Interest Increases in Using Plants For Environmental Remediation

In an effort to meet environmental regulations of the last three decades, environmental remediation has developed into a multibillion dollar industry. The high cost of many traditional methods is causing many organizations to look to lower cost alternatives. Bioremediation is a commercial remediation technology with a growing market and continuing research. Phytoremediation is another potential low-cost technology that is currently being investigated for many remediation applications.

Health and environmental risks of pollution have become more apparent throughout the world over the past several decades. Air, water, and soil contaminants can include numerous organic and inorganic substances, such as municipal waste and sewage, various gaseous emissions, fertilizers, pesticides, chemicals, heavy metals, and radionuclides (radioactive substances). Contaminants can cause land and groundwater to be unusable. In addition, animals and insects may come in contact with a contaminant, thus introducing a toxic substance into the food chain. Because of increased public awareness and concern, environmental regulations have been created to not only prevent pollution, but also to remediate areas where environmental contamination has occurred. As a result, environmental remediation is a rapidly developing multibillion dollar industry.

Remediation Technologies Are Evolving

Environmental remediation technologies use physical, chemical, or biological processes that attempt to eliminate, reduce, isolate, or stabilize a contaminant or contaminants. Depending on the technology used, the process may either take place at the location of the contamination (*in situ*), or the contaminated soil or water may be removed for *ex situ* treatment (table 14). Every remediation technology has certain limitations and disadvantages. Therefore, site-specific evaluations must be made to assure the appropriate technologies are applied. If multiple contaminants are involved, it may be necessary to use a combination of techniques to reduce the concentrations of pollutants to acceptable levels.

The economic costs of environmental remediation can be tremendous. Various studies have estimated that cleanup of current hazardous waste sites with conventional technologies would cost from $400 to $750 billion in the United States alone (*5*, *7*). Over the next 5 years, remediation of U.S. sites contaminated with heavy metals could cost over $7 billion, and sites contaminated with a mixture of heavy metals and organics could cost another $35 billion (*1*). Remediation of radionuclides from soil and water at identified U.S. Department of Energy (DOE) and Department of Defense (DOD) sites could cost over $10 billion using current treatment technologies (*5*).

The high cost of remediation is perhaps the driving factor in the development of new remediation technologies. For example, incineration and landfilling are two of the oldest and most widely used methods of soil remediation. They are both highly effective in eliminating contaminants from their current environment, but both are relatively expensive compared to other methods. In addition, incineration also raises the question of air pollution, and landfilling simply moves the contaminated soil from one location to another.

Table 14--Soil remediation technologies

Method	*In situ*	*Ex situ*
Physical	Soil vapor extraction Thermally enhanced soil vapor extraction Containment systems and barriers	Landfilling Incineration Thermal desorption Soil vapor extraction
Chemical	Soil flushing Solidification Stabilization	Soil washing Solidification Stabilization Dehalogenation Solvent extraction Chemical reduction and oxidation
Biological	Bioremediation Phytoremediation	Land farming Bioreactors

Source: European Institute for Environmental Education and Training.

Bioremediation, the systematic use of microorganisms for environmental contaminant treatment, is a developing technology that is currently used (though on a relatively small scale) to clean some sites of halogenated and nonhalogenated volatile and semivolatile organic compounds and petroleum hydrocarbons. The contaminants are degraded by naturally occurring microbes that are stimulated by introducing nutrients, oxygen, and other amendments to the soil or water. Considerable research is being done on this technology, and the potential market for well-developed techniques is large. Burt Ensley, president of Phytotech, Inc., a Monmouth Junction, New Jersey, phytoremediation company, estimates that the current market for bioremediation in North America and Europe is around $500 million, and by the year 2000 could be $1 billion or more.

Phytoremediation Is a Potential Low-Cost Alternative

Another potential biobased low-cost alternative technology is phytoremediation—the systematic use of plants for environmental contaminant treatment. Phytoremediation is a combination of technologies that use "plant-influenced biological, chemical, and physical processes that aid in the remediation of contaminated substrates" (*3*). For phytoremediation to be possible, contaminants must be within the plant's root zone, and must be biologically absorbed and/or processed (bioavailable).

The four main technologies of phytoremediation are: rhizofiltration, phytoextraction, phytostabilization, and phytodegradation. In rhizofiltration, plants (primarily their root systems) absorb contaminants, such as heavy metals and radionuclides, from water and, in some cases, translocate the contaminants to stems and leaves. Phytoextraction uses plants to absorb contaminants, such as heavy metals, from soil into roots and harvestable parts, such as stems and leaves. Phytostabilization uses plants that are tolerant of a contaminant in soil, such as heavy metals, to reduce the contaminant's mobility and prevent further environmental contamination, such as leaching into ground water or becoming airborne by wind erosion. Phytodegradation is plant-assisted bioremediation, in which degradation of contaminants, such as various organic compounds, occurs during a plant's metabolic process or is influenced by plant-root and soil microbial activity (rhizodegradation).

Constructed Wetlands Clean Wastewater

Commercial use of phytoremediation is currently very limited, as most technologies are still primarily experimental. Perhaps the most developed and widely used phytoremediation application is the use of constructed wetlands (artificial marshes) for wastewater treatment. Artificial marshes, a rhizofiltration technology, have been constructed to help treat wastewater from municipal sewage treatment facilities and several industrial processing operations.

Two such artificial marshes were constructed in Magnolia, Arkansas, to treat rainwater runoff and noncontact process water from Albemarle Corporation's bromine production facilities. Each marsh consists of thousands of plants like bulrush, maiden cane, and cattails. The first marsh, about 54 acres in size, was created at the South bromine facility and began operation in 1993. The second marsh, constructed at the West facility, is about one-fourth the size of the South facility, and began operation in October 1995. The marshes are less expensive to create, and have a considerably lower operating cost, than a mechanical wastewater treatment system. The marshes have been referred to as "the cheapest alternative for dealing with the increased demands of the Clean Water Act" (*4*).

Another constructed wetland is used by Chevron at its Richmond, California, crude oil refinery to reduce selenium waste from crude oil refining. In high doses, selenium can be toxic to fish and wildlife. The 90-acre wetland can take in 1 to 3 million gallons of wastewater per day. It takes approximately 7 days for the water to work its way through the system, which consists of primarily bulrush and cattails, resulting in a reduction in selenium. The wetland can periodically be dried and the vegetation harvested for proper disposal. Recent research sponsored by Chevron at the University of California-Berkeley indicates that a portion of the selenium removed by the wetland plants is volatilized in a less toxic form.

Sunflowers Remove Radionuclides From Water

Other rhizofiltration applications seem to be among the most promising phytoremediation technologies. Because of the Clean Water Act, water quality has become a major concern of regulatory agencies and industrial producers. As a result, research and development opportunities for potential low-cost water remediation methods, such as rhizofiltration, have developed.

Successful rhizofiltration techniques require identification of species of plants that have the ability to process large quantities of water and sequester certain contaminants in plant biomass. An example of such a plant is a special strain of sunflower that, when grown hydroponically on rafts, has removed radionuclides from water. The system was developed and patented by Phytotech, Inc. According to the company, the sunflower rhizofiltration system can successfully reduce uranium, strontium, and cesium levels in water to below cleanup standards set by the U.S. Environmental Protection Agency (EPA). Accumulation of uranium occurs primarily in the roots, whereas strontium and cesium accumulate throughout the plant.

The system has worked effectively at test sites near the Chernobyl nuclear plant in Ukraine, as well as at a DOE site in Ohio. Phytotech estimates the cost to remove radionuclides from water would be between $2 and $6 per 1,000 gallons, including disposal costs. A standard treatment of microfiltration and precipitation would cost nearly $80 per 1,000 gallons, according to DOE estimates. If approved by EPA regulators and site owners, the process could be commercialized within 1 year.

Poplar Trees Protect Groundwater And Streams

Trees have many potential phytoremediation applications simply due to their structure and physiology. They typically have extensive root systems, with the ability to penetrate the soil several feet down, sometimes to groundwater tables. Extensive root systems often support growth and diversity of soil microorganisms, which aid in degrading contaminants. Many species of trees also offer other advantages, such as transpiration of large quantities of water (absorbing water from soil and emitting it as water vapor through foliage), large plant biomass, long life spans, ability to grow on low-fertility soil, and the promotion of ecosystem diversity (*7*).

Some species of trees are currently being used to remediate organic pollutants. Hybrid poplar trees, for example, are used as buffers and caps to prevent pollutants—for instance, from landfills—from reaching waterways and groundwater. The poplar-tree systems were developed at the University of Iowa and are now being used commercially by Ecolotree, Inc., of Iowa City, Iowa, a private spinoff company. Since 1990, Ecolotree has installed caps and buffers at 30 permitted sites in 11 States and Europe.

Seven landfills in Virginia, Iowa, and Oregon are using poplar trees to manage water. An example of a full-scale Ecolotree Cap is at Lakeside Landfill in Beaverton, Oregon. In its seventh year of operation, the cap has been successful in keeping the landfill free of leachate problems. Another full-scale site at Riverbend Landfill in McMinnville, Oregon, uses an Ecolotree Buffer of 14.3 acres of hybrid poplars to transpire landfill leachate, which is irrigated onto the poplar stand. According to the company, this is an effective, low-cost alternative to pumping the leachate to a wastewater treatment facility.

Ecolotree has also planted the hybrid poplars as buffer systems to filter water and air, while stopping erosion and degrading pollutants in the soil. For example, in Amana, Iowa, poplars were planted in four rows along a stream in an effort to intercept nitrate pollutants from nearby farmland before they reached the stream and groundwater. According to Ecolotree president, Louis Licht, in the second year of establishment, the tree-lined stream contained 50 percent less nitrate nitrogen and 85 percent less sediment compared to an adjacent unbuffered watershed. Nitrate nitrogen in groundwater flowing through the buffer was also decreased significantly. Ecolotree Buffer systems have also been used at agrochemical dealerships owned by Clarence Cooperative of Clarence, Iowa. The hybrid poplars have been used to remove chemicals at urea fertilizer spills, old herbicide-equipment rinsing areas, and perimeter buffers as a final filter for surface and ground water.

Poplar tree research is continuing at the University of Iowa, focusing on the fate and movement of solvents, ammunition (such as TNT), herbicides, fuels, and organic intermediaries for various plastics. Other organizations involved in poplar research include the EPA Laboratory in Athens, Georgia, the National Salinity Laboratory in Riverside, California, the Bioresource Engineering Department at Oregon State University, and Phytokinetics of North Logan, Utah. Phytokinetics has commercial applications using poplar technologies, which have been used in several States to remediate groundwater.

Phytoremediation of Inorganics in Soil

In addition to the development and commercial applications of rhizofiltration, research and development are underway on using phytoextraction and phytostabilization to sequester inorganic elements and compounds. (Some organic compounds may also be destroyed by these technologies.) Potential remediation sites and their inorganic contaminants include abandoned mines and smelting operations (heavy metals), military sites (heavy metals and radionuclides), and nuclear energy and waste sites (heavy metals and radionuclides).

Because of the high cost of current heavy-metal remediation methods, much of the soil phytoremediation research has focused on their removal. Scott Cunningham, a scientist at Dupont Central Research and Development in Newark, Delaware, suggests that potential phytoremediation techniques could cost significantly less than current heavy metal remediation methods. In a recent presentation at a phytoremediation conference in Arlington, Virginia, Cunningham compared potential costs. He said that remediation of 10 acres contaminated with lead using current technologies could cost as much as $12 million. This includes planning and documenting the project, as well as the actual decontamination process. In comparison, potential phytoremediation methods for the same area could cost as little as $500,000. In addition, many phytoremediation costs can be spread out over the life of the project (which may be years), whereas traditional remediation technologies typically call for large up-front expenditures. This lower cost potential of phytoremediation is driving organizations like Dupont, Phytotech, Argonne National Laboratory, DOE's Office of Science and Technology, and USDA's Agricultural Research Service (ARS) to research the removal or stabilization of heavy metals by plants. Much of the research is centered on hyperaccumulators, plants that absorb levels of metal that would be toxic to most other plants.

Though many hyperaccumulator plants are relatively small in size (low biomass) and take a long time to grow, several species are showing some promise as heavy metal phytoextractors. One such plant is Alpine pennycress (*Thalaspi caerulescens*), which hyperaccumulates zinc and smaller amounts of cadmium. Field trials are currently being conducted by ARS at a Superfund cleanup site in Palmerton, Pennsylvania, to test ways to remove zinc and cadmium. The site is managed by the Zinc Corporation of America, and is thought to have been contaminated by a zinc smelter that operated in Palmerton from 1890 to 1980. The low harvestable biomass of pennycress is a restricting factor that scientists from USDA, the University of Maryland, and the University of Sheffield in the United Kingdom are trying to overcome. *Thalaspi* strains are being collected and crossbred in an attempt to maximize cadmium and zinc concentration in the plant, as well as create plants that grow faster and taller. This work will also likely lead to genetic screening in an attempt to isolate genes responsible for metal uptake, so they can potentially be transferred to other higher yielding biomass plants.

Another potential technology for heavy metal remediation is phytostabilization, also referred to as IINERT (in-place inactivation and environmental restoration). This technology is currently being investigated by Dupont and others for use at sites where extraction is logistically difficult. The objective is to use soil amendments to reduce the bioavailability of the metals in the soil matrix. Certain plants are then grown to trap the remaining contaminants in the roots. This further reduces the bioavailability of the metals to other plants and animals and helps prevent leaching and off-site migration of the metals (*2*). Contaminants are likely to be phytostabilized more quickly than they can be phytoextracted. However, phytostabilization is not yet accepted by EPA, as research is still needed to determine overall effectiveness and long-term stability achieved by this technology.

Indian Mustard Plant Extracts Heavy Metals And Radionuclides from Soil

Some current research and development is also being done on plants that can remediate both heavy metals and radionuclides. For example, Indian mustard (*Brassica juncea*), a high-biomass crop that traditionally has been grown in Southeast Asia as a source of cooking oil, has recently shown some promise in uptake of some heavy metals, radionuclides, and other inorganic chemicals. ARS's Water Management Research Laboratory in Fresno, California, has had success in using Indian mustard to dramatically reduce selenium levels in soil. In some areas of California where irrigation is vital to agriculture, evaporation ponds for drainage water may leave a high selenium residue behind. Making Indian mustard part of a proper crop rotation can help control selenium levels and minimize the selenium load deposited into the agricultural effluent. In addition, some of the harvested mustard can be blended with hay and fed to animals in nearby areas where selenium deficiency is a problem. In order to see if *Brassica* species used for selenium uptake could be used as viable oil crops, scientists currently are evaluating the effects of higher selenium concentrations on oil content.

Based on Indian mustard germplasm collected by ARS, studies conducted by Phytotech, Rutgers University, and the International Institute of Cell Biology have also shown that Indian mustard has the ability to accumulate heavy metals such as lead, chromium, cadmium, nickel, and zinc. The approach requires adding a chelating agent to the soil to solubilize the soil lead, and allow it to move from the roots into the shoots. Field trials are being conducted this year in Trenton, New Jersey. However, it is not clear whether future environmental regulation will allow adding such high levels of chelating agents to the soil, as increased mobilization of contaminants may pose a threat to ground water. Phytotech has also had some success in using Indian mustard to remove radionuclides such as cesium-137 and strontium-90 at a site near Chernobyl.

Phytoremediation of Organics in Soil

Although heavy metals and radionuclides are a problem at many hazardous waste sites, a large number of sites are contaminated primarily with organic substances such as petrochemicals, chlorinated solvents, aromatic hydrocarbons, various pesticides and insecticides, explosives, wood preservatives, and surfactants. In many cases, phytoremediation of these contaminants in soil is a potential alternative to traditional cleanup methods. However, a major determining factor is the age of the contamination. Organic contaminants that have been in the soil for a long time tend to be less available for plant uptake, making phytoremediation improbable if not impossible.

Various types of phytoremediation can be used for soil-based organic contaminants. Phytoextraction could be used to target moderately hydrophobic organics, such as chlorinated solvents (*6*). The contaminants may then be stored in plant biomass or, in some cases, volatilized. One form of phytodegradation involves uptake of organic contaminants and degradation through metabolic processes within the plant. Another form of phytodegradation is rhizodegradation, in which organic contaminants in soil (such as TNT, chlorinated solvents, and petroleum hydrocarbons) are degraded by plant-root and/or soil microbes within the plant's root zone. Some organic contaminants may be degraded because of enzymes, sugars, alcohols, and acids released by plant roots. Other organic contaminants may be affected by soil microbes that are stimulated by various root exudates and/or the oxygen and organic carbon supplied by root systems.

As with most phytoremediation techniques, extensive research is being conducted by numerous public and private organizations to evaluate the effectiveness of various plants in removing or reducing organic pollutants. Phytokinetics is one company that has a number of laboratory and field trials in progress. Phytokinetics is working with Chevron Research and Technology Company to remove petroleum hydrocarbons from soil and groundwater, as well as to investigate the fate of volatile organic compounds in soils planted with vegetation. Phytokinetics also is working with Exxon Research and Engineering Company on the removal of petroleum hydrocarbons from soil. Recently, Phytokinetics was accepted into EPA's Superfund Innovative Technology Evaluation Program, which was created to encourage development and commercialization of new technologies for environmental cleanup. The 2-year project will evaluate the efficacy of phytoremediation of soil at a Portland, Oregon, Superfund site contaminated with wood preservatives.

As with heavy metal and radionuclide phytoremediation research, various Federal departments and agencies are working with universities and private organizations on organic-contaminated soil remediation research. One such project is being conducted by Kansas State University scientists in cooperation with the U.S. Navy at the Navy's Craney Island Fuel Terminal (CIFT) Biological Treatment Facility. CIFT, located in Portsmouth, Virginia, is the Navy's largest fuel facility in the United States. Small field trials are being conducted evaluating the abilities of bermuda grass, rye grass, tall fescue, and white clover to remediate soil contaminated with petroleum compounds. The project will also evaluate the plants' abilities to control leaching of contaminants. The field trials should be completed by May 1997.

The Future of Phytoremediation

Though phytoremediation technologies are still primarily in research and development phases, various applications have shown potential for success. This has helped to increase interest and research in both public and private sectors, in an attempt to develop phytoremediation into a commercially viable industry. Some key technical hurdles that must be overcome for an industry to develop and grow are:

- identifying more species that have remediative abilities,
- optimizing phytoremediation processes, such as appropriate plant selection and agronomic practices,
- understanding more about how plants uptake, translocate, and metabolize contaminants,
- identifying genes responsible for uptake and/or degradation for transfer to appropriate high-biomass plants,

- decreasing the length of time needed for phytoremediation to work,

- devising appropriate methods for contaminated biomass disposal, particularly for heavy metals and radionuclides that do not degrade to harmless substances, and

- protecting wildlife from feeding on plants used for remediation.

In addition to technical barriers, government regulations will also determine the overall success of phytoremediation. Because the remediation industry is compliance driven, phytoremediation technologies must demonstrate their effectiveness at meeting State and Federal regulations. This simply might not be possible in all situations with many current phytoremediation technologies, due to the nature of the contamination (for example, the age of contamination and relative bioavailability of the contaminants). For these technologies, changes in regulatory status and/or continuing technical improvements will be necessary for commercialization.

Because of all the factors needed for success, the likely size and growth rate of a phytoremediation industry are difficult to predict. Because contaminated soils tend to present more bioavailability problems, Scott Cunningham of Dupont believes most initial phytoremediation successes will come in treatment of contaminated surface and ground waters. Industry sources suggest potential sites for soil phytoremediation are areas with low to moderate amounts of contaminants near the surface. Because it may take a relatively long time for phytoremediation to work, the first target contaminants will also likely have to pose no immediate threat to health or risk of further environmental damage.

How soon phytoremediation will succeed as an industry is also uncertain. It offers many potential advantages over traditional remediation technologies, particularly its public acceptance and considerably lower cost. If these factors continue to drive government and private research and development, phytoremediation technologies could continue to evolve. If so, some industry experts believe commercialization of certain technologies could occur within the next 5 years. [Charles Plummer, ERS, (202) 219-0717, cplummer@econ.ag.gov]

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