ADVANCES IN BIOLOGICAL WASTEWATER TREATMENT

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Introduction

Increase in the population since the 19th century had initiated demand for more food products and housing. Thus the production of wastewater and the subsequent deterioration of environment due to wastewater being discharged into watercourses have been increasing since the 1800's. As a result biological wastewater treatment emerged in 1880's in the form of trickling filters, septic tanks and sedimentation tanks. The activated sludge process for treating wastewater was introduced in the beginning of the 20th century. In the 1960's, an increase in nitrogen in wastewater was attributed to the rapid increase in the production of NH_3 fertilizers, while the phosphorous levels increased due to the increased production of detergents.

In biological wastewater treatment, microorganisms are utilized to treat wastewater as they can uptake organic matter and nutrients (such as nitrogen and phosphorus) that are present in wastewater for their growth. Thus the organic and inorganic contaminants are removed from biologically treated wastewater to a great extent. The microorganisms that treat wastewater require carbon sources for their cell synthesis (growth) and energy sources for both cell synthesis and maintenance. The principal carbon sources used in cell synthesis are either carbon dioxide or organic substances present in wastewater and the source for energy production is either light or chemical compounds that are present in wastewater. Thus microorganisms are classified according to carbon and energy sources they use for their cell synthesis and maintenance (see Table 1).

Table 1 Classification of microorganisms based on the type of energy and carbon sources they use in cell synthesis and maintenance

Energy source	Carbon source	
	Carbon dioxide	Organic substances
Light	*Photoautotrophs* Higher plants, algae, photosynthetic bacteria	*Photoheterotrophs* Purple and green bacteria
Chemical	*Chemoautotrophs* Enengy from reduced organic compounds such as NH_3, NO_2^-, H_2, reduced forms of sulphur (H_2S, S, $S_2O_3^{2-}$) or ferrous iron	*Chemoheterotrophs* Carbon and energy can usually be derived from the metabolism of a single organic carbon

In order to adsorb substrates that are present in wastewater, first microbial cells secrete extracellular enzymes called *hydrolases.* These enzymes hydrolyze substrates that are present in the form of complex molecules (such as cellulose and other polysaccharides, proteins etc.) in wastewater to simple molecules (such as sugars, amino acids, fatty acids etc.). These simple molecules then dialyze through the cell walls. Once entered inside the cells these simple molecules are oxidized to produce energy. The intracellular enzymes called *desmolases* or respiratory enzymes act as catalysts to the oxidation-reduction reactions.

Substrates such as carbohydrates, proteins, fatty acids, methanol etc. present in wastewater thus can act as electron donors in the above mentioned oxidation-reduction reactions to produce energy as well as to provide carbon for cell synthesis. The chemoheterotrophic microorganisms utilizing these substrates require electron acceptors such as oxygen, nitrate (NO_3^-), sulfate (SO_4^{2-}) or carbon dioxide (CO_2) as well for the oxidation. For example if the wastewater is under aerobic condition, specific chemoheterotrophic microorganisms will utilize the oxygen (as electron acceptor) and organic substances (as electron donor) present in wastewater to produce energy. Similarly, under anoxic conditions, the electron acceptor is nitrate (NO_3^-) and under anaerobic conditions it is either sulfate (SO_4^{2-}) or carbon dioxide (CO_2), which oxidize organic substances (electron donor) present in wastewater. In addition, more energy is produced from oxidation-reduction reactions that occur under aerobic conditions. Therefore the aerobic microorganisms have more energy for cell synthesis compared to those of anaerobic microorganisms. Thus the production of microbial mass (or sludge) is higher in aerobic and anoxic treatment processes than in the anaerobic processes. These phenomena are brought into practice in biological wastewater treatment.

Conventional Biological Wastewater Treatment

In conventional biological treatment, microorganisms (mostly bacterial cultures) are used to uptake the dissolved organic matters from wastewater. This is carried out as secondary treatment. Prior to this the wastewater undergoes preliminary and primary treatments. In the preliminary treatment, large and floating objects are separated from the wastewater by screens. The wastewater is then pumped to grit chamber where grits are allowed to settle out of the wastewater. In primary treatment, suspended solids and part of organic matter are allowed to settle in primary sedimentation tanks. Thus the wastewater that enters the secondary treatment processes mainly contains dissolved organic matter along with nutrients such as nitrogen and phosphorus. The nutrients are present in both organic and inorganic forms.

The concentration of biodegradable organic matter in the wastewater is measured by biological oxygen demand (BOD). Samples of wastewater is aerated and seeded with microorganisms to observe the utilization of oxygen by the microorganisms in decomposing biologically degradable organic matters that are present in the wastewater. Microbial activity in the samples is allowed to occur for five days and the 5-day biological oxygen demand (BOD_5) is computed. For example, a municipal wastewater would contain organic matter with a BOD_5 content of 200 mg l^{-1}.

Aerobic Treatment

In conventional secondary treatment, wastewater is treated aerobically. However, the bacterial biomass decomposing the organic matter in the wastewater can either be suspended in the wastewater or attached to a supporting medium. While aeration tanks used for activated sludge process allows suspended growth of bacterial biomass to occur in secondary treatment, tricking filters support attached growth of bacterial biomass. Tricking filters were in operation since 1880's and the activated sludge process came into practice at the beginning of the 20th century. In an activated sludge process, wastewater is aerated in an aeration tank to allow suspended microbial growth to occur in the tank. Microorganisms present in the aeration tank utilize the organic matter in the wastewater for their growth and cell maintenance. In tricking filters, wastewater is sprayed over a bed of crushed rocks. The bed is generally 1.8 m deep and the bacterial growth occurs on the rock surface and forms a slime layer. As wastewater flows over the slime layer, the microorganisms in the slime layer absorb organic matter and dissolved oxygen for their growth.

Activated sludge plants operating with low organic matter (food) to microorganisms ratio (F/M) and long sludge ages may experience operational problems due to filamentous organisms causing bulking sludge. Providing a selector tank at the head of a bioreactor would reduce and control both these reactions. The high F/M ratio within the selector tanks promotes the growth of floc forming microorganisms while suppressing filamentous growth. Anoxic conditions within the selector tend to buffer nitrification, promote denitrification and recover approximately 3.3 kg $CaCO_3$ per kg NO_3^--N denitrified. The high oxygen demand in the anoxic zone is met by NO_3^- instead of O_2 and up to 2.86 kg O_2 per kg NO_3^- reduced can be recovered. A hydraulic retention time of 5 to 25 minutes for the selector tank is recommended to operate the activated sludge process satisfactorily.

The critical elements in designing the aeration system are: (i) Sizing aeration tank volume and estimating the suitable sludge age to produce effluent that meets the required standards; (ii) Estimating oxygen demand requirements by the microorganisms; (iii) Estimating the motor power required to supply the required oxygen in the mixed liquor; (iv) Estimating the excess sludge production.

Although the aerobic process is favored over anaerobic process due to its stability, reliability and better process understanding, the anaerobic process have some clear advantages as discussed in the next section.

Anaerobic Treatment

Anaerobic treatment processes produce less sludge (0.1 to 0.2 kg biomass or sludge per kg BOD removed) compared to aerobic treatment processes (0.5 to 1.5 kg biomass per kg BOD removed). Also the methane gas produced in anaerobic processes can be used as an energy source. Further, the energy required for mixing in the anaerobic processes is less than the energy required for aeration in aerobic processes. However, slower reaction rates in anaerobic processes lead to larger treatment plants.

Anaerobic treatment is employed for wastewaters with high BOD and for sludge produced in conventional biological wastewater treatment plants that use either aeration basins (activated sludge process) or trickling filters. In an anaerobic treatment process, the organic matter in wastewater such as cellulose, protein and lipids is first hydrolyzed by fermentative bacteria and converted to acetate, saturated fatty acids, organic acids, alcohols, H_2, CO_2, NH_4^+ and S^{2-}. The fatty acids is then converted to acetate, H_2 and CO_2 by hydrogen producing *acetogenic* bacteria. Finally, methanogenic bacteria produce methane and CO_2 by utilizing acetate and hydrogen. Sulfate, sulfite and nitrate are also reduced under anaerobic conditions by certain bacteria. Sulphur reducing bacteria (SRB) are involved in sulfur reduction, and use sulfate or sulfite as electron acceptors and organic matters such as acetate and propionate as electron donors that produce sulfides. This is the cause for the rotten egg smell from wastewater that is being kept under anaerobic conditions for long periods. Denitrification is preceded by denitrifying bacteria (DB), which reduce nitrates to nitrogen gas using the organic matter in the wastewater.

Advanced Wastewater Treatment

In order to achieve better effluent quality for different purposes, advanced wastewater treatment can be employed as detailed in Table 2. All the treatment technologies proposed in Table 2 are generally followed by conventional secondary treatment. Subsequent discussions are limited to biological treatment of wastewaters that are employed to remove nutrients.

Table 2 Purpose and processes involved in advanced wastewater treatment schemes

Purpose of Treatment	Target Pollutants	Treatment Technologies
Additional removal of suspended matters	BOD, COD, TOC and SS	Rapid sand filtration, coagulation, ultra/membrane filtration
Additional removal of dissolved organics	DOC, TDS, Soluble BOD/COD	Activated carbon, coagulation, biological processes, ozonation
Prevention of eutrophication	N	Ammonia stripping, ion exchange, break-point chlorination, denitrification
	P	Bio-P removal, coagulation, adsorption, ion exchange, crystallization
Reuse	Soluble inorganics	Reverse-osmosis, filtration, electrodialysis and ion exchange
	Virus, bacteria	Ozonation, UV radiation, chlorination

Nutrients in Wastewater

Nitrogen and Phosphorus are the major nutrients in wastewaters. If treated wastewaters are discharged into receiving water bodies with high levels of nitrogen and phosphorus they can cause adverse effects on the aquatic environments. Algal growth in lakes and reservoirs is one example of excessive presence of nitrogen and phosphorus in those waters. If excessive nitrogen and phosphorus cause eutrophication in a marine environment, for example in reefs, then the algal growth can shade the corals from sunlight that is essential for their growth. Excessive phosphorus can also weaken the coral skeleton and makes it more susceptible to storm damage. Although the algal growth depends on the availability of organic carbon, nitrogen and phosphorus in the water, one of them becomes a critical nutrient to trigger or limit algal bloom. It is unlikely that all three nutrients become limiting simultaneously, so in any given case, only one would be critical. Usually phosphorus is the limiting nutrient in freshwater and nitrogen is the limiting nutrient in seawaters. The algal synthesis can be expressed by the following chemical equation, in order to identify the limiting nutrient as illustrate in the example below:

$$106\ CO_2 + 16\ NO_3^- + HPO_4^{2-} + 122\ H_2O + 18\ H^+ \xrightarrow[\text{Trace elements}]{\text{Sun light}} C_{106}H_{263}O_{110}N_{16}P\ \text{(algae)} + 138\ O_2$$

For example, if a population of 10,000 produces 200 liters per person per day of wastewater that contains 15 mgl^{-1} NO_3-N and 5 mgl^{-1} PO_4-P, the above chemical equation can be used to find the nutrient that limits the algal growth. The amounts of nitrogen and phosphorus required to produce 3550 kg algae are 224 kg and 31 kg respectively. However, the community discharges 30 kg nitrogen and 10 kg phosphorus per day. Therefore, algal production is limited by nitrogen to 475 kg per day. Of the four basic elements such as nitrogen, phosphorus, carbon dioxide and sunlight that are involved in algal bloom, only nitrogen and phosphorus can be controlled to a certain extent.

Biological Nitrogen Removal

Organic nitrogen present in the wastewater is hydrolyzed and converted to ammonia nitrogen (NH_4^+-N) under aerobic conditions and NH_4^+-N is oxidized to nitrite-nitrogen (NO_2^--N) by *Nitrosomonas* and thereafter to nitrate-nitrogen (NO_3^--N) by *Nitrobacter*. The conversion of NH_4^+-N to NO_3^--N is called nitrification. Under anaerobic conditions NO_3^--N is reduced to nitrogen gas by denitrifying bacteria (denitrifiers), which is called denitrification. While *Nitrosomonas* and *Nitrobacter* are autotrophs, the denitrifiers (*pseudomonas*) are heterotrophs. Therefore, in order to remove nitrogen from wastewater by an activated sludge process, it is necessary to create both anaerobic as well as aerobic zones in the treatment process. Also, the sludge retention time, θ_c required in an activated sludge process for the removal of BOD and denitrification are different than that for nitrification. For example, θ_c required for organic removal is around 2 to 5 days (in the activated sludge process) and for denitrification is around 1 to 5 days. But, θ_c for nitrification is around 10 to 20 days. An arrangement similar to that shown in Figure 1a will provide BOD reduction as well as nitrification and denitrification. In reality this is achieved by oxidation ditches, rotating biological contactors and sequence batch reactors (SBR), which can provide aerobic, anoxic and anaerobic zones (see Figures 1b through d).

Insert Figure 1

Biological Phosphorus Removal

Discharge of nitrogen and/or phosphorus stimulates algal growth. The threshold concentration of phosphorus causing eutrophication in lakes is about 0.02 mg phosphorus per liter. Therefore, in most countries the effluent discharge limit for phosphorus is set as 0.2 to 1.0 mgl^{-1}. A phosphorus balance and a carbon (or BOD_5) balance performed for a secondary treatment processes as shown in Figure 2 can be used to find ways in increasing phosphorus removal. From the final expression shown in figure 2, the following can be considered to increase the removal of phosphorus: (i) increase BOD removal (which is not practical) (ii) increase the yield coefficient, Y (which is difficult to control) and (iii) increase the phosphorus content, P_x in the sludge.

Insert Figure 2

In order to increase P_x, an anaerobic zone at the influent end of the aeration basin should be introduced. This would induce a metabolic function in the microorganisms to release phosphorus in the anaerobic phase and to uptake phosphorus in the aerobic phase drastically. Organic matter (or BOD) will be up taken anaerobically (figure 3a). Thus phosphorus accumulation in the sludge is stimulated and sludge with high P_x (3 to 10 %) could be produced. While the overall performance of biological phosphorus removal is satisfactory and inexpensive, accidental increase of effluent phosphorus concentration is unavoidable. However, phosphorus removal is enhanced when biological removal is combined with chemical removal (coagulation using alum or ferric chloride or lime) as shown in Figure 3b.

Insert figure 3

Removal of both nitrogen and phosphorus can be achieved by combining the treatment processes discussed above (figure 4). This process is termed *Biological Nutrient Removal (BNR).* All aerobic, anoxic and anaerobic processes are involved in the BNR of nitrogen and phosphorus.

Insert Figure 4

Suggested Reading

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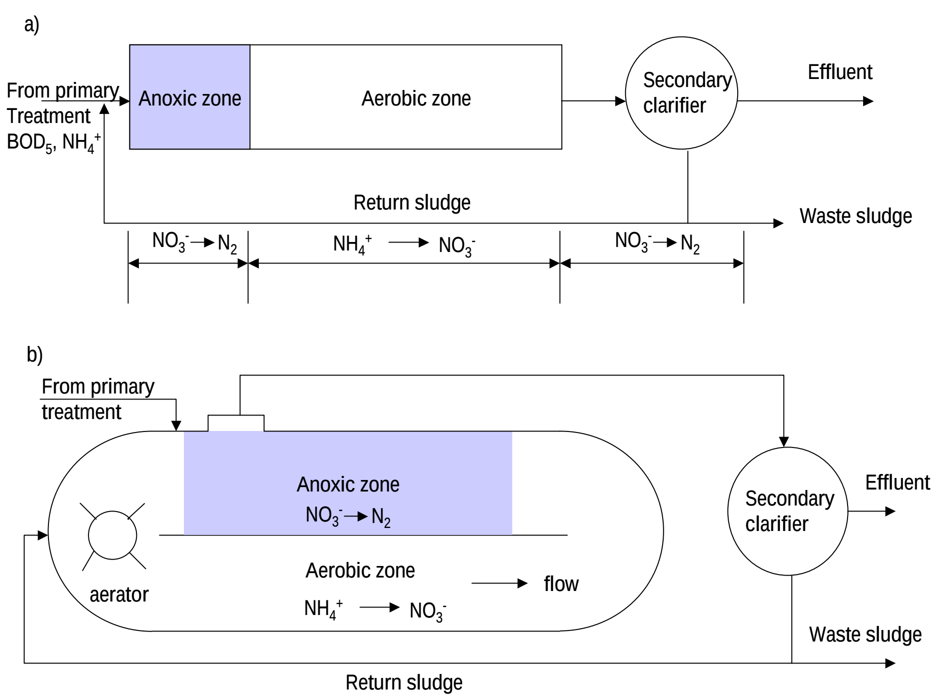


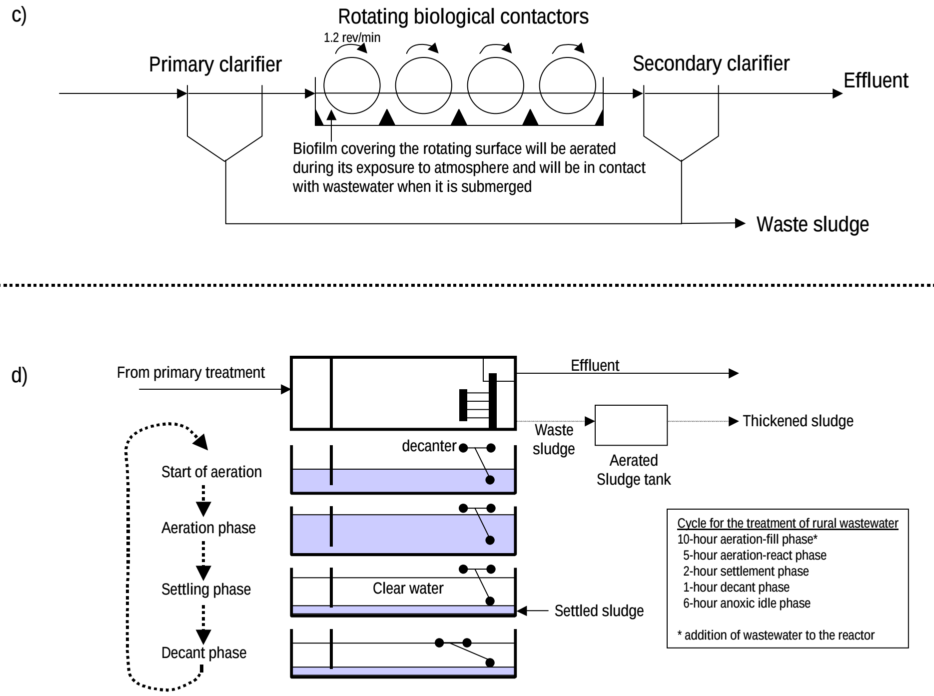
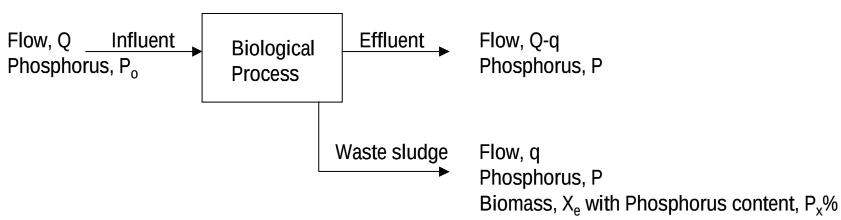


Figure 1
a) Nitrogen removal using anoxic and aerobic zones in a secondary treatment system
b) Oxidation ditch used for the removal of organic matters and nitrogen
c) Rotating biological contactors used for the removal of organic matters and nitrogen
d) Fill and draw method used in the sequencing batch reactor for the removal of organic matter and nitrogen



Phosphorus balance:
$QP_o = (Q\text{-}q)\ P + q\ (P + X_eP_x) = QP + qX_eP_x$
$Q\ (P_o\text{-}P) = qX_eP_x$

Carbon (or BOD_5) balance:
$QC_o = (Q\text{-}q)\ C + qX_eC_x + C_{gas}$
$Q\ (C_o\text{-}C) = qX_e/Y$, where Y = sludge produced/ carbon (or organic matter) utilised

$[Q(P_o\text{-}P)]/[Q(C_o\text{-}C)] = \Delta P/\Delta C = YP_x$
$\Delta P = (Y\ \Delta C)\ P_x$

Phosphorus removed = sludge produced x phosphorus content in the sludge

Q, q	- $[L]^3[T]^{-1}$
P_o, P, C_o, C, X_e	- $[M][L]^{-3}$
C_{gas}	- $[M][T]^{-1}$

Figure 2 Material balance for organic matters and phosphorus around a biological process unit

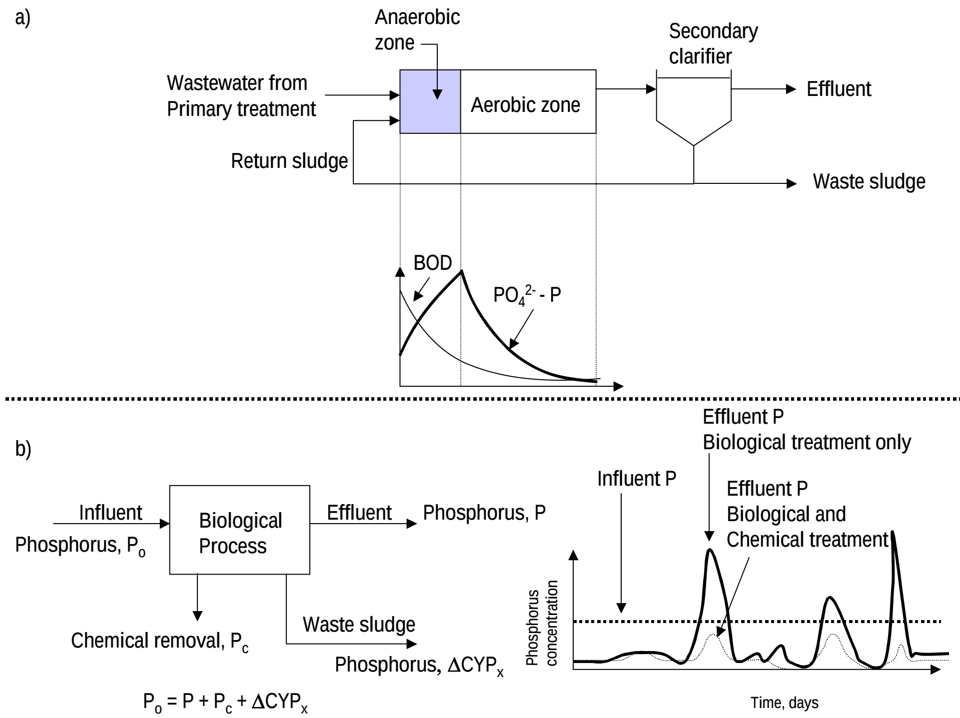


Figure 3 a) Phosphorus removal using anaerobic and aerobic zones in a secondary treatment system
b) Phosphorus removal by chemical and biological treatment

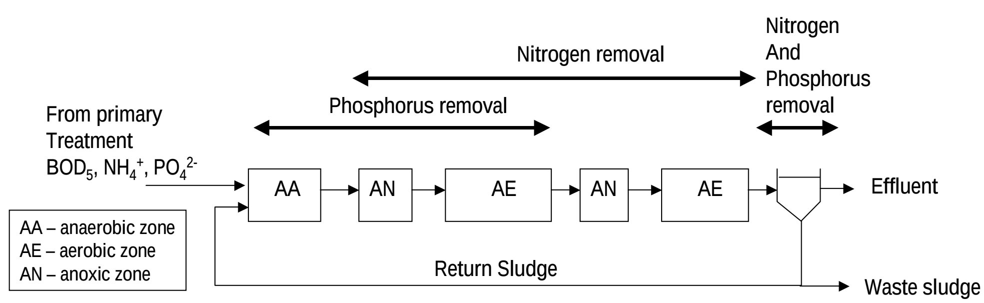


Figure 4 Biological nutrient removal (BNR) process