Environmental Science and Technology: A Wiley-Interscience Series of Texts and Monographs
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PHYTOREMEDIATION
Transformation and Control of Contaminants

Edited by
Steven C. McCutcheon
Jerald L. Schnoor

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ENVIRONMENTAL SCIENCE AND TECHNOLOGY

A Wiley-Interscience Series of Texts and Monographs

Edited by JERALD L. SCHNOOR. *University of Iowa*
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A JOHN WILEY & SONS, INC., PUBLICATION

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey.

Published simultaneously in Canada.

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Library of Congress Cataloging-in-Publication Data is available.

ISBN: 0-471-39435-1

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

Dedication

To the U.S. Environmental Protection Agency Office of Research and Development Contaminated Sites Program, the U.S. Strategic Environmental Research and Development Program, and the European COST 837 project for the seminal support and organization of phytoremediation research and development.

In memory of

Rajiv Bhadra (1964–2002), a member of the Editorial Review Board and a rising star in phytoremediation who will be sorely missed
Eugene P. Odum (1913–2002) and **Howard T. Odum** (1924–2002), outstanding and exceptional brothers who pioneered systems ecology and ecological engineering that will be vital to the future of phytoremediation

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Series Preface

Environmental Science and Technology

We are in the third decade of the Wiley-Interscience Series of texts and monographs in Environmental Science and Technology. It has a distinguished record of publishing outstanding reference texts on topics in the environmental sciences and engineering technology. Classic books have been published here, graduate students have benefited from the textbooks in this series, and the series has also provided for monographs on new developments in various environmental areas.

As new editors of this Series, we wish to continue the tradition of excellence and to emphasize the interdisciplinary nature of the field of environmental science. We publish texts and monographs in environmental science and technology as it is broadly defined from basic science (biology, chemistry, physics, toxicology) of the environment (air, water, soil) to engineering technology (water and wastewater treatment, air pollution control, solid, soil, and hazardous wastes). The series is dedicated to a scientific description of environmental processes, the prevention of environmental problems, and preservation and remediation technology.

There is a new clarion for the environment. No longer are our pollution problems only local. Rather, the scale has grown to the global level. There is no such place as "upwind" any longer; we are all "downwind" from somebody else in the global environment. We must take care to preserve our resources as never before and to learn how to internalize the cost to prevent environmental degradation into the product that we make. A new "industrial ecology" is emerging that will lessen the impact our way of life has on our surroundings.

In the next 50 years, our population will come close to doubling, and if the developing countries are to improve their standard of living as is needed, we will require a gross world product several times what we currently have. This will create new pressures on the environment, both locally and globally. But there are new opportunities also. The world's people are recognizing the need for sustainable development and leaving a legacy of resources for future generations at least equal to what we had. The goal of this series is to help understand the environment, its functioning, and how problems can be overcome; the series will also provide new insights and new sustainable technologies that will allow us to preserve and hand down an intact environment to future generations.

JERALD L. SCHNOOR AND ALEXANDER J. B. ZEHNDER

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Preface

SCOPE AND COVERAGE

This book covers phytotransformation, phytodegradation, rhizosphere degradation, and phytocontainment of xenobiotic organic pollutants and select inorganic compounds that plant enzymatic processes transform or mineralize. Consistent with this coverage, the term phytoremediation is defined to encompass the use of green plants, fungi, algae, bacteria, and microbial mats when one of three vital plant processes is involved in waste management. These processes include (1) photoautotrophic conversion of sunlight to useful energy and use of atmospheric carbon dioxide to synthesize new biomass, thus fueling plant and rhizosphere microbial control and metabolism of contaminants; (2) green-liver metabolism involving transformation, conjugation, and sequestration of contaminants and the resulting by-products (*e.g.*, plant and fungal glycosylation and lignification); and (3) plant transpiration to control the movement of contaminants in water, soil, and air. Other recent books (cited in Chapter 1 of this book) cover phytoextraction of toxic metals, phytovolatilization of selenium, and phytostabilization of metals and organics. Where necessary for complete coverage of phytoremediation terminology and fundamentals, a few overlaps occur to maintain consistency. In one case, McIntyre (Chapter 30 of this book) introduces two new plant databases—one for rhizodegradation of petroleum hydrocarbons, and one for metals accumulation. In the other case, Rock (Chapter 31 of this book) reviews several field evaluations of phytoremediation; include some disappointing field results for phytoextraction of lead.

To broadly cover the latest advances from fundamental investigation to field testing of concepts, seven sections are the basis of organization for this book *Phytoremediation*. Each section starts with fundamental contributions that define the state-of-the-science and ends with chapters on the applications of fundamental and heuristic concepts in practical settings. The first three chapters overview the state of the science and practice, including review of technical, economic, social, and regulatory issues in translating the research to date into practical cleanup applications. Burken (Chapter 2 of this

book) covers the vital green-liver concept of Heinrich Sandermann, Jr. for plant metabolism. Section II covers fundamental and important advances involving enzymatic metabolic processes, proteomic and genomic bases of plant tolerance, phytotoxicity of selected xenobiotic chemicals, and fundamental physiological processes that include rooting and root ecology, and evapotranspiration. Sections III, IV, and V cover the spectrum of fundamental investigation to field testing for aromatic and hydrocarbon contaminants, explosives, and chlorinated solvents, respectively. Section VI covers the latest modeling, design, and field application advances, starting with the latest in phytohydraulic control and modeling that establish the state-of-the-practice, then concentrates on applied management techniques for wastewaters, leachates, and brines. Section VII presents the latest advances in genetic engineering and screening of plants that may be useful in managing atmospheric nitrous oxides and halocarbon pollution, use of plants to control methyl *tertiary*-butyl ether (MTBE), phytodegradation of cyanide in soil, and rhizodegradation and phytodegradation of dissolved perchlorate. The final two chapters of this section, and of the book, introduce the first plant databases and review current field evaluations of important types of phytoremediation. The heuristic plant-based practices of land farming (including sewage spraying), constructing treatment wetlands, and developing riparian buffers that predate coining the term phytoremediation in 1991 are covered to unify recent chemical-specific treatment approaches with the ecological engineering of wetlands, buffers, or tree, grass, and cultivar plantings. The appropriate practices are introduced and evaluated in the scientific context of specific pathways, transformation products, kinetics, and efficiency in achieving cleanup standards or acceptable residual risks. The exceptions involve a few cases where field experience with trees, grasses, and other vegetation establish some beneficial effects, but the scientific basis has not yet been fully explored.

INTENDED AUDIENCE

This book is intended to be a definitive reference for leaders in the research and practice of phytoremediation as well as those students entering the field. Practicing engineers, ecologists, foresters, agronomists, and extension agents; waste site managers; and regulatory experts will find this book to be a definitive reference on the phytoremediation that is possible, feasible, and proven for organic and some inorganic pollutants in water, soil, and air. Each chapter has a summary of practical implications. Where necessary to define fundamental principles for broad audiences, a glossary and definitions in the text are judiciously applied. Système International (SI) units are used (along with English common in most practical chapters) and care taken to avoid confusion over decimal points and numerical expression. (The U.S. practice of using a period as the decimal point and avoiding the use of the comma in favor of a space in denoting thousands is used for numbers greater than 9999,

e.g., 99 800.) Attention has also been paid to the consistent use of significant digits and scientific nomenclature in each chapter to facilitate practical applications of the knowledge worldwide.

The coverage of existing and new practices includes wetland construction, land farming, tree and crop plantation, riparian buffer management, and biotechnology-based waste treatment unit processes to treat most of the major organic xenobiotic contaminants (*e.g.*, phenols, hydrocarbons, surfactants, pesticides, explosives, and chlorinated solvents) and a few inorganic contaminants that plants mineralize or volatilize. The underlying theme is the use of *in situ*, sustainable, and renewable biotechnology to protect humans and the environment, but heuristic, short-term, energy-intensive methods are described and evaluated when necessary for complete waste management coverage of this innovative, evolving field. In some cases, design guidance can be distilled from this book.

Experts and students in allied fields will also find this book to be the definitive introduction to the science and practice of phytoremediation. Some of the allied fields include plant, fungal, and bacterial biochemistry, genetics, and proteomics; enzymology and metabolic engineering; biotechnology; ecology and ecological engineering; wetland ecology and hydrobiology; plant biology and other life sciences; plant, crop, and soil sciences and agronomy; forestry and silviculture; botany, plant physiology, and root ecology; plant toxicology; environmental chemistry and science; environmental, biological, bioresource, irrigation, agricultural, chemical, and civil engineering; microbiology and bioremediation; hazardous waste management; groundwater hydrology and hydrogeology; biometeorology; water resource management; alternative biofuel production; biogeochemistry, global change modeling, and risk assessment involving plants as sinks and sources; indoor and outdoor air pollution control; landscaping; land use planning and management; and environmental and ecological economics and management.

Graduate and undergraduate students interested in phytoremediation should find this book to be an indispensable reference to practical case studies as well as definitive process research on why phytoremediation works and where current gaps in knowledge exist that can be filled by enterprising thesis and dissertation research over the next decade or longer. Course instructors and curricula planners in the evolving phytoremediation and ecological engineering programs of study will find this book an adequate text to provide fundamental background and case studies until texts are tailored to this purpose. Assignments should be easily derived from the practical elements and practical implications summarized in each chapter. For course organization and planning, the sections group together all the work on major contaminant problems such as aromatic and hydrocarbon contaminants, explosives, and chlorinated solvents following the overview and the basics of phytoremediation—green-liver metabolism, tissue culturing and enzymology, proteomics and useful plant biochemistry approaches, basis of plant tolerance, root ecology and control, and evapotranspiration. The latest advances available for

study include new approaches to treating air pollutants, MTBE, and perchlorate in groundwater and wastewater, and cyanide in soil, especially from the numerous abandoned town gas sites that was the source for street and home lighting in the late nineteenth and early twentieth centuries. Hopefully, an instructors' guide with assignments and engineering design will follow soon.

ORGANIZATION AND PEER REVIEW

The extensive involvement of many research groups was also intended to be exceptional. The authors of the various chapters represent almost all of the leading teams developing phytoremediation of organic contaminants. In some cases, authorship is shared among some of the most productive teams for focused, concise coverage of important topics. Other chapters were specifically directed to full coverage of all known work of importance, especially to involve younger collaborators and future leaders in the field. Despite the outreach involved, a few have surged into prominence in this dynamic field since the writing began 2 years ago. The Editorial Review Board was therefore set up to engage some emerging leaders during the process, some who were constrained by time, but mostly those with review skills and foresight into the coverage necessary.

A remarkable trait of almost all of the research and development teams engaged in phytoremediation became evident early on, as authors were selected. Almost all U.S. teams have dual leadership from a science discipline and from engineering. European research and development is a bit different, where the strength and leadership in the field comes from the marvelous organization and coordination of the COST 837 project led by Jean-Paul Schwitzguébel of the Swiss Federal Institute of Technology in Lausanne, Switzerland, and Tomas Vanek of the Czech Academy of Sciences in Prague. Despite the inadequate funding for research and development noted in Marmiroli and McCutcheon (Chapter 3 of this book), the outlook for phytoremediation based on these productive teams and organizations is very good. Government and industry leaders and the public should look forward to the development of additional cost-saving methods that effectively manage widespread, moderately toxic contamination and some more toxic hot spots using sustainable, natural processes that can be easily engineered for the benefit of humankind and the ecosystem of this planet.

To ensure the best quality coverage, all chapters including McCutcheon and Schnoor (Chapter 1 of this book) were independently peer reviewed and accepted for the book by one of the editors not associated with the authors. In the case of McCutcheon and Schnoor (Chapter 1 of this book), a senior member of the Editorial Review Board, Alan Baker, was empowered as acting editor to assess the independent reviews and determine if the chapter was sufficient. The reviews started with outlines of each chapter to ensure

coverage and coordination. Because of these reviews by the Editorial Review Board and authors of other chapters, some gaps in coverage were filled with a second round of invited contributions. Board members and the editors also highlighted the fast-developing work and the important topics. Once the chapters were completed, three to seven reviews were undertaken. One editor, one member of the Editorial Review Board, and one of the better-known experts in the area (if this did not involve the editor or Board member) reviewed each chapter. Authors of other chapters commented on overlaps in coverage, but also provided outstanding technical criticism. Most of the reviews were focused on chapters that defined a consensus on the state-of-the-practice that hopefully will lead to several design guidance documents after this book is published. All revisions were further evaluated editorially. Despite the rigor in review, only one chapter was declined.

EXPRESSIONS OF APPRECIATION

We thank the authors of each chapter for the quality coverage, especially those who teamed with others to cover gaps in knowledge. Christina Negri and Paul Schwab took on the daunting tasks of distilling extensive work on tree and grass root ecology, respectively, into a phytoremediation context. The support of Hector Flores on the Editorial Review Board was important in the editors enlarging the scope of the book to cover this important, but previously neglected area. Victor Medina led the international coverage of plant tolerance and worked with Elena Maestri to translate extensive literature on pesticides and metals toxicity into knowledge that supports the phytoremediation of other classes of xenobiotic compounds. Jerry Schnoor organized coverage of work involving MTBE. Paul Olson covered vital work at the University of Oklahoma and the developing work at Colorado State University with experience from the University of California at Berkeley *via* the work of Elizabeth Pilon-Smits. Hans Harms and his coauthors also put the independent axenic tissue culture investigations of John Fletcher at the University of Oklahoma and the U.S. Environmental Protection Agency laboratory at Corvallis into a fuller and more practical context with his extensive work over the years. Jim Jordahl reached out to Kenth Hasselgren of SWECO VBB VIAK AB on the valuable experience in tree plantation in Sweden and northern Europe. Similar leadership of Sandy Eberts, Larry Davis, Stefan Trapp, and Hiromichi Morikawa was also vital to the quality and coverage of this book and is much appreciated by the editors. In addition, the outstanding reviews of other chapters by Larry Davis and Tomas Vanek were notable and much appreciated.

We also thank the Editorial Review Board members for the outstanding reviews of outlines and final chapter drafts. Rajiv Bhadra, before his untimely death, reviewed all the chapters on explosives and provided insightful criticism and suggestion for improvement and consistency. Alan Baker served as

acting editor to avoid a conflict of interest in accepting Chapter 1 by the editors. Sridhar Susarla provided valuable reviews and assistance with the final proofs. Evelyn Drake provided broad insights that led to better coverage of hydrocarbon phytoremediation and root ecology, and enabled the Board to foresee some developments in allied areas. Rashalee Levine was an early advocate in providing precise plant nomenclature and quality assurance information so that many more insights can be distilled after publication of the book.

In addition, the reviews of other experts are very much appreciated for the rigor in examining the technical quality of the work and suggesting better forms of expression when appropriate. These reviewers include Pedro Alvarez of the University of Iowa; Ellie Best of the U.S. Army Waterways Experiment Station; Om Parkash Dhankher of the University of Georgia; Shoeleh Di Julio of California State University; Steve Dwyer of the U.S. Department of Energy Sandia National Laboratory; Andre Gerth of BioPlanta; Leon Kochian of the U.S. Department of Agriculture Plant, Soil and Nutrition Laboratory; Peter Kulakow of Kansas State University; Louis Licht of EcoloTree; Steven Link of Washington State University; Ed Mead of the U.S. Army Corps of Engineers; Anu Ramaswami of the University of Colorado, Denver; Paul Thomas of Thomas Consultants, Inc.; William J. (Jody) Waugh of the U.S. Department of Energy Environmental Sciences Laboratory; Jody Wireman of the U.S. Air Force Human Systems Centre; Keith Halford of the U.S. Geological Survey; Paul Brantley of the U.S. Geological Survey; and John Fletcher of the University of Oklahoma.

We also thank David Tsao of the BP Corp. for the coordination of coverage of the field in another publication. David edited the monograph *Phytoremediation* for the Springer-Verlag series *Advances in Biochemical Engineering/Biotechnology* (vol. 78) during the time this book was being produced.

Bob Esposito of John Wiley was most helpful in organizing and maintaining momentum for this effort along with Danielle Lacourciere in the final stages. Vera Madison provided outstanding editorial and office support in Athens that was much appreciated, especially in final stages. Most importantly, we appreciate the support of our families and colleagues during this immense undertaking.

Finally, we find three remarkable sources of support for the international authorship of this book. The U.S. Environmental Protection Agency Office of Research and Development Contaminated Sites Program supported both editors and several authors, especially through the Hazardous Substance Research Centers. This program funded a 1991 proposal of Ila Raskin in which the term phytoremediation was first defined. Next, the U.S. Strategic Environmental Research and Development Program also has supported both editors and several authors directly and indirectly. This program was conceived in 1991 by former U.S. Senators Sam Nunn of Georgia and Al Gore of Tennessee as an appropriate way to redirect the peace dividend of defense technology development to the international clean up of cold war facilities in

the U.S. and Europe. Madelyn Creedon of the Senate Defense Appropriations Committee suggested the appointment of a renowned Science Advisory Board to ensure use of the best science in developing phytoremediation and other innovative waste management techniques. Finally, the European project COST 837 is a wonderful organization of much needed fundamental research on phytoremediation that has supported or aided many authors in the last several years. Other government, industrial, and commercial support for the field of phytoremediation has also been important and is acknowledged in the chapters where appropriate. For example, Marmiroli and McCutcheon (Chapter 3 this book) note the entrepreneurial and government leadership that has occurred in making phytoremediation a useful technology.

DISCLAIMER

This contribution has been reviewed in accordance with the U.S. Environmental Protection Agency peer and administrative review policies and approved for publication but reflects the views of the editors and not necessarily those of the Agency.

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