

See discussions, stats, and author profiles for this publication at: <https://www.researchgate.net/publication/358459929>

# Phytoremediation Technology for the Removal of Heavy Metals and Other Contaminants from Soil and Water

Book · February 2022

DOI: 10.1016/C2020-0-02583-1

CITATIONS

0

READS

357

3 authors, including:



Vineet Kumar

GD Goenka University Gurgaon

139 PUBLICATIONS 1,103 CITATIONS

[SEE PROFILE](#)



Maulin Shah

217 PUBLICATIONS 963 CITATIONS

[SEE PROFILE](#)

Some of the authors of this publication are also working on these related projects:



Call for Papers: Special Issue on Microorganisms in Screening and Degradation of Endocrine disrupting chemicals (EDCs); Journal: Frontiers in Microbiology [View project](#)



Call for Paper (American Journal of Environmental Sciences " Special IssueRecent Advances in Green Technology for Industrial Pollution Control [View project](#)



Phytoremediation  
Technology for the  
Removal of Heavy  
Metals and Other  
Contaminants from  
Soil and Water



# Phytoremediation Technology for the Removal of Heavy Metals and Other Contaminants from Soil and Water

**Edited by**

**Vineet Kumar**

Waste Re-processing Division, CSIR-National  
Environmental Engineering Research Institute  
(CSIR-NEERI), Nagpur-440020, Maharashtra, India

**Maulin P. Shah**

Applied and Environmental Microbiology,  
Bharuch, India

**Sushil Kumar Shahi**

Department of Botany, School of Life Sciences,  
Guru Ghasidas Vishwavidyalaya (A Central University),  
Bilaspur, Chhattisgarh, India



ELSEVIER

Elsevier

Radarweg 29, PO Box 211, 1000 AE Amsterdam, Netherlands  
The Boulevard, Langford Lane, Kidlington, Oxford OX5 1GB, United Kingdom  
50 Hampshire Street, 5th Floor, Cambridge, MA 02139, United States

Copyright © 2022 Elsevier Inc. All rights reserved.

No part of this publication may be reproduced or transmitted in any form or by any means, electronic or mechanical, including photocopying, recording, or any information storage and retrieval system, without permission in writing from the publisher. Details on how to seek permission, further information about the Publisher's permissions policies and our arrangements with organizations such as the Copyright Clearance Center and the Copyright Licensing Agency, can be found at our website: [www.elsevier.com/permissions](http://www.elsevier.com/permissions).

This book and the individual contributions contained in it are protected under copyright by the Publisher (other than as may be noted herein).

#### **Notices**

Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

#### **British Library Cataloguing-in-Publication Data**

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

#### **Library of Congress Cataloguing-in-Publication Data**

A catalog record for this book is available from the Library of Congress

ISBN: 978-0-323-85763-5

For Information on all Elsevier publications visit our website at  
<https://www.elsevier.com/books-and-journals>

*Publisher:* Susan Dennis

*Acquisitions Editor:* Susan Dennis

*Editorial Project Manager:* Maria Elaine D. Desamero

*Production Project Manager:* Kumar Anbazhagan

*Cover Designer:* Mark Rogers



Typeset by Aptara, New Delhi, India

*Dedicated to our teachers, and mentors, from whom I continue to learn, and to my family for their support, blessings, motivation, and love. —*  
**Vineet Kumar**

*Dedicated to my family especially my wife without whose support this book would not have been possible. —*  
**Maulin P. Shah**

*This book is dedicated to my daughter and my wife. Their patience and understanding have given me the time and inspiration to research and editing this project. —*  
**Sushil Kumar Shahi**

# Contents

Contributors .....	XXV
About the Editors .....	XXXV
Preface .....	XXXIX
Acknowledgments .....	xliii

<b>CHAPTER 1</b>	<b>Phytoremediation and environmental bioremediation</b>	<b>1</b>
	<i>Arjun Mahato, Dipita Ghosh and Subodh Kumar Maiti</i>	
<b>1.1</b>	Introduction	1
<b>1.2</b>	Constructed wetlands as phytoremediation tool of wastewater	2
1.2.1	Types of constructed wetland	3
<b>1.3</b>	Design criteria and calculations	6
1.3.1	Site selection	6
1.3.2	Hydrological factors	6
1.3.3	Vegetation	7
1.3.4	Substrates	9
<b>1.4</b>	Metal removal mechanisms in constructed wetlands	10
<b>1.5</b>	Case studies	12
1.5.1	Treatment of dairy wastewater with hybrid macrophyte assisted vermifilter	12
1.5.2	Macrophytes for salinity remediation of wastewater	12
<b>1.6</b>	Phytoremediation and environmental bioremediation in other areas	13
1.6.1	Phytoremediation in mine spoil	13
1.6.2	Phytoremediation of radionuclides	13
1.6.3	Phytoremediation of E-wastes	13
1.6.4	Phytoremediation of oil contamination in coastal ecosystem	14
<b>1.7</b>	Conclusion	14
	Acknowledgments	15
	References	15



<b>CHAPTER 2</b>	<b>Phytoremediation: The ultimate technique for reinstating soil contaminated with heavy metals and other pollutants</b>	<b>19</b>
	<i>A.F. Ogundola, E.A. Adebayo and S.O. Ajao</i>	
2.1	Introduction	19
2.2	Attributes of soil in relation to pollution/contamination	21
2.3	Sources of soil and water contamination and the consequences	22
2.4	Different types of pollutants and their fate in the soil environment	23
2.5	Different cleaning techniques and their shortcomings	24
2.5.1	Traditional methods	24
2.6	Components of phytoremediation	30
2.6.1	Phytoaccumulation/phytoextraction	30
2.6.2	Phytostabilization	33
2.6.3	Phytovolatilization	34
2.6.4	Phytodegradation	35
2.7	Hydraulic control	36
2.8	Hyperaccumulating plants for different environments	37
2.9	Enhancement of phytoremediation process	37
2.9.1	Genetically engineered plants	38
2.9.2	Phytoremediation enhanced techniques (plant–microbe combination systems)	38
2.9.3	Energy crops	38
2.9.4	Post–treatment of phytoremediation biomass	39
2.9.5	The outstanding reports on phytoremediation technique	39
2.10	Conclusion	39
	References	40
<b>CHAPTER 3</b>	<b>Phytoremediation: A sustainable green approach for environmental cleanup</b>	<b>49</b>
	<i>Rafael de Souza Miranda, Cácio Luiz Boechat, Marcela Rebouças Bomfim, Jorge Antonio Gonzaga Santos, Daniel Gomes Coelho, Sara Julliane Ribeiro Assunção, Kaíque Mesquita Cardoso and Emanuelle Burgos Cardoso</i>	
3.1	Introduction	49
3.2	Phytoremediation as a cleanup technology	50
3.2.1	Definition	50
3.2.2	Mechanisms of plant phytoremediation	51
3.3	The potential of phytoremediation	52
3.3.1	Related to plants	52

3.3.2	Interface of the soil-tolerant plant	56
<b>3.4</b>	Case of study	61
3.4.1	Selection of tolerant plants for remediation of mining waste contaminated with multimetals	61
<b>3.5</b>	Final considerations	69
	References	69
<b>CHAPTER 4</b>	<b>Recent developments in aquatic macrophytes for environmental pollution control: A case study on heavy metal removal from lake water and agricultural return wastewater with the use of duckweed (<i>Lemnaceae</i>)</b>	<b>75</b>
	<i>Günay Yıldız Töre and Özge Bahar Özkoç</i>	
<b>4.1</b>	Introduction	75
<b>4.2</b>	Phytoremediation technology: an overview	77
4.2.1	Phytoextraction	78
4.2.2	Phytostabilization	79
4.2.3	Phytovolatilization	80
4.2.4	Phytodegradation/phytotransformation	81
4.2.5	Rhizodegradation/phytostimulation	82
4.2.6	Phytofiltration/rhizofiltration	83
<b>4.3</b>	Phytoremediation of heavy metals	83
4.3.1	Zinc	83
4.3.2	Copper	84
4.3.3	Nicel	84
4.3.4	Cadmium	85
4.3.5	Lead	86
4.3.6	Chromium	87
<b>4.4</b>	Aquatic macrophytes for environmental pollution control	87
4.4.1	Benefits of macrophytes as bioindicators in water pollution	87
4.4.2	Benefits of macrophytes as bioindicators in water pollution	89
4.4.3	Macrophytes types for removing heavy metals	91
4.4.4	Biosorption and bioaccumulation mechanisms of heavy metals	98
4.4.5	Factors affecting for heavy metal removal in Phytoremidation	100
4.4.6	Waste management and disposal in phytoremidation	102
<b>4.5</b>	Case study	106

4.5.1	Investigated area	106
4.5.2	Materials & methods	106
4.5.3	Results and discussion	107
<b>4.6</b>	<b>Conclusions</b>	<b>112</b>
	Acknowledgment	113
	References	113
<b>CHAPTER 5</b>	<b>Weed plants: A boon for remediation of heavy metal contaminated soil</b>	<b>127</b>
	<i>Chinmayee M. Devi and T.S. Swapna</i>	
<b>5.1</b>	Introduction	127
<b>5.2</b>	Heavy metals	128
<b>5.3</b>	Categories of plants growing on metal contaminated soils	128
5.3.1	Metal excluders	129
5.3.2	Metal accumulators or hyperaccumulators	129
5.3.3	Metal indicators	129
<b>5.4</b>	Technologies for the reclamation of polluted soils	129
<b>5.5</b>	Mechanism of phytoremediation	130
<b>5.6</b>	Weeds	130
5.6.1	Types of weeds	131
<b>5.7</b>	Weed plants as phytoremediator	132
<b>5.8</b>	Future of phytoremediation using weed plants	137
<b>5.9</b>	Conclusion	137
	References	138
<b>CHAPTER 6</b>	<b>Oxidoreductase metalloenzymes as green catalyst for phytoremediation of environmental pollutants</b>	<b>141</b>
	<i>Anindita Hazarika, Shilpa Sakia, Bidyalaxmi Devi, Meera Yadav and Hardeo Singh Yadav</i>	
<b>6.1</b>	Introduction	141
<b>6.2</b>	Phytoremediation	142
<b>6.3</b>	Degradation of organic pollutants by phytoremediation	145
<b>6.4</b>	Oxidoreductase enzymes in phytoremediation of organic pollutants	145
6.4.1	Laccases	145
6.4.2	Oxygenases	145
6.4.3	Peroxidases	146
6.4.4	Nitroreductase	147
<b>6.5</b>	Transgenic plants used in phytoremediation of organic pollutants	148

6.6	Phytoremediation of dyes and effluents mediated	149
6.7	Heavy metal detoxification by phytoremediation	154
6.8	Role of phytochelatin and metallothioneine in plant metallic stress	156
6.9	Role of antioxidant enzymes against plant metallic stress	157
6.10	Transgenic plants in the phytoremediation of heavy metals	160
6.11	Conclusion	162
	Acknowledgment	162
	References	162
<b>CHAPTER 7</b>	<b>Phytoextraction of heavy metals: Challenges and opportunities</b>	<b>173</b>
	<i>Jitendra Prasad, Shikha Tiwari, Bijendra Kumar Singh and Nawal Kishore Dubey</i>	
7.1	Introduction	173
7.2	Phytoremediation: a sustainable green approach for environmental issues	174
7.2.1	Phytoextraction	177
7.2.2	Phytodegradation	177
7.2.3	Phytodesalination	177
7.2.4	Phytostabilization	177
7.2.5	Phytovolatilization	178
7.2.6	Phytofiltration	178
7.3	Phytoextraction: promising strategy to remediate heavy metal pollution	178
7.3.1	Metal hyperaccumulating plants: key assets of phytoextraction	180
7.3.2	Factors affecting phytoextraction	181
7.4	Challenges associated with phytoextraction process	182
7.5	Advancements in phytoextraction technique	182
7.6	Conclusion	183
	Reference	184
<b>CHAPTER 8</b>	<b>Potential and prospects of weed plants in phytoremediation and eco-restoration of heavy metals polluted sites</b>	<b>187</b>
	<i>Vivek Rana, Sneha Bandyopadhyay and Subodh Kumar Maiti</i>	
8.1	Introduction	187
8.2	Phytoremediation: a green technology	189
8.2.1	Phytoremediation strategies	190

8.2.2	Potential of weed plants for phytoremediation	194
<b>8.3</b>	<b>Eco-restoration of metal-polluted sites</b>	<b>194</b>
8.3.1	Wetlands	194
8.3.2	Mine soils	194
8.3.3	Fly ash deposits	197
8.3.4	Tannery sludge	200
<b>8.4</b>	<b>Conclusion</b>	<b>200</b>
	References	200
<b>CHAPTER 9</b>	<b>Biochemical and molecular aspects of heavy metal stress tolerance in plants</b>	<b>205</b>
	<i>Bhupendra Koul, Simranjeet Singh, Siraj Yousuf Parray, Daljeet Singh Dhanjal, Praveen C. Ramamurthy and Joginder Singh</i>	
<b>9.1</b>	<b>Introduction</b>	<b>205</b>
<b>9.2</b>	<b>Mechanism of heavy metal tolerance</b>	<b>206</b>
9.2.1	Amino acids	206
9.2.2	Phytochelatins	206
9.2.3	Metallothioneins	207
<b>9.3</b>	<b>Role of metallothioneins in heavy metal tolerance</b>	<b>209</b>
<b>9.4</b>	<b>Heavy metal tolerance</b>	<b>210</b>
<b>9.5</b>	<b>Toxicity and heavy metal resistance in plants</b>	<b>213</b>
<b>9.6</b>	<b>Heavy metal deposition molecular pathway in plants</b>	<b>213</b>
<b>9.7</b>	<b>Conclusion and future scope</b>	<b>214</b>
	Acknowledgment	215
	References	215
<b>CHAPTER 10</b>	<b>Monitoring the process of phytoremediation of heavy metals using spectral reflectance and remote sensing</b>	<b>219</b>
	<i>Balaji Bhaskar Maruthi Sridhar, Fengxiang X. Han and Yi Su</i>	
<b>10.1</b>	<b>Introduction</b>	<b>219</b>
<b>10.2</b>	<b>Arsenic and chromium contamination</b>	<b>221</b>
<b>10.3</b>	<b>Spectral reflectance and remote sensing</b>	<b>223</b>
<b>10.4</b>	<b>Uptake and accumulation of As and Cr in fern</b>	<b>223</b>
<b>10.5</b>	<b>Uptake and accumulation of Cr in mustard</b>	<b>225</b>
<b>10.6</b>	<b>Internal structural changes of fern</b>	<b>227</b>
<b>10.7</b>	<b>Heavy metal-induced structural changes in mustard</b>	<b>233</b>
<b>10.8</b>	<b>Plant spectral reflectance</b>	<b>235</b>
<b>10.9</b>	<b>Spectral reflectance of brake fern</b>	<b>237</b>

10.10 Conclusion	239
Acknowledgment	240
References	240
<b>CHAPTER 11 Phytostabilization of metal mine tailings— a green remediation technology</b>	<b>243</b>
<i>Lavanya Muthusamy, Manikandan Rajendran, Kavitha Ramamoorthy, Mathiyazhagan Narayanan and Sabariswaran Kandasamy</i>	
11.1 Introduction	243
11.2 Impact of mine tailing on environmental	244
11.3 Phytostabilization of mine tailings	246
11.4 Phytomining of mine tailing	247
11.5 Conclusions	249
References	249
<b>CHAPTER 12 Phytoremediation of heavy metals, metalloids, and radionuclides: Prospects and challenges</b>	<b>253</b>
<i>Simranjeet Singh, Vijay Kumar, Daljeet Singh Dhanjal, Parul Parihar, Praveen C. Ramamurthy and Joginder Singh</i>	
12.1 Introduction	253
12.2 Special characteristics of phytoremediating plants	254
12.3 Various mechanisms for removal of heavy metal metalloids and radionuclides	255
12.3.1 Phytodegradation	255
12.3.2 Phytoextraction	259
12.3.3 Phytofiltration	260
12.3.4 Phytostabilization	261
12.3.5 Phytovolatilization	261
12.4 Methods for enhancing phytoremediation capabilities	262
12.5 Genetic engineering	262
12.6 Utilization of microbes for improving performance of plant	264
12.7 Challenges associated with phytoremediation strategies	265
12.8 Conclusion and future prospects	265
Acknowledgment	266
References	266
<b>CHAPTER 13 Phytoremediation of metals: Lithium</b>	<b>277</b>
<i>Sevinc Adiloglu, Deniz Izlen Cifci and Süreyya Meric</i>	
13.1 Introduction	277

<b>13.2</b>	<b>Materials and methods</b>	<b>279</b>
13.2.1	The characteristics of the plant used in plant toxicity experiments	279
13.2.2	Experimental design	281
13.2.3	Plant analyses	281
13.2.4	Soil analyses	281
13.2.5	Statistics	282
<b>13.3</b>	<b>Results and discussion</b>	<b>282</b>
13.3.1	Some chemical characteristics of the experimental soil	282
13.3.2	Chemicals in soil and plant	283
<b>13.4</b>	<b>Conclusion</b>	<b>287</b>
	Acknowledgment	287
	References	287
<b>CHAPTER 14</b>	<b>Aquatic macrophytes for environmental pollution control</b>	<b>291</b>
	<i>Santosh Kumar, Nagendra Thakur, Ashish K. Singh, Bharat Arjun Gudade, Deepak Ghimire and Saurav Das</i>	
<b>14.1</b>	<b>Introduction</b>	<b>291</b>
<b>14.2</b>	<b>Macrophyte</b>	<b>292</b>
<b>14.3</b>	<b>Free-floating macrophytes</b>	<b>295</b>
<b>14.4</b>	<b>Submerged macrophytes</b>	<b>296</b>
<b>14.5</b>	<b>Emergent macrophyte</b>	<b>296</b>
<b>14.6</b>	<b>Sources of aquatic pollutants and their effects</b>	<b>296</b>
14.6.1	Domestic sewage	296
14.6.2	Industrial waste	297
14.6.3	Mining industry	297
<b>14.7</b>	<b>Pesticides and fertilizers</b>	<b>297</b>
<b>14.8</b>	<b>Heavy metal pollution</b>	<b>298</b>
<b>14.9</b>	<b>Phytoremediation: a green and an eco-friendly technology</b>	<b>298</b>
<b>14.10</b>	<b>Phytofiltration (Rhizofiltration)</b>	<b>299</b>
<b>14.11</b>	<b>Potential role of macrophytes for environmental pollution control</b>	<b>300</b>
14.11.1	<i>Azolla</i>	301
14.11.2	<i>Eichhornia</i>	301
14.11.3	<i>Lemna minor</i>	302
14.11.4	<i>Potamogeton</i>	302
14.11.5	<i>Wolfia</i> and <i>Wolfiella</i>	303
<b>14.12</b>	<b>Conclusion</b>	<b>304</b>
	References	304

**CHAPTER 15 Role of rhizobacteria from plant growth promoter to bioremediator 309**

*Shailja Sharma, Simranjeet Singh, Daljeet Singh Dhanjal, Akshay Kumar, Sadaf Jan, Praveen C. Ramamurthy and Joginder Singh*

<b>15.1</b>	Introduction	309
<b>15.2</b>	Characteristics of plant growth-promoting rhizobacteria	310
<b>15.3</b>	Influence of different bacterial species on rhizobacteria plant growth-promoting rhizobacteria activity	311
	15.3.1 <i>Pseudomonas</i> species	311
	15.3.2 <i>Bacillus</i> species	312
	15.3.3 <i>Rhizobium</i> species	312
<b>15.4</b>	Mechanism of plant growth-promoting rhizobacteria	312
	15.4.1 Direct mechanism	313
	15.4.2 Indirect mechanism	315
<b>15.5</b>	Plant growth-promoting rhizobacteria as bioremediators	316
<b>15.6</b>	Potential role of plant growth-promoting rhizobacteria in stress management	316
<b>15.7</b>	Conclusions	319
	Acknowledgment	319
	References	319

**CHAPTER 16 Role of nanomaterials in phytoremediation of tainted soil 329**

*Sonali Mohanty, Srishti Chakraborty, Moumita Das and Subhankar Paul*

<b>16.1</b>	Introduction	329
<b>16.2</b>	Nanotechnology in soil remediation	330
	16.2.1 Removal of heavy metals	330
	16.2.2 Removal of pesticides	334
	16.2.3 Removal of organic materials	336
<b>16.3</b>	Phytoremediation and contaminant removal	337
	16.3.1 Phytoextraction	338
	16.3.2 Phytodegradation	339
	16.3.3 Phytovolatilization	339
	16.3.4 Phytostabilization	339
	16.3.5 Rhizodegradation	340
<b>16.4</b>	Nanomaterial facilitated phytoremediation and contaminant removal	341
	16.4.1 Potential nanomaterials in phytoremediation of soil	342



16.5	Conclusion and future prospects	348
	References	349
<b>CHAPTER 17</b>	<b>Green technology: Phytoremediation for pesticide pollution</b>	<b>353</b>
	<i>Simran Takkar, Chitrakshi Shandilya, Rishabh Agrahari, Archi Chaurasia, Kanchan Vishwakarma, Swati Mohapatra, Ajit Varma and Arti Mishra</i>	
17.1	Introduction	353
17.2	Classification of pesticides	354
17.2.1	Classification of pesticides based on toxicity	354
17.2.2	Classification on the basis of entry	355
17.2.3	Classification on the basis of chemical composition and structure	355
17.2.4	Classification on the basis of the target pests they kill	358
17.3	Hazardous impact of obsolete pesticides	358
17.3.1	Impact of pesticides on environment	360
17.3.2	Impact of the use of pesticides on human health	362
17.4	Salient features of green technology	363
17.4.1	Ozone	363
17.4.2	Bioaugmentation	364
17.4.3	Phytoremediation	365
17.5	Process of phytoremediation in pesticide removal	365
17.6	Antioxidant defense: a key mechanism of pesticide tolerance and phytoremediation	367
17.7	Roles of transgenic plants in pesticide detoxification	368
17.7.1	Advantages of transgenic plants	369
17.7.2	Pesticide degrading enzymes in transgenic plants	370
17.7.3	Production of antibodies by transgenic plants for pesticide detoxification	371
17.8	Conclusion	371
	References	372
<b>CHAPTER 18</b>	<b>Phytoremediation of persistent organic pollutants: Concept challenges and perspectives</b>	<b>375</b>
	<i>Prathmesh Anerao, Roshan Kaware, Akshay Kumar Khedikar, Manish Kumar and Lal Singh</i>	
18.1	Introduction	375
18.2	History, sources, and classification of persistent organic pollutants	377
18.2.1	History of persistent organic pollutants	377

18.2.2	Sources of persistent organic pollutants	378
18.2.3	Classification of persistent organic pollutants	378
<b>18.3</b>	<b>Phytoremediation</b>	<b>381</b>
18.3.1	Mechanism of phytoremediation	381
18.3.2	Endophytic associated phytoremediation	390
<b>18.4</b>	<b>Polycyclic aromatic hydrocarbons phytoremediation</b>	<b>393</b>
<b>18.5</b>	<b>Conclusion and prospective</b>	<b>397</b>
	Acknowledgment	397
	References	398
<b>CHAPTER 19 Gene mediated phytodetoxification of environmental pollutants</b>		<b>405</b>
<i>Sakshi Agrawal, Vineet Kumar, Simranjeet Singh and Sushil Kumar Shahi</i>		
<b>19.1</b>	<b>Introduction</b>	<b>405</b>
<b>19.2</b>	<b>Heavy metals as major soil contaminants</b>	<b>407</b>
19.2.1	Heavy metals	407
19.2.2	Heavy metals' sources into the environment	407
19.2.3	Impact of heavy metals in environment	408
<b>19.3</b>	<b>Plant strategies in phytoremediation of heavy metals</b>	<b>409</b>
19.3.1	Phytoextraction	409
19.3.2	Phytovolatilization	410
19.3.3	Phytostabilization	410
19.3.4	Phytofiltration	410
19.3.5	Phytostimulation	410
<b>19.4</b>	<b>Hyperaccumulator plants with their characteristics and mechanism of action</b>	<b>411</b>
19.4.1	Heavy metal ion transporter	411
19.4.2	Indigenous plant in phytoremediation of metal	412
19.4.3	Weed plants as natural hyperaccumulators	412
19.4.4	Genetically engineered plants as hyperaccumulators in phytoremediation of heavy metals	413
19.4.5	How do plants hyperaccumulate heavy metals?	414
<b>19.5</b>	<b>Mechanisms of heavy metal accumulation, tolerance, and detoxification in plants</b>	<b>414</b>
19.5.1	Avoidance in plants	419
19.5.2	Tolerance in plants	419
19.5.3	Cellular and molecular pathways in phytoremediation	419
<b>19.6</b>	<b>Phytoremediation with transgenics</b>	<b>423</b>

19.6.1	Phytoremediation of organic pollutants with transgenic plants	423
19.6.2	Metal phytoremediation using transgenic plants	424
<b>19.7</b>	<b>Increasing bioavailability of heavy metals</b>	<b>426</b>
<b>19.8</b>	<b>Conclusion</b>	<b>427</b>
19.8.1	Concerns and future outlook	427
	Acknowledgment	428
	References	428
<b>CHAPTER 20</b>	<b>Nano-phytoremediation technology in environmental remediation</b>	<b>433</b>
	<i>Kiran Mustafa, Iqra Shakeel, Javaria Kanwal, Sarah Farrukh, Sara Mussaddiq, Nadia Saddiq and Muhammad Younas</i>	
<b>20.1</b>	<b>Introduction</b>	<b>433</b>
<b>20.2</b>	<b>Nano-phytoremediation technology for pesticides hazards</b>	<b>434</b>
<b>20.3</b>	<b>Nano-phytoremediation of contaminated soil</b>	<b>437</b>
20.3.1	Different soil pollutants and their nano-phytoremediation	438
20.3.2	Synthesized nanoparticles for decontamination of pollutants in soil	440
<b>20.4</b>	<b>Nano-phytoremediation for heavy metal contamination</b>	<b>442</b>
20.4.1	Heavy metal accumulator plants	443
20.4.2	Nanoparticles used for removal of heavy metals	446
<b>20.5</b>	<b>Nano-phytoremediation for water contamination</b>	<b>448</b>
20.5.1	Nanoparticles used for decontamination of water	449
<b>20.6</b>	<b>Nano-phytoremediation bioenergy crops</b>	<b>450</b>
<b>20.7</b>	<b>Conclusion and future prospective</b>	<b>451</b>
	References	451
<b>CHAPTER 21</b>	<b>Nanophytoremediation technology: A better approach for environmental remediation of toxic metals and dyes from water</b>	<b>459</b>
	<i>Sohel Das, Uma Sankar Mondal and Subhankar Paul</i>	
<b>21.1</b>	<b>Introduction</b>	<b>459</b>
<b>21.2</b>	<b>Sources of contamination in water</b>	<b>460</b>
<b>21.3</b>	<b>Conventional treatment for removal of metals and dyes from waste water</b>	<b>460</b>
<b>21.4</b>	<b>Nanophytoremediation and its advantages</b>	<b>461</b>
21.4.1	Biosynthesis of nanoparticles	462
21.4.2	Nanoparticles synthesized from plants	463

21.4.3	Nanoparticles synthesized from microorganism	468
<b>21.5</b>	<b>Different strategies for detection and removal of metals and dyes from water</b>	<b>469</b>
21.5.1	Adsorption based metal and dye removal	471
21.5.2	Fluorescence-based metal detection and removal	471
21.5.3	Photocatalysis-based dye removal techniques	473
<b>21.6</b>	<b>Toxicity and environmental impact of nanophytoremediation</b>	<b>475</b>
<b>21.7</b>	<b>Limitations and future prospects</b>	<b>476</b>
<b>21.8</b>	<b>Conclusion</b>	<b>477</b>
	References	477
<b>CHAPTER 22</b>	<b>Constructed wetlands plant treatment system: An eco-sustainable phytotechnology for treatment and recycling of hazardous wastewater</b>	<b>481</b>
	<i>María Alejandra Maine, Hernán Ricardo Hadad, Gabriela Cristina Sanchez, María de las Mercedes Mufarrege, Gisela Alfonsina Di Luca, María Celeste Schierano, Emanuel Nocetti, Sandra Ester Caffaratti and María del Carmen Pedro</i>	
<b>22.1</b>	<b>Introduction</b>	<b>481</b>
<b>22.2</b>	<b>Wastewater from metallurgical industries</b>	<b>482</b>
<b>22.3</b>	<b>Sanitary effluents of a pet-care center</b>	<b>485</b>
<b>22.4</b>	<b>Fertilizer factory wastewater</b>	<b>486</b>
<b>22.5</b>	<b>Landfill leachate</b>	<b>489</b>
<b>22.6</b>	<b>Recycled paper industry</b>	<b>490</b>
<b>22.7</b>	<b>Conclusions</b>	<b>492</b>
	Acknowledgments	493
	References	493
<b>CHAPTER 23</b>	<b>Ecological aspects of aquatic macrophytes for environmental pollution control: An eco-remedial approach</b>	<b>497</b>
	<i>Jaqueline S. Santos, Montcharles S. Pontes, Gilberto J. Arruda, Anderson R.L. Caires, Sandro M. Lima, Luis H.C. Andrade, Marcelo L. Bueno, Valéria F.B. da Silva, Renato Grillo and Etenaldo F. Santiago</i>	
<b>23.1</b>	<b>Introduction</b>	<b>497</b>
<b>23.2</b>	<b>Macrophytes: From adverse effects to environmental solution</b>	<b>498</b>

<b>23.3</b>	Macrophytes and the contaminated environment: Discriminating between bioindication and phytoremediation	500
<b>23.4</b>	Phytoremediation mechanisms related to macrophytes	501
<b>23.5</b>	Nanoparticles: A potential contaminant and the role of macrophytes in its phytoremediation	504
<b>23.6</b>	Spectroscopic methods in monitoring and evaluation: investigation to understand the interaction between macrophytes and the environment	506
<b>23.7</b>	Macrophytes as a biological model: Chlorophyll-a fluorescence technique for detecting stress due to environmental contamination	508
<b>23.8</b>	Electrochemical sensors applied to the study of aquatic phytoremediation by macrophytes	515
<b>23.9</b>	Conclusions	517
	References	517
<b>CHAPTER 24</b>	<b>Phytoremediation of trace elements from paper mill wastewater with <i>Pistia stratiotes</i> L.: Metal accumulation and antioxidant response</b>	<b>523</b>
	<i>Kisholay Mazumdar and Suchismita Das</i>	
<b>24.1</b>	Introduction	523
<b>24.2</b>	Materials and methods	524
	24.2.1 Paper mill effluent (PME) collection and analysis of trace elements	524
	24.2.2 Plant sample collection	524
	24.2.3 Experimental set up	525
	24.2.4 Harvesting and plant growth estimation	525
	24.2.5 Determination of membrane injury index (MI)	525
	24.2.6 Estimation of total chlorophyll and carotenoid	525
	24.2.7 Lipid peroxidation, soluble protein, and free amino acid contents	525
	24.2.8 Determination of hydrogen peroxide (H <sub>2</sub> O <sub>2</sub> ) and superoxide radical (O <sub>2</sub> <sup>-</sup> )	526
	24.2.9 Measurement of antioxidant enzyme activity	526
	24.2.10 Determination of heavy metal in plant, wastewater	526
	24.2.11 Calculation of phytoremediation potential of plants	526
	24.2.12 Statistical analysis	526
<b>24.3</b>	Results	527
	24.3.1 Effect of paper mill wastewater on plant growth parameters and plant pigments	527

24.3.2	Effect of paper mill wastewater on oxidative stress levels	527
24.3.3	Effect of PME on antioxidant activity	528
24.3.4	Metal content in plant tissue	528
24.3.5	Translocation factor (TF), and enrichment coefficient (EC) of trace elements	529
24.3.6	<i>Pistia stratiotes</i> improved the wastewater quality in terms of trace elements	529
<b>24.4</b>	Discussion	530
	References	533
<b>CHAPTER 25</b>	<b>Electrokinetic-assisted phytoremediation of heavy metal contaminated soil: Present status, challenges, and opportunities</b>	<b>537</b>
	<i>Claudio Cameselle, Susana Gouveia, Adrián Cabo and Krishna R. Reddy</i>	
<b>25.1</b>	Remediation of contaminated soil	537
<b>25.2</b>	Phytoremediation	538
<b>25.3</b>	Electrokinetic remediation	540
<b>25.4</b>	Coupled technology electrokinetics phytoremediation	541
25.4.1	Electrophytoremediation at lab scale	542
25.4.2	Effect of the DC electric field	544
25.4.3	Enhancement with chelating agents	545
25.4.4	Application of AC/DC electric field	546
<b>25.5</b>	Influence of electrode configuration	548
<b>25.6</b>	Impacts on soil properties and microbial community	550
<b>25.7</b>	Patents and applications	551
<b>25.8</b>	Conclusions	552
	References	553
<b>CHAPTER 26</b>	<b>Microbes-assisted phytoremediation of contaminated environment: Global status, progress, challenges, and future prospects</b>	<b>555</b>
	<i>Santosh Kumar, Nagendra Thakur, Ashish K. Singh, Bharat Arjun Gudade, Deepak Ghimire and Saurav Das</i>	
<b>26.1</b>	Introduction	555
<b>26.2</b>	Fundamentals concept of phytoremediation practices	557
<b>26.3</b>	Microorganisms-assisted phytoremediation: An optimistic tools for remediation of environmental pollutants	558
<b>26.4</b>	Plant growth-promoting rhizobacteria assisted phytoremediation	559

26.5	Endophyte-assisted phytoremediation of organic and inorganic pollutants	559
26.6	Genetically modified microbe-assisted phytoremediation	561
26.7	Microbe-assisted phytoremediation of heavy metal	562
26.8	Microbe-assisted phytoremediation of agricultural chemicals: Herbicides, pesticides, and fertilizers	563
26.9	Microbe-assisted phytoremediation of petroleum and aromatic compounds	564
26.10	Worldwide emerging issues and challenges	565
	References	566
<b>CHAPTER 27 Electricity production and the analysis of the anode microbial community in a constructed wetland-microbial fuel cell</b>		<b>571</b>
	<i>Sen Wang and Fanlong Kong</i>	
27.1	Introduction of constructed wetland microbial fuel cell	571
27.1.1	Construction of constructed wetland microbial fuel cell	571
27.1.2	The principle of CW-MFC	576
27.1.3	The application of CW-MFC in environmental remediation	578
27.2	Power generation performance & its influencing factors of CW-MFC	578
27.2.1	Influence of CW-MFC structure	578
27.2.2	Effect of electrode materials	580
27.2.3	Effect of electrode spacing	585
27.2.4	Impact of plants	587
27.2.5	Matrix effects	589
27.3	Analysis of microbial community structure in anode of CW-MFC	591
27.3.1	Influencing factors of anode microbial community	591
27.3.2	The development of detection technology for anode microorganism	592
27.4	Summary	596
	References	596
<b>CHAPTER 28 Phytocapping technology for sustainable management of contaminated sites: case studies, challenges, and future prospects</b>		<b>601</b>
	<i>Komal Prasad, Hemant Kumar, Lal Singh, Ankush D. Sawarkar, Manish Kumar and Sunil Kumar</i>	
28.1	Introduction	601

<b>28.2</b>	Phytocapping	603
<b>28.3</b>	Mechanism and strategy of phytocapping	606
<b>28.4</b>	Case studies	608
28.4.1	Case study 4.1	608
28.4.2	Case study 4.2	608
28.4.3	Case study 4.3	608
28.4.4	Case study 4.4	609
28.4.5	Case study 4.5	609
<b>28.5</b>	Opportunities, challenges, and future aspects	609
28.5.1	Opportunities	609
28.5.2	Challenges	610
28.5.3	Future prospects	611
<b>28.6</b>	Conclusion	611
	Acknowledgment	612
	References	612
Index	.....	617





# Contributors

## **E.A. Adebayo**

Microbiological Unit, Pure and Applied Biology Department, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria

## **Sevinc Adiloglu**

Tekirdag Namik Kemal University, Agricultural Faculty, Department of Soil Science and Plant Nutrition, Tekirdag, Turkey

## **Rishabh Agrahari**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

## **Sakshi Agrawal**

Department of Botany, School of Life Sciences, Guru Ghasidas Vishwavidyalaya (A Central University), Bilaspur, Chhattisgarh, India

## **S.O. Ajao**

Environmental Unit, Pure and Applied Biology Department, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria

## **Luis H.C. Andrade**

Universidade Estadual de Mato Grosso do Sul (UEMS), Centro de Estudos em Recursos Naturais, Grupo de Espectroscopia Óptica e Fototérmica, Dourados, MS, Brasil

## **Prathmesh Anerao**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur, Maharashtra, India

## **Gilberto J. Arruda**

Universidade Estadual de Mato Grosso do Sul (UEMS), Centro de Estudos em Recursos Naturais, Grupo de Estudos em Eletroquímica, Dourados, MS, Brasil

## **Sara Julliane Ribeiro Assunção**

Federal University of Sergipe, São Cristóvão, Brazil

## **Sneha Bandyopadhyay**

Restoration Ecology Laboratory, Department of Environmental Science and Engineering, Indian Institute of Technology (ISM), Dhanbad, India

## **Cácio Luiz Boechat**

Campus Professora Cinobelina Elvas, Federal University of Piauí, Bom Jesus, Brazil

## **Marcela Rebouças Bomfim**

Federal University of Recôncavo da Bahia, Cruz das Almas, Brazil

**Marcelo L. Bueno**

Universidade Estadual de Mato Grosso do Sul (UEMS), Mundo Novo, MS, Brasil

**Adrián Cabo**

PhD Student, BiotecnIA, Department of Chemical Engineering, University of Vigo, Vigo, Spain

**Anderson R.L. Caires**

Universidade Federal de Mato Grosso do Sul (UFMS), Instituto de Física, Grupo de Ótica e Fotônica, Campo Grande, MS, Brasil

**Claudio Gemeselle**

Associate Professor, BiotecnIA, Department of Chemical Engineering, University of Vigo, Vigo, Spain

**Emanuelle Burgos Cardoso**

Federal University of Viçosa, Viçosa, Brazil

**Kaíque Mesquita Cardoso**

Federal Institute of Education, Science and Technology of Norte de Minas Gerais, Araçuaí, Brazil

**María Celeste Schierano**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral (UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**Srishti Chakraborty**

Department of Biotechnology & Medical Engineering, National Institute of Technology Rourkela, Orissa, India

**Archi Chaurasia**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

**Gabriela Cristina Sanchez**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral (UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**Daniel Gomes Coelho**

Federal University of Viçosa, Viçosa, Brazil

**Valéria F.B. da Silva**

Universidade Estadual de Mato Grosso do Sul (UEMS), Mundo Novo, MS, Brasil

**Moumita Das**

Department of Biotechnology & Medical Engineering, National Institute of Technology Rourkela, Orissa, India

**Saurav Das**

Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE, United States

**Sohel Das**

Structural Biology and Nanomedicine Lab, Department of Biotechnology & Medical Engineering, National Institute of Technology, Rourkela, Orissa, India

**Suchismita Das**

Aquatic Toxicology and Remediation Laboratory, Department of Life Science and Bioinformatics, Assam University, Silchar, Assam, India

**Bidyalaxmi Devi**

Department of Civil Engineering, North Eastern Regional Institute of Science and Technology, Itanagar, Arunachal Pradesh, India

**Chinmayee M. Devi**

Department of Botany, Sree Ayyappa College for Women, Nagargoil, Tamil Nadu, India

**Daljeet Singh Dhanjal**

Department of Biotechnology, Lovely Professional University, Phagwara, Punjab, India

**Gisela Alfonsina Di Luca**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral (UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**Nawal Kishore Dubey**

Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

**Sandra Ester Caffaratti**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral (UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**Sarah Farrukh**

SCME National University of Sciences and Technology (NUST), Islamabad, Pakistan

**Deepak Ghimire**

Department of Agronomy and Horticulture, University of Nebraska-Lincoln, Lincoln, NE, United States

**Dipita Ghosh**

Department of Environmental Science and Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand, India

**Susana Gouveia**

Postdoctoral Researcher, BiotecnIA, Department of Chemical Engineering,  
University of Vigo, Vigo

**Renato Grillo**

Universidade Estadual Paulista (UNESP), Departamento de Física e Química,  
Faculdade de Engenharia, Ilha Solteira, Brasil

**Bharat Arjun Gudade**

Spice Park, Spices Board, Chhindwara, Madhya Pradesh, India

**Hernán Ricardo Hadad**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del  
Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral  
(UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET),  
Santiago del Estero, Santa Fe, Argentina

**Fengxiang X. Han**

Department of Chemistry and Biochemistry, Jackson State University, Jackson,  
MS, United States

**Anindita Hazarika**

Department of Chemistry, North Eastern Regional Institute of Science and  
Technology, Itanagar, Arunachal Pradesh, India

**Deniz Izlen Cifci**

Tekirdag Namik Kemal University, Corlu Engineering Faculty, Environmental  
Engineering, Corlu, Turkey

**Sadaf Jan**

Department of Biotechnology, Lovely Professional University, Phagwara, Punjab,  
India

**Javaria Kanwal**

Department of Chemistry, The Women University Multan, Pakistan

**Kavitha Ramamoorthy**

Department of Biotechnology, Periyar University PG Extension Centre,  
Dharmapuri, Tamil Nadu, India

**Roshan Kaware**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI),  
Nagpur, Maharashtra, India

**Akshay Kumar Khedikar**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI),  
Nagpur, Maharashtra, India

**Komal Prasad**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI),  
Nagpur, Maharashtra, India

**Fanlong Kong**

College of Environmental Science and Engineering, Qingdao University,  
Qingdao, China

**Bhupendra Koul**

School of Bioengineering and Biosciences, Lovely Professional University,  
Phagwara, Punjab, India

**Akshay Kumar**

Department of Biochemistry, DAV University, Jalandhar Punjab, India

**Hemant Kumar**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI),  
Nagpur, Maharashtra, India

**Manish Kumar**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI),  
Nagpur, Maharashtra, India

**Santosh Kumar**

Department of Microbiology, School of Life Sciences, Sikkim University,  
Gangtok, Sikkim, India

**Sunil Kumar**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI),  
Nagpur, Maharashtra, India

**Vijay Kumar**

Department of Chemistry, Regional Ayurveda Research Institute for Drug  
Development, Madhya Pradesh, India

**Vineet Kumar**

Waste Re-processing Division, CSIR-National Environmental Engineering  
Research Institute (CSIR-NEERI), Nagpur-440020, Maharashtra, India

**Lavanya Muthusamy**

Department of Biotechnology, Periyar University PG Extension Centre,  
Dharmapuri, Tamil Nadu, India

**Sandro M. Lima**

Universidade Estadual de Mato Grosso do Sul (UEMS), Centro de Estudos em  
Recursos Naturais, Grupo de Espectroscopia Óptica e Fototérmica, Dourados,  
MS, Brasil

**Arjun Mahato**

Department of Environmental Science and Engineering, Indian Institute of  
Technology (Indian School of Mines), Dhanbad, Jharkhand, India

**María Alejandra Mainé**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del  
Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral

(UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**Subodh Kumar Maiti**

Department of Environmental Science and Engineering, Indian Institute of Technology (Indian School of Mines), Dhanbad, Jharkhand, India

**Manikandan Rajendran**

Department of Biotechnology, Padmavani Arts and Science College for Women, Salem, Tamil Nadu, India

**Mathiyazhagan Narayanan**

PG and Research Centre in Biotechnology, MGR College, Adhiyamaan Educational Research Institute, Hosur, Tamil Nadu, India

**Kisholay Mazumdar**

Aquatic Toxicology and Remediation Laboratory, Department of Life Science and Bioinformatics, Assam University, Silchar, Assam, India

**Süreyya Meric**

Tekirdag Namik Kemal University, Corlu Engineering Faculty, Environmental Engineering, Corlu, Turkey

**Rafael de Souza Miranda**

Campus Professora Cinobelina Elvas, Federal University of Piauí, Bom Jesus, Brazil

**Arti Mishra**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

**Sonali Mohanty**

Department of Biotechnology & Medical Engineering, National Institute of Technology Rourkela, Orissa, India

**Swati Mohapatra**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

**Uma Sankar Mondal**

Structural Biology and Nanomedicine Lab, Department of Biotechnology & Medical Engineering, National Institute of Technology, Rourkela, Orissa, India

**María de las Mercedes Mufarrege**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral (UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**Sara Mussaddiq**

Department of Chemistry, The Women University Multan, Pakistan

**Kiran Mustafa**

Department of Chemistry, The Women University Multan, Pakistan; Higher Education Department, Punjab, Pakistan

**Emanuel Nocetti**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral (UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**A.F. Ogundola**

Environmental Unit, Pure and Applied Biology Department, Ladoke Akintola University of Technology, Ogbomoso, Oyo State, Nigeria

**Özge Bahar Özkoç**

Department of Environmental Engineering, Tekirdağ Namık Kemal University, Tekirdağ, Turkey

**Parul Parihar**

Department of Botany, Lovely Professional University, Phagwara, Punjab, India

**Siraj Yousuf Parray**

Department of Botany, Government Degree College, Bijbehara, Jammu and Kashmir, India

**Subhankar Paul**

Structural Biology and Nanomedicine Lab, Department of Biotechnology & Medical Engineering, National Institute of Technology, Rourkela, Orissa, India

**María del Carmen Pedro**

Laboratorio de Química Analítica Ambiental, Instituto de Química Aplicada del Litoral (IQAL), Facultad de Ingeniería Química, Universidad Nacional del Litoral (UNL), Consejo Nacional de Investigaciones Científicas y Técnicas (CONICET), Santiago del Estero, Santa Fe, Argentina

**Montcharles S. Pontes**

Universidade Estadual de Mato Grosso do Sul (UEMS), Centro de Estudos em Recursos Naturais, Grupo de Estudos dos Recursos Vegetais, Dourados, MS, Brasil

**Jitendra Prasad**

Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

**Praveen C. Ramamurthy**

Interdisciplinary Centre for Water Research (ICWaR), Indian Institute of Science, Bangalore, India

**Vivek Rana**

Central Pollution Control Board, Ministry of Environment, Forest, and Climate Change, Delhi, India



**Krishna R. Reddy**

Professor, University of Illinois at Chicago, Department of Civil and Materials Engineering, Chicago, IL, United States

**Sabariswaran Kandasamy**

Institute for Energy Research, Jiangsu University, Zhenjiang, Jiangsu Province, P.R. China

**Nadia Saddiq**

Department of Chemistry, The Women University Multan, Pakistan

**Shilpa Sakia**

Department of Chemistry, North Eastern Regional Institute of Science and Technology, Itanagar, Arunachal Pradesh, India

**Etenaldo F. Santiago**

Universidade Estadual de Mato Grosso do Sul (UEMS), Centro de Estudos em Recursos Naturais, Grupo de Estudos dos Recursos Vegetais, Dourados, MS, Brasil

**Jaqueline S. Santos**

Universidade Estadual de Mato Grosso do Sul (UEMS), Centro de Estudos em Recursos Naturais, Grupo de Estudos dos Recursos Vegetais, Dourados, MS, Brasil

**Jorge Antonio Gonzaga Santos**

Federal University of Recôncavo da Bahia, Cruz das Almas, Brazil

**Ankush D. Sawarkar**

Department of Computer Science and Engineering, Visveshvaraya National Institute of Technology (VNIT), Nagpur, Maharashtra, India

**Sushil Kumar Shahi**

Department of Botany, School of Life Sciences, Guru Ghasidas Vishwavidyalaya (A Central University), Bilaspur, Chhattisgarh, India

**Iqra Shakeel**

SCME National University of Sciences and Technology (NUST), Islamabad, Pakistan; IESE, SCEE National University of Sciences and Technology (NUST), Islamabad, Pakistan

**Chitrakshi Shandilya**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

**Shailja Sharma**

School of Applied Sciences and Biotechnology, Shoolini University of Biotechnology and Management Sciences, Solan, Himachal Pradesh, India

**Bijendra Kumar Singh**

Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

**Lal Singh**

CSIR—National Environmental Engineering Research Institute (CSIR-NEERI), Nagpur, Maharashtra, India

**Simranjeet Singh**

Interdisciplinary Centre for Water Research (ICWaR), Indian Institute of Sciences, Bangalore, India

**Joginder Singh**

School of Bioengineering and Biosciences, Lovely Professional University, Phagwara, Punjab, India

**Ashish K. Singh**

Department of Microbiology, School of Life Sciences, Sikkim University, Gangtok, Sikkim, India

**Balaji Bhaskar Maruthi Sridhar**

Department of Earth and Environment, Florida International University, Miami, FL, United States

**Yi Su**

School of Science and Computer Engineering, University of Houston-Clear Lake, Houston, TX, United States

**T.S. Swapna**

Department of Botany, Sree Ayyappa College for Women, Nagarcoil, Tamil Nadu, India; Department of Botany, University of Kerala, Kerala, India

**Simran Takkar**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

**Nagendra Thakur**

Department of Microbiology, School of Life Sciences, Sikkim University, Gangtok, Sikkim, India

**Shikha Tiwari**

Centre of Advanced Study in Botany, Institute of Science, Banaras Hindu University, Varanasi, India

**Ajit Varma**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

**Kanchan Vishwakarma**

Amity Institute of Microbial Technology, Amity University, Noida, Uttar Pradesh, India

**Sen Wang**

College of Environmental Science and Engineering, Qingdao University,  
Qingdao, China

**Meera Yadav**

Department of Chemistry, North Eastern Regional Institute of Science and  
Technology, Itanagar, Arunachal Pradesh, India

**Hardeo Singh Yadav**

Department of Chemistry, North Eastern Regional Institute of Science and  
Technology, Itanagar, Arunachal Pradesh, India

**Günay Yıldız Töre**

Department of Environmental Engineering, Tekirdağ Namık Kemal University,  
Tekirdağ, Turkey

**Muhammad Younas**

Chemical Engineering Department, University of Engineering & Technology,  
Peshawar, KPK, Pakistan

## About the editors

**Vineet Kumar** is currently working as a Senior Project Associate in the Waste Re-processing Division at CSIR-National Environmental Engineering Research Institute (NEERI), Nagpur, Maharashtra, India. Before his joining, he worked as Assistant Professor (Ad-hoc) in the Department of Botany at Guru Ghasidas Vishwavidyalaya, Bilaspur, India. He was an Assistant Professor and Academic Coordinator at Vinayak Vidyapeeth, Meerut, Uttar Pradesh. Dr. Kumar received his M.Sc. and M.Phil. degrees in Microbiology from Ch. Charan Singh University, Meerut, India. He received the Ph.D. degree in Environmental Microbiology from Babasaheb Bhimaro Ambedkar (A Central) University, Lucknow, India, and later worked at the Dr. Shakuntala Misra National Rehabilitation University, Lucknow, India, as a Guest Faculty where he taught courses in General Microbiology, Microbial Genetics, Molecular Biology, and Environmental Microbiology to students of post-graduate-level. He was a Senior Researcher in the School of Environmental Sciences, Jawaharlal Nehru University, Delhi, India, and worked on biodiesel production from oleaginous microbes and industrial sludge. He awarded a Rajiv Gandhi National Fellowship by the University Grants Commission, India, to support his doctoral work on “Distillery Wastewater Treatment” in 2013. His research interests include bioremediation, phytoremediation, metagenomics, wastewater treatment, environmental monitoring, and bioenergy and biofuel production. Currently, his research mainly focuses on the development of integrated and sustainable methods that can help in minimizing or eliminating hazardous substances in the environment. He is the author of numerous research/review articles published in international peer-reviewed journals from Springer Nature, Frontiers, Wiley, and Elsevier on the different aspects of bioremediation, phytoremediation, and metagenomics of industrial waste polluted sites. In addition, he has published 14 Books on different aspects of Phytoremediation, Bioremediation, Wastewater Treatment, Omics, Genomics, and Metagenomics by CRC Press (Taylor & Francis Group), Springer, Wiley etc. His recently published books are “Recent Advances in Distillery Waste Management for Environmental Safety” (From CRC Press; Taylor & Francis Group, USA), and Microbe-Assisted Phytoremediation of Environmental Pollutants: Recent Advances and Challenges (from CRC Press; Taylor & Francis Group, USA). Dr. Kumar has been serving as a guest editor and reviewer in many prestigious International Journals, including Frontiers in Microbiology, Environmental Research, Chemosphere, Journal of Basic Microbiology; International Journal of Environmental Science and Technology; CLEAN-Soil, Air, Water etc. He is an active member of numerous scientific societies and has served on the editorial board of the journal Current Research in Wastewater Management. As part of his interest in teaching biology, he is founder



of the Society for Green Environment, India (website: [www.sgeindia.org](http://www.sgeindia.org)). He can be reached at [drvineet.micro@gmail.com](mailto:drvineet.micro@gmail.com); [vineet.way18@gmail.com](mailto:vineet.way18@gmail.com).

**Maulin P. Shah** is an Active Researcher and Scientific Writer in his field for over 22 years. He received the Ph.D. degree (2009) in Microbiology from Sardar Patel University, Vallabh Vidyanagar (Gujarat), India. His research interests include biological wastewater treatment, environmental microbiology, biodegradation, bioremediation, & phytoremediation of environmental pollutants from industrial wastewaters. He has published more than 250 research papers in national and international journals of repute on various aspects of microbial biodegradation and bioremediation of environmental pollutants. He has edited 52 books published from Elsevier, Springer, CRC Press, RSC, De Gruyter. He has been presented several papers relevant to his research areas in national and international conferences. He has been also serving as a regular reviewer for various scientific journals in his research areas. He is the Founder Editor-in-Chief of the *International Journal of Environmental Bioremediation & Biodegradation* (Science and Education Publishing, USA; from 2011 to 2014) and the *Journal of Applied & Environmental Microbiology* (Science and Education Publishing, USA; from 2011 to 2014). He is the Editor-in-Chief of the *Journal of Advances in Biotechnology* (JBT). He is also the Editor and Associate Editor of many scientific journals in his field. He is also serving as a member of the Editorial Board of the more than 200 scientific journals published by the reputed publisher.



**Sushil Kumar Shahi** is currently working as an Associate Professor in the Department of Botany, School of Life Sciences, Guru Ghasidas Vishwavidyalaya (GGV), Bilaspur, Chhattisgarh, India. He received the Ph.D. degree in 1998 from Allahabad University, Allahabad, Uttar Pradesh (UP), India, on Antimycotic studies of some plants (control of dermatophytoses in human beings). After completion of his education, he joined Allahabad University as a Research Scientist and worked for up to 6 years and in 2004 he joined the J.V. College, Baraut, UP, as Lecturer in Microbiology for teaching and research. In 2007, he left the College and joined Ch. Charan Singh University, Meerut, UP, India, as Assistant Professor in Microbiology for teaching and research, after 7 years of servicing in CCS University he joined GGV as Associate Professor in Botany in 2013. He has experience of 25 years in teaching and research environmental microbial technology, nanobiotechnology, herbal technology, herbal antimicrobials, and IPR. He has published more than 56 original research articles in various reputed national and international journals. He has been awarded a Fellow of various national level scientific societies, namely, Indian Botanical Society, Indian Phytopathological Society, Indian Society of Plant Pathologist, International Young Scientist Association. He has developed herbal



medicine for the control of dermatophytosis and onychomycosis, tinea in animal and human beings; he has also developed various microbial and herbal formulations for the control of plant disease. Some products are as follows: PROTECTON (Postharvest spoilage in fruits (apple and Grapes), NAILGUARD (Onchomycosis (fungal nail infection), PESTOBAN (Herbal pesticide for post harvested food grains), and SKINPRO (Dermatophytosis). He obtained Patents on some herbal products for the control of fungal disease in humans from the USA, UK, Japan, and India. Currently, he is trying to develop some eco-friendly technology as microbial-based fuel-cells, biodegradable polythene, and bioremediation of toxic pollutant from the environment.



# Preface

Environmental pollution with heavy metals and refractory organic chemicals is a global problem that has resulted from rapid mining, military, industrial, agricultural farming, and waste management practices. In addition to their negative effects on aquatic and terrestrial ecosystems and other natural resources, these pollutants accumulate in the food chain through agricultural products or leach into ground water and pose a great harm to humans, animals, plants, and the whole environment of our modern society. There are several evidence that this cocktail of pollutants is a contributor to the global epidemic of cancer and other degenerative diseases. Thus, there is an immediate demand at the regional, local, and global level to decontaminate polluted soil, water, and air to counteract the adverse effects on human health and conserve the environment for our future generations. Since conventional and physicochemical technologies employed for remediating the polluted habitats have many potential drawbacks including expensive and not environment friendly as they generate toxic by-products and large amounts of sludge, which also requires safe disposal and can also cause secondary pollution and lower sustainability. Increased need for the remediation of the heavy metals, organic chemicals, and other contaminants from polluted soil and water has created a demand for improved and newer remediation technologies that are applicable at economical, low waste generation, and environmentally friendly ways to restore the contaminated sites for human rehabilitation and agricultural production in an effective and more sustainable manner, and have a wider scope of waste management.

Phytoremediation in recent years has emerged as an energy-efficient and eco-friendly technology for decontamination of soil, surface and groundwater, air, or other polluted media. Phytoremediation refers to a set of techniques emphasizing the efficient use of plants, their related enzymes, and associated microbes for transportation, sequestration, detoxification, and mineralization of toxicants through complex natural biological, physiological, and chemical processes. This technology can be used to clean up and/or stabilize both inorganic and organic contaminants and has been considered to be the most promising technology due to its minimal site disturbance and low cost and higher public acceptance when compared with conventional remediation methods. It is an emerging green approach where plants are grown in contaminated soil, sediment, and water to increase the decomposition or removal rate of inorganic and organic pollutants *in planta* as well as *ex planta*.

The present book, *Phytoremediation Technology for the Removal of Heavy Metals and Other Contaminants From Soil and Water*, as the title implies, describes the numerous phytoremediation technologies which can be and has been applied to the cleanup of soil, water, and sediment contaminated with various toxic and hazardous *Heavy Metals And Other Contaminant*, to protect the environment and human health for sustainable development. Written for both academics and practitioners, the book



provides detailed knowledge of various phytoremediation research, recent development, real-world applicability of that knowledge, and success stories related to phytoremediation of polluted habitats. In this book, we have attempted in several ways to attempt to explore the recent advances in plant-microbes based technologies and their diverse applications to the sustainable development of human life. This whole book is spread over 28 diverse chapters and offers an updated and detailed account of the latest research and development in different aspects of phytoremediation for the removal/remediation of heavy metals and other contaminants from soil and water for safety to public health.

Chapter 1 discusses the numerous bioremediation and phytoremediation technologies for environmental cleanup. Chapter 2 presents a detailed account of the phytoremediation as an ultimate approach for reinstating soil contaminated with heavy metals and other pollutants.

Chapter 3 describes the prospects of numerous plant species that display expressive mechanisms for efficiently uptake, translocate, and sequester the heavy metals and chemical pollutants from the contaminated environment. Chapter 4 discusses the recent developments in aquatic macrophytes for environmental pollution control with a case study grown on heavy metal removal from lake water and agricultural return wastewater with the use of Duckweed (*Lemnaceae*). Chapter 5 provides comprehensive information about the phytoremediation potential of various weed plants belonging to the families Amaranthaceae and Euphorbiaceae grown on heavy metal contaminated soil. Chapter 6 describes the role of oxidoreductase metalloenzymes in the phytoremediation of environmental pollutants. Chapter 7 deals with an updated account of phytoextraction as an effective sustainable green approach to remediate the major environmental pollutants along with its challenges and future perspectives. Chapter 8 discusses and highlights the prospects and potential of various weed plants in phytoremediation and eco-restoration of heavy of metal-contaminated environments. Chapter 9 gives a brief account of the biochemical and molecular events in plants undergoing inorganic stress and the various strategies developed by the plants to ameliorate the metal toxicity. Chapter 10 discusses the monitoring of the process of phytoremediation of heavy metals using spectral reflectance and remote sensing. Chapter 11 emphasizes the environmental and health impacts of mine tailings and a potential method of removal and reduction of leaching toxic metals in mine tailings via phytostabilization as a green remediation technology. Chapter 12 discusses the applicability and drawbacks of phytoremediation along with the strategies for improving and modifying certain traits of plants to ascertain effective phytoremediation of heavy metals, metalloids, and radionuclides. Chapter 13 explains the role of Cress (*Lepidium sativum* L.) in phytoremediation of lithium, a toxic metals. Chapter 14 summarizes the advancement in macrophytes' use for bioremediation of different chemical compounds and the management of the aquatic environment. Chapter 15 provides a summary and discusses the role of PGPR in improving crop productivity and health. It also discusses its influence on other bacterial species, the mechanism involved, role in bioremediation and stress management. Chapter 16 discusses the different approaches for remediation of contaminated soil by using plants and explains role

of nanomaterials in phytoremediation of tainted soil. Chapter 17 gives an overview of different classes of pesticides, focuses on the role of phytoremediation technology on pesticide pollution, processes uptaken by plants in eliminating these pollutants, and shedding light on the rhizospheric plant bacterial association for the enhanced degradation. Chapter 19 discusses the role of plant's genes in detoxification and mitigation of heavy metals and organic contaminants pollution abatement. Chapter 20 explains the role of nano-phytoremediation technology in environmental remediation along with future endeavors. Chapter 21 describes the various biosynthesis procedures for the production of nanoparticles from plants, microorganisms and fungi, and their different strategies for the potential application in environmental clean-up, especially heavy metals. Chapter 22 explains the role and potential of constructed wetlands plant treatment system for the treatment and recycling of hazardous wastewater. Chapter 23 gives general and specific information on the ecological characteristics and biological mechanisms involved in the phytoremediation process by aquatic macrophytes. Chapter 24 presents a case study on phytoremediation of trace elements from paper mill wastewater with *Pistia stratiotes* L. and explains metal accumulation and antioxidant response during remediation. Chapter 25 discusses the role of the coupled phytoremediation-electrokinetic technology in phytoremediation of heavy metals contaminated soils. Chapter 26 presents a comprehensive review of the role of microbes-assisted phytoremediation in remediation of environmental contaminants. Chapter 27 describes the recent progressions application of constructed wetland microbial fuel cell in electricity production and the analysis of the anode microbial community during wastewater treatment. Chapter 28 gives a critical insight about eco-friendly phytocapping technology for sustainable management of landfill sites.

All the chapters in the book are written by authors in a more comprehensive way and are meticulously prepared with fabulous figures, graphs, and tables to make the information easier to understand, and are supported by an extensive list of references and URLs for readers interested in learning further details about the subject matter. The main aim of the book is to focus on the use of phytoemediation technologies in cleanup the polluted environment and make the depleted or degraded fields/water bodies fertile and rejuvenated in order to maintain sustainability.

This book generally brings a contemporary outlook on the modern aspects of environmental decontamination technologies. We are hopeful that this book will be useful to researchers, students, academics, scientists, engineers, government officers, process managers, and practicing professionals, who are interested and/or working in the area of phytoremediation or bioremediation of the environment and related subjects. As an excellent state-of-the-art reference material, the book will contain rich knowledge on the principles and provide them in-depth understanding and comprehensive information of current green technologies, their different environmental applications, recent advantages and disadvantages, critical analysis and modeling of the processes, and future perspective toward research directions and development.

Phytoremediation is still very much an evolving technology; there is a need for more research and development to identify and overcome the limitations and a real need to establish a critical dialogue among scientists, engineers, and environmental

Last but not the least, Dr. Vineet Kumar would like to acknowledge his family members with love and affection in particular his parents (Mr. Niranjan Singh and Mrs. Pawan Devi), younger brother Rohit Chowdhary, and sister Ms. Khushboo.

Finally, I would like to apologize in advance for any errors that may occur in the text, and express my heartfelt embarrassment

We should be pleased to receive any comments on the content and style of *Phytoremediation Technology for the Removal of Heavy Metals and other Contaminants from Soil and Water* from students, professionals, environmentalist, and policy makers, all of which will be given serious consideration for inclusion in any further editions.

**Vineet Kumar**

*Maharashtra, India*

**Maulin P. Shah**

*Gujarat, India*

**Sushil Kumar Shahi**

*Chhattisgarh, India*