Microbiology of Environmental Engineering Systems

Microbial Ecology in Environmental Systems

The biosphere is the home of a diverse population of microorganisms found on and in plants, animals, and ecosystems. Microbes sustain the whole life of the living world and provide essential nutrients directly to higher forms of plants and animals. Their diverse role is demonstrated by the important processes involved in the carbon, nitrogen, oxygen, and sulfur cycles, underpinning life on Earth. They are both the benefi- cial plants on the surface and the degrading forces behind rocks and minerals. Environmental processes, such as the decomposition of natural and synthetic materials, rely on the microbial ecology of the involved ecosystems to produce hydrocarbon-degrading and toxic metallic-compound-transforming microbes. The analysis of the quality of water, air, and food is thus crucial for regulating the microbial community to safeguard human health. However, environmental microbes can also pose risks. Microbial pathogens are significant factors in controlling the environment for safety of life and property. Monitoring the overall activity of microbial community functions, both aerobic and anaerobic, is necessary for assurance of quality control.

Cultivation plays a definitive role in characterizing microbial communities and the metabolic pathways involved in different functions, as demonstrated by the success of sewage treatment through aerobic and anaerobic micro- bial mechanisms. Recently, microbe-mediated fuel cells have been used to generate electricity from treated sewage. Within these ecosystems, microbial interactions can be harmful or beneficial to the host. Characterizing these interactions can thus provide ecological insight and shed light on various physiological, structural, and functional relationships within the environment.

Roles of Microorganisms

The diversity of microbial life in the environment is enormous, with different compartments such as soil, water, food and plants containing their own microbial communities. Microbial populations are distinguishable from one compartment to another as well as the species included in each of the groups.

Microbes play a key role in all engineering systems. Detailed knowledge of the different microbial groups is essential in order to understand the functions of the systems and the influence of the different parameters that can influence their behaviour. The role of microorganisms should be understood and frequently emphasized in all the environmental engineering systems. It should be taken into account that despite their essential role in the process, they might be neglected by many students of Environmental Engineering. The interactions among the different microbial groups also play an important role. These interactions can occur within a particular group, among different groups or among different species in the same group.

Several microbial activities contribute to the removal of contaminants in water and wastewater. The most essential process for the removal of dissolved organic carbon is the degradation by heterotrophic aerobic bacteria. Microbial degradation may occur both under aerobic and anaerobic conditions. It is electrons from the oxidation of organic compounds (for instance acetate or other products of the acidogenesis) that can be used as an energy source rather than oxygen itself. The reduction of nitrate to form nitrogen gas is performed by autotrophic bacteria or by heterotrophic bacteria when organic carbons are available in the water and wastewater. Phosphorus is removed biologically by the uptake of phosphorus in excess offered by specific microbial groups (polyphosphate accumulating organisms). Another important function is the degradation of hydrogen sulphide produced at the water and wastewater works.

Microbial Interactions

Three different types of microbial interactions have been recognized and defined in life science categories: mutualism, synergism, and commensalism. In mutualism, both interacting partners benefit, making their relationship obligatory. In synergism, the interaction is nonobligatory, with both benefiting, but if separated, survival remains possible. Examples include organisms that degrade complex compounds into simpler forms that other organisms utilize. Commensalism describes a nonobligatory relationship where one organism benefits without affecting the other; for instance, fermenting bacteria produce amino acids and vitamins that support lactic acid bacteria growth.

Microorganisms work collectively in ecosystems, with some organisms responsible for the degradation of complex compounds that result in by-products utilized by others. For example, together with the production of methane, anaerobic bacteria generate amino acids, vitamins, and other nutrients required by lactic acid bacteria. The organic acids and aldehydes generated in soil as a result of plant growth may eventually be converted into methane by methanogenic bacteria.

Microbial Processes in Water Treatment

Many of the water, wastewater and groundwater systems in operation today rely on the natural metabolic activities of microbes to conduct the essential processes. Some of the microbial-driven mechanisms operating within both water supply systems and sewerage systems include biological filtration, nitrification and denitrification, biological activated carbon (BAC) adsorption, activated sludge, anaerobic digestion, biological phosphorus removal and pathogen control. Because of the metabolic activity of bacteria and other microorganisms involved in these processes, the water produced is purified by the removal of carbonaceous and nitrogenous materials, toxic materials, pathogenic microorganisms and other suspended solids.

In addition to these well-established processes, research continues on the use of other microbial functions for water treatment and particularly the removal of specific pollutants. Under the right conditions, microorganisms are capable of treating a wide variety of pollutants, including complex organic compounds, inorganic nitrogen compounds and metals, explosives and agricultural chemicals. For some of these treatments, particularly those applied to contaminated soils and sediments, the term bioremediation is more commonly used. Two other examples of processes that take advantage of microbial metabolism are microbial fuel cells (MFCs) and microbial desalination cells (MDCs). Much of the early work on MFCs was focused on generating electricity; however, the application of these processes within wastewater treatment plants is now being actively investigated.

1. Biological Filtration

In biological filtration, water passes through a fixed filter bed that supports a microbial biofilm or activated sludge. The biofilm comprises attached heterotrophic and nitrifying bacteria alongside protozoan grazers and higher filter-feeders. Both oxygen transfer and substrate diffusion into the biofilm limit microbial activity. The thicker the biofilm, the greater the concentration gradient of the oxygen and substrate in use. This usually results in heterotrophic bacteria toward the branching end of the biofilm and nitrifying bacteria near the substratum, where the supply of substrate is high, but oxygen concentration low.

Suspended films (activated sludge) are usually better oxygenated than attached biofilms (trickling filters). The microbial biomass is regularly separated from the treated effluent by clarification in order to maintain high biomass concentrations within a suitable biological environment. The combination of a well-mixed suspension and high biomass concentration gives activated sludge plants very high rate constants, which respond rapidly to changes in a wide variety of wastewaters. The flexible operation of the process allows variations in parameters including the solids retention time, substrate concentration, reactor holding time, and oxygen concentration. Despite this, most wastes are, in comparison to trickling filters or filter beds, biologically expensive to treat by activated sludge.

2. Activated Sludge Processes

The activated sludge process was first implemented in England in the early 20th century and thereafter rapidly adopted worldwide for the treatment of sewage and wastewaters. Microorganisms play a pivotal role: they assimilate organic compounds in a mixed–liquor suspension in a reactor. The oxidation of the organic compounds leads to the microbial reduction of oxygen (biological oxidation), with simultaneous generation of new cells which convert the organics into biomass. Aeration provides the oxygen required for the oxidation of the organic matter contained in the sewage and facilitates intimate mixing of the microbes with the organic wastewater substrate. The suspended growth of the biomass means that the excess biomass must be recycled through a settler or thickener. The reaction kinetics of the activated sludge process are dependent on growth rate and rate of substrate utilization by the microbes. Relationships between rate of microbial growth and substrate utilization have been developed for a range of different types of bacteria, as discussed earlier.

The activated sludge process posits that wastewater is a substrate containing organic material, microorganisms rely on the organic material as a substrate source, and that microorganisms are extracted by wastewater; hence, the organics contain a substrate. The activated sludge process yields remarkable decontamination. It not only results in the removal of organic carbon in the waste but also oxidizes and removes ammonia from the liquid. This is achieved by cultivating two different bacterial populations: organotrophic bacteria (activated sludge) and nitrobacteria. Organotrophic bacteria require an adequate supply of organic material in order to survive. It is the population of heterotrophic bacteria—that is, the activated sludge—that is normally used to remove carbonaceous organics from sewage. Another group of bacteria—namely, nitrobacteria—utilizes the nitrogen compounds present in the sewage. Both these processes can be represented by simple empirical reactions such as Yaramtsev's equation:

Wastewater → activated sludge biomass + gases

3. Anaerobic Digestion

Anaerobic digestion is a process extensively applied in the treatment of sewage sludges and industrial wastewaters that contain elevated levels of readily biodegradable organic matter. The process occurs naturally in some environments such as bottom sediments within lakes and ponds, particularly in regions covered by anoxic, or without dissolved oxygen, water. It can be utilized under engineered conditions to convert these waste streams to biogas, which consists primarily of methane and carbon dioxide that can be used as an alternative source of energy. In addition to biogas production, anaerobic digestion processes are capable of removing suspended solids and reducing the volumes of biosolids. The process also generates stabilized material that is not putrescible and is less likely to be attacked by pathogenic microorganisms. Other applications include biohydrogen production.

Organic matter is degraded in anaerobic environments through a number of sequential steps. The reactions are ordinarily catalyzed by different groups of microorganisms; thus, the activity and stability of the whole community are essential for efficient and robust operation. The process is normally divided into four categories: hydrolysis, acidogenesis, acetogenesis and methanogenesis. The initially complex organic materials are hydrolyzed into simpler compounds by the formation of acids. As digestion proceeds, the pH decreases due to acid accumulation. These lower pH conditions satisfy the carbon requirements of acetogenic bacteria, which produce acetate and carbon dioxide. These neutral products—acetic acid and acetate—together with hydrogen gas and carbon dioxide, serve as the major substrates for methanogenic bacteria. Methanogens are strict anaerobes, concentrating enzymes in membrane-bound organelles called methanoms. Methane production also increases the pH of the system; however, this occurs at a slower rate, relative to acid formation, which accounts for the pH decrease at the front end of the process.