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Edited by Gokare A. Ravishankar,
Ambati Ranga Rao, and Se-Kwon Kim

Algae Mediated Bioremediation

Industrial Prospectives

Volumes 1–2

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Volume 1

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Editors

Prof. Gokare A. Ravishankar
Dayananda Sagar Institutions
Bengaluru
India

Dr Ambati Ranga Rao
Vignan's Foundation for Science
Technology and Research (Deemed to be
University)
Andhra Pradesh
Guntur, 522213
India

Prof. Se-Kwon Kim
Hanyang University ERICA
55 Hanyangdae-ro
Sangnok-gu, Ansan-si
Gyeonggi-do, 11558
South Korea

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Contents

About the Editors

Gokare A. Ravishankar, Ph.D., is an adjunct honorary Vice President of Research & Development (R&D) in Life Sciences and Biotechnology (partly remote position) at Dayananda Sagar Institutions [Dayananda Sagar University; Dayananda Sagar College of Engineering affiliated to Visvesvaraya Technological University (VTU)], Bengaluru, India. He is also an international consultant in the domains of biomass production, agro-technologies, food science and technologies in the United States.

Earlier, he had a distinguished research career of over 30 years at the Central Food Technological Research Institute (CFTRI), Mysore and in the institutions of the Government of India. At CFTRI, he served as Director-Grade Scientist and Head of the Plant Cell Biotechnology Department for 18 years till his voluntary retirement in 2012. Later, he served as Chairman of the board of studies in biotechnology at the Visvesvaraya Technological University and Academic Council Member of Dayananda Sagar University. He has also been a member of the boards of eight universities. He served as Visiting Professor/Scientist to universities in Japan, Korea, Taiwan, and Russia. He is also a research advisory committee member of ICAR-Indian Institute of Horticultural Research, Bengaluru and a member of the expert committee on All India Coordinated Project on Seaweeds, Council of Scientific and Industrial Research, New Delhi. He was the founding director of E2E Biotech Pvt Ltd, Bengaluru and is now the honorary advisor.

He is an internationally recognized expert in the areas of food science and technology, plant biotechnology, algal biotechnology, food biotechnology and postharvest technologies, plant physiology, plant secondary metabolites, functional foods, herbal products, genetic engineering, microbial technologies, plant–microbe interactions, biomass production, and biofuels. He is listed in the top 2% of the world's scientists reported by Stanford University, United States.

Dr. Ravishankar holds a master's and a Ph.D. degree from Maharaja Sayajirao University of Baroda. He mentored over 40 Ph.D. students, 62 master's students, 7 postdocs, and 8 international guest scientists. He has authored over 265 peer-reviewed research papers, 30 review articles, 70 Book chapters, and 55 patents in India and abroad and edited 7 books. His research publications have received over

25,000 citations with an h-index of 73. He has presented over 220 lectures at various scientific meetings in India and abroad, including visits to about 30 countries.

Dr. Ravishankar has received international honors as a Fellow of the International Academy of Food Science and Technology (Canada), Institute of Food Technologists (United States), Institute of Food Science and Technology (United Kingdom), and as a Certified Food Scientist, United States.

He was honored as a fellow of several organizations in India, namely, the National Academy of Sciences, National Academy of Agricultural Sciences, Association of Microbiologists of India, Society of Agricultural Biochemists, Society of Applied Biotechnologists, Indian Botanical Society, Biotechnology Research Society of India, and the Association of Food Scientists and Technologists of India. He is also an elected member of the Plant Tissue Culture Association of India. He is an Executive Council Member of the Indian Academy of Microbiological Sciences.

Dr. Ravishankar received several coveted awards as follows: Young Scientist Award (Botany) by the then Prime Minister of India in 1992; National Technology Day Award of the Government of India in 2003; Laljee Goodhoo Smarak Nidhi Award for food biotechnology R&D of Industrial Relevance; the Prestigious, Professor V. Subramanyan Food Industrial Achievement Award; Professor S.S. Katiyar Endowment Lecture Award in New Biology by Indian Science Congress; Professor Vyas Memorial Award of Association of Microbiologists of India; Professor V.N. Raja Rao Endowment Lecture Award in Applied Botany, University of Madras; Lifetime Achievement Award by the Society of Applied Biotechnologists, Dr. Diwaker Patel Memorial Award by Anand Agricultural University, Anand; Prof. C.S. Paulose Memorial Oration Award by Society for Biotechnologists of India; Prof. Gadgil Memorial Lecture Award from Plant Tissue Culture Association of India; and Lifetime Achievement Award of the Association of Microbiologists of India.

He has held honorary positions as President of the Society of Biological Chemists, Mysore Chapter; President of the Association of Microbiologists of India, Mysore, and Bangalore Chapters; and Vice President (HQ) of the Association of Food Scientists and Technologists of India. He is a lifetime member of the Nutrition Society of India and several biotechnology societies including the Plant Tissue Culture Association of India, Society for Biotechnologists of India, Biotechnology Research Society of India, International Coffee Genome Network, American Society of Plant Biologists, Global Harmonization Initiative (Austria), and many more.

He has also served as an advisor and resource person in international conferences, seminars, workshops, and short courses and has convened national and international seminars in biology, biotechnology, and food science and technology. He is an associate editor and reviewer of a large number of reputed research journals. Dr. Ravishankar has served on advisory committees of the Government of India, namely, Department of Science and Technology (DST), Department of Biotechnology (DBT), and Council of Scientific and Industrial Research (CSIR), among many others for the selection of national/international research projects, recruitment of scientists, and HRD-related activities. He also participated as a member of the working group on biotechnology at Institute of Food Technologists (IFT), United States.

Ambati Ranga Rao, Ph.D., is Senior Scientist and Associate Professor in the Department of Biotechnology, School of Biotechnology and Pharmaceutical Sciences at Vignan's Foundation for Science, Technology, and Research (Deemed to be University), Andhra Pradesh, India. He is also serving as Director for the Center of Excellence. He is involved in teaching cum research for graduate and undergraduate students. Recently, he is listed in the Top 2% of the World's Scientists reported by Stanford University, United States.

Dr. Ranga Rao holds a bachelor's and master's degree from Acharya Nagarjuna University, Andhra Pradesh, India and a Ph.D. degree from the University of Mysore. He started his research career in 2004 as a research assistant at the Department of Plant Cell Biotechnology, Council of Scientific and Industrial Research (CSIR)-Central Food Technological Research Institute (CFTRI), Mysuru, India, under the supervision of Dr. G. A. Ravishankar and Dr. R. Sarada. He was awarded Senior Research Fellow of the Indian Council of Medical Research (ICMR), New Delhi in the year 2007. His Ph.D. work at CFTRI focused on the production of astaxanthin from cultured green alga, *Haematococcus pluvialis,* and its biological activities.

He worked extensively on process optimization of algal biomass production, the mass culture of various algal species in raceway ponds and photobioreactors, and downstream processing of algal metabolites, and evaluation of their possible nutraceutical applications in *in vitro* and *in vivo* models. Furthermore, Dr. Ranga Rao was involved in a project on "Studies on filed cultivation and harvesting of seaweeds-*Porphyra, Enteromorpha, Eucheuma* and their use in processed foods."

Dr. Ranga Rao worked as Lead Scientist in Algal Technologies, Carot Labs Pvt. Ltd, India; Postdoctoral Research Associate in Laboratory of Algal Research and Biotechnology, Arizona State University, United States, under the supervision of Prof. Milton Sommerfeld and Prof. Qiang Hu; Visiting Assistant Professor in Food Science and Technology Program, Beijing Normal University and Hong Kong Baptist University, United International College, China, under the supervision of Prof. Bo Lei; and Visiting Senior Research Fellow (Associate Professor Grade) in Institute of Ocean and Earth Sciences, University of Malaya, Malaysia, under the guidance of Prof. Phang Siew-Moi.

He is the author of 55 peer-reviewed publications, 76 International/national conferences/symposia/invited talks/Faculty Development Programme (FDPs)/workshops/Quality Improvement Programme (QIP)-short-term courses, refresher courses, and 30 chapters in books. His research citations exceed 4550 with h-index (23) and i10-index (37) in Google Scholar. He has delivered lectures as Invited Speaker at international/national conferences/symposia in the United States, Canada, Brazil, Russia, China, Malaysia, Indonesia, and Oman.

He has edited five books (CRC Press, Academic Press, Springer Nature) as editor and co-editor, namely, *Sustainable Global Resources of Seaweeds: Industrial Perspectives-Volume-I; Bioresources, cultivation, trade, and multifarious applications; Sustainable Global Resources of Seaweeds: Industrial Perspectives-Volume II: Food,*

pharmaceutical and health applications. Handbook of Algal Technologies and Phytochemicals: Volume-I Food, Health, and Nutraceutical Applications; Handbook of Algal Technologies and Phytochemicals: Volume II Phycoremediation, Biofuels, and Global Biomass Production; and *Global Perspectives on Astaxanthin: from Industrial Production to Food, Health, and Pharmaceutical Application*.

He was honored with the award of The World Academy of Sciences (TWAS) as Young Affiliate (2014–2018) by the Regional Office of South East Asia and the Pacific Chinese Academy of Sciences (CAS), China. His credentials were recognized to induct him as Young Affiliate of the International Union of Food Science and Technology (IUFoST), Canada, at the World Food Science Congress 2014. He is a recipient of the Carl Storm International Diversity Fellowship Award (2010) by Gordon Research Conferences, United States. He was selected for the Junior Scientist of the Year Award (2015) by National Environmental Science Academy, New Delhi, India.

He is a lifetime member of the Association of Food Scientists and Technologists of India, the Association of Microbiologists of India, the Society of Applied Biotechnology of India; the National Environmental Science Academy of India; Asia PGPR Society of Sustainable Agriculture of India, the Global Harmonization Initiative, and Andhra Pradesh Academy of Sciences.

He is an associate fellow of the Andhra Pradesh Academy of Sciences (2019), Government of Andhra Pradesh, India, and also a fellow of the Society of Applied Biotechnology (2013), India. He has received research grants and travel grant fellowships as both international and national awards, under Young Scientist schemes. He is also serving as an editorial board member, guest editor for special issues, and reviewer for reputed international and national journals.

Se-Kwon Kim, **Ph.D.,** is presently working as a Distinguished Professor at Hanyang University. He worked as a Distinguished Professor at the Department of Marine Bio Convergence Science and Technology and as Director of the Marine Bioprocess Research Center (MBPRC) at Pukyong National University, Busan, South Korea.

He received his M.Sc. and Ph.D. degrees from Pukyong National University and conducted his postdoctoral studies at the Laboratory of Biochemical Engineering, University of Illinois, Urbana-Champaign, Illinois, United States. Later, he became a visiting scientist at the Memorial University of Newfoundland and the University of British Colombia in Canada.

Dr. Kim served as President of the "Korean Society of Chitin and Chitosan" in 1986–1990, and the "Korean Society of Marine Biotechnology" in 2006–2007. To the credit for his research, he won the Best Paper Award from the American Oil Chemists' Society in 2002. Dr. Kim was also the chairman for the "7th Asia-Pacific Chitin and Chitosan Symposium," which was held in South Korea in 2006. He was the chief editor of the "Korean Society of Fisheries and Aquatic Science" during 2008–2009. In addition, he is a board member of the International Society of Marine

Biotechnology Associations (IMBA) and the International Society of Nutraceuticals and Functional Food (ISNFF).

His major research interests are the investigation and development of bioactive substances from marine resources. His immense experience in marine bio-processing and mass-production technologies for the marine bio-industry is the key asset in holding majorly funded Marine Bio projects in Korea. Furthermore, he expanded his research fields up to the development of bioactive materials from marine organisms for their applications in oriental medicine, cosmeceuticals, and nutraceuticals. To this date, he has authored around 750 research papers, 70 books, and 120 patents.

Foreword

Clean water and effective treatment of wastewater are critically important factors for environmental sustainability and human well-being. This importance is recognized by the United Nations Sustainable Development Goal (SDG) 6 "Clean water and sanitation." Increasing population pressures and environmental damage to lake, river, estuarine, and ocean ecosystems due to the discharge of inadequately treated or untreated wastewater are significant problems globally resulting in economic losses and risks to human health. Existing wastewater treatment methods are generally very energy-intensive, making them expensive as well as generating large amounts of greenhouse gases. They are also inadequate for treating wastewater high in heavy metals or xenobiotics such as pharmaceuticals, pesticides, and plasticizers. Thus, alternative, efficient, and environmentally friendly wastewater treatment methods must be developed to supplement existing methodologies.

Algae, especially microalgae, can play an important part in achieving the UNSDG goal of effective treatment of wastewater. The application of microalgae in wastewater treatment has a long history, with studies starting in the 1950s and expanding rapidly since the 1970s, with the main focus on urban and agricultural wastewater. This work has already led to many full-scale algae-based wastewater treatment plants for treating urban wastewater in several countries, as illustrated in this volume.

This volume highlights the importance of both microalgae and macroalgae for bioremediation, with specific examples of industrial effluent treatments. It also encompasses studies on (a) the roles of algae in wastewater treatment and bioremediation via photosynthesis in high rate algal oxidation ponds (HRAPs), where the algae operate synergistically with bacteria to break down organic molecules reducing BOD and COD, (b) the uptake of N and P by the algal cells, reducing the concentration of these nutrients in the wastewater and preventing eutrophication of the receiving water bodies, (c) biding and uptake of heavy metals by the algal cells, (d) uptake of complex recalcitrant organic molecules such as dyes, estrogens, pharmaceuticals and pesticides, and the metabolism/detoxification of these molecules by the algae. This diversity of roles is provided by an equal diversity of algal species, with different species required for treating different wastewater sources. Various chapters in this volume also discuss the significant barriers to large-scale applications and methods to innovate the processes for industrial applications.

Although some of the biomass, such as that used to treat food processing or animal wastes, may be suitable as an agricultural fertilizer or, in some cases, even as an animal feed additive, in many cases, alternative disposal methods need to be found. Often, the algal biomass will be contaminated with heavy metals or toxic chemicals, greatly restricting possible applications, or the biomass may present a health hazard due to associated bacteria, fungi, or viruses originating from the wastewater source.

It also needs to be recognized that the scale of wastewater production, especially urban wastewater in large cities, presents an enormous challenge for the operation of an algae-based wastewater process. Algal wastewater treatment is often more suited to small-scale regional applications.

Given the great need to reduce the environmentally detrimental impact of wastewater and the need to cost-effectively treat it so that critical water resources can be reused, this book provides a timely and extensive overview of this topic. It contains papers spanning a wide range of types of wastewater, on the range of strategies that can be applied, as well as on the potential uses and valorization of the algal biomass produced. Case studies of the application of algal wastewater bioremediation in various countries in Asia are also presented.

Algae-mediated bioremediation of waste streams has come a long way since the early studies and has moved from the laboratory to actual applications. The research presented in this book highlights new approaches and developments in meeting the ongoing challenges of effectively and economically remediating wastewater. I congratulate the editors and contributors for this timely publication, which provides an important current reference for industry, policymakers, environmental experts, and researchers as a source of comprehensive information for immediate applications and future use.

Michael A. Borowitzka
Algae R&D Center, Murdoch University,
Murdoch, WA 6150, Australia
3rd October, 2023

Preface

The world is currently grappling with an alarming increase in population growth, which is placing immense pressure on the health of the planet. This surge in anthropogenic activities has led to unprecedented global warming and climate change as the environment deteriorates due to irresponsible human interference in the ecosystem. It is crucial to address this issue urgently by transitioning to an eco-friendly path of human progress, employing multiple approaches to meet global demands sustainably.

One promising avenue to achieve this is by harnessing photosynthetic forms to fulfill the goods and services required for the human population. Embracing the potential of photosynthesis can significantly contribute to a more sustainable future. Additionally, finding innovative ways to manage industrial waste without harming the ecosystem is of utmost importance. This urgent necessity calls for responsible waste management practices that minimize environmental impact and ensure long-term sustainability.

To combat the challenges posed by overpopulation and anthropogenic activities, we must collectively prioritize eco-friendly initiatives and implement sustainable practices at both regional and global levels. By doing so, we can work toward safeguarding the health of our planet and securing a better future for generations to come.

The algal forms are some of the oldest inhabitants of Earth, and they play a crucial role in supporting the ecosystem by acting as primary producers of food through their ability to harness solar energy. Notably, they showcase remarkable adaptability, thriving in a wide range of environments, from marine to freshwater ecosystems, from cold polar regions to hot deserts, and from plains to mountainous terrains. Moreover, they can also grow autotrophically, heterotrophically, and mixotrophically. This adaptability allows them to endure and flourish in inhospitable conditions.

Algae exhibit diverse forms, including unicellular and multicellular organisms as well as highly differentiated macroalgal seaweeds. Their significance extends beyond their role as food producers, as they also offer solutions to global warming. Through their capability to sequester carbon dioxide from the environment, they contribute to mitigating the effects of climate change.

Furthermore, algae possess unique biosynthetic machinery that enables them to uptake pollutants from their surroundings. They can either utilize these pollutants for their growth or metabolize them into nontoxic or less toxic forms. This aspect has caught the attention of researchers who are exploring algae's potential as agents of bioremediation for pollution abatement.

This publication aims to focus on the various ways algae can be utilized in bioremediation efforts to reduce pollution burdens. By highlighting their adaptability, carbon sequestration abilities, and their potential to transform pollutants into benign forms, we hope to shed light on the valuable role algae can play in environmental conservation.

The task of comprehensive coverage of the topic was made easy by the participation of 135 authors from 20 countries including Australia, Bangladesh, Brazil, China, Colombia, Germany, India, Indonesia, Iran, Italy, Malaysia, Mexico, Pakistan, Slovenia, South Africa, Spain, Thailand, Turkey, United States, and Vietnam. Their contributions have been presented in 35 chapters that are classified under the following broad headings: (I) Phycoremediation strategies; (II) Anaerobic digestion for removal of pollutants and sewage treatment; (III) Treatment of agricultural wastes; (IV) Treatment of food industry-wastewaters; (V) Detoxication and pollution abatement of industrial waste streams; (VI) Carbon dioxide sequestration strategies; (VII) Valorization of algal biomass; and (VIII) Global perspectives of algae-based bioremediation.

The above areas highlight the following aspects: the management of heavy loads of pollutants in wastewaters; removal of heavy metals from the industrial wastewaters; bioreactors and immobilization strategies for remediation processes; treatment of piggery wastes; treatment of aquaculture wastes; treatment of food industry wastes including palm oil industry effluents; detoxification of industrial wastes, including micropollutants, paper and pulp industrial wastewaters, dyes and textile industry effluents, tannery wastes, petrochemical industry effluents, and pharmaceutical industry wastewaters; carbon dioxide sequestration through microalgae and seaweeds, including a focus on carbon credits; and valorization of biomass for the production of valuable metabolites, bioenergy, biochar, biofertilizers, and plant-bio stimulants.

This publication goes beyond exploring the significance of algae in pollution abatement and bioremediation; it also delves into the experiences of various countries in adopting algae-mediated strategies. Our contributors have meticulously presented the efforts of their respective countries, offering insights from Asian nations such as India, Malaysia, Pakistan, Thailand, and Vietnam. Additionally, the international scope of this volume is enriched by the valuable contributions of scientists from 20 countries, who have shared their findings on algae-mediated bioremediation.

As a result, this volume stands as a comprehensive and invaluable resource for individuals interested in science and technological interventions for pollution abatement. It caters to a diverse readership, including environmental scientists, biologists, biochemical engineers, specialists in biomass production/utilization, industrial professionals, environmentalists, policymakers, and all science enthusiasts alike.

The information and perspectives gathered here will undoubtedly serve as a treasure trove of knowledge, empowering readers to understand the potential of algae-based solutions in addressing pollution challenges. With its wide-ranging coverage and international collaboration, this publication marks a significant step toward advancing sustainable practices for a cleaner and healthier environment through algae-mediated processes for pollution abatement.

Gokare A. Ravishankar
Bengaluru, 9th August, 2023

Ambati Ranga Rao
Andhra Pradesh, 9th August, 2023

Se-Kwon Kim
South Korea, 9th August, 2023