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Review

# Phytoremediation and rhizoremediation of organic soil contaminants: Potential and challenges

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ABSTRACT

Over the past few decades there has been avid interest in developing *in situ* strategies for remediation of environmental contaminants. Major foci have been on persistent organic chemicals and metals. Phytoremediation, a strategy that uses plants to degrade, stabilize, and/or remove soil contaminants, has been extensively investigated. Rhizoremediation, a specific type of phytoremediation that involves both plants and their associated rhizosphere microbes, can occur naturally, or can be actuated by deliberately introducing specific microbes. These microbes can be contaminant degraders and/or can promote plant growth under stress conditions. Because initial phytoremediation research showed great promise as a cost-effective remedial strategy, considerable effort has been devoted to making the transition from the laboratory to commercialization. Despite our understanding of the mechanisms of remediation, and the success of studies in the laboratory and greenhouse, efforts to translate phytoremediation research to the field have proven challenging. Although there have been many encouraging results in the past decade, there have also been numerous inconclusive and unsuccessful attempts at phytoremediation in the field. There is a need to critically assess why remediation in the field is not satisfactory, before negative perceptions undermine the progress that has been made with this promising remedial strategy. Two general themes have emerged in the literature: (1) Plant stress factors not present in laboratory and greenhouse studies can result in significant challenges for field applications. (2) Current methods of assessing phytoremediation may not be adequate to show that contaminant concentrations are decreasing, although in many cases active remediation may be occurring. If phytoremediation is to become an effective and viable remedial strategy, there is a need to mitigate plant stress in contaminated soils. There is also a need to establish reliable monitoring methods and evaluation criteria for remediation in the field. This review will focus on the challenges and the potential of phytoremediation, particularly rhizoremediation, of organic contaminants from soils.



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## 1. Introduction

An increasingly industrialized global economy over the last century has led to dramatically elevated releases of anthropogenic chemicals into the environment. Prevalent contaminants include petroleum hydrocarbons (PHC), polycyclic aromatic hydrocarbons (PAHs), halogenated hydrocarbons, pesticides, solvents, metals, and salt. The resulting stresses on human and ecosystem health are well documented [1–3]. Although the use of plants to remediate radionuclide-contaminated soils was explored in the 1950s, the term phytoremediation was not invoked until the 1980s, and rapid expansion in this field only began in the last decade [4]. Phytoremediation has now emerged as a promising strategy for *in situ* removal of many contaminants [5–11]. Microbe-assisted phytoremediation, including rhizoremediation, appears to be particularly effective for removal and/or degradation of organic contaminants from impacted soils, particularly when used in conjunction with appropriate agronomic techniques [12–21]. The introduction will briefly review some of the laboratory and greenhouse research that preceded implementation of microbe-assisted phytoremediation in the field. The subsequent focus of the review will be on the challenges and potential of this remedial strategy for *in situ* removal of organic chemicals from contaminated sites.

### 1.1. Developing phytoremediation as a remedial strategy for organic contaminants

Prior to phytoremediation field trials, extensive research was performed in laboratories and greenhouses. Some of this work explored the effects of plants on removal of contaminants from spiked soil and soil excavated from contaminated sites [13,18,19,22,23]. Many of these experiments provided valuable insights into the types and specific mechanisms of phytoremediation of organic contaminants [5,11,24]. Some organic compounds can be transported across plant membranes. Of these, the low molecular weight compounds can often be removed from the soil and released through leaves via evapotranspiration processes (phytovolatilization). Some of the non-volatile compounds can be degraded or rendered non-toxic via enzymatic modification and sequestration *in planta* (phytodegradation, phytoextraction). Other compounds are stable in the plants and can be removed along with the biomass for sequestration or incineration.

Greenhouse experiments have also been conducted with spiked and/or excavated soil to determine how contaminated soils affect plant growth [5,13,19,24–27]. These experiments allowed researchers to explore methods for overcoming contaminant stress, without the confounding effects of field-dependent variables such as weather and nutrient limitation. It has been reported that plants can have more than 100 million miles of roots per acre, which suggests great potential for phytoremediation in natural environments [28]. One problem is that high concentrations of contaminants tend to inhibit plant growth, including root growth, in part due to oxidative stress [13,19,25,27]. The resulting stress will limit the rate of phytoremediation *in situ* [18,19,26]. Contaminated soils also tend to be nutrient poor and/or lack microbial diversity, which contributes to sub-optimal plant biomass accumulation, as well as impeded rates of remediation [13,26,29,30].

When using spiked soils for remediation experiments in the greenhouse, the focus has often been on the ability of a given plant to survive and grow in the presence of a specific compound and/or to remediate it. However, soils at contaminated sites generally contain complex mixtures of chemicals, and often include both organic and inorganic components. In spiked soils, chemicals tend to be bioavailable, whereas contaminants in naturally weathered soils are often not readily bioavailable. For instance, germination and plant growth of seven plant species was assessed in soil spiked with a pure PAH mixture, soil spiked with coal tar, and weathered soil from a former coking plant [31]. These conditions led to significantly different results, which highlighted the need to perform greenhouse experiments with soils collected from contaminated sites before implementing a field-level remediation.

Concomitant with phytoremediation garnering widespread interest, the field of microbial bioremediation has also been expanding [32–36]. Contaminant-degrading microbes have been isolated from impacted soils and characterized [14,23,36], and it is postulated that contaminant-degrading bacteria can be found in virtually all soils [15]. Mechanistic studies using these microbial isolates have been performed on spiked and field-isolated soils [13,35,37]. Following isolation and characterization of contaminant-degrading microbes, attempts were made to inoculate contaminated field soils with the isolates; however, this remedial strategy has proven to be largely unsuccessful [11,14,34,35]. There are several potential reasons for this general lack of success [14,38]. These include the inability of introduced microbes to compete with existing microflora and microfauna in the soil environment; the inability of the microbes to grow to sufficient depths to reach sub-surface contaminants; insufficient nutrients in contaminated soils to support microbial growth; low bioavailability of contaminants; preferential utilization of carbon compounds other than the contaminant of interest; and the presence of toxicants at the site that inhibit microbial growth. One way to increase the potential of microbial remediation is to add natural analogues of contaminants to soil (analogue enrichment), which can stimulate bioremediation by inducing degradative pathways [39,40].

A convergence of phytoremediation and microbial bioremediation strategies led to a more successful approach to remediation of contaminants, particularly organic compounds. Microbe-assisted phytoremediation, with both naturally occurring microbes and deliberately stimulated via seed innoculation, has been investigated in the laboratory, greenhouse and field [10,13–15,18,19,22,41]. A variety of contaminant-degrading enzymes can be found in plants, fungi, endophytic bacteria and root-colonizing bacteria. These include peroxidases, dioxygenases, P450 monooxygenases, laccases, phosphatases, dehalogenases, nitrilases, and nitroreductases [5,13,15,42–58] (Table 1). Although there are some organisms that can completely degrade a specific organic contaminant (e.g., *Sphingobium chlorophenolicum* strain ATCC 39723 can mineralize pentachlorophenol [47,59]), individual species generally do not contain entire degradation pathways.