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Review article

Opinion: Taking phytoremediation from proven technology to accepted practice

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ABSTRACT

Phytoremediation is the use of plants to extract, immobilize, contain and/or degrade contaminants from soil, water or air. It can be an effective strategy for on site and/or *in situ* removal of various contaminants from soils, including petroleum hydrocarbons (PHC), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), solvents (e.g., trichloroethylene [TCE]), munitions waste (e.g., 2,4,6-trinitrotoluene [TNT]), metal(loid)s, salt (NaCl) and radioisotopes. Commercial phytoremediation technologies appear to be underutilized globally. The primary objective of this opinion piece is to discuss how to take phytoremediation from a proven technology to an accepted practice. An overview of phytoremediation of soil is provided, with the focus on field applications, to provide a frame of reference for the subsequent discussion on better utilization of phytoremediation. We consider reasons why phytoremediation is underutilized, despite clear evidence that, under many conditions, it can be applied quite successfully in the field. We offer suggestions on how to gain greater acceptance for phytoremediation by industry and government. A new paradigm of phytomanagement, with a specific focus on using phytoremediation as a "gentle remediation option" (GRO) within a broader, long-term management strategy, is also discussed.

Contents

Abbreviations: EDTA, ethylene-diamine-tetra-acetate; GRO, gentle remediation options; PAHs, polycyclic aromatic hydrocarbons; PCBs, polychlorinated biphenyls; PEPS, PGPR-enhanced phytoremediation system(s); PGPR, plant growth promoting rhizobacteria; PHC, petroleum hydrocarbon(s); TCE, trichloroethylene; TNT, trinitrotoluene.

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1. Introduction

Several classes of contaminants have negative impacts on the environment. They are released either accidentally (e.g., oil and brine spills during petroleum exploration, production or transport of petroleum, leakage from chemical storage tanks, and mining and processing of metals) or deliberately (e.g., pesticides, military activities and combustion of fossil fuels). Contaminants should be remediated to prevent or mitigate entry into terrestrial, atmospheric and aquatic environments. Phytoremediation is the use of plants to extract, immobilize, contain and/or degrade contaminants from soil, water or air. It can be an effective strategy for on site and/or *in situ* removal or stabilization of various contaminants from soils, including petroleum hydrocarbons (PHC), polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), solvents (e.g., trichloroethylene [TCE]), munitions waste (e.g., 2,4,6-trinitrotoluene [TNT]), metal(loid)s, salt (NaCl) and radioisotopes [1–11].

Over the past 20 years, we have developed plant growth-promoting rhizobacteria (PGPR)-enhanced phytoremediation systems (PEPS) that have been used to remediate PHC to below generic regulatory criteria at more than ten Canadian sites [1,12–16]. PEPS have also been deployed to revegetate salt-impacted soils and decrease NaCl soil concentrations at more than 12 sites in Canada [15,17]. Based on our involvement in the phytoremediation industry, both in academic research and commercial capacities, it has become apparent to us that despite the success of phytoremediation research for PHC and NaCl in the field, the degree of acceptance for phytoremediation and PEPS in Canada is lacking. In addition, reviews of the literature indicate that commercial phytoremediation technologies appear to be underutilized globally [18–20]. Although interest in phytoremediation continues to rise, as indicated by the increasing trend in publications between 1993 and 2016, there is no concomitant increase in phytoremediation-related patents, which suggests that commercial investments in these green technologies are not commensurate with successful academic research (Fig. 1A,B).

An extensive review of current phytoremediation publications is not the primary objective of this opinion piece. Rather, it is to discuss how to take phytoremediation from a proven technology to an accepted practice. For detailed descriptions of the various types of phytoremediation of numerous organic and inorganic compounds, the reader is referred to other reviews [1–5,7–9,21]. An overview of phytoremediation of soil is provided in Section 2, to provide a frame of reference for the subsequent discussion. Because success in a controlled environment does not always translate to comparable results in the field [1,22–27], the main focus of the overview is on field applications of phytoremediation. After this overview, we consider reasons why phytoremediation is underutilized, despite clear evidence that, under many conditions, it can be applied quite successfully in the field (Table 1). We offer suggestions for how to gain greater acceptance for phytoremediation by industry and government. A new paradigm of phytomanagement, with a specific focus on using phytoremediation as a "gentle remediation option" (GRO) within a broader, long-term management strategy, is also discussed.

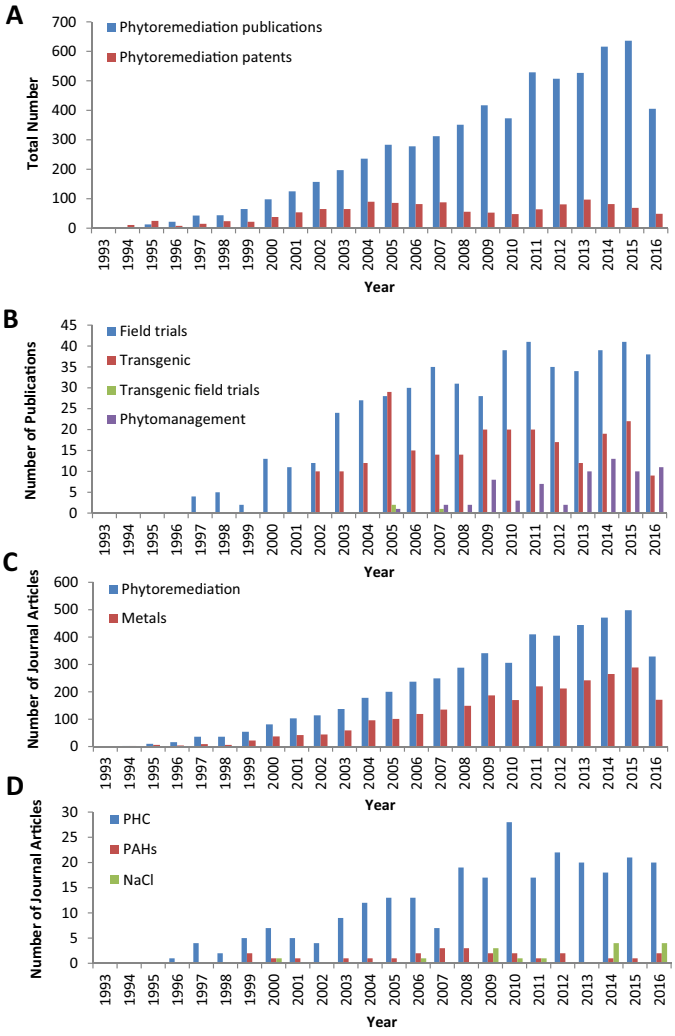

Fig. 1. Phytoremediation publications, 1993–2016. Scopus searches of Life Sciences and Physical Sciences publications were performed on August 22, 2016. (A) *Total publications and patents.* Searched for total publications using the key words "phytoremediation and soil" in titles, abstracts and keywords of articles, reviews, articles in press, books, book chapters, conference papers, conference reviews, letters, editorials, notes, short surveys, business articles or press, and errata. (B) *Phytoremediation publications reporting field work, transgenic research, transgenic field trials and phytomanagement approaches.* Key words for "field trials" were "phytoremediation and soil and field trial or experiment". Note that this search resulted in an overestimation of actual field trials, based on perusals of the articles for inclusion in Table 1. Key words for "transgenic" were "phytoremediation and soil and transgenic*". Key words for "transgenic field trials" were "phytoremediation and soil and transgenic* and field trial or experiment". Key words for "phytomanagement" were "phytomanagement and soil". (C) *Number of journal articles for phytoremediation (all) and phytoremediation of metals.* Searched for total number of journal articles using the key words "phytoremediation and soil" in titles, abstracts and keywords. For articles on phytoremediation of metals, the keywords "phytoremediation and soil and metal" were used. (D) *Number of journal articles for phytoremediation of PHC, PAHs and NaCl.* Same as for metals, but instead of the key word "metal", the keywords "petroleum or PHC"; "PAH"; and "salt or saline or salinity or sodic or NaCl" were used; respectively.