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Fact Sheet

Fact Sheet 764

PHYTOREMEDIATION–PLANT-BASED STRATEGIES FOR CLEANING UP CONTAMINATED SOILS

Organic Contaminants

A previous fact sheet, "Bioremediation of Contaminated Soils," (FS 757), described several biologically based strategies currently employed for cleaning environmental contamination. Collectively known as bioremediation, these strategies have now become well-accepted alternatives to increasingly costly and environmentally undesirable traditional cleanup methods such as landfilling or incineration. One of the strategies described in Fact Sheet 757 is the use of plant systems for pollution cleanup, a strategy known as *phytoremediation*. Phytoremediation takes advantage of specific attributes of naturally occurring, specifically selected, or genetically engineered plant systems for removal, destruction, transformation, and/or stabilization of pollutants so they no longer pose threats to humans and vulnerable ecosystems.

Like many other biologically based strategies, the use of plant systems for treating or mitigating pollution is not new. Plant-based cleanup systems were reported to have been used to treat municipal wastes more than three centuries ago, laying the groundwork for their present-day application in secondary treatment of wastewater from various sources. In its current ascendancy to cleanup prominence, the use of plants (and, for that matter, other biologically based methods) represents a more concerted effort at the managed manipulation of natural processes to clean up contamination from man-made (synthetic) chemicals, or from naturally occurring ones that have become environmental hazards as a result of human activity.

When the use of natural systems reemerged about two decades ago as a highly desirable environmental cleanup option, most of the attention was focused on the use of microbes and microbial systems. Now, plants are receiving the level of attention that was once almost exclusively reserved for microbes. This resurgence is not accidental. Phytoremediation practices employ familiar systems–plants, using energy derived from the sun–to clean up pollution. In contrast, the use of purely microbial systems has often engendered apprehension and skepticism largely because it involves entities that are neither visible nor well understood.

Phytoremediation has other obvious appealing attributes. It is an *in situ* cleanup strategy, which means that contaminants can be treated in place, thereby eliminating or lessening costs and liabilities associated with cleanup methods that involve excavation and transportation for off-site disposal. Perhaps more importantly, phytoremediation strategies can be used on sites that are polluted with heavy metals as well as organic chemicals. This flexibility is afforded by a number of plant adaptations: First, certain plants have evolved the capacity to take up and *hyperaccumulate* selected metals in their shoots at levels that are toxic to ordinary plants. In a remediation scheme, these plants can be used to remove metal contaminants from soil; then the metals can be recovered by extraction. If the metal contaminant has high enough economic value, the extracted material can be sold to recover the cost of, or even make a small profit from, the remediation process.

Plants can also directly transform or stabilize pollutants through production and release of specific chemicals that react with contaminants in ways that eliminate or diminish their hazards in the environment. In addition, many organic contaminants can be taken up directly by plants and metabolized to byproducts, or sequestered as harmless byproducts. Finally, plants have evolved interactions and associations with microorganisms that can cause accelerated breakdown or transfor-

mation of certain pollutants in the plant root zones into innocuous products. The discussion below focuses on current knowledge of the processes that make phytoremediation work on organic contaminants. Phytoremediation of metal contaminants is discussed in a separate fact sheet, FS 768.

Phytoremediation of Organic Contaminants

Researchers generally describe phytoremediation of organic contaminants in terms of 'direct' and 'indirect' effects of plants on the contaminant. The direct effects of plants on organic contaminants involve uptake, transport, and metabolism of particular contaminants, or production and release into the environment of substances, such as enzymes, that transform the contaminants into harmless products. Indirect plant effects involve interactions between plant roots and microbes in the immediate vicinity of roots, a zone called the *rhizosphere*. Through these interactions, substrates and growth factors supplied by the plant drive microbial metabolic activities that in turn can cause destruction of specific contaminants.

Direct Effects of Plants on Organic Contaminants

Plant Uptake, Transport, and Metabolism. Many organic contaminants can enter plants through plant roots and be translocated into the aboveground parts. The most important factor that controls uptake and subsequent translocation of an organic contaminant by plants is its availability in soil. A contaminant's availability is governed by the nature of the chemical, which determines whether the contaminant partitions more readily into the water phase (i.e., its water solubility, also described as *hydrophilicity*), or the lipid, or natural organic phases of a particular soil (i.e., *lipophilicity*).

A measure of the propensity of an organic molecule to partition between water and lipid phases is known as the octanol-water partition coefficient ($\mathbf{K_{ow}}$). This coefficient is defined as the ratio of the concentration of contaminant in the organic solvent, octanol, to the concentration in a water phase when the contaminant is added to a solution containing both solvents. As a general rule, compounds that are most readily taken up and translocated in plants are those that have moderate lipophilicity, with $\mathbf{K_{ow}}$ values that lie within a narrow range ($\mathbf{K_{ow}}$: $10\text{-}10^3$). At average $\mathbf{K_{ow}}$, below this range (i.e., high water solubility), contaminants do not bind (sorb) strongly enough at the root surface for uptake or translocation through plant cell membranes; such contaminants preferentially tend to leach into the subsurface. At high $\mathbf{K_{ow}}$, above this range (high lipophilicity), contaminants that reach the root surface (if they are not already tightly held by lipid fractions in soil) are strongly sorbed by plant cell membrane components, which restricts their translocation within the plant.

As would be expected, $\mathbf{K_{ow}}$ values for organic contaminants range just as wide as the broad range of organic contaminants that enter the environment. In general, $\mathbf{K_{ow}}$'s of many agricultural chemicals fall within the range that allows some uptake and translocation in plants. However, contaminants such as PCBs have high $\mathbf{K_{ow}}$ values, which limit their movement in soil as well as in plants.

Once within a plant an organic contaminant is subjected to a wide range of processes. The chemical can be transformed by a wide array of plant enzymes. The soluble products of partial transformation processes are stored in vacuoles, while the insoluble ones are deposited in cell walls. In addition, parent compounds or transformation products that are volatile can be released into the atmosphere following transpiration pathways.

The metabolism of organic contaminants by plants resembles closely the processes used by animal systems to metabolize and detoxify foreign (*xenobiotic*) compounds. Indeed, the enzymes involved in both systems have been shown to be so remarkably similar as to win plants the appellation 'green livers'.

Transformations by Exuded Plant Enzymes. In addition to being metabolized within the plant, contaminants can also be transformed outside the plant by enzymes that are exuded into a contaminated matrix. Several enzymes released into the environment this way have been shown to transform contaminants into harmless compounds. Contaminants for which this process has been shown include munitions wastes such as TNT and organic degreasers such as TCE.

Indirect Effects of Plants on Organic Contaminants

Enhanced Rhizosphere Biodegradation. Perhaps the greatest impact of plants on many organic contaminants is exerted through complex interactions between plant roots and soil microorganisms, an association that affords the participating members nutrient exchanges and protection from environmental toxicants. It is estimated that between 10 and 30 percent of carbonaceous mate-

rials produced annually by plants are deposited within the root zone. The materials include sugars, amino and non-amino organic acids, vitamins, nucleotides, flavons, enzymes, and a large number of unidentified substances that influence growth of microorganisms.

The rich endowment of substrates in plant rhizospheres produces an overall robust activity of general-purpose microorganisms, resulting in enhanced biodegradation of pollutants. Some substrates can also cause induction of specific enzymes in certain microbes for the enhanced degradation of specific compounds. The amount and quality of material exuded in the rhizosphere vary considerably among plant species. Accordingly, the numbers and activities of microbial consortia, and consequently contaminant degradation competence, differ from one plant rhizosphere to another.

In addition to providing substrates, certain plant products and processes can create conditions that favor degradation of specific contaminants. For example, biofilms formed on root surfaces from plant mucilage substances can promote the assemblage and development of microbial consortia capable of degrading specific contaminants through 'shared metabolism' of those compounds. Also, respiratory activities of the plant-microbe complexes can reduce oxygen concentrations, thereby creating reduced environments essential for the transformation of certain contaminants, especially highly chlorinated compounds.

Phytoremediation Applications

Plant-microbe interactions have been the subject of extensive studies since it was first discovered that some of these associations are important determinants of soil quality (e.g., nitrogen fixation, mycorrhizae). Also, the role of plant rhizospheres in transformations and dissipation of synthetic organic compounds has been known since the first man-made pesticides were applied to soil. Now, enhanced rhizosphere biodegradation is receiving intensive research activity in attempts by researchers and entrepreneurs alike to capitalize on the enormous potentials that the phenomenon can offer to contaminant bioremediation.

Between laboratory and pilot scale studies on the one hand, and full scale operations on the other, phytoremediation has now attained a status as perhaps the most desirable method for the cleanup of a broad range of both organic and inorganic pollutants. Organic contaminants that have now been shown to be amenable to clean-up by phytoremediation range from petroleum hydrocarbons, including persistent polycyclic aromatic hydrocarbons (PAHs), herbicides such as atrazine, munitions wastes like trinitrotoluene (TNT), and chlorinated solvents such as trichloroethylene (TCE).

One of the longest running and well-coordinated efforts in this area is work by researchers at the University of Iowa. For more than a decade, Dr. Gerald Schnoor, Professor of Civil Engineering, and coworkers studied the use of deep-rooted trees for dealing with an old, intractable problem–agrochemical contamination of subsurface environments resulting from nonpoint sources. Their investigations showed that deep-rooted hybrid poplar trees can take up and metabolize the ubiquitous subsurface contaminant atrazine in their shoots, or harbor specific microbes in their rhizospheres for breaking down the pollutant. The high rate of transpiration of poplar trees also helps to remove nitrates that have leached to the subsurface from fertilizer applications. The strategies developed by these researchers have now been implemented at over a dozen field locations.

Within the Soil Biochemistry/Bioremediation Program at the University of Maryland, researchers are investigating strategies for enhancing bioremediation potentials of specific forage crops that were found to cause accelerated disappearance of environmental contaminants, such as PCB, in soil. The potential for use of forage crops in bioremediation schemes is a particularly attractive proposition because growth and cultural conditions of these crops are very well known, making them most amenable for managed manipulation to enhance contaminant biodegradation.

Future Phytoremediation Needs for Organic Contaminants

Without a doubt, the use of plant systems for remediating environmental pollution is an enormously appealing proposition. Research and development to capitalize on the full potential of the technology is still in its infancy. Great strides have been made; however, considering its infancy, many fundamental issues remain to be addressed for successful development of phytoremediation.

The following is a partial list of needs relating to phytoremediation of organic contaminants:

- Search for plants with superior phytoremediation potentials. At this relatively early stage of exploration, it is presumptuous to think that all plant species that can produce rhizosphere conditions for enhanced degradation of every organic contaminant have been discovered. It is likely that plants are yet to be found that exude specific com-

pounds, in needed amounts to stimulate the breakdown of some of the most recalcitrant organic contaminants.

- Elucidate mechanisms by which plants transform, degrade, or stabilize contaminants. Understanding these mechanisms is essential for manipulating the systems to further enhance phytoremediation capabilities.
- Determine products that are formed as plants transform or metabolize organic contaminants; determine how transformation products are distributed in plant and environment alike. This will address one of the most commonly asked questions about phytoremediation–what do you do with the plants used to clean up contamination?
- Educate the public, regulators, and private industry. They need to be brought in early on this technology–some uneasiness might eventually arise when plants used for environmental cleanup become less and less the naturally occurring type and more and more the genetically engineered variety.

References

Additional technical and nontechnical information on phytoremediation can be obtained from these selected references.

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Phytonet Links: http//www.dsa.unipr.it/phytonet/links.htm.

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