Increased industrial and agricultural activity this century has led to vast quantities of the earth's soil and groundwater resources becoming contaminated with hazardous chemicals. Bioremediation provides a technology based on the use of living organisms, usually bacteria and fungi, to remove pollutants from soil and water, preferably *in situ*. This approach, which is potentially more cost-effective than traditional techniques such as incineration of soils and carbon filtration of water, requires an understanding of how organisms transform chemicals, how they survive in polluted environments and how they should be employed in the field. This book examines these issues for many of the most serious and common environmental contaminants, resulting in a volume which presents the most recent position on the application of bioremediation to the cleanup of polluted soil and water.

Biotechnology Research Series: 6
Series Editor: James Lynch

Bioremediation: Principles and Applications

Biotechnology Research

This series of contributed volumes provides authoritative reviews of selected topics in biotechnology aimed at advanced undergraduates, graduate students, university researchers and teachers, as well as those in industry and government research. The scope of the series is as broad-ranging as the applications of the research itself, encompassing those topics in applied science and engineering, ranging from agriculture to the design of pharmacueticals, which are not well served by the existing literature. Each volume therefore represents a significant and unique contribution to the literature, comprising chapters by the leading workers in the field who review the current status of the specialisms and point the way to future research and potential applications.

Titles in the series

1. Plant Protein Engineering
   Edited by P. R. Shewry and S. Gutteridge
2. Release of Genetically Engineered and Other Microorganisms
   Edited by J. C. Fry and M. J. Day
3. Transformation of Plants and Soil Microorganisms
   Edited by K. Wang, A. Herrera-Estrella and M. Van Montagu
4. Biological Control: Benefits and Risks
   Edited by H. M. T. Hokkanen and J. M. Lynch
5. Microbial Biofilms
   Edited by H. Lappin-Scott and J. Costerton

(Volumes 1–5 were originally published under the title Plant and Microbial Biotechnology Research Series.)

Bioremediation: Principles and Applications

Ronald L. Crawford and Don L. Crawford

University of Idaho, Moscow, Idaho, USA

CAMBRIDGE UNIVERSITY PRESS

CAMBRIDGE UNIVERSITY PRESS
Cambridge, New York, Melbourne, Madrid, Cape Town, Singapore, São Paulo

Cambridge University Press
The Edinburgh Building, Cambridge CB2 2RU, UK

Published in the United States of America by Cambridge University Press, New York

www.cambridge.org
Information on this title: www.cambridge.org/9780521470414

First published 1996
Reprinted 1998
This digitally printed first paperback version 2005

A catalogue record for this publication is available from the British Library

Library of Congress Cataloguing in Publication data

Bioremediation: principles and applications / R.L. Crawford and D.L. Crawford.
p. cm. – (Plant and microbial biotechnology research series; 5)
Includes index.
ISBN 0-521-47041-2 (hardcover)
1. Bioremediation. I. Crawford, Ronald L., 1947– .
II. Crawford, Don L. III. Series.
TD192.5.B5573 1996
628.5′2–dc20 95-51193 CIP

ISBN-13 978-0-521-47041-4 hardback
ISBN-10 0-521-47041-2 hardback

ISBN-13 978-0-521-01915-6 paperback
ISBN-10 0-521-01915-X paperback

Contents

Contents

Contributors

W. Admassu Department of Chemical Engineering, University of Idaho, Moscow, ID 83844-1021, USA

M. E. Caldwell Department of Botany and Microbiology, The University of Oklahoma, Norman, OK 73019, USA

C. E. Cerniglia National Center for Toxicological Research, Division of Microbiology, 3900 NCTR Road, HFT-250, Jefferson, AR 72079, USA

D. L. Crawford Department of Microbiology, Molecular Biology, and Biochemistry, University of Idaho, Moscow, ID 83844–3052, USA

R. L. Crawford Center for Hazardous Waste Remediation Research, University of Idaho, Moscow, ID 83844-1052, USA

S. C. Francesconi US Environmental Protection Agency, Gulf Ecology Division, Gulf Breeze, FL 32561, USA

S. B. Funk Department of Microbiology, Molecular Biology and Biochemistry, University of Idaho, Moscow, ID 83844-3052, USA

R. A. Korus Department of Chemical Engineering, University of Idaho, Moscow, ID 83844-1021, USA

L. Krumholz Department of Botany and Microbiology, The University of Oklahoma, Norman, OK 73019, USA

E. S. Melin Nordic Envicon Oy, Kanslerinkatu 8, FIN-33720 Tampere, Finland

R. M. Miller Soil and Water Science Department, The University of Arizona, Tucson, AZ 85721, USA

Contributors

M. J. Morra Department of Plant Soil and Entomological Sciences, University of Idaho, Moscow, ID 83844-2339, USA

J. G. Mueller U.S. EPA Environmental Research Laboratory, 1 Sabine Island Drive, Gulf Breeze, FL 32561, USA

L. I. Pepper Soil and Water Science Department, The University of Arizona, Tucson, AZ 85721, USA

P. H. Pritchard U.S. EPA Environmental Research Laboratory, 1 Sabine Island Drive, Gulf Breeze, FL 32561, USA

J. A. Puhakka Institute of Water and Environmental Engineering, Tampere University of Technology, FIN-33101 Tampere, Finland

T. M. Roane Soil and Water Science Department, The University of Arizona, Tucson, AZ 85721, USA

E. Z. Ron Department of Molecular Microbiology and Biotechnology, Tel Aviv University, Ramat Aviv, Israel

E. Rosenberg Department of Molecular Microbiology and Biotechnology, Tel Aviv University, Ramat Aviv, Israel

M. S. Shields The Center for Environmental Diagnostics and Bioremediation, The University of West Florida, Pensacola, FL 32514-5751, USA

J. M. Suflita Department of Botany and Microbiology, The University of Oklahoma, Norman, OK 73019, USA

R. Unterman Envirogen, Inc., 4100 Quakerbridge Road, Lawrenceville, NJ 08648, USA

L. P. Wackett Department of Biochemistry & Institute for Advanced Studies in Biological Process Technology, University of Minnesota, St Paul, MN 55108, USA

Preface

Bioremediation is not a new concept in the field of applied microbiology. Microorganisms have been used to remove organic matter and toxic chemicals from domestic and manufacturing waste effluents for many years. What is new, over the past few decades, is the emergence and expansion of bioremediation as an industry, and its acceptance as an effective, economically viable alternative for cleaning soils, surface water, and groundwater contaminated with a wide range of toxic, often recalcitrant, chemicals. Bioremediation is becoming the technology of choice for the remediation of many contaminated environments, particularly sites contaminated with petroleum hydrocarbons.

Bioremediation has also become an intensive area for research and development in academia, government, and industry. Partly because of new laws requiring stricter protection of the environment and mandating the cleanup of contaminated sites, funding for both basic and applied research on bioremediation by government agencies, as well as by private industry, has increased dramatically over the past decade. As a result, rapid progress has been made in developing effective, economical microbial bioremediation processes. In an even broader sense, this increased activity has led to a surge of interest in 'environmental microbiology', a field covering a spectrum of disciplines, including microbial physiology and ecology, molecular genetics, organic chemistry, biochemistry, soil and water chemistry, geology, hydrology, and engineering. In the academic research environment, bioremediation has, in effect, become so scientifically broad and complex in both its basic and applied aspects that it has of necessity evolved into a multidisciplinary field that requires a 'research center' approach. At the University of Idaho, as just one example, we have built our multidisciplinary environmental remediation research program within the University of Idaho Center for Hazardous Waste Remediation Research. While difficult to quantify, the total amount of research funding now being devoted to bioremediation is quite substantial. A recent estimate suggests that in 1997, industry will spend over $4 billion on

designing, engineering, constructing, and equipping wastewater systems (*HazTech News*, May 11, 1995, p. 72).

It is a challenge for researchers to stay abreast of this rapidly advancing field, particularly in light of the diversity of environments and contaminants, as well as the varied approaches to bioremediation that have emerged in recent years. It is even more challenging to predict where the field is headed in the future, an important consideration for staying on the leading edge technologically. Indeed, perhaps even more than in other areas of scientific endeavor, it is easier to become a follower than it is to be a leader in research in bioremediation. Many scientists jump on a specific bandwagon and embrace their favorite approach to bioremediation – the 'intrinsic', the genetic engineering, the *in situ* approach. As a result, much repetitive research takes place, at considerable cost. The bioremediation field needs more scientists who understand the broader implications of various approaches, and who can work with colleagues in a multidisciplinary environment to advance both the basic and applied science of bioremediation.

In this book, we have attempted in several ways to broaden the perspectives of students and scientists working on bioremediation. First, since we wanted to review the principal topics relevant to bioremediation of contaminated soils, sediments, surface waters, and aquifers, we asked each author to provide, in effect, a status report on current research and development in his or her topic area. However, in such a rapidly changing field, even the best reviews become historic within a few years. Therefore, we also asked our authors to offer some thoughts on what knowledge is lacking within their specific research areas, and to comment on where future research emphasis should be placed. Finally, we asked them to be forward looking and offer some conjectures about the potential utility of bioremediation in their specific area of expertise. We think that our authors have accomplished these goals, producing a book that will be particularly useful to teachers and thesis advisors, as well as offering a predictive, paradigm-challenging resource for bioremediation researchers. We hope that the words of our authors will help generate new ideas and approaches to research and development in the field of bioremediation.

We appreciate the hard and thorough work of the authors of the chapters in this book. Thanks for a job well done. Also, we thank Ms. Connie Bollinger at the University of Idaho for the considerable effort she put into preparing the manuscripts as they arrived. She helped us greatly by taking care of the necessary details before the manuscripts were submitted to the publisher. We thank the editors at Cambridge University Press who have been involved in this book – Dr. Robert M. Harington, who got the project underway; Dr. Alan Crowden, who gave us valuable advice on preparing the manuscripts, and Dr. Maria Murphy, who saw the book to completion. Finally, we would like to thank Professor James M. Lynch of the University of Surrey, who first convinced us that this book would be a worthwhile project. His encouragement is deeply appreciated.

Don L. Crawford Ronald L. Crawford June 1995