Keynote papers

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Interactions of Soil Components and Microorganisms and their Effects on Soil Remediation

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Minerals, organic matter and microorganisms are intimately associated in soils and closely interact in environmental processes. These interactions are especially important in the soil rhizosphere and the sediment-water interface, where low-molecular weight biochemicals are abundant and microbial activity is intense.

Current research is driven by the widespread contamination of our soils with organic pollutants and the desire to apply the knowledge acquired during earlier basic research to practical applications in the field (Atlas and Philp, 2005). These explorations not only increase our understanding of the interactions between microorganisms and other soil components, but also assist us in establishing and applying methods for waste remediation and the cleanup of contaminated soils. As the importance of bioavailability has been recognized and is being considered in regulatory decision-making, a greater understanding of the factors affecting the bioavailability of contaminants to plants and organisms is necessary. Increased knowledge will provide more realistic information about how to take bioavailability and toxicity into consideration for risk assessment and site remediation.

Human activities and industrialization development generate by-products and waste that must be disposed of in a way that should not affect the environment. Even when such by-products are used on agricultural lands as a resource, e.g. organic waste that may contribute to maintain or increase the organic matter and nutrient content in the soil, there are growing concerns about the fate of undesirable constituents they may contain.

Soil Pollution

The soil has become increasingly subjected to various chemical stresses, not only because of our need for more food and fiber, but also because of ever-increasing industrialization. Various anthropogenic substances, either organic or inorganic in nature, upon entering the soil, may not only adversely affect its productivity potential, but may also compromise the quality of the food chain and groundwater. This situation may require risk assessment and evaluation of remedial techniques in order to restore the quality of the soil so that safe food products and clean groundwater and air may be obtained once again.

A wide variety of naturally occurring toxic and recalcitrant organic compounds exist on earth. In addition, various man-made materials have been dumped on land adjacent to industrial plants in landfills and on unregulated dumping grounds. As a result, the soils at many of these sites contain a complex mixture of contaminants, such as petroleum products, organic solvents, metals, acids, bases, brine, and radionuclides. Over a very long period of time, natural degradation activities may eventually destroy most of these organic contaminants. However, affordable technologies are needed to speed up the natural remediation processes. Furthermore, natural degradation activities would not solve the problems of metal contaminants. Therefore, risk management through remediation is essential to reducing health risks and restoring natural balances. The treatments currently used to remove or destroy contaminants include physical, chemical and biological technologies.

Cleanup of the environment

The cleanup of soils polluted by hazardous man-made materials has become a matter of urgent public concern. Traditional methods of waste handling, such as landfilling or incineration, often exchange one problem with another. For instance, landfilling merely confines the pollution while doing little to remove it; certain kinds of garbage are known to remain intact for decades in a landfill. Incineration removes wastes, but disposal of ash or residues remains to be dealt with, and new concerns about air pollution are created. As a result, society has turned to new technologies to devise better methods of disposal; one such method is bioremediation (Atlas and Philp, 2005).

Microorganisms are ultimately responsible for degrading most organic matter to carbon dioxide, minerals and water. Bioremediation utilizes the natural potential of microorganisms to cause transformation, mineralization or complexation by directing those capabilities toward environmental pollutants.

The enhancement of microbial degradation as a means of bringing about the in situ clean up of contaminated soils has spurred much research. The most common methods to stimulate degradation rates include supplying inorganic nutrients and oxygen, but the addition of degradative microbial inocula or enzymes as well as the use of plants (phytoremediation) should also be considered (Dec and Bollag, 2001). Basic research is needed to better understand the biological, chemical, and physical factors affecting transformation pathways and reaction rates.

Over a very long period of time, natural degradation might remove many of the organic contaminants, but may possibly result in an accumulation of heavy metals. Affordable novel technologies are needed to enhance natural remediation processes (natural attenuation) and reduce health risks by restoring natural balances. Therefore, ecosystem restoration can best be achieved through development of innovative management strategies involving interactive processes.

Research into the interactions between microorganisms, humic materials and minerals in the soil continues to impact the fields of environmental remediation and regulation through the development of new techniques and an expanding base of knowledge about the relationships between microorganisms and soil particles. Mixed biotic/abiotic mechanisms by which xenobiotic chemicals are transformed and degraded in soil environments will be an important area of future investigations.

Soil is undoubtedly the most complex of all microbial habitats. Largely because of this complexity, there is insufficient information on how and where most microbial activity occurs in situ and which microorganisms are the most important participants. There is considerable evidence that certain particulate soil components, especially some types of clay minerals, significantly affect microbial life (Stotzky, 1986; Huang, 1990). Clay minerals appear to exert their primary influence by modifying the physicochemical characteristics of microbial habitats; this either enhances or attenuates the growth and metabolism of individual microbial populations, which, in turn, influence the growth and activity of other populations. In contrast to these indirect effects of clay minerals, relatively little is known about the mechanisms of direct surface interactions (e.g., adhesion) between clays and microorganisms.

Transformation of Organic Pollutants

The transformation of xenobiotics in a multicomponent system, such as soil, is a result of the combined activity of microorganisms, extracellular enzymes, mineral colloids and humic materials (Huang and Bollag, 1998). Each of these important components of the soil system not only participates in the transformation of xenobiotics but also modifies the activity of the other components. Humic substances associated with mineral colloids add an additional aspect to the process of xenobiotic biodegradation in soil environments. Humic substances are strong adsorbents themselves, and the adsorption of microorganisms, enzymes and xenobiotics on the organic fraction may be difficult to distinguish from that occurring on the mineral surfaces. Humic acids are believed to catalyze certain transformation reactions, but their major impact is their ability to adsorb e.g. microorganisms, enzymes and chemicals or to be adsorbed e.g. on soil minerals. Minerals exhibit mixed functions as well. They transform naturally occurring and xenobiotic substrates abiotically; at the same time, they act as sorbents, thus altering the impact of microorganisms, enzymes, and chemicals. Adsorption and other binding interactions that occur on both mineral and humic surfaces are believed to reduce the bioavailability of xenobiotics.

Fate and Transformation of Metals

The transformation of metals is governed by abiotic and biotic processes in soil and related environments (Huang, 2000; Huang and Germida, 2002). Abiotic processes include solution complexation, adsorption – desorption, precipitation – dissolution, redox reactions, and catalysis.

Redox reactions are important in controlling the chemical speciation and toxicity of a number of contaminant metals, notably As, Se, Cr, Pu, Co, Pb, Ni, and Cu (Sparks, 2002). Redox reactions are also important in controlling the transformation and reactivity of Mn and Fe oxides in soils, which have enormous capacities to adsorb metal pollutants and are the major sinks of these pollutants. Furthermore, reduction of sulfate and sulfide in aerobic environments may also affect metal speciation and solubility. In addition microbial activity has a very important role in influencing the dynamics of metals in the terrestrial ecosystem. Microbes can dissolve minerals by direct or indirect action under aerobic and anaerobic conditions (Kurek, 2002). Indirect dissolution of minerals can be the result of microbial activity connected with the productions of organic and inorganic acids. Volatilization of metals and metalloids or biomethylation of metals and metalloids from the soil into the atmosphere can be a mechanism of detoxification of toxic elements such as Hg, As, and Se.

Biotic Processes

Nature has evolved ways of mineralizing many contaminants or xenobiotics without human intervention. Soil organic matter is recycled by a diverse array of soil organisms including bacteria, fungi, actinomycetes, protozoa, earthworms and insects. Microorganisms are usually responsible for mineralizing most organic matter to carbon dioxide, water and inorganic components. However, soil mineral colloids also play a significant role in abiotic transformation of organic compounds through catalysis (Huang, 2000).

Microorganisms are the primary factors that influence the fate of organic xenobiotics in soil. Environmentally, the most desired result of microbial activity is the complete degradation (mineralization) of toxic chemicals of both natural and synthetic origin. Some anthropogenic compounds may be used by microorganisms as a source of energy and nutrients for growth. Another important process of microbial transformation, however, is cometabolism, in which microorganisms transform the xenobiotic molecules, but are unable to use these molecules as a source of carbon or energy. The cause of microbial transformation is the activity of intracellular and extracellular enzymes produced by microorganisms. Xenobiotics having chemical structures similar to organic compounds that occur in nature are usually more susceptible to biodegradation than those whose structures bear little resemblance to natural products. This is because the microbial enzymes that specifically degrade toxic chemicals of natural origin may also be able to degrade structurally analogous xenobiotics. On the other hand, when microorganisms are exposed to structurally different xenobiotics, they usually need a prolonged acclimation period during which they may undergo genetic mutations, resulting in the production of novel degrading enzymes (van der Meer et al., 1992).

Soils contaminated with recalcitrant xenobiotics or environments hostile to indigenous microorganisms may benefit from microbial inoculation. Using classic enrichment techniques or gene transfer technology, large populations of bacteria may be developed, and then inoculated into the contaminated soil.

Our present knowledge of the microbial degradation of xenobiotics has been achieved through numerous *in vitro* experiments in which xenobiotic compounds were exposed to specific microorganisms isolated from soil or other natural environments. Monitoring the transforming or degradative activities of microorganisms under field conditions may, however, generate ambiguous results, because it is difficult to distinguish between physico-chemical and microbial transformation reactions. The ability of microorganisms to transform xenobiotics relies largely on four major processes: oxidation, reduction, hydrolysis, and synthetic reactions, which are all catalyzed by microbial enzymes.

Also of great importance is the fact that the microbial activity in soil is strongly influenced by mineral colloids and humates that bind organic chemicals, inorganic ions and water films to their surfaces (Huang 1990). In addition, extracellular enzymes are rapidly sorbed at clay and organic surfaces. Immobilized through these events, enzymes usually acquire greater stability but may modify their activity. Some immobilized enzymes in soils are associated with the humic fraction by the formation of enzyme-phenolic copolymers during the generation of humic substances Enzymes are vital biotic catalysts in the transformation of organic pollutants (Bollag, 1992).

Much research has been conducted on the use of bioremediation as a tool for cleaning many environmental contaminants such as polycyclic aromatic hydrocarbons, explosives, pesticides polychlorinated biphenyls and other organic toxicants (Atlas and Philp, 2005). The application of bioremediation technology to decontaminate polluted sites is still a developing science. The mechanisms driving microbial activity and the degradation pathways of specific pollutants need to be further elucidated before successful and better-controlled site-specific treatments can be applied. Recent advances in biotechnology have enabled the modification of organisms at the molecular level for improved degradative performance. This approach has already contributed new tools for the analysis and monitoring of complex environmental processes.

Abiotic Processes

Abiotic factors, such as the catalytic activity of mineral and organic colloids, may make a substantial contribution to the degradation of organic compounds in soil. To date, however, the reports of abiotic transformation have been limited to include only a relatively narrow group of xenobiotics. The significance of soil mineral-catalyzed abiotic transformation of naturally occurring and xenobiotic compounds in the environment has become widely recognized only in recent years (Huang, 1990). Clay minerals, with their high concentration in soils, their large surface area and relatively high charge density, contribute to the overall xenobiotic transformation at least as much as does the organic matter. Even in soil environments where biological activity is intense, abiotic transformation is of importance.

Keywords: Organic pollutants; biotic and abiotic processes; soil remediation.

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