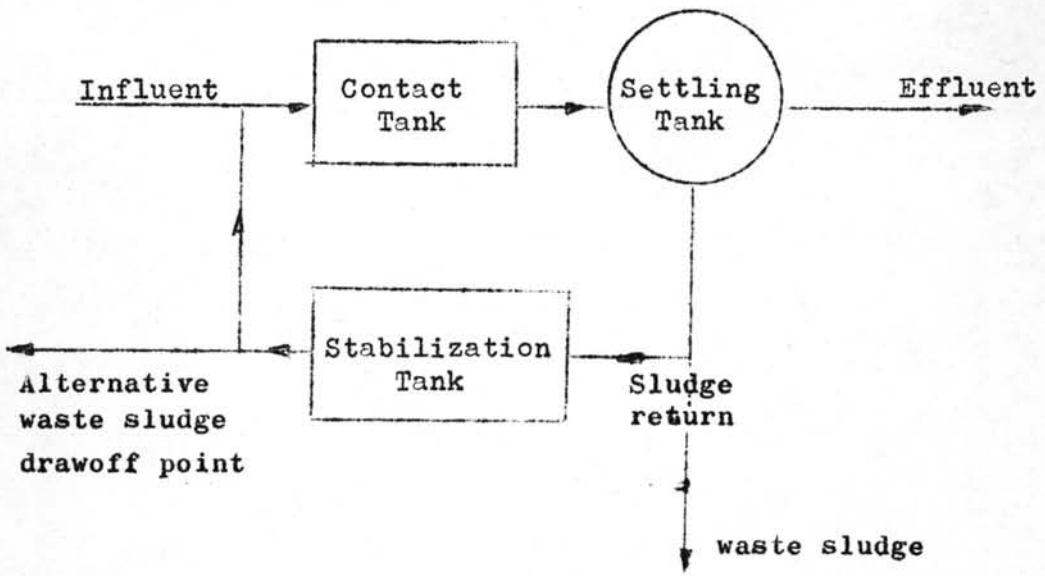


Figure 3.2[6] Contact Stabilization

3.1.3 Extended - Aeration

The extended - aeration process operate in the endogeneous respiration phase of the growth curve, which necessitates a relatively low organic loading and long aeration time. Thus it is generally applicable only to small treatment plants of less than 1-mgd. capacity.

This process is used extensively for prefabricated package plants that provide treatment for housing subdivisions, isolated institutions, small communities, schools, etc. Although separate sludge wasting generally is not provided, it may be added where the discharge of the excess solids is objectionable. Aerobic digestion of the excess solids, followed by dewatering on open sand beds, usually follows separate sludge wasting. Primary sedimentation is omitted from the process to simplify the sludge treatment and disposal.

3.2 Principles of Biological Oxidation

When an organic waste is contacted with biological sludge, BOD is removed by several mechanisms. Suspended and finely divided solids are removed by adsorption and coagulation. A portion of the soluble organic matter is initially removed by absorption and stored in the cell as a reserve food source. Additional dissolved organic matter is progressively removed during the aeration process, resulting in the synthesis of sludge and the production of carbon dioxide and water. Availability for oxidation decreases as the complexity of the organic compounds increases. Large particles undergo subdivision by hydrolysis prior to oxidation. The rate of BOD removal after initial absorption depends primarily upon the concentration of BOD to be removed and the concentration of sludge solids.

The reactions involved in the removal of BOD from solution during bio-oxidation can be interpreted as a 3-phase

process.[7]

(1) An initial removal of BOD on the contact of a waste with a biologically active sludge which is stored in the cell as a reserve food source.

(2) Removal of BOD in direct proportion to biological sludge growth.

(3) Oxidation of biological cellular material through endogenous respiration.

These reactions are illustrated by the following equations:

Organic Matter Oxidation

$$C_x H_y O_z + O_2 \xrightarrow{\text{enzyme}} CO_2 + H_2O - \Delta H \quad \text{----------(3-1)}$$

Cell Material Synthesis

$$(C_x H_y O_z) + NH_3 + O_2 \xrightarrow{\text{enzyme}} \text{cells} + CO_2 + H_2O - \Delta H \quad \text{----------(3-2)}$$

Cell Material Oxidation

$$(\text{cells}) + O_2 \xrightarrow{\text{enzyme}} CO_2 + H_2O + NH_3 - \Delta H \quad \text{----------(3-3)}$$

The term ΔH represents the heat of reaction. These generalized equations must be modified for organic compounds containing nitrogen or sulfur.

Equation (3-1) is the conventional equation of combustion. If nitrogen is present, it will be oxidixed to nitrate;

sulfur will be oxidized to sulfate.

Equation (3-2) represents the synthesis of cell material from organic substrates.

Equation (3-3) represents the oxidation of cellular material previously synthesized.

The synthesis of activated sludge as shown by Equation (3-2)

Tamiya has stated that all cell synthesis reactions are exothermic and hence energy is supplied by the reaction.[7] Exact quantitative relations can be determined only be experiment since they will vary depending upon the specific environment.

3.3 BOD Removal and Sludge Growth

The growth of a biological sludge mass in a batch oxidation follows the sigmoidal curve shown in Fig. 3-3. This type of growth is followed by all biological populations. The lower portion of the growth curve is concave upward and represents a geometric increase in sludge mass (a-b). This is called the logarithmic growth phase, during which regular and maximum multiplication of the sludge cells is taking place. This growth phase occurs in the presence of an abundant supply of food.

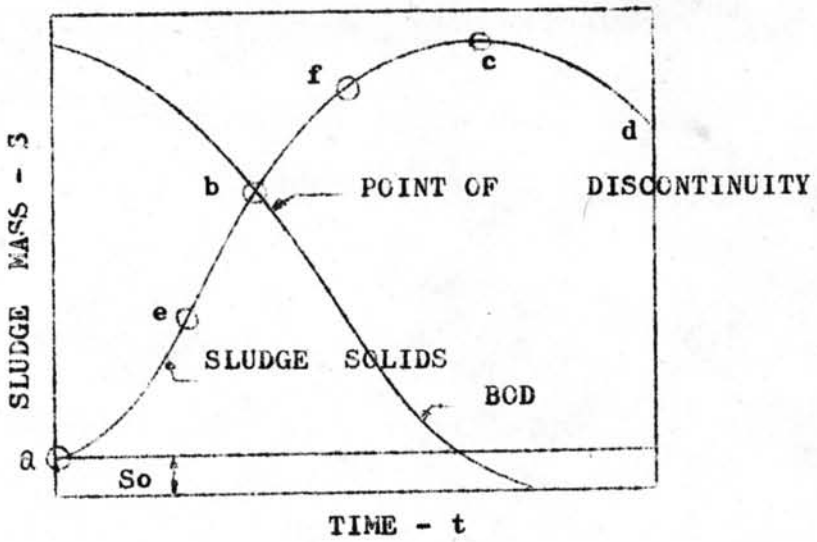


Fig 3.3[7] BOD removal and sludge growth relationship

The middle portion of the curve is approximately linear. As the available food supply becomes exhausted, a declining growth phase occurs in which cellular division occurs at less frequent intervals (b-c). The upper portion of the curve (b-c) follows a first order reaction. The sludge growth curve becomes asymptotic to a limit which is dependent upon the concentration of available food.

The portion of the growth curve (c-d), following the sigmoidal curve, represents the decrease in sludge mass resulting from autooxidation which occurs after the depletion of the available food. This is often called the endogenous respiration phase of activated sludge. The auto-oxidation initially follows first-order kinetics, followed by a decreasing oxidation rate as the bacterial substrate becomes less available for oxidation.

In some cases a lag phase may exist in the growth relationship. This will occur when a dissimilar food supply is introduced (i.e., sewage organisms to industrial wastes) or by employing sludge which is in the advanced endogenous phase. A lag phase of 2-5 days to attain full purification capacity was found by Sawyer et al. when employing a sludge aerated under starvation conditions for 21-22 days.(7)

3.4 Kinctics of Microbial Growth and Substrate Utilization

The theoretical development of continuous culture models was originaly pressented by Monod and Novick and Szilard and later amplified by Herbert, Elsworth and Telling.(8) Numerous review have described important applications of such models in microbiology and biochemical engineering. The use of similar models in biological waste treatment studies is increasing.

The relationship between biological growth and substrate utilization can be formulated in two basic equations. The first equation describes the relationship between net rate of growth of microorganisms and rate of substrate utilization as

$$\frac{dx}{dt} = Y\left(\frac{dF}{dt}\right) - b\,x \qquad \text{---------- (3-4)}$$

where:

$\frac{dx}{dt}$ = net growth of microorganisms per unit volume of reacter, mass/volume-time

Y = growth yield coefficient, mass/mass

$\frac{dF}{dt}$ = rate of microbial substrate utilization per unit volume, mass/volume - time

b = microorganism decay coefficient, $time^{-1}$

x = microbial mass concentration, mass/volume

This equation was developed empirically from waste treatment studied, and more recently has been shown to apply to pure culture microbial systems as well.

The second basic equation relates the rate of substrate utilization both to the concentration of microorganisms in the reactor and to the concentration of substrate surrounding the organisms. The equation, in only a slightly different from that used by Monod,[8] is

$$\frac{dF}{dt} = \frac{k\,SX}{K_s + S} = \frac{dS}{dt} \qquad \text{----------(3-5)}$$

where:

k = maximum rate of substrate utilization per unit weight of microorganisms (occuring at high substrate concentration), $time^{-1}$

S = concentration of substrate surrounding the microorganisms, mass/volume

Ks = half velocity coefficient, equal to the substrate concentration when $dF/dt = \frac{1}{2}k$, mass/volume.

This equation indicates that the functional relationship between substrate utilization rate and substrate concentration is continuous over the total range of substrate concentrations. In the two extreme case (1) when S is very high ($S >> K_s$), and (2) when S is very low ($S << K_s$), Equation 2 can be approximated by

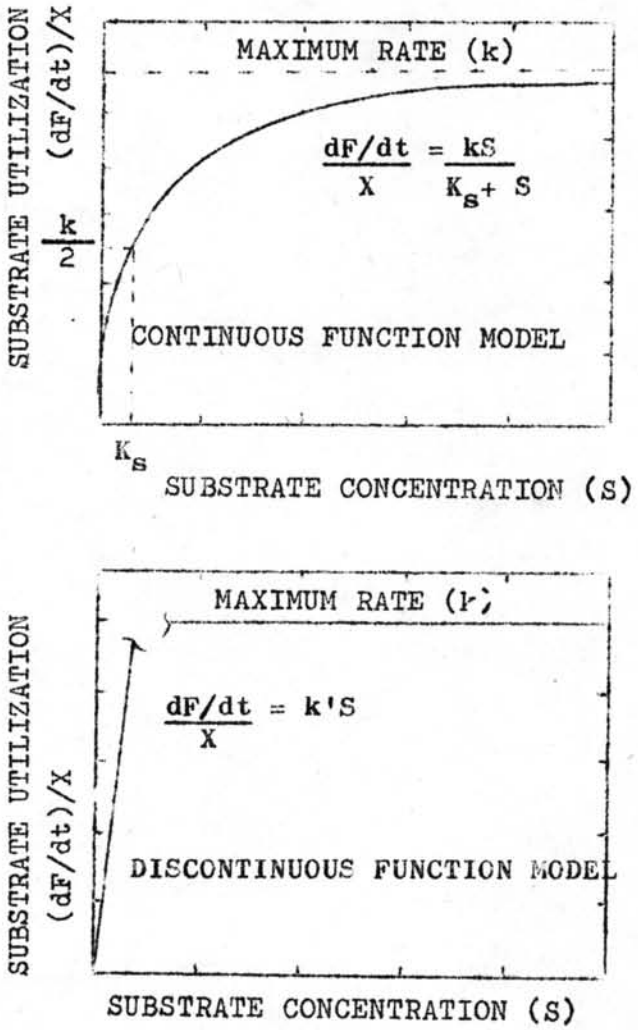


Figure 3.4[8] Schematic Representation of Substrated Removal rate as a Function of Substrate Concentration.

the following discontinuous functions:

$$\frac{dF}{dt} = k\,X;\quad S >> Ks \qquad \text{---------- (3-6)}$$

$$\frac{dF}{dt} = k^{1}\,X\,s;\quad S << Ks \qquad \text{---------- (3-7)}$$

where $k^{1} = \frac{k}{K_s}$

Equation (3-6) is a zero order reaction with respect to substrate concentration while Equation (3-7) is first order.

Figure 3-4 shows the form of the continuous and discontinuous relationships given by Equation (3-5) through (3-7). While the merits of the two models have been debated, it should be emphasized that both are empirical and a choice between the two should properly be based more upon convenience and ability to furnish a satisfactory solution than upon any fundamental considerations. The practical value of the discontinuous functions has been demonstrated in activated sludge research and design. The estimation of substrate utilization by this approach leads to a less significant approximation than do the use of COD or BOD as a measure of waste concentration; and the complexities involved with additive and sequential substrate utilization. Use of a continuous function is in many ways more satisfying and allows comparison of results with studies reported in the microbial literature. For example, by combining equations (3-4) and (3-5) the resulting a relationship between growth rate and substrate concentration is identical to the equation proposed by

van Uden for pure culture microbial systems. This relationship is

$$\mu = \frac{Y\ k\ S}{K_s + S} - b \qquad \text{---------- (3-8)}$$

where:

$$\mu = \frac{dx/dt}{X}$$

= the net specific growth rate of microorganism, time^{-1}

Also, the parameter Ks of the continuous function provides valuable information about the shape and limits of the process efficiency curve.

The notes of Canale was written,[9] "Monod (1942), and many workers in the field of waste treatment, have shown that a linear relation exists between limiting element utilization and bacterial growth as described by equation (3-9)

$$\left(\frac{dS}{dt}\right)_{uptake} = -\left(\frac{dX}{dt}\right)_{growth} \frac{1}{Y} \qquad \text{----------(3-9)}$$

where Y is the cell yield

$$Y = \frac{\text{mass of bacteria produced}}{\text{mass of limiting element consumed}} \qquad \text{------(3-10)}$$

(Note that the minus sign is necessary since a positive change in X results in a negative change in S)

The decreases in bacteria due to death and endogeneous respiration may be accounted for by writting.

$$\left(\frac{dX}{dt}\right)_{e.r.} = bX \qquad \text{---------- (3-11)}$$

where: $\left(\frac{dX}{dt}\right)_{e.r.}$ = rate of decrease in bacteria concentration due to endogeneous respiration

b = microorganism decay coefficient, time^{-1}

X = microbial mass concentration, mass/volume.

It has been shown previously that the total oxygen requirements in a biological system are related to the oxygen consumed to supply energy for synthesis and the oxygen consumed for endogeneous respiration. This assumes that oxygen must be supplied to the system in order to:[10]

(a) provide oxygen for biological organic removal ($a^1 S_r Q$)

(b) provide oxygen for endogenous respiration where cells lyse and release soluble oxidizable organic compound ($b^1 X_a V$)

(c) provide oxygen required for chemical oxidation as measured by the immediate oxygen demand ($k^* Q$)

$$R_r V = a^1 S_r Q + b^1 X_a V + k^* Q \qquad \text{----------(3-12)}$$

where:

R_r = oxygen utilization per day

V = volume of aeration basin

a^1 = fraction of substrate (BOD or COD) used for oxidation

Sr = substrate (BOD or COD) removed

Q = flow

b^1 = fraction per day of VSS oxidized (oxygen basis)

Xa = average MLVSS in aeration tank

K* = chemical oxygen demand coefficient (as measured by immediate demand)

Sludge accumulation in the activated aludge system from the biological oxidation of wastewaters can be estimated using a similar approach. The components of a mathematical relationship would include:

(a) increase in sludge attributable to influent ss (QXo)

(b) increase in sludge due to cellular synthesis (aSrQ)

(c) decrease in sludge due to cellular oxidation or endogenous respiration (bXaV)

(d) decrease in sludge due to effluent ss (QXe)

$$\Delta X = QX_o + a\,SrQ - (bXaV + QXe) \qquad (3\text{-}13)$$

where:

ΔX = sludge production per day

V = Volume of aeration basin

Q = flow

a = fraction of substrate converted to new cells

Sr = substrate removed (So - Se)

b = fraction per day of VSS oxidized (sludge basin)

Xa = average MLVSS in aeration tank

Xo = influent ss

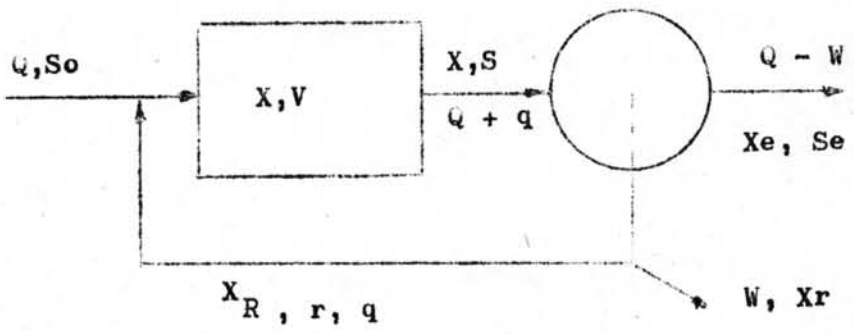
Xe = effluent ss

rearrang Equation (3 - 10) neglecting influent and effluent suspended solids:

$$\frac{\Delta X}{Xa} = \frac{a(SO - Se)}{Xat} - b \quad \text{----------(3-14)}$$

3.5 Design Parameters

The design of the activated sludge process involves selection of the proper F:M or SRT to produce a desired effluent organic concentration. The design parameters of importance are aeration tank size, mixed liquor suspanded solids concentration, sludge recycle ratio, exess sludge production, and oxygen requirement. Figure 3.5 shows a schematic of the activated sludge process. The only known parameters are flow and feed strength.



	= wastewater flow, gpd	So	= influent organic concentration, mg/l BOD, or COD
Se	= effluent soluble organic concentration, mg/l BOD, or COD	X	= aeration tank mixed liquor suspended solids (MLSS), mg/l
V	= aeration tank volume, gal	q	= recycle flow, gpd
r	= recycle ratio, g/Q	X_R	= clarifier underflow suspended solids concentration, mg/l
W	= rate of excess sludge wasted, gpd	Xe	= effluent suspended solids concentration, mg/l

Figure 3.5[11] Activated sludge system of wastewater treatment

The definitions and fundamental relationships used for the F:M ratio and SRT design technique are given below. The definitions and equations were developed and presented by Stensel & Shell and Lawrence & McCarty.(11)

$$F : M = \frac{Q\ So}{X\ V} \qquad \text{---------- (3-15)}$$

$$SRT = \frac{M}{\Delta X/\Delta t} = \frac{X\ V}{X_r W + Xe\ (Q-W)} \qquad \text{---------- (3-16)}$$

$$U = \frac{\Delta S/\Delta t}{M} = \frac{Q(so-se)}{X\ V} \qquad \text{---------- (3-17)}$$

$$\frac{1}{SRT} = Y\ U - b \qquad \text{---------- (3-18)}$$

$$HRT = \frac{V}{Q} = \frac{Y(So-Se)\ SRT}{(1+b(SRT))\ X} \qquad \text{---------- (3-19)}$$

$$\frac{1}{SRT} = E\ (\frac{F}{M})\ Y - b \qquad \text{---------- (3-20)}$$

$$E = \frac{So - Se}{So} \qquad \text{---------- (3-21)}$$

Where:

F : M = food to microorganism ratio

SRT = sludge retention time, days

X = aeration tank MLSS concentration, mg/l

Xr = recycle suspended solids (SS) concentration mg/l

Xe = clarifier effuent SS concentration, mg/l

M = biological mass in system, lb

$\Delta X/\Delta t$ = biological mass waste per day, lb/day

$\Delta S/\Delta t$ = substrate removal per day, lb/day

U = Specific substrate utilization rate, 1/day

HRT = hydraulic retention time, day

Y = solids yield coefficient,

b = microorganism decay coefficient, 1/day.

E = fraction of substrate removed.

3.6 Character of Biological Sludge

The microbial sludge or biological floc employed in bio-oxidation process is a miscellaneous collection of micro-organisms such as bacteria, yeasts, molds, protozoa, rotifers, worms and insect larvae in a gelatinous mass. Algae will also be present in those areas exposed to sunlight.

An excellent compendium of the ecology of activated sludge and trickling filters has been presented by Hawkes. The bacteria are primary non-nitrifrying aerobic spore formers, many of which are of the B. subtilis group. Nitrifying bacteria are primary Nitrosomonas spp. and Nitrobacter spp. In most activated sludge process the sludge appears as zoogleal masses intermixed with filamentous bacteria. One of the principal forms in the zoogleal mass is Zooglea ramigera which has been defined as a gram-negative, non-spore forming, motile, capsulated rod. Since most bacteria under proper conditions can flocculate, Zooglea ramigera may not be a true species, but rather a growth form of many species. Other common forms of bacteria found in activated sludge include Flavobacterium spp, Pseudomonas spp.

and filamentous organisms, the most common of which is Sphaerotilus natans. Fungi are more common in trickling filters than in activated sludge. These forms generally exist in the presence of low oxygen tension, low pH or low nitrogen content. Of the protozoa, stalked ciliates are the most common, including Vorticella spp. , Opercularia spp. and Epistylis spp. Free swimming types include Paramoecium spp., Linnotus spp. and Trichoda spp. Some forms of Flagellata and Rhizopoda are also found. The relationship between the type of protozoa which predominates and the bacterial population seems to dopend on the degree of flocculation. In a well flocculated sludge, stalked ciliates and attached forms are common since they feed on the zoogleal mass. With low flocculation free swimming forms dominate. The interrelationship between bacteria and protozoa on treatment efficiency is not well defined. It is generally conceded, however, that protozoa aid in clarification. Englegrect and McKinney found that sludge developed on structurally related compounds possessed similar morphological characteristics and produced similar biochemical changes. For example, they found that dense flocs were produced from the pentose sugars xylose and arabinose and that filamentous floc was produced from the hexose sugars, glucose and fructose.(7)(12)

3.7 Nutrient requirements

Several mineral elements are essential for the metabolism organic matter by microorganisms.

The quantity of nitrogen required for effective BOD removal and microbial synthesis has been the subject of much research. Early work by Frame et al. indicated a nitrogen requirement of 4.3 lb N/100 lb BOD removed and a phosphorous requirement of 0.6 lb P/100 lb BOD removed. These represent average values derived from the treatment of several nitrogen-supplemented industrial wastes. Porges et al. showed that treatment of dairy wastes yielded a cell with the empirical formula $C_5H_7NO_2$, containing 12.3 percent nitrogen. Cells of similar composition were found by Symons. When insufficient nitrogen is present, the amount of cellular material synthesized per unit of organic matter removed increases as an accumulation of polysaccharide. At some point nitrogen-limiting conditions restrict the rate of BOD removal.

Not all organic nitrogen compounds are available for synthesis. Ammonia is the most readily available form, and other nitrogen compounds must be converted to ammonia. Nitrite, nitrate, and about 75 percent of organic nitrogen compounds are also available.

As can be seen from Fig. 3.6, endogenous respiration releases nitrogen from cellular material, and the nitrogen is again available for synthesis. Symons recently showed that the nonoxidizable residue after extended aeration contains 7 percent nitrogen by weight. On the basis of a residue of 23 percent

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of the cellular material formed, the maximum recovery of nitrogen is 87.5 percent.[13]

3.8 Nitrification

The most work on nitrification in recent years has been reported by Downing and his co-workers and by Wuhrmann. Nitrification results from the oxidation of ammonia by Nitrosomonas to nitrite and the subsequent oxidation of the nitrite to nitrate by Nitrobacter. Since a buildup of nitrite is rarely observed, it can be concluded that the rate of conversion to nitrite controls the rate of the overall reaction.

In order for effective nitrification to occur, the sludge retension period or sludge age must be greater than the growth rate of the nitrifying organisms. Shorter sludge ages will result in a washout of these organisms. The results of Downing and Wuhrmann show that these resultant retention periods are usually sufficient to effect substantially complete nitrification.[12][13]

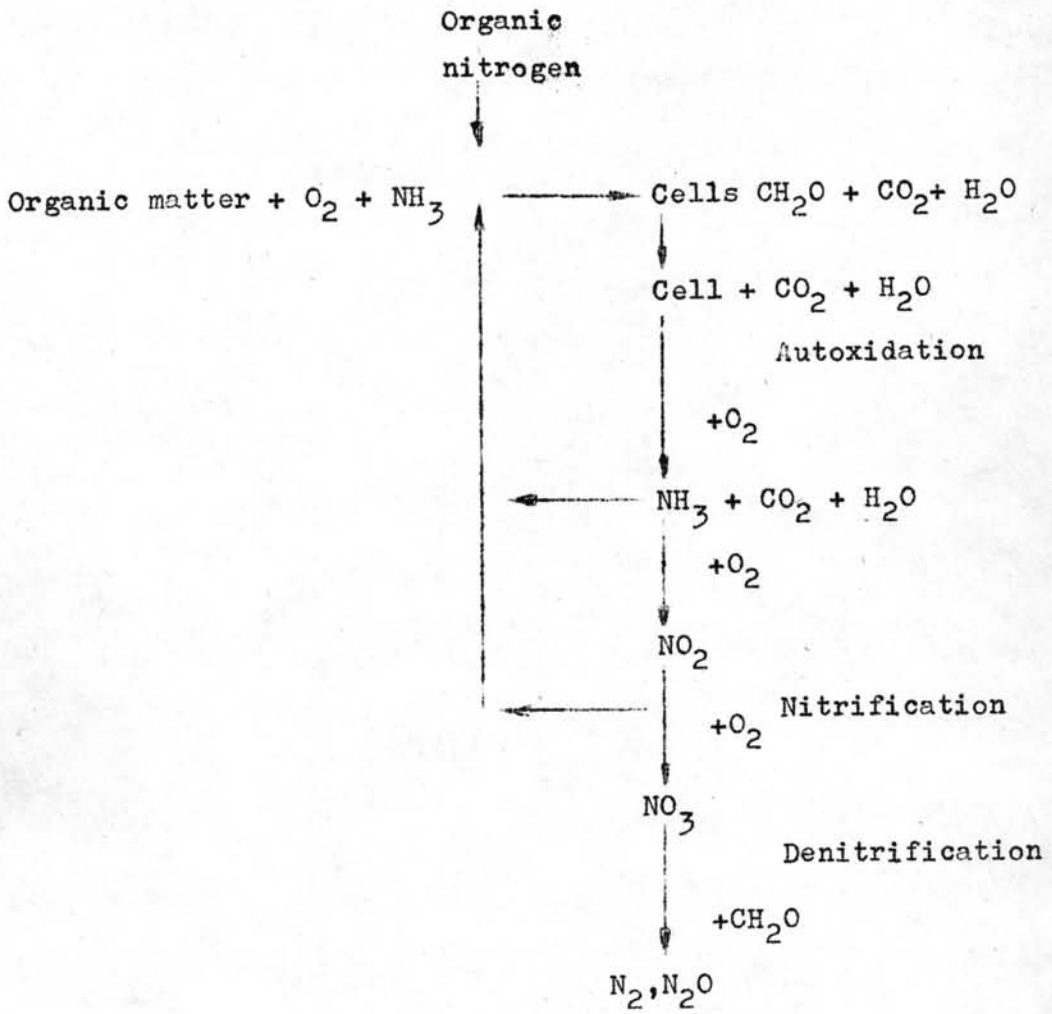

Figure 3.6 [12] The nitrogen cycle in biological oxidation processes.

3.9 Denitrification

Recently, emphasis has been placed on the removal of nitrogen from sewage and waste effuents to minimize the eutropication of receiving waters. Nitrogen removal occurs by denitrification, which first reguires conversion of ammonia to nitrate. Since nitrification does not occur to any marked

extent until most of the carbonaceous material is removed, it must be accompanied by considerable autoxidation of cellular material releasing additional nitrogen to solution. Denitrification is accomplished by facultative heterotrophic anaerobic bacteria in which nitrates are reduced to N_2, N_2O, and NO. Most of the reduction is to nitrogen gas. Although the dissolved oxygen level does not have to be zero, the process is considerably slower at higher dissolved oxygen levels depending on the pH. An available carbon source is important to provide energy for the denitrifying bacteria. This has been accomplished by the addition of some waste to the denitrifying end of the aeration tank or through the endogenous respiration of the biological cells.(12)

3.10 Effect of Temperature

Variations in temperature affect all biological processes. The rate of the biological reaction will increase with temperature to an optimum value, approximately 30°C for most aerobic waste systems. Further increases in temperature result in a decrease in rate for mesophilic organisms. Thermophilic organisms will exert a maximum rate over a temperature range of 35 to 65°C. The magnitude of the temperature effect, however, depends in great measure on the nature of the process.(12)

3.11 Effect of pH

A relatively narrow effective pH range will exist for most biooxidation systems. For most processes this covers a range of pH 5 to 9 with optimum rates occurring over the range pH 6 to 8. It is significant to note that this relates to the pH of the mixed liquor in contact with the biological growths and not the pH of the waste entering the system. The influent waste is diluted by the aeration tank contents and is neutralized by reaction with the CO_2 produced by microbial respiration. In the case of both caustic and acidic wastes, the end product is bicarbonate (HCO_3), which effectively buffers the aeration system at near pH 8.0[12]

3.12 Toxicity

Toxicity in biological oxidation systems may be due to one of several causes:

1. An organic substance, such as phenol, which is toxic in high concentrations but biodegradable in low concentrations.

2. Substances, such as heavy metals, which have a toxic threshold depending on the operation conditions.

3. Inorganic salts and ammonia which exhibit a retardation at high concentrations

The toxic effects of organics can be eliminated by employing the complete mixing system in which the influent is

diluted by the aeration tank contents, and the microorganisms are only in contact with the effluent concentration. In this way waste with concentration many times the toxic threshold can be sucessfully treated.(12)