WASTEWATER TREATMENT

1. Introduction

At present there is a scarcity of good quality water and it will be more of a problem in the future (1).

Sewage is the spent water supply of a community. Because of infiltration of groundwater into loose-jointed sewer pipes, the total amount of water treated may exceed the amount consumed. The higher the per capita consumption of water, the weaker (more dilute) is the sewage, which is also affected by industrial wastes. Sewage flow is greater during daylight hours and varies little in large cities, whereas in many small communities, the late-night flow is almost all groundwater.

Because of large equipment and land requirements, capital costs for wastewater-treatment plants are high. A collection system that conveys both sanitary and storm flows must be designed to deal with high peak flows at the treatment plant; detention basins are usually provided in order to smooth the flow into the plant and reduce the sudden peak flow. In the absence of such precautions, it may be necessary to by-pass a portion of the flow.

Legislation in the United States has added several new parameters to the requirements for effluent permits. Parameters to be considered, depending on the plant location, are biochemical oxygen demand (BOD), total suspended solids (TSS), chemical oxygen demand (COD), volatile organic compounds (VOC), priority pollutants, aquatic toxicity, heavy metals, nitrogen, and phosphorus.

Wastewater treatment technologies differ from each other in terms of their principles, scope of application, speed and economy.

2. Waste Minimization

Reduction and recycling of waste are inevitably site- and plant-specific, but a number of generic approaches and techniques have been used successfully across the United States to reduce many kinds of industrial wastewaters.

Generally, waste minimization techniques can be grouped into four major categories: inventory management and improved operations, modification of equipment, production process changes, and recycling and reuse. Such techniques can have applications across a range of industries and manufacturing processes, and can apply to hazardous as well as nonhazardous wastes.

Many of these techniques involve source reduction, the preferred option in the U.S. Environmental Protection Agency's (EPA's) hierarchy of waste management techniques. Others deal with on- and off-site recycling. The best way to determine how these general approaches can be designed to fit a particular company's needs is to conduct a waste minimization assessment. In practice, waste minimization opportunities are limited only by the extent of the ingenuity of the generator. In the end, a company looking carefully at overall returns of waste minimization may well conclude that the most feasible strategy would be to use a combination of source reduction and recycling projects. Waste minimization approaches as developed by the EPA are shown in Table 1.

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The six major ways of reducing pollution are as follows:

(1) Recirculation. In the paper board industry, white water from a paper machine can be put through a saveall to remove the pulp and fiber and then be recycled to various points in the paper-making process.
(2) Segregation. Clean streams are separated for direct discharge. Concentrated or toxic streams are separated for separate treatment.
(3) Disposal. In many cases, concentrated wastes can be removed in a semidry state. In the production of ketchup, the kettle bottoms after cooking and preparation of the product are usually flushed to the sewer. The total discharge BOD and suspended solids can be markedly reduced by removal of this residue in a semidry state for disposal. In breweries, the secondary storage units have a sludge in the bottom of the vats that contains both BOD and suspended solids. Removal of this as a sludge rather than flushing to the sewer will reduce the organic and solids load to treatment.
(4) Reduction. It is common practice in many industries, such as breweries and dairies, to have hoses continuously running for clean-up purposes. The use of automatic cutoffs can substantially reduce the wastewater volume.
(5) The use of drip pans to catch products, in cases such as a dairy or ice-cream manufacturing plant, instead of flushing this material to the sewer, considerably reduces the organic load. A similar case exists in the plating industry where a drip pan placed between the plating bath and the rinse tanks will reduce the metal dragout.
(6) Substitution. The substitution of chemical additives of a lower pollutional effect in processing operations, eg, substitution of surfactants for soaps in the textile industry.

Water reuse is usually a question of the tradeoff between the costs of raw water and the costs associated with treatment for reuse and for discharge. If biological treatment is to be employed, several factors must be considered. These are an increase in concentration of organics, both degradable and nondegradable. This may have a negative effect in terms of final effluent toxicity. An increase in temperature or total dissolved solids may adversely affect the performance of the biological process.

3. Characterization of Wastewaters

A comprehensive analytical program for characterizing wastewaters should be based on relevance to unit treatment process operations, the pollutant or pollutants to be removed in each, and effluent quality constraints. The qualitative and quantitative characteristics of waste streams to be treated not only serve as a basis for sizing system processes within the facility, but also indicate streams having refractory constituents, potential toxicants, or biostats. Such streams are not amenable to effective biological treatment, as indicated by the characterization results, and require treatment using alternative processes.

It should be recognized that the total volume of wastewater as well as the chemical analyses indicating the organic and inorganic components are required, backed by statistical validity, before the conceptualizing of the overall treatment plant design can begin. The basic parameters in wastewater characterization are summarized in Table 2.

3.1. Industrial Wastewater Flow. The design flows for industrial complexes generally consist of the following: (*1*) base process flows resulting from normal production operations; (*2*) sanitary sewage; (*3*) contaminated storm runoff; (*4*) other sources, eg, extraordinary dumps, tank draining, and ballast discharge. The base flow and sanitary contribution can be measured in open channels or closed conduits using a variety of methods, such as automatic metering devices, weirs, or less sophisticated devices. Care should be taken to ensure flows are measured during workday and weekend operations, different work shifts, and over a sufficiently long period of time to reflect statistical reliability.

Since the mid-1980s, contaminated storm runoff has become an object of increasing concern within industrial complexes. Storm flow is intermittent and unpredictable in nature. The level of flow and degree of contamination not only varies within an installation; it has its own geometric characteristics, which influence patterns of surface runoff.

3.2. Definition of Wastewater Constituents. Parameters used to characterize wastewaters can be classified as organic and inorganic analyses. The organic content of wastewater is estimated in terms of oxygen demand using biochemical oxygen demand (BOD), chemical oxygen demand (COD), or total oxygen demand (TOD). Additionally, the organic fraction can be expressed in terms of carbon, using total organic carbon (TOC). It should be understood that these parameters do not necessarily measure the same constituents. Specifically, they reflect the following: (*1*) BOD: biodegradable organics in terms of oxygen demand; (*2*) COD: organics amenable to chemical oxidation as well as certain inorganics, such as sulfides, sulfites, ferrous iron, chlorides, and nitrites; (*3*) TOD: all organics and some inorganics in terms of oxygen demand; and (*4*) TOC: all organic carbon expressed as carbon.

It is important to identify volatile organic carbon (VOC) and the presence of specific priority pollutants, in addition to the total organic content. The organic characteristics of various industrial wastewaters are shown in Table 3.

The inorganic characterization schedule for wastewaters to be treated using biological systems should include those tests which provide information concerning (*1*) potential toxicity, such as heavy metal, ammonia, etc; (*2*) potential inhibitors, such as total dissolved solids (TDS) and chlorides; (*3*) contaminants requiring specific pretreatment such as pH, alkalinity, acidity, suspended solids, etc; and (*4*) nutrient availability.

Aquatic toxicity is a permit requirement on all discharges. Aquatic toxicity is generally reported as an LC_{50} the percentage of wastewater which causes the death of 50% of the test organisms in a specified period ie, 48 or 96 h, or as a no observed effect level (NOEL), in which the NOEL is the highest effluent concentration at which no unacceptable effect will occur, even at continuous exposure.

Toxicity is also frequently expressed as toxicity units (TU), which is 100 divided by the toxicity measured:

$$TU = \frac{100}{LC_{50} \text{ or NOEL}}$$

in which the LC_{50} or the NOEL is expressed as the percent effluent in the receiving water. Therefore, an effluent having an LC_{50} of 10% contains 10 toxic units.

Effluent toxicity can also be defined as a chronic toxicity in which the growth or reproduction rate of the species is affected.

4. Wastewater Treatment and Recycling Technologies

Water treatment technologies are used for three purposes: water source reduction, wastewater treatment, and recycling. At present, unit operations and processes are combined to provide what are called primary, secondary, and tertiary treatment. Primary treatment includes a very preliminary physical purification process (filtration by bar screen, grit chamber, etc). Secondary treatment deals with chemical and biological processes for treating wastewater. In the tertiary (advanced) treatment process, wastewater (treated by primary and secondary processes) is converted into good quality water which can be used for different purposes such as drinking, industrial, and medicinal. In the tertiary process, up to 90 to 99% of the pollutants are removed, and water is safe for the specific use. In a complete water treatment plant, all three processes are combined to produce good and safe quality water (1).

Despite various advanced technologies for water treatment and reclamation, economic, effective, and rapid water treatment and reclamation on a commercial level is still a challenging problem. Prior to water treatment and reclamation, one should be aware of the qualitative and quantitative nature of water pollutants. Managing the removed pollutants (sludge) should also be kept in mind. A systematic approach to water treatment and recycling technologies involves understanding the technology which includes construction and operating cost, maintenance, and management of removed pollutants. A comparison of these wastewater treatment and reclamation technologies is presented in Table 4. A detailed literature survey of water treatment and recycling technologies has been carried out through analytical, chemical, water abstracts, and other journals, and a brief discussion of them is presented here. Water treatment and recycling technologies are classified on the basis of their working principles.

4.1. Physical Technologies. Treatment and recycling technologies involving physical forces are known as physical technologies. These include screening, filtration and centrifugal separation, micro- and ultrafiltration, reverse osmosis, crystallization, sedimentation and gravity separation, flotation, and adsorption.

Screening, Filtration, and Centrifugal Separation. Pieces of cloth, paper, wood, cork, hair, fiber, kitchen refuse, and fecal solids in wastewater are removed by screening. The main idea of screening is to remove solid wastes from wastewater. Generally, screening is used as the very first step in a wastewater treatment plant. Screens of various sizes are used for this purpose, the size of the screen selected is based on the size of the solids in the wastewater.

Filtration is a very simple physical process in which insoluble contaminants are removed by passing the water through a setup of pores of different sizes, depending on the presence of solid contaminants. It is used to remove suspended solids, greases, oils, and bacteria. Various types of filters such as membranes and cartridges, made of sand, gravel and other granular materials are used. The filtration technique is applicable below 100 mg/L suspended solids and 25 mg/L oil and grease. These constituents can be reduced up to 99%. Filtration is used for both water treatment and recycling. Water produced by filtration is used in adsorption, ion exchange, or membrane separation processes. Potable water is also produced by filtration (3,4).

In centrifugal separation, suspended noncolloidal solids (up to 1 μ) are separated from water by centrifugal forces. Wastewater is placed in centrifugal devices and rotated at different speeds, and the solids (sludges) are separated and discharged. The extent of separation of suspended solids depends on their densities and the speed of the centrifuge. The applications include source reduction and separation of oils and greases. The different types of centrifuges available and in use are solid-bowl, basket type, directflow, and countercurrent flow (3,4).

Micro- and Ultrafiltration. Particles and other microbes from 0.04 to 1 μ are removed by microfiltration provided that the total suspended solids do not exceed 100 mg/L. The filters used are in the form of cartridges. Commercially available cartridges are made of cotton, wool, rayon, cellulose, fiberglass, polypropylene, acrylics, nylon, asbestos, and fluorinated hydrocarbon polymers. These are arranged in as tubular, disc, plates, spiral, and hollow fiber forms. The life of cartridges varies from 5 to 8 years depending upon the concentration of dissolved solids. Preremoval of suspended solids is an important factor in the life of cartridges. The operating pressure in this process ranges from 1 to 3 bar. Applications include removal of solids and microbes. Water purified by this technique is used for the food and drink industries, soft drinks, pharmaceuticals, photofilm processing, swimming pools, and drinking (4,5). It has also been used as a wastewater source reduction technique.

Ultrafiltration is a low-pressure membrane separation process that removes high molecular weight materials, colloids, pyroxenes, microorganisms, and suspended solids from wastewater. Ultrafiltration membranes are manufactured from a wide variety of polymers, and minerals in the range of 0.005 to 0.10 μ. The membranes are made of polysulfonates, polyacrylonitriles, polyamides, PVDF, and zirconium oxides. To achieve the required filtration, membranes are arranged in tubular, disc, plates, spiral, and hollow fiber forms. The life of membranes varies from 5 to 8 years and may be increased as discussed above (4).

Reverse Osmosis. Reverse osmosis (RO), also known as hyperfiltration, is a classical method of purification that came into existence since the advancement of semipermeable membranes. At present, it has received great attention as the best water recycling technique. The separation and concentration of a dissolved species is achieved due to the hydraulic gradient across the semipermeable membrane. Pressure greater than osmotic pressure is applied for the process. The most commonly used membranes are made of cellulose, nylon, polyether, polyethyl urea, polyphenyl oxides, phenylenes, and polyamide. To achieve the required filtration, membranes are arranged in tubular, disc, plate, spiral, and hollow fiber forms. The partition coefficients of solutes between water and the membrane play an important role in removing water pollutants. The free energy of interaction between water and membrane sites is also responsible for the RO process. The pH, pressure, size, and molecular weight of the solute and time of operation are considerable factors in RO.

RO has been used as a separation and concentration technique at macro- and microlevels for removing large, nonpolar, ionic, and toxic substances. Up to 85–99% total dissolved solids (TDS), organic dissolved matter (ODM), and bacteria can be removed by this method. It has been used for treating wastewater from sanitary wastes, municipal leachates, petrochemicals, electroplating, textiles, coal, gasification, pulp and paper, steel, and electronic industries (5,6). It rejects 100% of bacteria, viruses, and other microbes, and, therefore, it is used to prepare ultrapure water for pharmaceuticals, medicines, and electronics. In addition, it has been used for source reduction. RO is today's most economical process for potable water production from saline water.

The life of RO membranes is 2–5 years, depending on the nature of the wastewater treated. The flux and the quality of the permeate may decrease over a long period of time due to membrane fouling from humic acids, bacterial slimes, or scales that may accumulate on the RO membranes. Phenols also clog the membranes. To increase the efficiency and life of RO systems, pretreatment is necessary to minimize the concentration of colloidal and dispersed solids. Physicochemical coagulation with lime has been used to minimize colloids, turbidity, dispersed oil phases, metal ions, and suspended matters. Sodium hydroxide solution (pH 9–11) has been used to clean RO membranes in case of silica and sulfate fouling (7,8). Silica can also be removed from membranes by ion retarding resins that have high affinity for strong acids, together with conversion of the weak acid [$Si(OH)_4$] into much stronger acid (H_2SiF_6). Bacterial inhibitor solutions are circulated (to check the bacterial growth) into the RO tubules or discs before stopping the process for a long period (7). Phenolics may be removed from RO membranes by circulating hydrogen peroxide solution.

Crystallization. In this process, soluble constituents are removed by raising their concentrations to the point where they start to crystallize. This is done either by evaporation, by lowering the temperature of the water, or by adding other solvents. It is useful for treating wastewater that has high concentrations of TDS, including soluble organics and inorganics. During the process, other constituents such as bicarbonate, ammonia, and sulfite may break down and may be converted into various gases and, therefore, crystallization sometimes may be used for pH control. The treated water from this process is of high quality. Crystallization is generally used for wastewater released from cooling towers, coal and gas fired boilers, paper, and dyeing plants. It is also used for source reduction. The commonly used devices for crystallization include forced circulation, draft tube baffle, surface cooled crystallizers, and fluidized suspension (5,9).

Sedimentation and Gravity Separation. In this process, suspended solids, grit, and silt are removed by allowing water to remain undisturbed/semi-disturbed for different time periods. The suspended solids settle by gravity (3,4). The time period depends on the size and density of the solids. Various types of tanks are designed for this purpose. Some chemicals such as alum are used to adjust pH and augment the process. Gravity separation can reduce oil concentrations and suspended solids up to 99% and 60%, respectively. Generally, sedimentation is carried out prior to a conventional treatment process. It is a very useful method for treating effluents from the paper and refinery industries. Water treated in this process is used for industrial water supply, water for ion exchange, and membrane processing. The technique is also used for source reduction.

Flotation. This technique removes suspended solids, oils, greases, and biological solids by adhering them, to air or gas bubbles (3,4,10). The solids thus adhered to gas or air bubbles form agglomerates, which in turn accumulate at the water surface and are removed. Some chemicals such as alum and activated silica help in the flotation process. Compressed air is allowed to pass through water, which helps in the flotation process. Some workers have also used electroflotation as an effective process for water treatment and recycling. Up to 75% and 99% of suspended solids and oil/grease are removed, respectively, by this process. Flotation requires water tanks of different sizes. Flotation is a common and essential component of a conventional water treatment plant. It is a very effective technique for treating wastewater from the paper and refinery industries.

Adsorption. Adsorption (3,4,11) is a surface phenomenon defined as the increase in concentration of a particular component at the surface or interface between two phases. Adsorption efficiency depends on a number of parameters such as pH, temperature, concentration of pollutants, contact time, particle size of the adsorbent, and nature of adsorbents and pollutants. Suspended particles, oils, and greases reduce the efficiency of the process and, therefore, pre-filtration is required. It is considered a universal water treatment and reclamation process because it can be applied to remove soluble and insoluble organics, inorganics, and biological solids. Different types of adsorbents are used in the adsorption process. The most commonly used adsorbents are activated carbon, fly ash, metal oxides, zeolites, moss, biomass, and geothites. At the industrial level, pollutants are removed from wastewater by using columns and contactors filled with the required adsorbents. The extent of removal varies from 90 to 99%. Adsorption is used for source reduction, wastewater treatment, and reclamation for potable, industrial, and other purposes. The basic problems of adsorption are regeneration of columns and column life.

4.2. Chemical Technologies. Water treatment methods involving the use of chemicals are chemical technologies. Precipitation, coagulation, oxidation, ion exchange, and solvent extraction are the main chemical methods for wastewater treatment and reclamation (see Table 5).

Precipitation. Dissolved contaminants may be converted into solid precipitates by adding chemicals (4,12) that react with the soluble pollutants and form precipitates. The most commonly used chemicals for this purpose are different types of alum, sodium bicarbonate, ferric chloride, ferric sulfate, ferrous sulfate, and lime. pH and temperature are the controlling factors in the precipitation process. Precipitation is carried out in sedimentation tanks; 40 to 60% removal of pollutants by precipitation has been reported. The presence of oil and grease may cause a problem in precipitation. The applications of precipitation include wastewater treatment (from nickel and chromium plating) and water recycling. Specific applications include water softening and removal of heavy metals and phosphate from wastewater. The major problem in precipitation is managing the large volume of sludge produced.

Coagulation. The suspended nonsettleable solids in wastewater are allowed to settle by the addition of certain chemicals in a process called coagulation (3,13). The commercially available chemicals are alum, starch, iron compounds, activated silica, and aluminum salts. In addition, synthetic cationic, anionic, and nonionic polymers are very effective coagulants but are usually more costly. pH, temperature, and contact time are the most important controlling factors in the coagulation process. In a biological treatment plant, microbes and other organics floated on the surface are removed by the addition of certain coagulants. It is the main component of a wastewater treatment plant and its application includes wastewater treatment, recycling, and removal of heavy metal ions and fluoride.

Oxidation. In chemical oxidation, organic compounds are converted into water and carbon dioxide or some other products such as alcohols, aldehydes, ketones and carboxylic acids which are biodegradable (3,14). Chemical oxidation is carried out by potassium permanganate, chlorine, ozone, peroxides, air, and chlorine dioxides. The rate of chemical oxidation depends on the nature of the oxidants and pollutants. pH, and temperature also play a crucial role in the rate of chemical oxidation. Ammonia, cyanide, sulfides, phenols, hydrocarbons, and some pathogens may be removed by chemical oxidation. Chemical oxidation is used for wastewater treatment and recycling for industry and irrigation. It is also a useful and effective method for source reduction.

Ion Exchange. Ion exchange is a process in which ions in wastewater are exchanged with solid materials called ion exchangers (3,15). It is a reversible process and requires low energy. The ion exchangers are of two types, cation and anion exchangers, that can exchange cations and anions, respectively. Ion exchangers are resins of natural or synthetic origins that have active sites on their surfaces and, generally, are in the form of beads. The most commonly used ion exchangers are sodium silicates, zeolites, polystyrene sulfonic acid, acrylic and methacrylic resins. Ion exchange is used to remove low concentrations of inorganics and organics (up 250 mg/L). The concentration of organics and inorganics can be reduced up to 95%. Applications include the production of potable water, water for industries, pharmacy, research, and softening for boiler feed, fossil fuels, nuclear power stations, paper, and, electronic industries. It has also been used for source reduction. Pretreatment of water is required in the presence of oil, grease, and high concentrations of organics and inorganics.

Solvent Extraction. Organic solvents that are immiscible with water and can dissolve water pollutants are added to wastewater to remove pollutants. The technique is called solvent extraction (16). A maximum concentration of TDS of 2000 mg/L can be reduced up to 90% by solvent extraction. The most commonly used solvents are benzene, hexane, acetone, and other hydrocarbons. The technique is effective to remove only the dissolved organics, oils, and greases in wastewater. However, certain metal ions and actinide chemicals may be removed by the method. It is also used for water treatment and recycling in chemical process plants, phenol, gasoline, and acid industries. It has also been used for water source reduction. The presence of suspended solids may cause a problem in solvent extraction and, hence, requires pretreatment.

4.3. Electrical Technologies. Water pollutants are removed under the influence of electric current in electrical water treatment and recycling technologies. Electrical water treatment technologies are summarized below.

Electrodialysis. In this technique, water soluble ions are allowed to pass through ion selective semipermeable membranes under the influence of an electric current (3–5,17). The ion selective membranes are made of ion exchange material. They may be cation and anion exchangers, which permit outflow of cations and anions, respectively. The process, operated either in a continuous or batch mode, has two electrodes on which an emf. is applied. To obtain the desired degree of demineralization, membranes are arranged either in parallel or series. The dissolved solids removal depends on pH, temperature, the amount of current applied, the nature of the pollutants, selectivities of the membranes, the wastewater flow rate, fouling and scaling by wastewater, and the number and configuration of stages. Applications include production of potable water from brackish water. This technique has also been used for water source reduction. A maximum concentration of 200 mg/L of TDS can be reduced by 90% by electrodialysis. Membrane fouling occurs as in reverse osmosis. Cleanup and other precautions should be taken as discussed in the reverse osmosis section.

Electrolysis. The technique in which the soluble inorganics and organics are either deposited or decomposed on the surface of electrodes by an electrochemical redox reaction is called electrolysis (18). Metal ions are deposited on the electrode surface, and organics are decomposed into carbon dioxide and water or some other products. It has been used to remove turbidity and color from wastewater. This method is effective for the removal of TDS below 200 mg/L and, therefore, requires pretreatment of wastewater. The technique comprises a water tank or tanks in series with two or a series of electrodes of the required metal. The electrodes are specific with respect to the dissolved metal ions in wastewater. The most important controlling factors for this process are pH, temperature, amount of current applied, and contact time. Electrolysis as a technique for wastewater treatment is not yet developed completely and is still at the research and development stage. It has been rarely used commercially for wastewater treatment. However, its applications include treating some industrial effluents especially enriched with metal ions and some organics. It may be used as a water source reduction technique. The advantages of this technique comprise the further use of deposited metal ions without any waste management problem.

4.4. Thermal Technologies. Techniques involving the use of heat energy for water treatment and recycling are thermal technologies. The most commonly used techniques for wastewater treatment and recycling are evaporation and distillation.

Evaporation. Evaporation is a natural process and is generally used to reduce waste liquid volume. In modern development, it has been used as a water treatment method (4,5,19). The water surface molecules escape from the surface under natural conditions, and these escaped molecules are collected as pure liquid water. Mechanical evaporators have been used for water recycling. Sometimes, vacuum evaporation has been used for wastewater recycling, and these are operated by steam or electric power. Evaporation is effective for removing inorganic and organic (except volatile organics) contaminants, and it works even at very high concentrations (about 10%) of pollutants. Foaming, scaling, and fouling along with suspended solids and carbonates are the major problems in evaporation because they create maintenance problems. Evaporation applications include treating wastewater from the fertilizer, petroleum, pharmaceutical, and food processing industries. It is also used for water supply to ion exchangers and membrane processes. Water from evaporation has been used for cooling in towers and boilers. It can be used as a technique for water source reduction.

Distillation. In distillation, water is purified by heating it up to 100°C at which liquid water vaporizes and leaves the pollutants behind (3,20). The vapors generated are cooled to liquid water. The wastewater should be free of volatile impurities. Water produced by this technique is about 99% free from impurities. Various types of boilers with multistage and double distillation are used in this process. The size of the boilers depends on the quantity of water required. Applications of distillation in water treatment and reclamation include water supplies in laboratories, pharmacy, and medicinal preparations. Distillation is effective for preparing potable water from sea and brackish water.

4.5. Biological Technologies. *Biodegradation.* The biodegradation properties of various organics are shown in Table 6. The mechanism of aerobic degradation is shown in Figure 1.

Approximately one-half of the organics removed are oxidized to CO_2 and H_2O, and one-half synthesized to biomass. Three to 10 percent of the organics removed result in soluble microbial products (SMP). The SMP is significant because it causes aquatic toxicity.

Nitrogen and phosphorus are required in the reaction at an approximate ratio of BOD:N:P of 100:5:1. Nitrogen and phosphorus are amply available in municipal wastewaters, but frequently are deficient in industrial wastewaters. It should be noted that only ammonia nitrogen or nitrate is available for biosynthesis.

The reactions in an aerobic biological process are as follows:

$$\text{organics} + O_2 + N + P \xrightarrow[K]{\text{Cells}} \text{new cells} + CO_2 + H_2O + \text{SMP}$$

in which K is a reaction rate coefficient which is a function of the degradability of the wastewater and SMP is the nondegradable soluble microbial products and

$$\text{cells} + O_2 \rightarrow CO_2 + H_2O + N + P + \text{nondegradable cellular residue} + \text{SMP}$$

The generation of SMP is directly proportional to the degradable COD removed in the process. Some of the SMP is toxic to aquatic species.

In the activated sludge process, performance is related to the food-to-microorganism ratio (F/M), which is the kg BOD applied/d/kg volatile suspended solids (VSS).

For a soluble wastewater, the VSS is proportional to the biomass concentration. Process performance may also be related to the sludge age, which is the average length of time the organisms are in the process.

$$\text{sludge age} = \frac{\text{mass of organisms under aeration}}{\text{mass wasted/d}}$$

Figure 2 depicts a batch oxidation. Note that readily degradable organics will be sorbed by the floc forming organisms immediately on contact. As organics are removed, oxygen is consumed and biomass is synthesized, as shown. Continued aeration after organic removal will result in oxidation of the biomass, generally referred to as endogenous respiration.

The performance, therefore, is related to the F/M or sludge age and the degradability, K. As the F/M decreases or the sludge age increases, greater removals are achieved. It should be noted that the sludge age is proportional to the reciprocal of the F/M. The reaction rate coefficient, K, as related to wastewaters characteristics.

As shown in Figure 1, all of the organics removed in the process are either oxidized to CO_2 and H_2O or synthesized to biomass generally expressed as volatile suspended solids. As previously noted, a small portion of the organics removed results in SMP products.

The fraction of the organics removed that result in synthesis varies, depending on nature and biodegradability of the organics in question. A rough estimate is to assume that one-half is oxidized and one-half synthesized.

For a soluble wastewater, the net sludge to be wasted from the process may be computed as synthesis minus oxidation, ie, endogenous respiration.

$$\text{net sludge wasted} = \text{sludge synthesized} - \text{oxidation}$$

As the sludge age is increased, more of the sludge is oxidized and the net sludge wasted is decreased. If the wastewater contains influent volatile suspended solids, such as that in a pulp and paper mill, the solids not oxidized in the process must be added to the net wasted.

The oxygen requirements are computed in a similar manner:

$$\text{oxygen required} = \text{organic oxidation} + \text{endogenous oxidation}.$$

On average, it takes 1.4 kg oxygen to oxidize 1 kg cells as VSS. Therefore, for each kilogram of VSS substracted from the sludge yield, 1.4 kg oxygen must be added to the oxygen required.

Process performance is affected by temperature. The reaction rate decreases with temperature over a range of 4–31°C. As the temperature decreases, dispersed effluent suspended solids increase. In one chemical plant in West Virginia, the average effluent suspended solids was 42 mg/L during the summer and 105 mg/L during the winter. Temperatures above 37°C may result in a dispersed floc and poor settling sludge. It is therefore necessary to maintain aeration basin temperature below 37°C to achieve optimal effluent quality.

Biological sludges generally fall into one of three classifications. A flocculent sludge is one in which the major part of the biomass consists of flocculent organisms, with some filaments growing within the floc. The advantage this provides is that the filaments form a backbone which strengthens the floc. Filamentous bulking occurs when the filaments grow out from the floc in the bulk of the liquid. This condition hinders sludge settling. The pinpoint case occurs at very low loadings, causing floc dispersion, as shown in Figure 3.

Sludge quality is defined by the sludge volume index (SVI), ie, the volume occupied by one dry weight gram after settling for one-half hour, which therefore defines the bulkiness of the sludge. A bulking sludge is usually caused by an excess of filamentous-type organisms. Filamentous organisms thrive best with readily degradable organics as a food source. Wastewater containing complex organics is not subject to filamentous bulking because the filaments cannot degrade these organics. If all things are maintained equal, ie, adequate O_2, N and P, and BOD, the floc-forming organisms are predominant. In order to maintain conditions favorable to the floc formers, adequate oxygen, nutrients, and BOD must diffuse through the floc and reach all the organisms.

As the oxygen uptake or F/M increases, the dissolved oxygen must be increased to provide sufficient driving force to penetrate the floc. Minimum concentrations of nitrogen and phosphorus are necessary in the effluent.

Generalized flow configurations are shown in Figure 4. Refractory wastewaters can be treated in a complete mix basin because filamentous bulking is not an issue. For readily degradable wastewaters, high concentrations of BOD are necessary to penetrate the floc, requiring a plug flow configuration. Alternatively, a selector can be employed to absorb the readily degradable organics so they are not available as a food source for the filaments. The removal of specific priority pollutants follows the Monod kinetic relationship, which states that effluent quality is a function of sludge age. Thus the only way to reduce the effluent concentration of a specific organic is to increase the sludge age.

Biological Treatment. Biological treatment has a reputable place in various water treatment and recycling methods (3–5,21,22). Soluble and insoluble organic pollutants are oxidized by microbes in this process. Water is circulated in a reactor that maintains a high concentration of microbes, and the microbes convert organic matter into water, carbon dioxide, and ammonia. Sometimes, the organic matter is converted into other products such as alcohol, glucose, and nitrate. Wastewater should be free of toxic organics and inorganic pollutants. The maximum concentrations of TDS, heavy metals, cyanides, phenols, and oil should not exceed 16,000, 2.0, 60.0, 140, and 50 mg/L, respectively. Biological treatment includes aerobic and anaerobic digestion of wastewater (see Table 7).

Aerobic Process. When air or oxygen in dissolved form is available freely to wastewater, then the biodegradable organic matter undergoes aerobic decomposition, caused by aerobic and facultative bacteria. The extent of the process depends on oxygen availability, retention time, temperature, and the biological activity of the bacteria. The rate of biological oxidation of organic pollutants may be increased by adding chemicals required for bacterial growth. The technique is effective for removing dissolved and suspended volatile and nonvolatile organics. The concentration of biodegradable organics can be reduced up to 90%. Applications include treating industrial wastewater to reduce BOD, COD, nitrogen, and phosphorous. The disadvantage of this method is the production of a large quantity of biosolids, which require further costly management.

Anaerobic Process. If free or dissolved oxygen is not available to wastewater, then anaerobic decomposition called putrefaction occurs. Anaerobic and facultative bacteria convert complex organic matter into simpler organic compounds of nitrogen, carbon, and sulfur. The important gases evolved in this process are nitrogen, ammonia, hydrogen sulfide, and methane. The applications of the anaerobic process to organic pollutant digestion are as discussed in the aerobic process.

Anaerobic Treatment. Anaerobic treatment is usually employed for high strength wastewaters. In anaerobic treatment, complex organics are broken down through a sequence of reactions to end products of methane gas, CH_4, and carbon dioxide, CO_2:

$$\text{organics} \rightarrow \text{volatile fatty acids} \rightarrow CH_4 + CO_2$$

Because anaerobic treatment will not reach usual permit discharge levels, it is employed as a pretreatment process prior to discharge to a POTW or to a subsequent aerobic process. Therefore it is most applicable to high strength wastewaters. Whereas aerobic treatment requires energy to transfer oxygen, anaerobic processes produce energy in the form of methane gas. Successful anaerobic process operation depends on maintaining a population of methane organisms. It is therefore critical that the sludge age of the anaerobic sludge exceed the growth rate of the methane organisms. At 35°C the common design criterion is a solids retention time (SRT) of 10 d or more. Anaerobic sludge can be maintained dormant for long periods of time, thereby making the process attractive for seasonal industrial operations such as in the food processing industry. A disadvantage to the anaerobic process is that initial startup may take as long as 45–60 d. Should the process be killed by a toxic shock a long period will be required for a re-startup. Particular care must be taken, therefore, to avoid upset. From an economic perspective, anaerobic pretreatment should be considered when the BOD exceeds 1000 mg/L.

Types of Anaerobic Processes. There are five principal process variants which are propriety in nature. These are as follows:

(1) Anaerobic Filter. The anaerobic filter is similar to a trickling filter in that a biofilm is generated on media. The bed is fully submerged and can be operated either upflow or downflow. For very high strength wastewaters, a recycle can be employed.
(2) Anaerobic Contact. This process can be considered as an anaerobic activated sludge because sludge is recycled from a clarifier or separator to the reactor. Since the material leaving the reactor is a gas–liquid–solid mixture, a vacuum degasifier is required to separate the gas and avoid floating sludge in the clarifier.
(3) Fluidized Bed. This reactor consists of a sand bed on which the biomass is grown. Since the sand particles are small, a very large biomass can be developed in a small volume of reactor. In order to fluidize the bed, a high recycle is required.

(4) Upflow Anaerobic Sludge Blanket (UASB). Under proper conditions anaerobic sludge will develop as high density granules. These will form a sludge blanket in the reactor. The wastewater is passed upward through the blanket. Because of its density, a high concentration of biomass can be developed in the blanket.
(5) ADI Process. The ADI is a low rate anaerobic process which is operated in a reactor resembling a covered football field. Because of the low rate, it is less susceptible to upset compared to the high rate processes. Its disadvantage is the large land area requirement.

With the exception of the ADI process, anaerobic processes usually operate at a temperature of 35°C. In order to maintain this temperature, the methane gas generated in the process is used to heat the reactor. Anaerobic processes are shown in Figure 5. Anaerobic treatment performance data are shown in Table 8.

5. Alternative Biological Treatment Technologies

5.1. Lagoons. Where large land areas are available, lagooning provides a simple and economical treatment for nontoxic or nonhazardous wastewaters. There are several lagoon alternatives.

The impounding and absorption lagoon has no overflow or there may be an intermittent discharge during periods of high stream flow. These lagoons are particularly suitable to short seasonal operations in arid regions.

Anaerobic ponds are loaded such that anaerobic conditions prevail throughout the liquid volume. One of the major problems with anaerobic ponds is the generation of odors. The odor problem can frequently be eliminated by the addition of sodium nitrate at a dosage equal to 20% of the applied oxygen demand. An alternative is the use of a stratified facultative lagoon, in which aerators are suspended 3 meters below the liquid surface in order to maintain aerobic surface conditions, with anaerobic digestion occurring at the lower depths.

Aerobic lagoons depend on algae to produce oxygen by photosynthesis. This oxygen, in turn, is used by the bacteria to oxidize the organics in the wastewater. Since algae are aerobic organisms, the organic loading to the lagoons must be sufficiently low to maintain dissolved oxygen.

5.2. Aerated Lagoons. An aerated lagoon system is a two- or three-basin system designed to remove degradable organics (BOD). The first basin is fully mixed, thereby maintaining all solids in suspension. This maximizes the organic removal rate. A second basin operates at a lower power level, thereby permitting solids to deposit on the bottom. The solids undergo anaerobic degradation and stabilization. A third basin is frequently employed for further removal of suspended solids and enhanced clarification. In order to avoid groundwater pollution, these basins must usually be lined. The process is shown in Figure 6.

Aerated lagoons are employed for the treatment of nontoxic or nonhazardous wastewaters such as food processing and pulp and paper. Retention time varies from 3 to 12 d, so a large land area is usually required.

5.3. Activated Sludge. There are several generic activated sludge processes presently available. Complete Mix (CMAS) is applicable to refractory-type wastewaters in which filamentous bulking is not a problem. This process has the advantage of dampening fluctuations of influent wastewater quality.

Plug flow is applicable for readily degradable wastewaters subject to filamentous bulking. Upstream controls are required to avoid shock loadings.

The selector process is applicable for readily degradable wastewaters; it also requires upstream controls. In a selector, degradable organics are removed by the floc formers by biosorption and therefore are not available as a food source for the filaments.

The sequencing batch reactor (SBR) or intermittent process is a combination of complete mix and plug flow, and usually controls filamentous bulking. The nature of the process eliminates the need for an external clarifier.

The oxidation ditch process is usually considered when nitrogen removal is required.

Other processes include deep tank aeration such as the Biohoch, the use of high purity oxygen, and the Deep Shaft process.

Performance of the activated sludge process may be summarized as follows: effluent quality is related to the sludge age, with higher sludge ages required for the more refractory wastewaters; degradable priority pollutants can be reduced to μg/L levels under optimal operating conditions as related to sludge age; effluent soluble BOD levels <10 mg/L are achievable in most cases, and nitrification and denitrification can be achieved through process modifications.

6. Fixed-Film Processes

6.1. Trickling Filter. A trickling filter is a packed bed, usually plastic on which a biofilm grows. As a wastewater passes over the film, organics and oxygen diffuse into the film, where they undergo biodegradation, as shown in Figure 7. The variables affecting performance are the organic loading rate, the hydraulic loading rate, temperature, and the degradability of the wastewater. For the treatment of industrial wastewaters, a trickling filter is considered a pretreatment process usually designed to remove about 50% of the BOD. This is largely the result of economic considerations. Trickling filter performance data are shown in Figure 8.

6.2. Rotating Biological Contactor (RBC). An RBC is a fixed-film process in which a biofilm is developed on a rotating plastic cylinder which passes through the wastewater. As the cylinder passes through, the wastewater organics diffuse into the film. As the cylinder passes through the air, oxygen diffuses into the biofilm, causing degradation of the organics. Increased treatment is achieved by increasing the number of stages.

7. Advanced Treatment Processes

7.1. Nitrification. Ammonia nitrogen is converted to nitrate in a two-step process. Ammonia is first converted to nitrites, and the nitrites are then converted to nitrates. This conversion is oxygen intensive. For each milligram of ammonia converted to nitrate, 4.6 mg of oxygen is required. In addition, each milligram of ammonia converted consumes 7.14 mg of alkalinity (23) (see Fig. 9).

Nitrification may occur in the same tank as carbon oxidation in a single sludge process, or it may take place in a separate nitrification tank. Because nitrifying organisms have a slower growth rate than the organisms for carbon oxidation, the process requires longer detention time and longer mean cell retention time.

7.2. Biological Phosphorus Removal. Phosphorus removal can be enhanced in a biological system by first creating an anaerobic zone followed by an aerobic zone. In biological phosphorus removal, from 2.5 to 4 times more phosphorus can be removed than in a secondary treatment process (23).

To generate energy for cell growth in the anaerobic stage, phosphorus is released from the internal polyphosphates of the cell, resulting in an increase in the liquid phosphorus concentration. In the aerobic zone, there is a rapid uptake of the soluble phosphorus for the resynthesis of intracellular polyphosphates. More phosphorus is absorbed by the cells than was released in the anaerobic zone.

There are three major biological phosphorus removal methodologies: the Anaerobic/Oxic (A/O) process, the PhoStrip process, and the sequencing batch reactor. The A/O process is proprietary, and phosphorus removal depends on the influent ratio of BOD to P. The PhoStrip process is also proprietary. Phosphorus removal does not depend on the BOD:P ratio, but chemicals must be used to precipitate the phosphorus (23). The SBR can be designed to provide anaerobic conditions during the treatment cycle, which release phosphorus. When the reactor is then aerated, the phosphorus is absorbed from the wastewater and is incorporated into the biomass.

7.3. Denitrification. Denitrification is the removal of nitrogen from wastewater. In an anoxic environment, several species of bacteria can use nitrates, rather than oxygen, as their energy source. Denitrification converts the nitrates into nitrogen gas and additional biomass (23). The process requires a carbon source for completion. In wastewater treatment, it is common to use the wastewater itself for the carbon supply. The raw wastewater flows into an anoxic zone with return sludge and a large mixed liquor recycle. The recycle ratio is determined by the ammonia concentration and the required effluent nitrate concentration. The anoxic zone then denitrifies by using the nitrates created in the mixed liquor. Following the anoxic zone, the wastewater flows to an aerobic zone to strip nitrogen gas. The process may be repeated for additional nitrogen removal. Denitrification is normally done in a plug flow type system, an oxidation ditch, or a sequencing batch reactor (23).

7.4. Biological Dual-Nutrient Removal. Biological dual-nutrient removal is the reduction of both nitrogen and phosphorus in wastewater by biological methods. Biological dual-nutrient removal is achieved through several proprietary treatment processes, including the A^2O process, the Bardenpho process, the University of Capetown (UCT) process, and the Virginia Initiative (VIP) process (23). These processes use the aerobic process for carbon oxidation, the anoxic process for denitrification, and the anaerobic process for biological phosphorus removal, although arrangement of the processes varies. The UCT process and the VIP process are further complicated by the use of internal recycle streams.

7.5. Air Stripping. Air stripping is a method of removing volatile compounds from a solution. Air is introduced at the bottom of a packed tower. Wastewater flows down the tower from the top and contacts the air countercurrently. The driving force in air stripping is the concentration difference between the air and the wastewater. The tower medium may become fouled, resulting in high operating and maintenance costs.

7.6. Coagulation/Sedimentation. Coagulation/sedimentation uses chemicals to enhance the sedimentation of solids, precipitate pollutants, or remove phosphorus. The chemicals most commonly used in the coagulation/sedimentation process are lime, alum, iron salts, and polymers. Coagulation involves destabilizing colloidal particles through any of several processes, including double layer compression, charge neutralization, enmeshment, or interparticle bridging (24). The particles then aggregate and settle out.

Alum is typically used in the chemical removal of phosphorus, although iron salts may also be used. Phosphorus removal occurs by the formation of an insoluble precipitate of aluminum or iron phosphate. Alum and iron also react with hydroxyl radicals in the water, forming hydroxides in addition to phosphates.

7.7. Filtration. Filtration is the removal of wastewater solids by passing the wastewater through granular media. Some of the media that have been used include sand, anthracite coal, diatomaceous earth, perlite, and granular activated carbon. Sand filters are the most commonly used filters in wastewater treatment, although filters can also consist of multiple types of media, such as coal over sand or coal over silica sand over garnet sand (24).

Particles may be removed by interstitial straining. However, smaller particles must be transported to the surfaces of the media, where an attachment mechanism retains the particles. Transport mechanisms may include gravitation, diffusion, and interception. These processes depend on the physical characteristics of the media. The attachment mechanism may include electrostatic attraction, chemical bridging, or adsorption. These processes are functions of the coagulant and the chemical characteristics of the wastewater and media (24).

Filters are classified as slow filters, rapid filters, or pressure filters. Slow filters require a buildup of solids on the top surface of the filter through which the wastewater must pass, which requires a low application rate. This buildup strains particles from the wastewater. Rapid filters and pressure filters use the entire depth of the media and may be operated at higher loadings than slow filters.

7.8. Activated Carbon Adsorption. Adsorption is a process where molecules of a compound adhere to a solid surface. The most commonly used adsorbent in wastewater treatment is activated carbon. Activated carbon comes in two forms, powdered and granular. Powdered activated carbon (PAC) is added to the mixed liquor in the aeration tanks and is removed from the wastewater by settling. Granular activated carbon (GAC) is used in a packed bed (25).

The adsorptive capacity of the carbon is a function of the material and method used to create the activated carbon as well as the chemical properties of the compound to be adsorbed. In general, organics are completely removed until the adsorptive capacity is exhausted. At this point, the effluent concentrations increase (25). Spent activated carbon may be regenerated by heating.

7.9. Membrane Systems. Membrane processes use a semipermeable barrier that allows the water to flow through but retains the contaminants. There are several types of membrane systems in wastewater treatment, including reverse osmosis, nanofiltration, microfiltration, and ultrafiltration. All of these processes use pressure to force water through the membrane.

Ultrafiltration may be used to remove molecules that have a molecular weight of 500 or greater and have a low osmotic pressure at moderate concentrations. This includes bacteria, viruses, proteins, and clays (24). Reverse osmosis is used to separate small molecules whose osmotic pressure is high. Microfiltration and nanofiltration are membrane systems that lie between ultrafiltration and reverse osmosis.

Membrane processes are subject to fouling of membranes. These processes should be pilot tested to determine which process and membrane work best for any given application.

7.10. Disinfection Processes. *Chlorination/Dechlorination.* Chlorine has been used as a disinfectant for many reasons, including inactivation of a wide range of pathogens, maintenance of a residual, and cost. As chlorine dissolves in water, it forms hypochlorous acid, which dissociates into hypochlorite ions and hydrogen ions and decrease the pH. Lower pH values cause less dissociation, which is preferable, because hypochlorous acid is a much more effective disinfectant than hypochlorite. Sodium and calcium hypochlorites also form hypochlorous acid when dissolved, but they also liberate hydroxyl ions, and thus increase the pH of the wastewater. Chlorine is toxic, so dechlorination may be required, which is usually done by using sulfur dioxide to reduce the chlorine to chlorides. Sodium metabisulfite or sodium bisulfite may be used instead of sulfur dioxide in small facilities. The reactions are nearly instantaneous, and detention times are less than 2 minutes.

Ozonation. Ozone is a powerful oxidant that can disinfect wastewater using less contact time and lower dosages than other chemical methods. It has high germicidal efficiency against a wide range of organisms, and it does not leave a residual. Because of its instability, ozone must be generated on-site. Ozone is applied to wastewater in closed contactors. The off-gas from the contactors contains high concentrations of ozone, which must be destroyed before it is discharged to the atmosphere.

Ultraviolet Light Disinfection. Ultraviolet light is a form of electromagnetic radiation at wavelengths of 100–400 nm. Electromagnetic radiation at wavelengths from 240–280 nm inactivates microorganisms by damaging their nucleic acid. Ultraviolet lamps operate in much the same way as fluorescent lamps. The uv radiation is generated by passing a current through mercury vapor. The mercury lamps may be low-pressure or medium-pressure lamps. Low-pressure lamps emit most of their energy at a wavelength of 253.7 nm, which is in the optimal range. Medium-pressure lamps generate a lesser portion of their energy in the optimal range, but the intensity of the radiation is much greater than that of the low-pressure lamps, and fewer lamps are required. See Ref. 26 for further information discussed in section 7.

8. Advances in Wastewater Treatment

8.1. Advanced Oxidation Processes (AOP). Radicals produced by AOP are suitable for achieving complete abatement and mineralization of pollutants. AOP usually operate at or close to ambient temperature and pressure. The potentialities offered by AOP can be exploited to integrate biological treatments by oxidative degradation of toxic substances, entering or leaving the biological stage (27,28). The usual two AOP are the Fenton process and photocatalysis:

Fenton Process. Production of $OH^{\bullet}$ radicals by Fenton's reagent occurs when addition of H_2O_2 is added to Fe^{2+} salts (29): It has been demonstrated that Fenton's reagent can destroy toxic compounds such as phenols and herbicides in wastewaters. Irradiation by uv-vis light strongly accelerates the degradation rate of organic pollutants (30). The application of the Fenton process requires strict pH control; sludges can be formed which create disposal problems.

Photocatalysis. In this process, hydroxyl and other radicals are generated at the surface of an uv-absorbing powder (called a photocatalyst). The most widely used photocatalyst is the wide band-gap (3.2 eV) semiconductor TiO_2 in its anatase crystalline form (31,32). TiO_2 absorbs uv light at wavelengths below $\sim$380 nm creating an excess of electrons in the conduction band ($e^-{}_{cb}$) and holes in the valence band ($h^+{}_{vb}$):

$$\mathrm{TiO_2} \rightarrow (e^-{}_{\mathrm{cb}} + h^+{}_{\mathrm{vb}})$$

The carriers can diffuse to the surface where they react as follows:

$$h^+{}_{\mathrm{vb}} + \mathrm{OH^-} \rightarrow \mathrm{OH^{\bullet}}{}_{\mathrm{ads}}$$

and

$$e^-{}_{\mathrm{cb}} + \mathrm{O_2} \rightarrow \mathrm{O_2}^{\bullet -}{}_{\mathrm{ads}}$$

where ads = adsorbed to the surface of TiO_2 particles.

Organic pollutants may adsorb on the surface of TiO_2 particles, and there they are attacked by the adsorbed $OH^{\bullet}$ radicals and holes. The $O_2^{\bullet -}$ radicals can further disproportionate as follows:

$$2\,\mathrm{O_2}^{\bullet -}{}_{\mathrm{ads}} + 2\,\mathrm{H^+} \rightarrow \mathrm{H_2O_2} + \mathrm{O_2}$$

Although the quantum yield of TiO_2 photocatalyzed reactions is rather low, the system does have the advantage that it can use uv photons in the near uv (black-light uv fluorescent lamps or the uv portion of solar radiation). Compilations of substances which can be mineralized using photocatalysis are now available (33).

8.2. Complexation/Flocculation. It has been shown that dissolved humic substances (DHS), bind (complex) organic solutes via hydrophobic interactions, forming humic–contaminant complexes in the aqueous phase.

The treatment process follows two stages: (*1*) binding of dissolved humic acid (DHA) by the dissolved contaminants to form complexes (complexation stage) and (*2*) precipitation of DHA and the associated contaminant by using a flocculant (alum or ferric chloride, flocculation stage). This process can be applied to remove various classes of hydrophobic organic pollutants such as PAHs, PCBs and chloro-organo pesticides from industrial wastewater. Additionally, this technology has the advantage that it may be coupled to the general water treatment process (34).

8.3. Conducting Polymers. Conducting polymers have ion exchange properties induced by charging and discharging processes (35). For instance, polypyrrole (PPy) can function as an anion exchanger, whereas PPy modified with polystyrenesulfonate anions ($PPy/PSS^{\bullet}$) works as a cation exchanger (36,37). Such a modified polymer can be used as an electrochemically switchable ion exchanger for water softening (38). This ion exchanger can be regenerated without chemical additives or aqueous electrolysis.

8.4. Ionizing Irradiation. High energy irradiation (γ rays, X rays, and electron beams) interacts with water to generate a variety of free radicals, principally $OH^{\bullet}$, $H^{\bullet}$ and hydrated electrons. If H_2O_2 or O_3 is present in the water, the $H^{\bullet}$ and the hydrated electrons are converted efficiently to $OH^{\bullet}$ radicals. This process is based on electron accelerators. An attempt has been made to use combined electron beam and ozone for treating municipal wastewater in aerosol flow (39,40).

8.5. Membrane/Sonication/Wet Oxidation. Hybrid systems are becoming popular for treating waste streams that are otherwise difficult to handle. For instance, the powder-activated carbon–activated sludge system (PACT system by Zimpro Environmental, Inc.) is a classic example of such systems. OXYMEM is another hybrid process, where wet oxidation and nanofiltration were used together to treat bioresistant industrial wastewater containing polyethylene glycol. It has also been demonstrated that sonication followed by wet oxidation (SONIWO) is a useful hybrid process for treating refractory waste. Conventional bioprocesses may not be amenable to biodestruction of the effluent from reactive bath dye. "Membrane-sonication-wet oxidation" (MEMSONIWO) is a hybrid process applied to water conservation via recycling. The membrane unit allows concentrating the waste, and then the permeate (mostly water) can be recycled. The concentrate from the membrane unit can, then, be treated by sonication to make it suitable for wet oxidation. After wet oxidation, the water can be discharged or recycled (41).

8.6. Sorption by Zeolites. It is well established that the sorption characteristics of zeolite-type materials are defined by pore size and charge properties (42). Most naturally occurring zeolites bear a relatively high framework charge arising from Al^{3+} substitution for Si^{4+} in the crystal lattice; this results in a structure of high cation-exchange capacity. Such zeolites have been used as ion exchangers to treat water and are incorporated into systems for treating radioactive waste (removal of $^{137}Cs^{+}$ and $^{90}Sr^{2+}$) and for removing $NH_4{}^{+}$ from wastewater. Zeolites that have high SiO_2/Al_2O_3 ratios have a low capacity to retain cations but are more hydrophobic and can, therefore, sorb uncharged molecules. In laboratory studies using batch sorption equilibria, high Si large-pore mordenite (MOR) and ZSM-5, it was found, have sorption properties for methyl tert-butyl ether (MTBE) and trichloroethylene (TCE) that are superior to those of activated carbon (43).

8.7. Supercritical Water Oxidation. Supercritical water oxidation (SCWO) is considered a promising technology for treating several wastes (44–47). SCWO is a process where oxidation takes place in water above its critical point (647 K, 22.1 MPa). SCWO is an environmentally acceptable technology that produces a disposable clean liquid (pure water), clean solid (metal oxides, salts), and clean gas (CO_2, N_2). Recently, there has been increasing interest in using heterogeneous catalysts in SCWO. Catalysts can increase the oxidation rates, reduce the residence times and temperatures required for treatment, and possibly control the selectivity of the reaction pathways (48).

8.8. Ultrasonic Irradiation. Sonochemical effects are due to the phenomenon of "cavitation," the nucleation and the behavior of bubbles in a liquid (49,50). In wastewater treatment, a bubble of cavitation may function as a microreactor which destroys volatile organic compounds inside (51–53). The cavity may also be thought as a $H^{\bullet}$, $OH^{\bullet}$, $OOH^{\bullet}$ radical source that react with pollutants in the bulk of the solution. Several potential applications of ultrasonic irradiation have been reported recently.

See Ref. 54 for further information on these advances.

9. Sludge Handling and Disposal

9.1. Types of Sludges. Municipal primary sludge consists of organic and inorganic particulates. The sludge must be stabilized before land disposal. Biological sludge consists of organisms and other particulates not degraded in the biological process. Chemical sludges consist of chemical precipitates, heavy metals, and other contaminants such as color precipitated from industrial wastewaters.

9.2. Sludge Stabilization. Organic sludges need to be stabilized before ultimate disposal except in the case of incineration. This is usually achieved by either aerobic or anaerobic digestion. In aerobic digestion, the degradable volatile solids are liquefied and oxidized to CO_2 and H_2O. In anaerobic digestion the solids are liquefied and fermented to CH_4 and CO_2.

9.3. Sludge Thickening. The mechanisms of sludge dewatering are shown in Figure 10. Thickening of sludge usually precedes dewatering. Depending on the nature of the sludge, several techniques are available for thickening.

(1) Gravity thickening is applicable to primary municipal sludges and most chemical sludges.
(2) Another technique is one in which the sludge is passed in a thin sheet over a porous drainage belt. This technique is particularly applicable to waste-activated sludge.
(3) In dissolved air flotation, air bubbles float the sludge, which is then removed by a scraper. It is generally applicable to large volumes of waste-activated sludge.
(4) In a centrifuge technique, various centrifuge types are used for sludge thickening.

9.4. Sludge Dewatering. In a centrifuge technique for sludge dewatering, the solid bowl centrifuge concentrates the solids under centrifugal force. Both centrate and cake solids are continuously discharged from the machine. Polymer addition is required for most wastewater sludges.

A vacuum filter is a cloth-covered drum which operates under an applied vacuum. As the drum passes through the sludge vat, solids are deposited on the filter. As the drum passes through the air, drying of the cake occurs. The cake is continuously discharged to a conveyor belt.

A belt filter press consists of a gravity drainage belt, followed by a series of roller presses which squeeze out water.

A pressure filter is a plate-and-frame press which operates on an intermittent time cycle. Drier cakes are generally attainable from a filter press.

Sludge drying beds are usually used for smaller sludge volumes, which drain and dry rapidly. Their application is usually restricted to the more arid climates.

Thickening and dewatering of various sludges is shown in Table 9.

9.5. Sludge Disposal. Land disposal of wet sludges can be accomplished in a number of ways: Lagooning or the application of liquid sludge to land by truck or spray system, or by pipeline to a remote agricultural or lagoon site.

In lagoons sludge is stored and in the case of organic sludges anaerobically disgested. Odor control is achieved either by chemical addition to the overlaying water (Cl_2 or H_2O_2) to oxidize sulfides, or by installing aerators in the liquid layer to maintain aerobic conditions.

Biological sludges can be incorporated into the soil. An important consideration is the heavy metal content of the sludge, which will dictate the total number of years sludge can be applied. The available nitrogen content of the sludge will determine the maximum yearly application.

Dewatered sludges can be employed as a landfill.

Incineration can be accomplished in multiple-hearth furnaces, in which the sludge passes vertically through a series of hearths. In a fluidized-bed sludge, particles are fed into a bed of sand fluidized by upwardly moving air.

10. Storm-Water Control

Activities that take place at industrial facilities, such as material handling and storage, are often exposed to the weather. As runoff from rain or snowmelt comes into contact with these materials, it picks up pollutants and transports them to nearby storm sewer systems, rivers, lakes, or coastal waters. Stormwater pollution is a significant source of water quality problems for the nation's waters. Of the 11 pollution source categories listed in EPA's *National Water Quality Inventory: 2000 Report to Congress*, urban runoff/storm sewers was ranked as the fourth leading source of impairment in rivers, third in lakes, and second in estuaries (55).

Pollutional discharges can be minimized by providing adequate diking around process areas, storage tanks, and liquid transfer points, with drainage into the process sewer. Contaminated storm water is usually collected on the basis of a frequency for the area in question, eg, a 10-year storm, in a holding basin. The collected water is then passed through the wastewater treatment plant at a controlled rate.

11. Other Sewage and Disposal Considerations

11.1. Private and Rural Disposal Systems. In areas not served by sewers, human and other water-carried wastes are disposed of in primitive privies, cesspools, or septic tanks (56). In the more developed areas privies have almost disappeared. Cesspools are simply pits in the ground into which wastewater is allowed to flow, and in many parts of North America they are not permitted. Cesspool water seeps into the ground, leaving the solid matter in the pit, thus groundwater in the area might become contaminated. Septic tanks are widely used in smaller communities and outlying suburbs of larger communities. The tank is kept full of waste and functions as both a sedimentation tank and anaerobic digester. Sanitary and kitchen wastes flow into the tank; grease and light material rise to the top. Heavier materials settle to the bottom and decompose anaerobically. Baffles are placed at the inlet and outlet and a grease trap is usually provided in front of the tank, which has to be cleaned periodically of solids. Good practice requires a minimum volume of 5670 L (1500 gal). The effluent flows to a tile field where it is disposed of in the soil. The tile field is composed of perforated field tile fed by a manifold and underlain with granular material, usually gravel. Clogging of the soil under the tile field must be prevented. As more areas are served by municipal systems, septic tanks are becoming less common. Malfunctioning septic tanks cause odor problems and present a public health hazard. Furthermore, septic tanks and cesspools may form a closed system in which the waste discharged may return in the water supply. In many developing nations, human waste, called night soil, is not discarded, instead, it is used as crop fertilizer and for biogas production (57). Although it is not good public health practice, it is utilization of a valuable resource (see BIOMASS ENERGY; FUELS FROM WASTE).

The Imhoff tank is similar in many respects to the septic tank, operating as a sedimentation tank and digester. It is composed of two chambers, one above the other and the shape may be square, circular, or rectangular. The depth ranges from 7.7 to 10.6 m (58). Sewage flows slowly into the upper chamber at ca 0.3 m/s and solids settle out and slide through a slot into the lower chamber, where the flowing wastewater is detained for ca 2 h. Solids held in the lower, or digestion, chamber have an initial water content of ca 95%. After a digestion time of 30–60 d the water content of the digesting sludge is reduced to ca 80% which greatly reduces the volume. The sludge is withdrawn at intervals for further dewatering and disposal. Gases produced during digestion are allowed to escape to the atmosphere through vents located at the tank sides. Solids buoyed up by gas are prevented from escaping to the upper chamber by deflector plates.

11.2. Small Communities. Small communities and recent subdivision additions to larger communities, which have not yet been connected to municipal collection systems, must have a means of waste disposal. Septic tanks are a possibility, but require periodic servicing and cleaning. Furthermore, the soil is not always suitable for accepting the effluent. An alternative is the package plant. These units are commercially produced to serve small areas. They furnish primary treatment and some secondary treatment, and require only minimal operating supervision. Capacity can be varied as needs dictate. In general, public health authorities prefer such installations instead of septic tanks.

11.3. Watercraft-Waste Disposal. The popularity of recreational boating has brought with it the problem of disposing of wastes generated by the boat users. In many rivers and lakes, this has become a serious problem. A large number of pleasure craft can place, in a weekend, a pollutional load equivalent to a small community on a medium-sized water body. As legislation was passed by the states, it became apparent that this problem would require a solution at the national level. Various technologies are available, but no agreement could be reached on which to use. Units available include the holding tank, macerator–chlorinator, and on-board incinerators. The Coast Guard was given the task of recommending a solution but became mired in bureaucratic tugs-of-war. It was agreed that holding tanks would keep the waste from reaching the receiving waters directly from the boat. However, availability of facilities to receive the retained waste material ashore was limited. In many cases, the pumped-out waste was discharged to the receiving water as soon as the sun had set. After several years of indecision, rules were promulgated that allowed the use of the macerator–chlorinator for a period, followed by total conversion to holding tanks. Macerator–chlorinators chop the waste into fine particles for adequate chlorine contact and are regarded as potential sources of bacterial contamination. Incinerators did not achieve the same acceptance on pleasure craft as they did on railroads.

12. Health and Safety Factors

Wastewater-treatment plants have numerous hazards to be expected in a chemical-process plant. Worker safety is covered by applicable OSHA, state and local standards, but two hazards require special notice; the potential for infection by pathogenic organisms is always present, and plant workers require inoculation against the common waterborne diseases. In addition, since wastewater treatment plants utilize deep water-filled tanks, provision must be made against drowning. Proper railings should be installed around the tanks and life-saving equipment should be available for immediate use. A special hazard is the biomass concentration in aeration tanks. Ingestion of this floc has caused a number of fatalities.

13. Government Regulations

A succession of federal agencies and administrations has been charged with dealing with wastewater. At present this responsibility resides with the EPA. It has been proposed that most of the EPA functions be turned back to the states. It remains to be seen if the states, with conflicting needs and priorities, will be able to deal successfully with these problems.

The National Pollutant Discharge Elimination System (NPDES) is a cornerstone of the federal efforts to control water pollution. It determines what can be discharged to a publicly owned treatment plant. Indirect discharges may not be required to obtain an NPDES permit but must meet pretreatment effluent limitations and conditions of the NPDES permit of the treatment plant cannot be exceeded.

In order to minimize the impact of stormwater discharges from industrial facilities, the NPDES program includes an industrial stormwater permitting component. Operators of industrial facilities included in one of the 11 categories of stormwater discharges associated with industrial activity that discharge or have the potential to discharge stormwater to a municipal separate storm sewer system (MS4) or directly to waters of the United States require authorization under a NPDES industrial stormwater permit. (Construction activity is one of these 11 categories, but because of the nature of its operations, it is discussed separately from the other 10 categories.) The list provided below describes the types of industrial activities within each category.

- Category One (i): Facilities with effluent limitations
- Category Two (ii): Manufacturing
- Category Three (iii): Mineral, Metal, Oil and Gas
- Category Four (iv): Hazardous Waste, Treatment, or Disposal Facilities
- Category Five (v): Landfills
- Category Six (vi): Recycling Facilities
- Category Seven (vii): Steam Electric Plants
- Category Eight (viii): Transportation Facilities
- Category Nine (ix): Treatment Works
- Category Ten (x): Construction Activity
- Category Eleven (xi): Light Industrial Activity

Category Ten (x): Construction Activity that disturbs 5 or more acres of land is included in the definition of "stormwater discharges associated with industrial activity." However, EPA opts to permit these types of activities separately from other industrial activities because of the significant difference in the nature of these activities. In addition, EPA also requires permit coverage for small construction that disturbs from 1 to 5 acres of land. More information about stormwater discharges from construction activities is available (55).

The various U.S. EPA rules that apply to water supply systems also impact the selection of treatment processes. The Surface Water Treatment Rule, the Total Coliform Rule, the Lead and Copper Rule, and the Enhanced Surface Water Treatment Rule are examples of rules that deal with the removal or control of specific constituents and microorganisms (eg, *Cryptosporidium*). Thus, the requirements set forth in the various rules will also affect the selection, design, and operation of water treatment facilities. The challenge for the designer of water treatment facilities is to meet current regulations while at the same time trying to anticipate what changes will occur in regulations and rules over the useful life of the facility and how they might impact the design and operation of the facility in the future (59).

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Table 1. **Waste Minimization Approaches and Techniques**

Approach	Related techniques
inventory management and improved operations	inventory and trace all raw materials
	purchase fewer toxic and more nontoxic production materials
	implement employee training and management feedback
	improve material receiving, storage, and handling practices
modification of equipment	install equipment that produces minimal or no waste
	modify equipment to enhance recovery or recycling options
	redesign equipment or production lines to produce less waste
	improve operating efficiency of equipment
	maintain strict preventive maintenance program
production process changes	substitute nonhazardous for hazardous raw materials
	segregate wastes by type for recovery
	eliminate sources of leaks and spills
	separate hazardous from nonhazardous wastes
	redesign or reformulate end products to be less hazardous
	optimize reactions and raw material use
recycling and reuse	install closed-loop systems
	recycle on-site for reuse
	recycle off-site for reuse
	exchange wastes

Table 2. **Basic Parameters in Wastewater Characterization**[a]

Parameter	Examples
	Basic Parameters
	source information for the individual points of origin
	waste constituents (specific compounds or general composition)
	discharge rate (average and peak)
	batch discharges
	frequency of emergency discharges or spills
chemical composition	organic and inorganic constituents
	gross organics
	chemical oxygen demand (COD)
	total organic carbon (TOC)
	biochemical oxygen demand (BOD)
	extractables
	toxics, hazardous compounds, priority pollutants
	gross inorganics—total dissolved solids
	specific inorganic ions (As, Ba, Cd, CN, Hg, Pb, Se, Ni, Sn, nitrates)
	pH, acidity, alkalinity
	nitrogen and phosphorus
	oil and grease
	oxidizing reducing agents, eg, sulfides
	surfactants
	chlorine demand
physical properties	temperature range and distribution
	particulates: colloidal, settleable, and flotable solids
	color
	odor
	foamability
	corrosiveness
	radioactivity
biological factors	biochemical oxygen demand
	toxicity (aquatic life, bacteria, animals, plants)
	pathogenic bacteria
flow characteristics	average daily flow rate
	duration and magnitude of peak flow rate
	maximum rate of change of flow rate
	storm-water flow rate (average and peak)
	Causes of Variability in Waste Characterization
	changes in production rate
	variations in plant product mix
	batch operations
	variations in efficiencies of production units
	changes in raw materials
	upsets in production processes
	maintenance (equipment shutdown and cleanout)
	miscellaneous leaks and spills
	contaminated drainage and runoff from rainstorms

[a]Ref. 2.

Table 3. **Oxygen Demand and Organic Carbon of Industrial Wastewaters**

Waste	BOD, mg/L	COD, mg/L	TOC, mg/L	BOD/TOC	COD/TOC
chemical[a]		4,260	640		6.65
chemical[a]		2,410	370		6.60
chemical[a]		2,690	420		6.40
chemical		576	122		4.72
chemical	24,000	41,300	9,500	2.53	4.35
chemical–refinery		580	160		3.62
petrochemical		3,340	900		3.32
chemical	850	1,900	580	1.47	3.28
chemical	700	1,400	450	1.55	3.12
chemical	8,000	17,500	5,800	1.38	3.02
chemical	60,700	78,000	26,000	2.34	3.00
chemical	62,000	143,000	48,140	1.28	2.96
chemical		165,000	58,000		2.84
chemical	9,700	15,000	5,500	1.76	2.72
nylon polymer		23,400	8,800		2.70
petrochemical					2.70
nylon polymer		112,600	44,000		2.50
olefin processing		321	133		2.40
butadiene processing		359	156		2.30
chemical		350,000	160,000		2.19
synthetic rubber		192	110		1.75

[a]High concentration of sulfides and thiosulfates.

Table 4. **A Comparison of Wastewater Treatment and Recycling Technologies**

Wastewater technologies	Applicability[a]	Suitability[b]	Cost ($/ $\times 10^6$ L treated H_2O)
	Physical Technologies		
screening, filtration, and centrifugal separation	Ss & Sl IOB	RSrT	20–450
micro- and ultra-filtration	Sl IOB	RSrT	10–400
reverse osmosis	Sl IOB	RSrT	10–450
crystallization[c]	Sl IO	RSrT	50–150
sedimentation and gravity separation	Ss IOB	RSrT	2–10
flotation	Ss IOB	RT	5–25
adsorption	Ss & Sl IOB	RSrT	50–150
	Chemical Technologies		
precipitation[c]	Sl IO	RT	15–500
coagulation	Ss & Sl I	RT	20–500
oxidation	Sl IO	RSrT	100–2000
ion exchange	Sl IO	RSrT	50–200
solvent extraction	Sl OV	RSrT	250–2500
	Electrical Technologies		
electrodialysis	Sl IO	RSrT	10–400
electrolysis	Sl IO	RSrT	
	Thermal Technologies		
evaporation[c]	Sl & Ss IOB	RSrT	10–200
distillation	Sl IOB	RT	10–2000
	Biological Technologies		
aerobic	Sl & Ss O	RT	10–200
anaerobic	Sl & Ss O	RT	10–200

[a]Sl: soluble; Ss: suspended; I: inorganics; O: organics; V: volatiles; B: biologicals.
[b]R: reclamation; T: treatment; and Sr: source reduction.
[c]Rarely used.

Table 5. **Chemical Waste Treatment**

Treatment method	Type of waste	Mode of operation	Degree of treatment	Remarks
ion exchange	plating, nuclear	continuous filtration with resin generation	demineralized water recovery; product recovery	may require neutralization and solids removal from spent regenerant
reduction and precipitation	plating, heavy metals	batch or continuous treatment	complete removal of chromium and heavy metals	one day's capacity for batch treatment; 3-h retention for continuous treatment; sludge disposal or dewatering required
coagulation	paperboard, refinery, rubber, paint, textile	batch or continuous treatment	complete removal of suspended and colloidal matter	flocculation and settling tank or sludge blanket unit; pH control required
adsorption	toxic or organics, refractory	granular columns of powdered carbon	complete removal of most organics	powdered carbon (PAC) used with activated sludge process
chemical oxidation	toxic and organics, refractory	batch or continuous ozone or catalyzed hydrogen peroxide	partial or complete oxidation	partial oxidation to render organics more biodegradable
solvent extraction	dissolved organics, oils, grease		maximum concentration (TDS) of 2000 mg/L can be reduced 90%	may require pretreatment

Table 6. **Relative Biodegradability of Certain Organic Compounds**

Biodegradable organic compounds[a]	Compounds generally resistant to biological degradation
acrylic acid	ethers
aliphatic acids	ethylene chlorohydrin
aliphatic alcohols (normal, iso, secondary)	isoprene
	methyl vinyl ketone
aliphatic aldehydes	morpholine
aliphatic esters	oil
alkyl benzene sulfonates with exception of propylene-based	polymeric compounds
benzaldehyde	polypropylene benzene sulfonates
aromatic amines	selected hydrocarbons
dichlorphenols	aliphatics
ethanolamines	aromatics
glycols	alkyl−aryl groups
ketones	tertiary aliphatic alcohols
methacrylic acid	tertiary benzene sulfonates
methyl methacrylate	trichlorophenols
monochlorophenols	
nitriles	
phenols	
primary aliphatic amines	
styrene	
vinyl acetate	

[a]Some compounds can be degraded biologically only after extended periods of seed acclimation.

Table 7. **Biological Waste Treatment**

Treatment method	Mode of operation	Degree of treatment	Land requirements	Equipment	Remarks
lagoons	intermittent or continuous discharge; faculative or anaerobic	intermediate	earth dug; 10–60 days' retention (may require lining)		odor control frequently required groundwater considerations
aerated lagoons	completely mixed or faculative continuous basins	high in summer; less in winter	lined earth basin, 2.44–4.88 m deep; 8.55–17.1 $m^3/(m^3{\cdot}d)$	pier-mounted or floating surface aerators or subsurface diffusers	solids separation in lagoon; periodic dewatering and sludge removal groundwater considerations
activated sludge	completely mixed or plug flow; sludge recycle	>90% removal of organics	earth or concrete basin; 3.66–6.10 m deep; 0.561–2.62 $m^3/(m^3{\cdot}d)$	diffused or mechanical aerators; clarifier for sludge separation and recycle	excess sludge dewatered and disposed of
trickling filter	continuous application; may employ effluent recycle	intermediate or high, depending on loading	5.52–34.4 $m^3/(10^3\ m^3{\cdot}d)$	plastic packing 6.10–12.19 m deep	pretreatment before POTW or activated sludge plant
RBC	multistage continuous	intermediate or high		plastic disks	solids separation required
anaerobic	complete mix with recycle; upflow or down-flow filter, fluidized bed; upflow sludge blanket	intermediate		gas collection required; pretreatment before POTW or activated sludge plant	
spray irrigation	intermittent application of waste	complete; water percolation into groundwater and runoff to stream	6.24×10^{-7}–4.68×10^{-6} $m^3/(s{\cdot}m^2)$	aluminum irrigation pipe and spray nozzles; movable for relocation	solids separation required; salt content in waste limited

Table 8. **Performance of Anaerobic Processes**

Wastewater	Process[a]	Loading, kg/(m^3·d)	HRT, h	Temperature, °C	Removal, %
meat packing	anaerobic	3.2 (BOD)	12	30	95
meat packing	contact	2.5 (BOD)	13.3	35	95
Keiring		0.085 (BOD)	62.4	30	59
slaughter house		3.5 (BOD)	12.7	35	95.7
citrus		3.4 (BOD)	32	34	87
synthetic	upflow filter	1.0 (COD)		25	90
pharmaceutical		3.5 (COD)	48	35	98
pharmaceutical		0.56 (COD)	36	35	80
guar gum		7.4 (COD)	24	37	60
rendering		2.0 (COD)	36	35	70
landfill leachate		7.0 (COD)		25	80
paper-mill foul condensate		10–15 (COD)	24	35	77
synthetic	expanded bed	0.8–4.0 (COD)	0.33–6	10–3	80
paper-mill foul condensate		35–48 (COD)	8.4	35	88
skim milk	UASB	71 (COD)	5.3	30	90
sauerkraut		8–9 (COD)			90
potato		24–45 (COD)	4	35	93
sugar		22.5 (COD)	6	30	94
champagne		15 (COD)	6.8	30	91
sugar beet		10 (COD)	4	35	80
brewery		95 (COD)			83
potato		10 (COD)			90
paper-mill foul condensate		4–5 (COD)	70	35	87
potato	ADI-BFV	0.2 (COD)	360	25	90
corn starch		0.45 (COD)	168	35	85
dairy		0.32 (COD)	240	30	85
confectionery		0.51 (COD)	336	37	85

[a]UASB = upflow anaerobic sludge blanket.

Table 9. **Performance of Sludge Thickening and Dewatering Equipment**

Equipment, and type of sludge[a]	Loading	Resultant solids content, wt%
gravity thickener		
municipal WAS, $kg/m^2 \cdot d$	20–122	1–3
inorganic sludge, $kg/m^2 \cdot d$	122–366	10–20
flotation thickener		
municipal WAS, $kg/m^2 \cdot h$	15–29	4–7
centrifuge, per unit		
paper-mill WAS, L/min	227–379	11
citrus-processing WAS, L/min	95	9–10
vacuum filter		
municipal WAS, $kg/m^2 \cdot h$	10–39	10–15
belt filter press, per unit of belt width or area		
chemical WAS, $kg/m \cdot h$	149–343	13–17
paper-mill WAS, m^3/m-h	3–6	12–19
paper-mill primary sludge, m^3/m-h	12–30	18–37
meat processing WAS, m^3/m^2-h	3.6	17
tannery WAS, m^3/m^2-h	2.1	23
pressure filter		
chemical WAS		20–30
chemical WAS	4-h cycle	28
citrus-processing WAS	2-h cycle	27
tannery WAS, m^3/m^2-h	0.09	48

[a]WAS = waste-activated sludge.

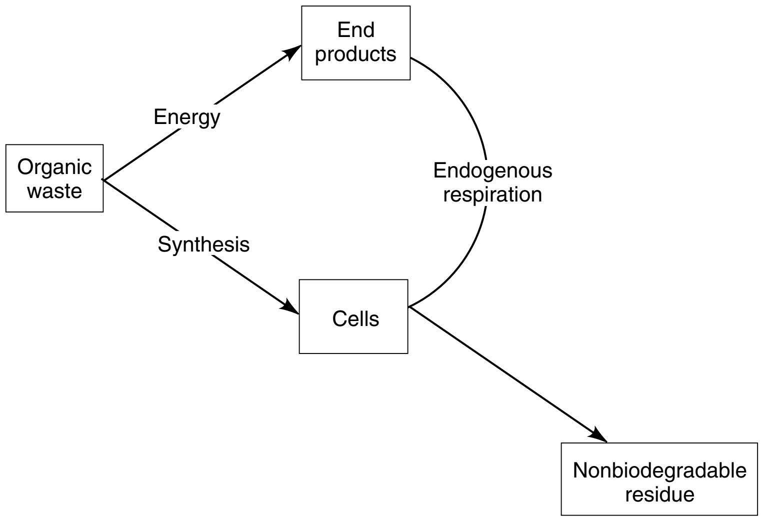

Fig. 1. The mechanism of aerobic biological oxidation.

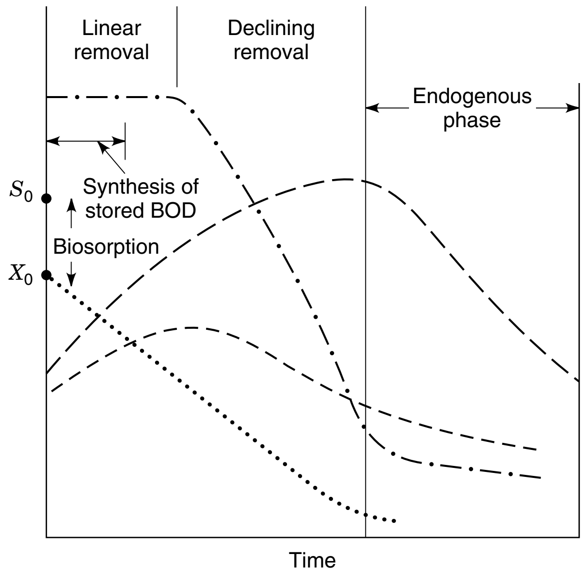

Fig. 2. Aerobic biological treatment, where S_0 = initial organic concentration and X_0 = initial biomass concentration; (———) total cell weight; (–·–) specific oxygen uptake rate; (– – –) cell N and P; (····) organic substrate remaining.

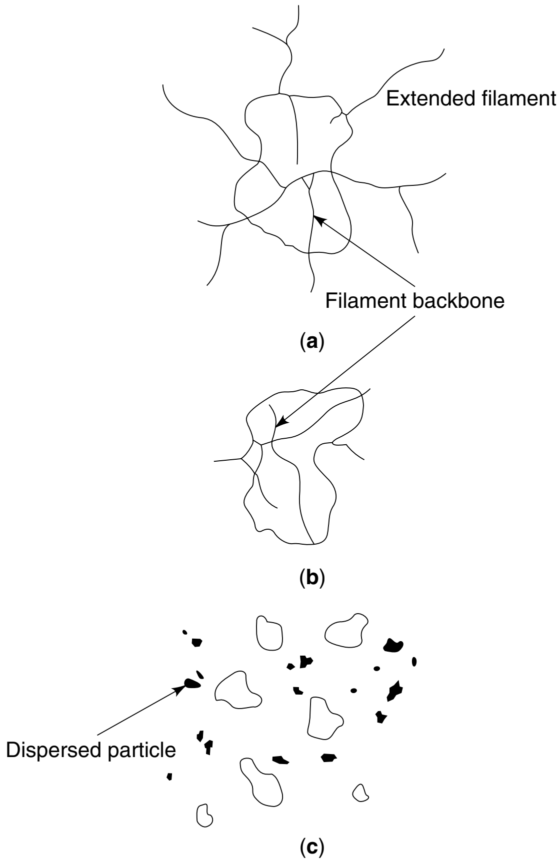

Fig. 3. Activated sludge types: (**a**) filamentous bulking; (**b**) nonbulking; (**c**) pinpoint.

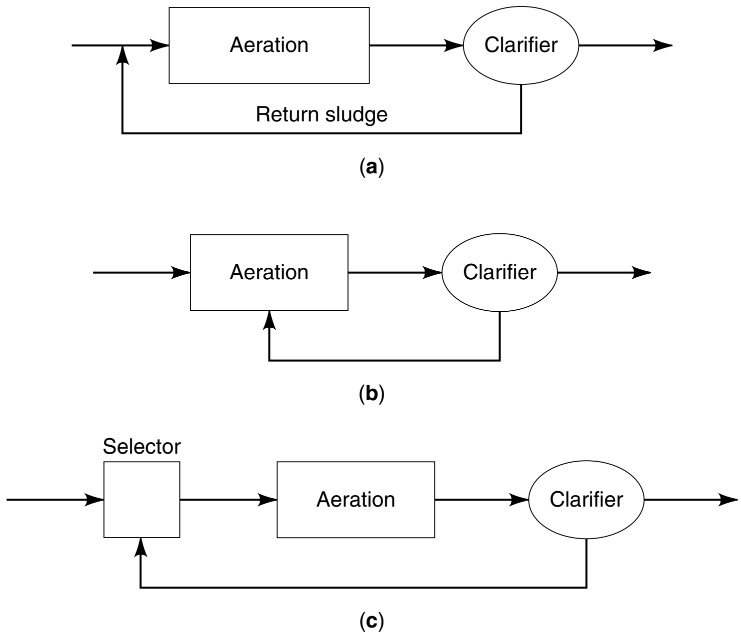

Fig. 4. Types of activated sludge processes: (**a**) plug flow; (**b**) complete mix; (**c**) selector-activated sludge.

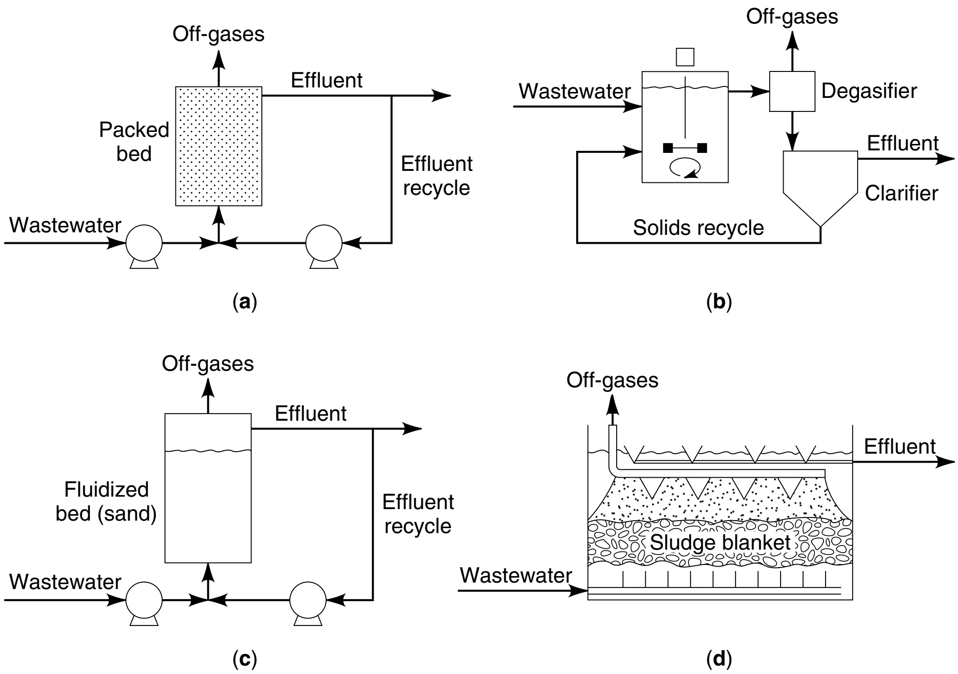

Fig. 5. Anaerobic wastewater treatment processes: (**a**) anaerobic filter reactor; (**b**) anaerobic contact reactor; (**c**) fluidized-bed reactor; (**d**) upflow anaerobic sludge blanket (UASB).

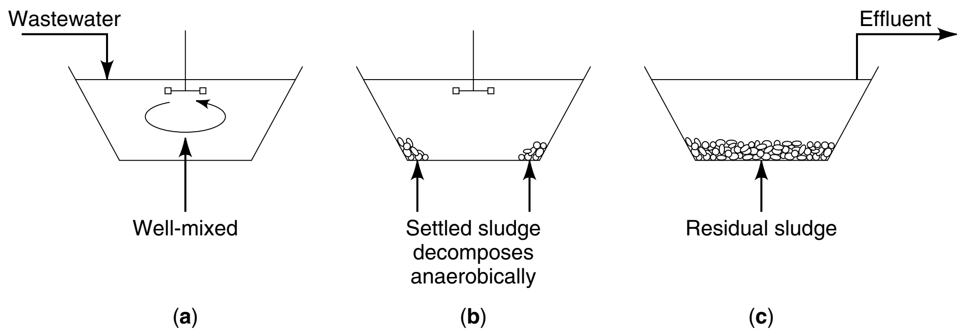

Fig. 6. Aerated lagoon types: (**a**) aerobic; (**b**) facultative; (**c**) settling.

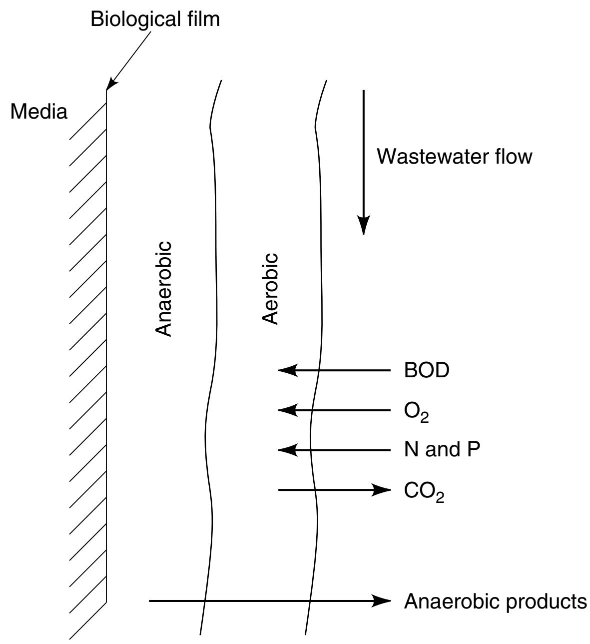

Fig. 7. Removal mechanisms in a fixed-film reactor.

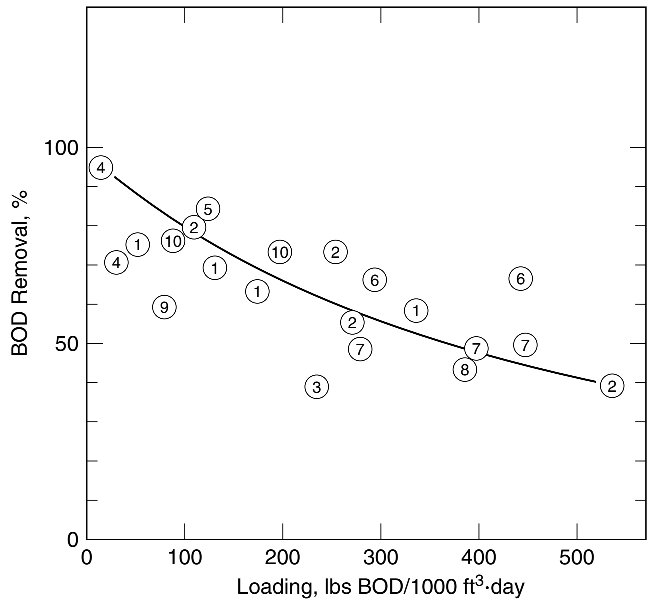

Fig. 8. Pretreatment of organic wastewater on trickling filters. Industry types for which coordinates have been plotted are 1, kraft pulp and paper; 2, mixed industry; 3, wet corn milling; 4, dairy; 5, tannery; 6, meat packing; 7, food; 8, pharmaceutical; 9, refinery; and 10, textile.

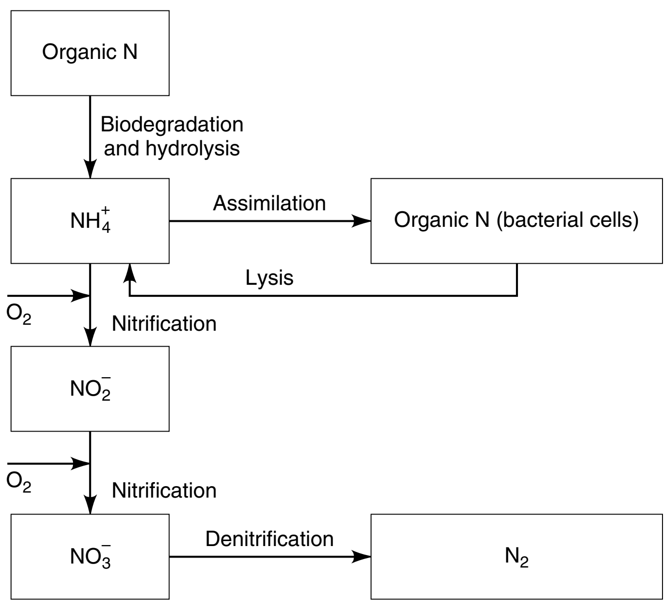

Fig. 9. Nitrogen transformation.

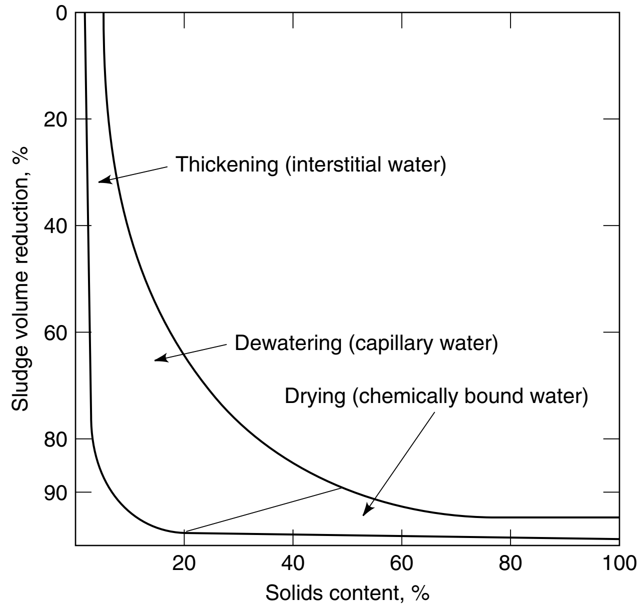

Fig. 10. Sludge thickening and dewatering relationships.