Phytoremediation

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1 Introduction

Ever since the Iron Age, humans have been polluting their environment with heavy metals, and these practices have increased tremendously as humans increased their numbers, particularly following the industrial revolution. Even unsuspecting materials such as commercial fertilizers contain toxic metals, and commercially grown fruits and grains accumulate them to dangerous levels. Humans and other animals then accumulate them even more. Tobacco is another rich source of heavy metals, such as lead (Pb^{2+}) and cadmium (Cd^{2+}), and fetal development is exquisitely sensitive to these toxins. This is in part why women are urged to refrain from smoking during pregnancy.

Humans have expanded their use of substances to include pesticides, all kinds of xenobiotics, and even antibiotics and antiviral agents. Particularly during the last century, industrial and military practices have contaminated huge surface areas within all of the developed and much of the underdeveloped world. In

Europe, for example, over 100 million acres, about 20% of the total land surface, suffer from harmful soil contamination and degradation.

The most extensively contaminated areas throughout the world invariably surround heavily populated, industrialized areas. It is precisely these areas that pose the greatest threat to human and ecosystem health. It is also these areas that we would most like to be safe for human use. These are areas where population densities are the highest and where children play. Moreover, even in rural areas, pollutants enter agricultural products and leach into water supplies. They poison plant and animal life alike. And when ecosystems suffer, the capacity to support human life diminishes correspondingly.

Decontaminating soil is incredibly costly and time consuming, and the methods currently available are insufficient for the task at hand. In 2002, reports to the European Union estimated that to even partially clean up their contaminated sites would cost over 100 billion dollars. Similarly, a report in the late 1990s estimated correspondingly high costs in the US. To clean up the over 500,000 contaminated sites was predicted to cost nearly one trillion dollars. In response, congress established a “superfund” program to begin to deal with this matter. Yet the job is so massive, that little has been done.

We all need to recognize the prices that must be paid to clean up the messes that have resulted from our sloppy practices. After all, money talks! But it is also clear that research is needed to develop cheaper and more efficient methods of decontamination. We

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must think less about the here and now and more about future generations and the surroundings they will inherit. This is the responsibility of everyone in our generation to those yet to be born.

Microbes provide practical solutions, but plants of many different varieties provide others. Phytoremediation uses natural or genetically modified plants, often together with their associated rhizospheric microorganisms which stimulate plant growth and decontaminate soil and water in conjunction with the plants. They extract heavy metals, natural aromatic and hydrocarbon compounds and man-made chemicals such as pesticides, herbicides, fungicides, and antibiotics. This approach proves to be relatively cheap, efficient, and environmentally friendly.

Plants use a variety of mechanisms to cope with heavy metals. They can sequester them in their cell walls, chelate them in the soil in inactive forms using secreted organic compounds, or complex them in their tissues after transporting them into specialized cells and cell compartments. They can store them in vacuoles, safe from the sensitive cell cytoplasm where most metabolic processes occur. Plants also make chelating cysteine-rich peptides and small proteins such as phytochelatins and metallothioneins that are stored safely in vacuoles. Phytochelatins remarkably serve a dual function, mediating long-distance transport of heavy metals between plant tissues as well as providing protection. Finally, plants, like microbes, can volatilize certain metals, as in the case of the highly toxic mercury (Hg^{2+}) and methyl mercury. They reduce them using the enzyme, mercuric reductase, to the volatile and less harmful Hg^0 . Moreover, it is sometimes possible to recover metals from plant tissues, a process termed “phytomining.” For example, burning dried contaminated plants produces potash residue that can be processed for the production of potassium (K^+) and magnesium (Mg^{2+}) as well as other metals.

Phytoextraction, followed by degradation of organic toxins, provides an alternative mechanism for decontamination. For example, plants can take up and metabolize harmful organic compounds, including abundant, environmental, aromatic pollutants such as polychlorinated biphenyl, halogenated hydrocarbons such as trichloroethylene, and ammunition wastes including nitroaromatics such as trinitrotoluene and glycerol trinitrate. Metabolism of these pollutants often results in degradation to non-toxic substances that can even be used by the plants and their microbial

partners as sources of carbon, phosphorous, nitrogen, sulfur, and in some cases, trace elements. Plants thus have the capacity to convert harmful substances into useful sources of nutrition.

So what metabolic processes are used by plants for these interconversion reactions? Organic pollutants are metabolized to less toxic substances by oxidation and reduction reactions, by hydrolysis of specific bonds within the toxins, or by conjugation/derivatization with small molecular moieties such as sugars and peptides. The most frequent derivatizing molecules include glucose and its oxidized derivatives, peptides such as glutathione, amino acids, and even simple methyl and acetyl groups. Pesticides, herbicides, and other xenobiotics are frequently detoxified by such reactions, and derivatization generally renders them more water-soluble. Synthesis of the enzymes that catalyze these reactions is often induced by the toxic substances they act on, arguing that defense is one of their primary functions.

Advantages of phytoremediation include the marginal costs involved if the species planted are appropriate for the region, requiring little care. Plants absorb CO_2 and do not require the consumption of fossil fuels as is true of many commercial decontamination processes. Moreover, plant growth provides the potential of yielding biomass that can be used for heat and energy production. Finally, some plants accumulate radioactive wastes such as depleted uranium, a serious problem now in Iraq, Afghanistan, nuclear reactor sites, and many US military training sites. The primary disadvantages of phytoremediation are (1) the time required to grow the plants and (2) the potential for loss by fire, freezing, and other natural or man-related disasters. It may take years, even decades, to halve contaminant levels. This is of particular importance when it is considered that during this period, the land may not be available for human or animal usage. It is possible that basic research concerning the best detoxification processes, and subsequent genetic engineering manipulations, can help to alleviate these problems.

Some plants have extraordinary capabilities to concentrate metals. Hyperaccumulating species can store essential nutrients such as copper, iron, zinc, and selenium as well as toxic metals such as aluminum, arsenic, cadmium, lead, and mercury. Concentrations of these heavy metals can be over 1,000-fold those observed in the environment. Clearly, certain plants, but not others, have specifically evolved the unusual

capacity to accumulate large amounts of these substances. But what would be the long-term survival benefit to the plant?

Botanists have pondered this question, and have conducted experiments to test their hypotheses. The roots of most plants take up but *don't* overaccumulate toxic metals and organics; rather, they defend themselves by pumping them out, into the external environment. So what is the advantage to other plants that accumulate them? It is clear that essential heavy metals such as iron and copper can be stored for later use, but what about the toxic metals and organics that serve no useful function? Usually, these substances are sequestered in inactive forms where they cause no damage to the plant. But is there truly an evolutionary advantage to storing them?

Current evidence has led investigators to conclude that their accumulation serves a protective function. These substances are foul-tasting and often toxic, causing animals that eat them to prefer other sources of nutrition. Following consumption, the animals may experience feelings of nausea, and even die if they eat too much. Consequently these plants are left alone by predators of all kinds, from insect larvae to large herbivores including man. Leaves, shoots, and flowers with unpalatable levels of organic toxins or heavy metals not only deter animal predators, they also serve to reduce pathogenic infection by plant viruses, bacteria and fungi.

The effectiveness of a plant for decontamination purposes depends on two factors: (1) the degree of bioconcentration, and (2) the biomass of the plant tissue where the toxins are stored. The ideal plant is large and accumulates the undesirable substances well over 100-fold over the concentrations present in the contaminated site.

What types of plants have been found to be the best hyperaccumulators? There are many. For example, ferns of the genus *Pteris* accumulate arsenic; thale cress species such as *Arabidopsis halleri* take up zinc and cadmium, and fast-growing trees of the genus *Populus* are useful for bioremediation because of their extensive root systems for wide coverage, rapid rates of water uptake, and their ability to take up a tremendous variety of contaminants. Moreover, they are adaptable to a wide range of climatic conditions, and maintenance costs are low. They are additionally useful for pulp and paper production, and they can be used as sources of fuel and lumber. Best of all, their

long-term growth provides effective protection against erosion and the spread of contaminated soil by wind and water. As a result, plant molecular geneticists have introduced foreign genes into poplars, over expressing sequestration genes, obtained, for example, from fungi, bacteria, and other plants. These transgenic trees appear to be superior for detoxification of both pesticides and heavy metals.

Field trials are already in progress to test their effectiveness in highly contaminated former heavy metal mining sites while assessing the biosafety risks and the stabilities of the genetically introduced materials. Evidence so far points to improved capacities for decontamination with maximal stability and safety. It is time to recognize that technological advances may not always be environmentally harmful. We need to fight fire with fire, to use advanced technology to overcome the devastation of technology. But as always, tremendous care must be taken. Often the detriments resulting from the use of a novel technology are not recognized for years, or even decades, after it is introduced.

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