Section B

Pollution Abatement a Review
The treatment of industrial and domestic wastes has a long history and in many countries treatment plants are installed initially some 120 years ago. These were built as the epidemiology of many infectious diseases which are the scourge of crowded population became known. There has been steady raising of the standards required by river authorities before wastes may be discharged into water course with severe financial penalties for failure to conform. Various parameters like biochemical oxygen demand (BOD), chemical oxygen demand (COD), etc are widely used to estimate and set up standards for industrial pollution. Industrial effluents sometimes contain recalcitrant xenobiotic compound, heavy metals etc. which require meticulous treatment procedures to meet the standard criteria. Failure to do this would result in drastic consequences in a water body due to eutrophication, concomitant fish kills, and then passing the ill effects to terrestrial organisms. In addition to toxic compounds present in industrial effluents would lead to biomagnification and cause deleterious effects on flora and fauna. Several methods of treatment such as precipitation, ion exchange, electrochemical reduction, reverse osmosis etc are known. Most of these methods require high capital cost and recurring expenses such as chemicals which are not suitable for long term practice.

Bioremediation seems an ideal alternative to chemical and physical methods. Scaling up of a bioremediation is designing and building a large scale system often results from small scale model or laboratory system. Engineering scale up process of bioremediation is
difficult *insitu* than *exsitu* situation. Factors that govern *insitu* bioremediation are not well defined and are difficult to sustain.

In contrast to *insitu* bioremediation *exsitu* bioremediation rates can be dominated by mixing process and *exsitu* process can be engineered to optimise mixing. Scale up method have been developed and tested for a wide range of industrial process and these methods are well suited to the scale up of *exsitu* bioremediation process. The process of encapsulating the biocatalyst in some matrices like carrageenan, agar etc. further enhances the suitability mainly because of reusability, easy product separation facility, easy separating out of the components of the system into distinct phases etc.

The major breakthrough for a scaling up of a tested laboratory scale method of bioprocessing is identifying the potential rate limiting steps. Transport phenomena become rate limiting as scale increases. A full scale bioremediation process cannot be a simulation of laboratory data.

Bioremediation of many compounds will occur under anaerobic conditions. Certain microorganisms are able to use compounds such as nitrate, sulphate, iron etc. as final electron acceptors instead of oxygen. The rising cost of both aerobic digestion and energy coupled with new developments in microbiology and engineering have renewed interests in anaerobic treatment of waste. The digestion of sewage sludge is the most common anaerobic treatment and is a well established technology. The limiting factor in anaerobic digestion is the slow growth rate of obligate anaerobic bacteria in the system.
Tremendous potential is offered by anaerobic waste treatment for production of fuel gas economically.

There are several advantages of anaerobic fermentation. The characteristic energy metabolism and subsequent formation of small quantities of ATP, anaerobic organisms usually produce less biomass than aerobic organisms. Thus more carbon can be converted to end products and high specific product yields can be obtained. Anaerobic process requires less mass transfer and energy input than aerobic process and may be more economical. The utilisation of mixed culture of microorganisms in anaerobic process enable the use of cheap and impure substrates including agricultural and industrial wastes.

Anaerobic process have some limitation as many process including anaerobiosis are prone to contamination, bacteriophage infection and spontaneous degeneration. Further the component species of microbial consortia can change according to environmental changes and availability of nutrients. This can lead to decrease in efficiency and disruption of the process. Obligate anaerobes are inactivated by oxygen. Considerable skill and meticulous methods are required for cultivation and maintenance of strictly anaerobic microorganisms. Some anaerobes produce toxic substances which cause physical damage to metals of the fermenter and concrete.

The many diverse activities of chemical industry generate plethora of waste compounds many of which are recalcitrant and are therefore persistent in the environment. Many of these recalcitrant compounds require prior physical or chemical treatment before
conventional biological treatment can be used. Some of the microorganisms able to degrade toxic chemicals are tabulated below.

<table>
<thead>
<tr>
<th>Xanthomonas</th>
<th>Hydrocarbons</th>
</tr>
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<tbody>
<tr>
<td><em>Streptomyces</em> sps.</td>
<td>Diazinon, phenoxy acetates</td>
</tr>
<tr>
<td><em>Psuedomonas</em></td>
<td>4 alkyl benzonates, alkyl ammonium, anthracene, benzene, hydrocarbons, malathion, naphthalene, organophosphates, polychlorinated biphenyls, p xylene, parathion, phenanthrene, rubber, toluene, phenolics</td>
</tr>
<tr>
<td><em>Alcaligens</em> sps</td>
<td>Polychlorinated biphenyls, polycyclic aromatics, sulphonates, halogenated hydrocarbons</td>
</tr>
<tr>
<td><em>Bacillus</em> sps.</td>
<td>Aromatics, long chain alkanes</td>
</tr>
<tr>
<td><em>Cornybacterium</em></td>
<td>Halogenated hydrocarbons, phenoxy acetates</td>
</tr>
<tr>
<td><em>Fusarium solani</em></td>
<td>Propanil</td>
</tr>
</tbody>
</table>

Most publicly owned treatment plants have four basic operations

1) Primary processing removes solids, which are either disposed or sent to a sludge digester.

2) Secondary processing degrades the dissolved organic compounds. This is affected by natural aerobic microorganisms. The resulting sludge is either disposed or sent to a digester. In activated sludge process some sludge is returned to the reactor tank.
3) Tertiary processing involves chemical precipitation and separation of phosphorous and nitrogen

4) Digestion processing is used to treat sludge from primary and secondary stages and is conventionally an anaerobic process which reduces the solid volume, the odour and the number of pathogens and in addition generates valuable organic fuel and methane.

Aerobic treatment of wastes is the largest controlled use of microorganisms in biotechnological industries. This process would result in the mineralisation of waste into water, simple salts and gases. The efficiency of treatment is proportional to the potential microorganisms utilizing the waste, their number and contact time of the waste with the biomass. Aerobic treatment system can be of two categories (1) percolating filter system and (2) activated sludge system.

Percolating or the trickling filter was the earliest system used in the biological treatment of wastes. Some of its advantages are easy maintenance, reliability, low running costs, small surplus biomass production and the longevity of plant life up to fifty years. A major limitation of the trickling filter system is the excessive growth of microorganisms in the filter causing blockage and failure of the filter. Modifications like altering double filtration, in which the order of the filter first receiving the effluent is periodically reversed and is widely used. Although the microbial community comprising a trickling filter is quite diverse Zoogloea ramigera are thought to be the bacterial group primarily active.
Activated sludge is another aerobic process for treating wastes. It requires higher running due to the requirement for mixing and aeration. This is a continuous or semi continuous fermentation process with fresh effluent being added and sludge removed in order to maintain a constant population of the organism. The sludge removed can be sent to aerobic digester or can be used as a potential fertilizer.

The interrelationship between the various organisms involved in the catabolism of organic and inorganic substrates is an important factor in the control of the activated sludge system of fermentation. Intermediates from the metabolic pathways of one organism can influence the degradative process of another. The efficiency of the process can be improved through a greater understanding of the metabolic control in the microbial flora of the activated sludge system. The control of biodegradation mediated bioremediation process is complex, but appreciation of the biochemistry of the process may allow one to meet the demanding situation of manipulating the control process of the system.

The same principles used for laboratory level fermentation with suitable modification can be used for treating industrial waste water particularly from chemical, petroleum, electroplating, metallurgical, nuclear power stations, thermal power stations, pulp and paper industries. Success in developing a system with modification for the above purpose relays on finding a microorganism or consortium to suit the need.
In addition to percolating and activated sludge system a few modifications of the aerobic process are commercialised. Some of them are rotating biological contactors or rotating disc contactors, biologically aerated filters, rotating drums, fluidized bed system etc. In all these process microorganisms form a biofilm on suitable substratum of specific design engineered as that a large surface area of contact is available for the process to mediate its purpose.

Environmental control plays a vital role in wastewater treatment. About all wastewater can be treated biologically. It is every essential for the environmental engineer to ensure that proper environment is produced and controlled effectively so as to maintain the characteristics of the biological process operating in the confined system. One aspect of this chapter is to present an overview of biological wastewater treatment, discuss key factors governing biological growth and waste treatment kinetics. The biological removals of nutrients and pond process are also discussed.

The objectives of the biological treatment of the wastewater are to coagulate and remove the nonsettiable colloidal solids and stabilise the organic matter. Reduction of organic content is the major objective of the treatment of domestic wastewater, in many cases the nutrient removal of nitrogen and phosphorus is essential. In many instances the removal of trace organic compounds that may be toxic is also an important treatment objective. For agricultural return wastewater the objective is to remove nutrients specifically nitrogen and phosphorous, that are capable of stimulating growth of aquatic plants. For industrial wastewater the objective is to remove or reduce the organic and inorganic compounds. Many of these wastewater
ingredients are toxic to microorganisms and so pre treatment is required.

A variety of microorganisms principally bacteria can be used for the removal of carbonaceous BOD, coagulation of nonsettitable colloidal solids and the stabilisation of organic matter. The microorganisms are used convert the colloidal and dissolved carbonaceous organic matter in the various gases and in the cell tissue. Gravity settling can be used to remove the resulting cells because of the slightly greater specific gravity.

Complete treatment has not been accomplished unless the cell tissue produced has organic matter removed from the solution because cell tissue which itself is organic will be measured as BOD in the effluent. If the cell tissue is not removed, the only treatment that has been achieved is that associated with the bacterial conversion of a portion of organic matter originally present as various gases and products.

An understanding of the biochemical activities of the important microorganisms is basic to the design of a biological treatment process. Two major aspects are to be considered for understanding biochemical metabolism.

1) General nutritional requirement of the microorganism commonly encountered in waste water treatment and

2) The nature of the microbial metabolism based on the need of molecular oxygen
To continue to reproduce and function properly an organism must have (1) source of energy (2) carbon for the synthesis of new cellular material and (3) inorganic elements such as nitrogen, phosphorous, sulfur, potassium, calcium and magnesium. Organic nutrients may also be required for cell synthesis. Carbon and energy sources usually referred to a substrate and nutrient and growth factors requirement for various types of organisms and considered in the following paragraphs.

Two of the most common sources of cellular carbon for microorganisms are organic matter and carbon dioxide. Organisms that use organic carbon for the cell tissue are called heterotrophs. Organisms that derive cell carbon from carbon dioxide are called autotrophs. Organisms that use light as energy source are called phototrophs. Organisms that derive their energy from chemical reactions are known as chemoautotrophs.

Bacteria require nutrient and growth factors other than carbon and at times be limiting material for microbial cell synthesis and growth. The principle inorganic nutrient needed by microorganisms are N, S, P, K, Mg, Ca, Fe, Na and Cl. Minor nutrient of importance include Zn, Mn, Mo, Se, Co, Cu, Ni, V and W (Stainier et al 1986).

In addition to inorganic nutrients, cited above organic nutrients may also be needed by some organisms. Required organic nutrients, known, as growth factors are compounds needed by an organism as precursors or constituents of organic cell material that cannot be synthesised from other carbon sources. All the growth factors differ
from organism to another, the major growth factors fall into the following classes:

1. Amino acids
2. Purines and Pyrimidines. and
3. Vitamins (Stainer et al 1986).

The major objective of the biological treatment process is the reduction of carbonaceous B.O.D. in the wastewater. In accomplishing this type of treatment the chemotrophic organisms are of primary importance because of the requirement for organic compounds in addition to carbon and energy source. When treatment objective include the conversion of ammonia to nitrate the chemoheterotrophic nitrifying bacteria are significant.

Municipal wastewater typically contain adequate amount of nutrients to support biological treatment for removal of carbonaceous B.O.D. In industrial wastewater nutrient was not be present in sufficient quantities. In these cases nutrient addition is necessary for proper growth of bacteria and significant degradation of organic wastes.

Chemoheterotrophic organisms may be further grouped according to their metabolic type and their requirement for molecular oxygen. Organisms that generate energy by enzyme mediated in electron transport from an electron donor to an external electron acceptor are said to have respiratory metabolism. In contrast fermentative metabolism does not involve participation of electron
acceptor. Fermentation is less efficient energy yielding process than respiration.

When molecular oxygen is used as the electron acceptor in respiratory metabolism the process is known as aerobic respiration. Organisms that are dependent on aerobic respiration to meet the energetic needs can exist when there is supply of molecular oxygen. These organisms are called obligately aerobic. Oxidised organic compound such as nitrate and nitrite can function as electron acceptor for some respiratory metabolism of organisms in the absence of molecular oxygen. In environmental engineering, process that makes use of these organisms often referred to as anoxic.

Organisms that generate energy by fermentation and that can exist only in an environment that is devoid of oxygen are obligately anaerobic. Facultative microbes have the ability to grow in either the presence or absence of molecular oxygen. The facultative organisms fall into two sub groups, based on metabolic abilities. The facultative anaerobes can shift from fermentative to aerobic respiratory metabolisms depending upon the presence or absence of molecular oxygen. Aerotolerant anaerobes have strictly fermentative metabolism that are relatively insensitive to the presence of molecular oxygen.

On the basis of cell structure and function micro organisms are commonly classified as eukaryotes, eubacteria and archaeabacteria. The prokaryotic groups eubacteria and archaeabacteria are primary importance in biological treatment and are generally referred as simply bacteria. The eukaryotic group includes plants, animals and protists.
Eukaryotes important in biological treatment includes; (1) Fungi
(2) Protozoa and Rotifers and (3) Algae.

Bacteria are single celled prokaryotic organisms. Their usual
mode of reproduction is binary fission, although some species
reproduce sexually by budding. Even though there are thousands of
different species of bacteria, their general form falls into three
categories; spherical, cylindrical and helical. Bacteria vary widely in
size. Representative sizes are 0.5 to 1.0 μM in diameter for this
spherical 0.5 to 1.0μm in width by 1.5 to 3.0μm in length for the
cylindrical (rods) 0.5 to 5 μm in width by 6 to 15 μm in length for the
helical (spiral). According to the temperature range in which the
function of bacteria may be classified psychrophiles, mesophiles or
thermophiles.

Some typical temperature ranges of various bacteria are:

<table>
<thead>
<tr>
<th>Type</th>
<th>Temperature°C</th>
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<tbody>
<tr>
<td></td>
<td>Range</td>
</tr>
<tr>
<td>Psychrophiles</td>
<td>10-30</td>
</tr>
<tr>
<td>Mesophiles</td>
<td>20-50</td>
</tr>
<tr>
<td>Thermophiles</td>
<td>35-75</td>
</tr>
</tbody>
</table>

Fungi are of importance in environmental engineering and are
considered to be multicellular non-photosynthetic, heterotrophic
protists. Fungi are usually classified by their mode of reproduction.
They reproduce sexually or asexually by fission, budding or spore formation. Molds or true fungi produce microscopic units, hyphae that collectively form a filamentous mass called mycelium. Yeasts are fungi that cannot from a mycelium and are therefore unicellular.

Most fungi are strict aerobes. They have the ability to grow under low moisture conditions and can tolerate an environment with relatively low pH. The optimum pH for most of the species is 5.6; the range is 2 to 9. Fungi also have a low nitrogen requirement, needing approximately one half as much as bacteria. The ability of fungi to survive under low pH and nitrogen limiting conditions, coupled with their ability to degrade cellulose, makes them very important in biological treatment of some industrialised waste waters and composting of solid organic wastes.

Protozoa are motile, microscopic protists that are usually single celled. The majority of protozoa are aerobic hetereotrophs, although a few are anaerobic. Protozoa are generally larger than bacteria and often consume bacteria as an energy sources. In effect, protozoa are polishers to effluents for biological wastewater treatment process by consuming bacteria and particulate organic matter.

The rotifer is an aerobic, hetereotrophic and multicellular animal. Its name is derived from the fact that it has two sets of rotating cilia on its head which are used for motility and capturing food. Rotifers are very effective in consuming dispersed and flocculated bacteria and small particles of organic matter. Their presence in an effluent indicates highly efficient aerobic biological purification process.
Algae are unicellular or multicellular autotrophic photosynthetic protists. They are of importance in biological treatment process for two reasons. In ponds the ability of algae to produce oxygen by photosynthesis is vital to the ecology of the water environment.

Algae are also important in biological treatment process because of the problem of preventing excessive algae growth in receiving water has to date, centered around nutrient removal in the treatment process. Some scientists advocate the removal of nitrogen from treatment plant effluents, others recommend the removal of phosphorous and still others recommended the removal of both. The choice of treatment objective reflects the type of biological process involved.

The activated sludge process was developed in England in 1914 by Ardern and Lockett and was so named because it involved the production of activated mass of microorganisms capable of stabilising a waste aerobically.

In activated sledge process organic waste is introduced into a reactor, where an aerobic bacteria culture is maintained in suspension. The reactor content are referred to as the mixed liquor. In the reactor bacterial culture carries out the conversion wastes in general accordance with the stoichiometry shown in the following equations.

\[
\text{COHNS} + \text{O}_2 + \text{nitrates} \rightarrow \text{CO}_2 + \text{NH}_3 + \text{C}_5\text{H}_7\text{NO}_2 + \text{other end products.}
\]

Endogenous Respiration:

\[
\text{C}_5\text{H}_7\text{NO}_2 + 5\text{O}_2 \rightarrow 5\text{CO}_2 + 2\text{H}_2\text{O} + \text{NH}_3 + \text{energy.}
\]
The aerobic environment in the reactor is achieved by the use of diffused or mechanical aeration which also serves to maintain the mixed liquor a completely mixed regime. After a specified period of time, the mixture of new cells and old cells is passed out to a settling tank where the cells are separated from the treated wastewater. The level at which the biological mass in the reactor should be kept depend on the desired treatment efficiency and other considerations related to growth kinetics.

To design and operate an activated sludge system efficiently, it is necessary to understand the importance of the microorganisms in the system. In nature, the key role of the bacteria is to decompose organic matter produced by other living organisms. In the activated sludge process, the bacteria are the most important microorganisms because they are responsible for the decomposition of the organic material in the influent. In the reactor or aeration tank, a portion of the organic waste is used by aerobic and facultative bacteria to obtain energy for the synthesis of the remainder of the organic material into new cells. Only a portion of the original waste is actually oxidised to low-energy compounds such as NO$_2^-$, SO$_4^{2-}$, and CO$_2$; the remainder is synthesised into cellular material. Also, many intermediate products are formed before the end products.

In general, the bacteria in the activated-sludge process include members of the genera *Pseudomonas*, *Zoogloea*, *Achromobacter*, *Flavobacterium*, *Nocardia*, *Bdellovibrio*, *Mycobacterium*, and the two most common nitrifying bacteria, *Nitrosomonas* and *Nitrobacter* (Hawkes 1963, Higgins et al 1975). Additionally, various filamentous forms, such as *Sphaerotilus*, *Beggiatoa*, *Thiothrix*, *Leucocystis*, and
Geotrichum may also be present (Hawkes 1963, Higgins et al 1975). While the bacteria are the microorganisms that actually degrade the organic waste in the influent, the metabolic activities of other microorganisms are also important in the activated sludge system. For example, protozoa and rotifers act as effluent polishers. Protozoa consumes dispersed bacteria that have not flocculated, and rotifers consume small biological floc particles that have not settled.

Although it is important that bacteria decompose the organic waste as quickly as possible, it is also important that they form a satisfactory floc, which is a prerequisite for the effective separation of the biological solids in the settling unit. It has been observed that as the mean cell residence time of the cells in the system is increased, the settling characteristics of the biological floc are enhanced. For domestic wastes, mean cell residence times on the order of 3 to 4 are required to achieve effective settling.

Even though excellent floc formation is obtained, the effluent from the system could still be high in biological solids such as a result of poor design of the secondary settling unit, poor operation of the aeration units, or the presence of filamentous microorganisms such as sphaerotilus, E. coli and fungi (Higgins et al 1975, Jenkins et al 1986).

It is important to note and remember that the sedimentation tank is an integral part of the activated sludge process. The design of the reactor cannot be considered independently of the design of the associated settling facilities. To meet discharge requirements for suspended solids and BOD associated with the volatile suspended solids in the effluent and to maintain mean cell residence time
independent of retention time of the reactor it must be possible to separate the mixed-liquor solids and to return a portion to the reactor.

Because of the variable process microbiology that is possible, it has been found that the settling characteristics of the biological solids in the mixed liquor will differ with each plant, depending on the characteristics of the wastewater and the many variables associated with process design and operation. For this reason, when settling facilities are designed for an existing or a proposed new treatment facility, column settling tests should be performed, and the design should be based on the results of these tests. If it is not possible to perform settling tests, the design should be based on an approach in which both the hydraulic and the solids loadings are considered.

“Bulking” is the term applied to a condition in which an overabundance of filamentous organisms is present in the mixed liquor in the activated-sludge process. The presence of filamentous organisms causes the biological flocs in the reactor to be bulky and loosely packed. The bulky flocs do not settle well and are often carried over in great quantities in the effluent from the sedimentation tank. The filamentous organisms found in the activated sludge process include a variety of filamentous bacteria, actinomycetes, and fungi (Jenkins et al 1986). Conditions favouring the growth of filamentous organisms are numerous and vary from plant to plant.

Control of filamentous organisms has been accomplished in a number of ways including the addition of chlorine or hydrogen peroxide to the return waste-activated sludge, alteration of the dissolved oxygen concentration in the aeration tank, the addition of
major nutrients, the addition of trace nutrients and growth factors, and more recently the use of selectors (Jenkins et al 1986, Albertson 1987, Wood et al 1974). Control of the growth of filamentous organisms in the complete-mix process has been achieved by mixing the return sludge with the incoming wastewater in a small anoxic contact tank known as a “selector” (Albertson 1987, Jenkins 1986).

Aerated lagoons (sometimes called “aerated ponds”) evolved from facultative stabilisation ponds when surface aerators were installed to overcome the odours from organically overloaded ponds. Although a number of definitions of aerobic aerated lagoon processes will be found in the literature, the following process description will be used.

The aerated lagoon process is essentially the same as the conventional extended-aeration activated sludge (mean cell residence time = 20 days), except that an earthen basin is used for the reactor, and the oxygen required by the process is supplied by surface or diffused aerators. In an aerobic lagoon, all the solids are maintained in suspension. In the past, aerated lagoons were operated as flow through activated sludge systems without recycle, usually followed by large settling ponds. To meet secondary treatment standards of the U.S. Environmental Protection Agency, many aerated lagoons are now used in conjunction with settling facilities and incorporate the recycle of biological solids.

Because the aerated lagoon process is essentially the same as the activated sludge process, the microbiology is also similar. Some differences occur because the large surface area associated
with aerated lagoons can cause more significant temperature effects than are normally encountered in the conventional activated sludge process.

Seasonal and continuous nitrification may be achieved in aerated lagoon systems. The degree of nitrification depends on the design and operating conditions within the system and on the wastewater temperature. Generally, with higher wastewater temperatures and lower loading (increased sludge retention time), higher degrees of nitrification can be achieved.

In conventional aerobic digestion, the sludge is aerated for an extended period of time in an open, unheated tank using conventional air diffusers or surface aeration equipment. The process may be operated in a continuous or batch mode. Smaller plants use the batch system in which sludge is aerated and completely mixed for an extended period of time, followed by quiescent settling and decantation. In continuous systems, a separate tank is used for decantation and concentration. High purity oxygen aerobic digestion is modification of the aerobic digestion process in which oxygen is used in lieu of air. The resultant sludge is similar to conventional aerobically digested sludge.

Aerobic digestion, as mentioned, is similar to the activated sludge process. As the supply of available substrate food is depleted, the microorganisms begin to consume their own protoplasm to obtain energy for cell maintenance reactions. When this occurs, the microorganisms are said to be in the endogenous phase. As shown in equation cell tissue is aerobically oxidised to carbon dioxide, water and ammonia. Actually, only about 75 to 80 percent of the cell tissue can be
oxidised: the remainder is composed of inert components and organic compounds that are not biodegradable. The ammonia from this oxidation is subsequently oxidised to nitrate as digestion proceeds.

In activated or trickling filter sludge is mixed with primary sludge and the combination is to be aerobically digested, there will be both direct oxidation of the organic matter in the primary sludge and endogenous oxidation of the cell tissue. Operationally, most aerobic digesters can be considered to be arbitrary flow reactors without recycle.

Aerobic attached growth biological treatment processes are usually to remove organic matter found in wastewater. They are also used to achieve nitrification (the conversion of ammonia to nitrate). The attached growth process include the trickling filter, the roughing filter, rotating biological contractor, and fixed film nitrification reactor. Because the trickling filter processes is used most commonly, it will be considered in greater detail than the other processes. Fixed film nitrification is used in which biological nutrient removal is considered.

The first trickling filter was placed in operation in England in 1893. The concept of a trickling filter grew from the use of contact filters, which were watertight basins filled with broken stones. In operation, the contact bed was filled with wastewater from the top, and the wastewater was allowed to contact the media for a short time. The bed was then drained and allowed to rest before the cycle was repeated. A typical cycle required 12 hours (6 hours for operation and 6 hours of resting). The limitations of the contact filter included a relatively high incidence of clogging, the long rest period and the relatively low loading that could be used.
The modern trickling filter consists of a bed of a highly permeable medium to which microorganisms are attached and through which wastewater is percolated or trickled and hence the name. The filter media usually consist of either rock (slag is also used) or a variety of plastic packing materials. In rock-filled trickling filters, the size of the rock typically varies from 1 to 4 inch (25 to 100mm) in diameter. The depth of the rock varies with each particular design but usually ranges from 3 to 8 ft (0.9 to 2.5m) and averages 6 ft (1.8 m) Rock filter beds are usually circular, and the liquid wastewater is distributed over the top of the bed by a rotary distributor.

Trickling filters that use plastic media have been built in round, square and other shapes with depths varying from 14 to 40 ft (4 to 12m). Three types of plastic media are commonly used: (1) vertical flow packing, (2) cross flow packing and (3) a variety of random packings.

Filters are constructed with an underdrain system for collecting the treated wastewater and any biological solids that have become detached from the media. This underdrain system is important both as a collection unit and as a porous structure through which air can circulate. The collected liquid is passed to a settling tank where the solids are separated from the treated wastewater. In practice, a portion of the liquid collected in the underdrain system or the settled effluent is recycled, usually to dilute the strength of the incoming wastewater and to maintain the biological slime layer in a moist condition.

The organic material present in the wastewater is degraded by a population of microorganisms attached to the filter media. Organic material from the liquid is adsorbed onto the biological film or slime layer.
In the outer portions of the biological lime layer, the organic material is degraded by aerobic microorganisms. As the microorganisms grow, the thickness of the slime layer increases, and the diffused oxygen is consumed before it can penetrate the full depth of the slime layer. Thus, an anaerobic environment is established near the surface of the media.

As the slime layer increases in thickness, the adsorbed organic matter is metabolised before it can reach the microorganisms near the media face. As a result of having no external organic source available for cell carbon, the microorganisms near the media face enter into an endogenous phase of growth and lose their ability to cling to the media surface. The liquid then washes the slime of the media and a new slime layer starts to grow. This phenomenon of losing the slime layer is called “sloughing” and is primarily a function of the organic and hydraulic loading on the filter. The hydraulic loading accounts for shear velocities, and the organic loading accounts for the rate of metabolism in the slime layer. In modern trickling filters, the hydraulic loading rate is adjusted to maintain a slime layer of uniform thickness.

The biological community in the filter includes aerobic, anaerobic, and facultative bacteria, fungi, algae, and protozoans. Higher animals, such as worms, insect larvae, and snails, are also present. Facultative bacteria are the predominating microorganisms in the trickling filter. Along with the aerobic and anaerobic bacteria, their role is to decompose the organic material in the wastewater. *Achromobacter*, *flavobacterium*, *Pseudomonas*, and *Alcaligenes* are among the bacterial genera commonly associated with the trickling filter. Within the slime layer, where adverse conditions prevail with respect to growth, the
filamentous forms *Sphaerotilus natans* and *Beggiatoa* will be found. In the lower reaches of the filter, the nitrifying bacteria *Nitrosomonas* and *Nitrobacter* will be present (Hawkes 1963, Higgins *et al.* 1975).

The fungi present are also responsible for waste stabilisation, but their contribution is usually important only under low pH conditions or with certain industrial wastes. At times, their growth can be so rapid that the filter clogs and ventilation becomes restricted. Among the fungi genera that have been identified are *Fuzarium, Mucor, Penicillium, Geotrichum, Sporotrichum,* and various yeasts (Hawkes 1963).

Algae can grow only in the upper reaches of the filter where sunlight is available. *Phormidium, Chlorella and Ulothrix* are among the algae species commonly found in trickling filters (Hawkes 1963, Higgins 1975). Generally, algae do not take a direct part in waste degradation, but during the daylight hours they add oxygen to the percolating wastewater. From an operational standpoint, the algae are troublesome because they can cause clogging of the filter surface, which produce odours.

The protozoa in the filter are predominantly of the ciliata group, including *Vorticella, Opercularia,* and *Epistulis* (Hawkes 1963, Higgins 1975). As in the activated sludge process, their function is not to stabilise the waste but to control the bacterial population. The higher animals, such as snails, worms, and insects, feed on the biological films in the filter and, as a result, help to keep the bacterial population in a state of high growth or rapid food utilisation. The higher animal forms are not as common in high rate lower trickling filters. Snails are
especially troublesome in nitrifying filters, where they have been known to consume most of the growth of nitrifying bacteria.

Variations in the individual population of the biological community occur throughout the filter depth with changes in organic loading, hydraulic loading, influent wastewater composition, pH, temperature, air availability and other factors.

In predicting the performance of trickling filters, the organic and hydraulic loadings and the degree of treatment required are among the important factors that must be considered. Over the years a number of investigators have proposed equations to describe the removals observed, including Atkinson (1974), Bruce and Merkens (1973), Eckenfelder (1963), Fairall (1956), Galler and Gotass (1966), Germain (1966) Logen et. al (1987), the National Research Council (1946) Schultz (1966) and Velz (1948). Both theoretical mass-balance approach can be used in the modelling of the trickling-filter process and a practical approach of developing models from an analysis of field data.

Roughing filters are specially trickling filters operated at high hydraulic loading rates. Roughing filters are used principally to reduce the organic loading on downstream processes and in seasonal nitrification applications where the purpose is to reduce the organic load so that downstream biological process will dependably nitrify the wastewater during the summer months.

Although the earliest roughing filters were shallow stone media systems, the present trend is towards the use of synthetic media or
redwood a depths of 12 to 40ft. As with other biological processes, roughing filter performance is temperature sensitive. When roughing filters are used for the removal of a portion of the organic material present, or to enhance downstream nitrification a drop in efficiency is not critical.

Roughing filters are typically operated at high hydraulic loading, necessitating the use of high recycle rates. The higher hydraulic loadings cause nearly continuous sloughing of the slime layer. If unsettled filter effluent is used for recycle, the sloughed biological solids in the recycle stream may contribute to organic removal within the filter as in a suspended growth process. If this mechanism is significant, process efficiency may be greater than predicted by an attached growth model.

The biological activity in a roughing filter is essentially the same as that described for the trickling filter. Some differences will be noted in the organisms present because of the higher shearing action resulting from the higher hydraulic flow rates applied to those units.

The biological growth is susceptible to the same heavy metals and organic substances as conventional suspended growth systems, but the process has shown greater resistance to shock loading than suspended growth systems. Because of the relatively short hydraulic retention time available, organics that are not readily biodegradable are not affected.

A rotating biological contactor consists of a series of closely spaced circular disks of polystyrene or polyvinyl chloride. The disks are submerged in wastewater and rotated slowly through it.
In operation, biological growths become attached to the surfaces of the disks and eventually from a slime layer over the entire wetted surface area of the disks. The rotation of the disks alternately contacts the biomass with the organic material in the wastewater and then the atmosphere for adsorption of oxygen. The disk rotation affects oxygen transfer and maintains the biomass in an aerobic condition. The rotation is also the mechanism for removing excess solids from the disks by shearing forces it creates and maintaining the sloughed solids in the suspension so they can be carried from the unit to a clarifier. Rotating biological contractors can be used for secondary treatment, and they can also be operated in the seasonal and continuous nitrification and denitrification modes.

Rotating biological contractors are usually designed on the basis of loading factors derived from pilot plant and full scale installations, although their performance can be analysed using an approach similar to that for trickling filters. Both hydraulic and organic loading rate criteria are used in sizing units for secondary treatment. The loading rates for warm weather and year round nitrification will be considerably lower than the corresponding rates for secondary treatment.

Properly designed rotating biological contractors generally are quite reliable because of the large amount of biological mass present. This large biomass also permits them to withstand hydraulic and organic surges more effectively. The effect of staging in this plug flow system eliminates short circuiting and dampens shock loadings.
Still another attached growth process is the packed bed reactor, used for both the removal of carbonaceous BOD and nitrification. Typically, a packed-bed reactor consists of a container that is packed with a medium to which the microorganisms can be become attached. Wastewater is introduced from the bottom of the container through an appropriate underdrain system or inlet chamber. Air or pure oxygen necessary for the process is also introduced with the wastewater.

In the past few years a number of different anaerobic process have been developed for the treatment of sludge and high strength organic wastes. The most common is anaerobic suspended growth digestion process. Because the complete mix anaerobic digestion process is of such fundamental importance in the stabilisation of organic material and biological solids, it will be emphasised in the following discussion. The anaerobic contract process and the up flow anaerobic sludge blanket process are also described.

Anaerobic digestion is one of the oldest processes used for the stabilisation of sludges. It involves the decomposition of organic and inorganic matter in the absence of molecular oxygen. The major applications have been, and remain today, in the stabilisation of concentrated sludges produced from the treatment of wastewater and in the treatment of some industrial wastes. More recently, it has been demonstrated that dilute organic wastes can also be treated anaerobically.

In the anaerobic digestion process, the organic material in mixtures of primary settled and biological sludge is converted biologically, under anaerobic conditions, to a variety of end products including methane and carbon dioxide. The process is carried out in an airtight
reactor. Sludge, introduced continuously or intermittently, retained in the reactor for varying periods of time. The stabilised sludge, withdrawn continuously or intermittently from the reactor, is reduced in organic and pathogen content and is nonputrescible.

The two types of commonly used anaerobic digesters are identified as standard rate and high rate. In the standard rate digestion process, the contents of the digester are usually unheated and unmixed. Detention time for the standard rates process vary from 30 to 60 days. In a high rate digestion process the contents of the digester are heated and mixed completely. The required detention time for high rate digestion is typically 15 days or less. A combination of these two basic processes is known as the “two stage process”. The primary function of the second stage is to separate the digested solids from the supernatant liquor: however, additional digestion and as production may occur.

The biological conversion of the organic matter in treatment plant sludge’s is thought to occur in three steps. The first step in the process involves the enzyme-mediated transformation (hydrolysis) of higher molecular mass compounds into compounds suitable for use as a source of energy and cell carbon. The second step (acidogenesis) involves the bacterial conversion of the compounds resulting from the first step into identifiable lower molecular mass intermediate compounds. The third step (methanogenesis) involves the bacterial conversion of the intermediate compounds into simpler end products, principally methane and carbon dioxide (Holland 1987, Mc. Carty 1964, Mc Carty 1966).

In a digester, a consortium of anaerobic organisms work together to bring about the conversion of organic sludges and wastes.
One group of organisms responsible for hydrolysing organic polymers and lipids to basic structural building blocks such as monosaccharides, amino acids, and related compounds. A second group of anaerobic bacteria ferments the breakdown products to simple organic acids, the most common of which in an anaerobic digester is acetic acid. This group of microorganism, described as nonmethanogenic, consists of facultative and obligate anaerobic bacteria. Collectively, these microorganisms are often identified in the literature as “acidogens,” or “acid formers.” Among the nonmethanogenic bacteria that have been isolated from anaerobic digesters are *Clostridium* sp., *Peptococcus anaerobus*, *Bifidobacterium* sp., *Desulphovibrio* spp., *Corynebacterium* sp., *Lactobacillus*, actinomycetes, *Staphylococcus*, and *Escherichia coli*. Other physiological groups present include those producing proteolytic, lipolytic, ureolytic, or cellulolytic enzymes.

A third group of microorganisms converts the hydrogen and acetic acid formed by the acid formers to methane gas and carbon dioxide. The bacteria responsible for this conversion are strict anaerobes and are called methanogenic. Collectively, they are identified in the literature as “methanogens,” or “methane formers.” Many of the methanogenic organisms identified in anaerobic digesters are similar to those found in the stomachs of ruminant animals and in organic sediments taken from lakes and rivers. The principal genera of microorganisms that have been identified include the rods (*Methanobacterium*, *Methanobacillus*) and spheres (*Methanococcus*, *Methanosarcina*) (Higgins 1975, Holland 1987). The most important bacteria of the methanogenic group are the ones that utilise hydrogen and acetic acid. They have very slow growth rates; as a result, their metabolism is usually considered, rate limiting in the
anaerobic treatment of an organic waste. Waste stabilisation in anaerobic digestion is accomplished when methane and carbon dioxide are produced. Methane gas is highly insoluble, and its departure from solution represents actual waste stabilisation.

It is important to note that methane bacteria can only use a limited number of substances for the formation of methane. Currently, it is known that methanogens use the following substrates: CO₂, H₂, formate, acetate, methanol, methylamines, and carbon monoxide. Typical energy yielding conversion reactions involving these compounds are as follows:

\[ 4H₂ + CO₂ \rightarrow CH₄ + 2H₂O \]

\[ 4HCOOH \rightarrow CH₄ + 3CO₂ + 2H₂O \]

\[ CH₃COOH \rightarrow CH₄ + CO₂ \]

\[ 4CH₃OH \rightarrow 3CH₄ + CO₂ + 2H₂O \]

\[ 4(CH₃)₃N + H₂O \rightarrow 9CH₄ + 3CO₂ + 6H₂O + 4NH₃ \]

In an anaerobic digester, the two principal pathways involved in the formation of methane (1) the conversion of hydrogen and carbon dioxide to methane and water and (2) the conversion of acetate to methane and carbon dioxide. The methanogens and the acidogens form a "syntrophic" (mutually beneficial) relationship in which the methanogens convert fermentation end products such as hydrogen, formate, and acetate to methane and carbon dioxide. The methanogens are able to utilise the hydrogen produced by the
acidogens because of their efficient hydrogenase. Because the methanogens are able to maintain an extremely low partial pressure of H₂, the equilibrium of the fermentation reaction is shifted towards the formation of more oxidised end products (e.g., formate and acetate). The utilisation of the hydrogen, produced by the acidogens and other anaerobes, by the methanogens is termed interspecies hydrogen transfer. In effect, the methanogenic bacteria remove compounds that would inhibit the growth of acidogens.

To maintain an anaerobic treatment system that will stabilise an organic waste efficiently, the nonmethanogenic and methanogenic bacteria must be in a state of dynamic equilibrium. To establish and maintain such a state, the reactor contents should be void of dissolved oxygen and free from inhibitory concentrations of such constituents as heavy metals and sulfides. Also, the pH of the aqueous environment should range from 6.6 to 7.6. Sufficient alkalinity should be present to ensure that the pH will not drop below 6.2 because the methane bacteria cannot function below this point. When digestion is proceeding satisfactorily, the alkalinity will normally range from 1000 to 5000 mg/L, and the volatile fatty acids will be less than 250 mg/L. Sufficient amount of nutrient, such as nitrogen and phosphorus, must also be available to ensure the proper growth of the biological community. Depending on the nature of the sludges or waste to be digested, growth factors may also be required. Temperature is another important environmental parameter. The optimum temperature ranges are the mesophilic, 85 to 100°F (30 to 38°C), and the thermophilic, 120 to 135°F (49 to 57°C).

Some industrial wastes that are high in BOD can be utilised very efficiently by anaerobic treatment. In the anaerobic contact process,
Untreated wastes are mixed with recycled sludge solids and then digested in a reactor sealed off from the entry of air (Speece 1983). The contents of the digester are mixed completely. After digestion, the mixture is separated in a clarifier or vacuum flotation unit, and the supernatant is discharged as effluent, usually for further treatment. Settled anaerobic sludge is then recycled to seed the incoming wastewater. Because of the low synthesis rate of anaerobic microorganisms, the excess sludge that must be disposed of is minimal. This process has been used successfully for the stabilisation of meat packing and other high strength soluble wastes. Typical process loading and performance data for the anaerobic contact processes are reported in Table 1.

In the upflow anaerobic sludge blanket (UASB) process, the waste to be treated is introduced in the bottom of the reactor. The wastewater flows upward through a sludge blanket composed of biologically formed granules or particles. Treatment occurs as the wastewater comes in contact with the granules. The gases produced under anaerobic conditions (principally methane and carbon dioxide) cause internal circulation, which helps in the formation and maintenance of the biological granules. The free gas and the particles with the attached gas rise to the top of the reactor. The particles that rise to the surface strike the bottom of the degassing baffles, which causes the attached gas bubbles to be released. The degassed granules typically drop back to the surface of the sludge blanket. The free gas and the gas released from the granules is captured in the gas collection domes located in the top of the reactor. Liquid containing some residual solids and biological granules passes into a settling chamber, where the residual solids are separated from the liquid. The separated solids fall
back through the baffle system to the top of the sludge blanket. To keep the sludge blanket in suspension, upflow velocities in the range of 2 to 3 ft/h (0.6 to 0.9 m/h) have been used. Typical process loading and performance data for the UASB process are reported in Table 1.

**Table 1**

**Typical process and performance data for anaerobic processes used for the treatment of industrial wastes**

<table>
<thead>
<tr>
<th>Process</th>
<th>Input COD, mg/L</th>
<th>Hydraulic detention time, h</th>
<th>Organic loading, lb COD/ft³.d</th>
<th>COD removal, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anaerobic contact process</td>
<td>1,500-5,000</td>
<td>2-10</td>
<td>0.03-0.15</td>
<td>75-90</td>
</tr>
<tr>
<td>Upflow anaerobic sludge-blanket (UASB)</td>
<td>5,000-15,000</td>
<td>4-12</td>
<td>0.25-0.75</td>
<td>75-85</td>
</tr>
<tr>
<td>Fixed-bed</td>
<td>10,000</td>
<td>24-48</td>
<td>0.06-0.30</td>
<td>75-85</td>
</tr>
<tr>
<td>Expanded-bed</td>
<td>5,000-10,000</td>
<td>5-10</td>
<td>0.30-0.60</td>
<td>80-85</td>
</tr>
</tbody>
</table>

Note: lb/COD/ft³.d x 16.0185 = kg COD/m³.d.

The two most common anaerobic attached growth treatment processes are the anaerobic filter and the expanded bed processes used for the treatment of carbonaceous organic wastes. Attached-growth treatment process used for denitrification are also considered. Typical process loading and performance data for the anaerobic filter and expanded bed processes are reported in table 1.

The anaerobic filter is a column filled with various types of solid media used for the treatment of the carbonaceous organic matter in
wastewater. The waste flows upward through the column, contacting the media on which anaerobic bacteria grow and are retained. Because the bacteria are retained on the media and not washed off in the effluent, mean cell residence times on the order of 100 days can be obtained. Large values of mean cell residence time can be achieved with short hydraulic retention times, so the anaerobic filter can be used for the treatment of low-length wastes at ambient temperature.

In the expanded bed process the wastewater to be treated is pumped upward through a bed of an appropriate medium (e.g., sand, coal, expanded aggregate) on which a biological growth has been developed. Effluent is recycled to dilute the incoming waste and to provide an adequate flow to maintain the bed in an expanded condition. Biomass concentrations exceeding 15,000 to 40,000 mg/L have been reported. Because a large biomass can be maintained, the expanded-bed process can also be used for the treatment of municipal wastewater, the presence of sulfate can lead to the formation of hydrogen sulfide. A number of methods have been proposed for the capture of the hydrogen sulfide in the solution phase. As the quantity of sludge produced in the expanded bed process is considerably less than that produced in aerobic systems, such as the activated sludge process, it is anticipated that greater use will be made of this and other attached growth anaerobic processes for the treatment of municipal wastewater. The recovery of methane, a usable gas, is another important advantage of the anaerobic processes.

Removal of nutrients from wastewater prior to disposal is being required more frequently. Because both nitrogen and phosphorus can impact receiving water quality, the discharge of one or both of these
constituents may have to be controlled (Water Pollution Control Federation 1987). Nutrient removal options that need to be considered include the following:

1. Nitrogen removal without phosphorous removal
2. Nitrogen and phosphorus removal
3. Phosphorus removal with or without nitrification

The information presented in this section is intended to serve as a brief introduction to biological nutrient removal. Biological nutrient removal is a relatively low cost means of removing nitrogen and phosphorus from waste water. Recent experience has shown that biological processes are reliable and effective in removing nitrogen and phosphorus.

Nitrogen can occur in many forms in wastewater and undergo numerous transformations in wastewater treatment. These transformations allow the conversion of ammonia-nitrogen to products that can easily be removed from the wastewater. The two principal mechanisms for the removal of nitrogen are assimilation and nitrification denitrification. Because nitrogen is a nutrient, microbes present in the treatment process will assimilate ammonia and incorporate it into cell mass. A portion of this ammonial nitrogen will be returned to the waste water on the death and lysis of the cells. In nitrification denitrification, the removal of nitrogen is accomplished in two conversion steps. In the first step, nitrification, the oxygen demand of ammonia is reduced by
converting it to nitrate. However, the nitrogen has merely changed forms and not been removed. In the second step, denitrification, nitrate is converted to a gaseous product for removal.

Phosphorus uptake by a microorganism occurs in staged reactors. By controlling the environmental conditions properly, microorganisms can be made to take up excess phosphorous. The removal of phosphorous is accomplished by wasting or by microbial leaching. Both methods of phosphorous removal are considered further in greater detail in Principles and Practice of Nutrient Removal from Municipal Waste Water (1988) and Eekenfelder (1987).

Pond systems can be classified as (1) aerobic, (2) maturation, (3) facultative and (4) anaerobic with respect to the presence of oxygen.

In their simplest form, stabilisation ponds are large, shallow earthen basins that are used for the treatment of wastewater by natural process involving the use of both algae and bacteria. Although it is common to group all pond systems together when discussing them, in this chapter they are discussed according to the classification. Their design is considered to be cheap.

An aerobic stabilisation pond contains bacteria and algae in suspension, and aerobic conditions prevail throughout its depth. There are two basic types of aerobic ponds. In the first type, the objective is to maximise the production of algae. These ponds are usually limited to a depth of about 0.5 to 1.5ft.
In the second type, the objective is to maximise the amount of oxygen produced, and pond depths of up to 5ft (1.5m) are used. In both types, oxygen, in addition to that produced by algae, enters the liquid through atmospheric diffusion. To achieve best results with aerobic ponds, their contents must be mixed periodically using pumps or surface aerators.

In aerobic photosynthetic ponds, the oxygen is supplied by natural surface reaeration and by algal photosynthesis. Except for the algal population, the biological community present in stabilisation ponds is similar to that present in an activated-sludge system. The oxygen released by the algae through the process of photosynthesis is used by the bacteria in the aerobic degradation of organic matter. The nutrients and carbon dioxide released in this degradation are, in turn, used by the algae. Lower animals such as rotifers and protozoa are also present in pond and their main function is to polish the effluent.