



NEXT- GENERATION ALGAE

VOLUME I: APPLICATIONS IN AGRICULTURE, FOOD AND ENVIRONMENT

Edited By
Charles Oluwaseun Adetunji
Julius Kola Oloke
Naveen Dwivedi
Sabeela Beevi Ummalyma
Shubha Dwivedi
Daniel Ingo Hefft
Juliana Bunmi Adetunji

 **Scrivener
Publishing**

WILEY

Next-Generation Algae

Scrivener Publishing

100 Cummings Center, Suite 541J
Beverly, MA 01915-6106

Publishers at Scrivener

Martin Scrivener (martin@scrivenerpublishing.com)
Phillip Carmical (pcarmical@scrivenerpublishing.com)

Next-Generation Algae

Volume I: Applications in Agriculture, Food and Environment

Edited by

Charles Oluwaseun Adetunji

Julius Kola Oloke

Naveen Dwivedi

Sabeela Beevi Ummalyma

Shubha Dwivedi

Daniel Ingo Hefft

and

Juliana Bunmi Adetunji



WILEY

This edition first published 2023 by John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, USA and Scrivener Publishing LLC, 100 Cummings Center, Suite 541J, Beverly, MA 01915, USA

© 2023 Scrivener Publishing LLC

For more information about Scrivener publications please visit www.scrivenerpublishing.com.

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise, except as permitted by law. Advice on how to obtain permission to reuse material from this title is available at <http://www.wiley.com/go/permissions>.

Wiley Global Headquarters

111 River Street, Hoboken, NJ 07030, USA

For details of our global editorial offices, customer services, and more information about Wiley products visit us at www.wiley.com.

Limit of Liability/Disclaimer of Warranty

While the publisher and authors have used their best efforts in preparing this work, they make no representations or warranties with respect to the accuracy or completeness of the contents of this work and specifically disclaim all warranties, including without limitation any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives, written sales materials, or promotional statements for this work. The fact that an organization, website, or product is referred to in this work as a citation and/or potential source of further information does not mean that the publisher and authors endorse the information or services the organization, website, or product may provide or recommendations it may make. This work is sold with the understanding that the publisher is not engaged in rendering professional services. The advice and strategies contained herein may not be suitable for your situation. You should consult with a specialist where appropriate. Neither the publisher nor authors shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages. Further, readers should be aware that websites listed in this work may have changed or disappeared between when this work was written and when it is read.

Library of Congress Cataloging-in-Publication Data

ISBN 978-1-119-85727-3

Cover image: Pixabay.Com

Cover design by Russell Richardson

Set in size of 11pt and Minion Pro by Manila Typesetting Company, Makati, Philippines

Printed in the USA

10 9 8 7 6 5 4 3 2 1

Contents

Preface	xv
1 Smart Microalgae Wastewater Treatment: IoT and Edge Computing Applications with LCA and Technoeconomic Analysis	1
<i>Mohd. Zafar, Avnish Pareek, Taqi Ahmed Khan, Ramkumar Lakshminarayanan and Naveen Dwivedi</i>	
1.1 Introduction	2
1.2 Importance and Potential of Extremophilic Microalgae-Based Wastewater Treatment (WWT) Plant	4
1.3 Status of Microalgae-Based WWT Plants	5
1.3.1 Conditions and Requirements (Abiotic and Biotic Requirements, Nutrients Requirement)	5
1.3.2 Microalgae-Based WWT System – Photobioreactor System in Suspension and Immobilized Model	12
1.3.3 Evaluation of Treatment Performance	12
1.4 IoT and Edge Computing-Based Monitoring and Modeling of Integrated Microalgae-Based WWT Plant	21
1.4.1 Machine Learning Approaches for Data Acquisition, Monitoring and Analysis System	22
1.5 Techno-Economic Analysis of Integrated Microalgae-Based Wastewater Treatment (WWT) System	28
1.6 Brief Case Studies of Commercially Available Microalgae-Based Wastewater Treatment (WWT) Plants	34
1.7 Conclusion	35
References	36

2	The Use of Microalgae in Various Applications	49
	<i>Fulden Ulucan-Karnak, Mirac Sabankay and M. Ozgur Seydibeyoglu</i>	
2.1	Introduction	49
2.1.1	Algae Classification	50
2.1.2	Cultivation of Microalgae	51
2.2	End Uses of Microalgae	53
2.2.1	Biofuel Applications	53
2.2.1.1	Biodiesel	53
2.2.1.2	Bioethanol	55
2.2.1.3	Biomethane (Syngas)	56
2.2.1.4	Biohydrogen	57
2.2.1.5	Bioplastic	59
2.3	Microalgal High-Value Compounds	60
2.3.1	Polyunsaturated Fatty Acids	60
2.3.2	Carotenoids	62
2.3.3	Phycocyanin	65
2.3.4	Sterols	66
2.3.5	Polysaccharides	67
2.3.6	Polyketides	68
2.4	Biomass	68
2.4.1	Health Food Products	68
2.4.2	Animal Feed	70
2.5	Potential Future Applications	71
2.6	Conclusion	73
	References	74
3	Arsenic Bioremoval Using Algae: A Sustainable Process	91
	<i>Sougata Ghosh, Jyoti Nayak, Md Ashraful Islam and Sirikanjana Thongmee</i>	
3.1	Introduction	92
3.2	Algae-Mediated Arsenic Removal	93
3.3	Conclusions and Future Perspectives	104
	Acknowledgment	104
	References	104
4	Plastics, Food and the Environment: Algal Intervention for Improvement and Minimization of Toxic Implications	109
	<i>Naveen Dwivedi, Pragya Sharma and V.P. Sharma</i>	
4.1	Introduction	110
4.2	Constituents of Chemicals in Plastics and Waste Generation	111

4.3	Packaging of Food and Minimization Through Concept of ®	112
4.4	Current World Production Rate of Plastics	112
4.4.1	Plastics, Food and Packaging to Distribution in Public and Strategic National Boundaries	113
4.4.2	Future Projection on Plastic Production	115
4.5	Toxic Implications of Microplastics from Food Packaging or Other Items	115
4.5.1	Biodegradable Polymers	116
4.5.2	Particulate Matter from Plastics and Implications	117
4.6	Conclusion	117
	References	118
5	Role of Algae in Biodegradation of Plastics	125
	<i>Piyush Gupta, Namrata Gupta, Subhakanta Dash and Monika Singh</i>	
5.1	Introduction	126
5.2	What are Microalgae?	128
5.3	Some Biodegradable Pollutants	128
5.4	Overview of Plastics	129
5.5	Bioremediation of Plastics	130
5.6	Microalgae's Effect on Microplastics	133
5.7	Microplastics' Effect on Microalgae	134
5.8	Techniques Used for Analysis of Plastic Biodegradation	135
5.9	Factors Influencing the Deterioration of Plastics Using Microorganisms	138
5.9.1	Biological Factors	138
5.9.2	Moisture and pH	138
5.9.3	Environmental Factors	139
5.10	Future Prospects	139
5.11	Conclusion	140
	References	141
6	Application of Algae and Bacteria in Aquaculture	147
	<i>Anne Bhambri, Santosh Kumar Karn and Arun Kumar</i>	
6.1	Introduction	148
6.2	The Major Problem of Nitrite and Ammonia in Aquaculture	150
6.3	Techniques for Nitrite, Nitrate and Ammonia Removal	151
6.4	Beneficial Application of Algae in Aquaculture	151
6.5	Algae and Bacteria for Nitrite, Nitrate and Ammonia Transformation	153

6.6	Conclusion	155
	Acknowledgments	156
	References	156
7	Heavy Metal Bioremediation and Toxicity Removal from Industrial Wastewater	163
	<i>Namrata Gupta, Monika Singh, Piyush Gupta, Preeti Mishra and Vijeta Gupta</i>	
7.1	Introduction	164
7.2	Environmental Heavy Metal Sources	165
7.3	Heavy Metal Sources of Water Treatment Plants	166
7.4	Heavy Metal Toxicity in Relation to Living Organisms	168
7.5	Remediation Technologies for Heavy Metal Decontamination	170
7.5.1	Conventional Methods	170
	7.5.1.1 Chemical Precipitation	170
	7.5.1.2 Ion Exchange	170
	7.5.1.3 Membrane Filtration	170
	7.5.1.4 Reverse Osmosis	171
7.5.2	Ultrafiltration	171
7.5.3	Microfiltration	171
7.5.4	Nanofiltration	171
7.5.5	Electrodialysis	171
7.6	Biological Approach in the Remediation of Heavy Metals	172
7.6.1	Bacteria as Heavy Metal Biosorbents	173
7.6.2	Algae as Heavy Metal Biosorbents	173
7.6.3	Fungi as Heavy Metal Biosorbents	174
7.6.4	Phytoremediation	174
7.7	Mechanism Involved in Biosorption	174
7.7.1	Intracellular Sequestration	179
7.7.2	Extracellular Sequestration	180
7.7.3	Extracellular Barrier of Metal Prevention in Microbial Cells	180
7.7.4	Metals Methylation	180
7.7.5	Heavy Metal Ions Remediation by Microbes	181
7.8	Alga-Mediated Mechanism	181
7.9	Application of Biosorption for Waste Treatment Technology	181
7.10	Microbial Heavy Metal Remediation Factors	183
7.11	Conclusion	185
7.12	Future Prospects	186
	References	186

8	The Application of DNA Transfer Techniques That Have Been Used in Algae	195
	<i>Thilini Jayaprada and Jayani J. Wewalwela</i>	
8.1	Introduction	195
8.2	Conventional DNA Transfer Techniques in Algae	198
8.2.1	Electroporation	198
8.2.2	Agrobacterium-Mediated Transformation	200
8.2.3	Bacterial Conjugation	201
8.2.4	Biolistic Particle Bombardment	202
8.2.5	Agitation with Glass Beads	203
8.3	Novel Emerging DNA Transfer Techniques in Algae	204
8.3.1	Protoplast Fusion	204
8.3.2	Liposome-Mediated Transformation	205
8.3.3	Metal-Organic Frameworks	206
8.3.4	Cell-Penetrating Polymers	206
8.3.5	Cell-Penetrating Peptides	207
8.3.6	Nanoparticle-Mediated Transformation	208
8.4	Limitations to Genetic Transformation in Algae	208
8.4.1	Cell Wall as a Significant Barrier	208
8.4.2	Native Antibiotics Resistance	209
8.4.3	Low Genetic Stability of Transgenes	210
8.5	Future Prospects of Algae Transformation	210
	References	214
9	Algae Utilization as Food and in Food Production: Ascorbic Acid, Health Food, Food Supplement and Food Surrogate	225
	<i>Abiola Folakemi Olaniran, Bolanle Adenike Akinsanola, Abiola Ezekiel Taiwo, Joshua Opeyemi Folorunsho, Yetunde Mary Iranloye, Clinton Emeka Okonkwo and Omorefosa Osarenkhoe Osemwegie</i>	
9.1	Introduction	226
9.2	The Utilization of Algae	227
9.2.1	Use of Algae in the Food Industry	227
9.2.2	Macroalgae with Application Prospects in Food	230
9.2.3	Microalgae Application Prospects in Foods	231
9.3	Pharmacological Potential of Algae in Foods	232
9.3.1	Algae Produced Vitamins	232
9.4	Future and Prospect of Edible Algae	233
9.5	Conclusion	235
	References	235

10 Seasonal Variation of Phytoplanktonic Communities in Fishery Nurseries in the City of Inhumas (GO) and Its Surroundings	241
<i>Renato Araújo Teixeira, Gustavo de Paula Sousa, Josué Nazário de Lima, Thaynara de Moraes Maia, Marajá João Alves de Mendonça Filho, Joy Ruby Violet Stephen and Angel José Vieira Blanco</i>	
10.1 Introduction	242
10.2 Material and Methods	246
10.2.1 Materials	246
10.2.2 Methods	246
10.3 Results	246
10.4 Conclusion	259
References	260
11 Role of Genetical Conservation for the Production of Important Biological Molecules Derived from Beneficial Algae	263
<i>Charles Oluwasun Adetunji, Muhammad Akram, Babatunde Oluwafemi Adetuyi, Umme Laila, Muhammad Muddasar Saeed, Olugbemi T. Olaniyan, Inobeme Abel, Ruth Ebunoluwa Bodunrinde, Nyejirime Young Wike, Phebean Ononsen Ozolua, Wadzani Dauda Palnam, Olorunsola Adeyomoye, Arshad Farid and Shakira Ghazanfar</i>	
11.1 Introduction	264
11.2 Application of Algae in Various Fuels	265
11.3 Algae and Their Pharmaceutical Application	266
11.4 Relevance of Some Algae Derivative Components as Well as Their Effects on Human Health	268
11.5 Genetic Resources and Algae	270
11.6 Conclusions	270
References	270

12	Relevance of Biostimulant Derived from Cyanobacteria and Its Role in Sustainable Agriculture	281
	<i>Charles Oluwaseun Adetunji, Muhammad Akram, Fahad Said, Olugbemi T. Olaniyan, Inobeme Abel, Ruth Ebunoluwa Bodunrinde, Nyejirime Young Wike, Phebean Ononsen Ozolua, Wadzani Dauda Palnam, Arshad Farid, Shakira Ghazanfar, Olorunsola Adeyomoye, Chibuzor Victory Chukwu and Mohammed Bello Yerima</i>	
12.1	Introduction	282
12.2	Biostimulants Derived from Cyanobacteria for Boosting Agriculture	283
12.3	Modes of Action Involved in the Application Microorganism as Biostimulant	285
12.4	Conclusion and Future Recommendations	287
	References	287
13	Biofertilizer Derived from Cyanobacterial: Recent Advances	295
	<i>Charles Oluwaseun Adetunji, Muhammad Akram, Babatunde Oluwafemi Adetuyi, Fahad Said Khan, Abid Rashid, Hina Anwar, Rida Zainab, Mehwish Iqbal, Victoria Olaide Adenigba, Olugbemi T. Olaniyan, Inobeme Abel, Ruth Ebunoluwa Bodunrinde, Nyejirime Young Wike, Olorunsola Adeyomoye, Wadzani Dauda Palnam, Phebean Ononsen Ozolua, Arshad Farid, Shakira Ghazanfar, Chibuzor Victory Chukwu and Mohammed Bello Yerima</i>	
13.1	Introduction	296
13.2	Biological Fertilizers	298
13.3	Biofuel Production Technology	306
13.4	Significant of Biofertilizers	307
13.5	Relevance of Cyanobacteria	308
13.6	Cyanobacteria as Biofertilizer	308
13.7	Conclusion	311
	References	311
14	Relevance of Algae in the Agriculture, Food and Environment Sectors	321
	<i>Olotu Titilayo and Charles Oluwasun Adetunji</i>	
14.1	Introduction	321
14.2	Fourth Generation Biofuel: Next Generation Algae	323
14.3	Next Generation Algae: Application in Agriculture	323

14.4	Next Generation Algae: Application in the Environment	324
14.5	Conclusion	325
	References	325
15	Application of Biofuels for Bioenergy: Recent Advances	331
	<i>Charles Oluwaseun Adetunji, Muhammad Akram, Babatunde Oluwafemi Adetuyi, Fahad Said, Tehreem Riaz, Olugbemi T. Olaniyan, Inobeme Abel, Phebean Ononsen Ozolua, Ruth Ebunoluwa Bodunrinde, Nyejirime Young Wike, Wadzani Dauda Palnam, Arshad Farid, Shakira Ghazanfar, Olorunsola Adeyomoye, Chibuzor Victory Chukwu and Mohammed Bello Yerima</i>	
15.1	Introduction	332
15.2	General Overview	334
15.3	Algae Production and Cultivation	335
15.3.1	Harvesting	336
15.3.2	Genetically Modified Organisms	337
15.3.3	Growth Control	338
15.3.4	Production of Biofuels from Algae	338
15.3.5	Biochemical Conversion	338
15.3.6	Thermochemical Process	339
15.3.7	Transesterification	339
15.4	Algal Biofuels from Macroalgae	339
15.5	Algal Biofuels from Cyanobacteria and Microalgae	339
15.6	Types of Algal Biofuels	341
15.6.1	Hydrocarbons	341
15.6.2	Bioethanol	341
15.6.3	Isobutanol	341
15.6.4	Isoprene	342
15.6.5	Biodiesel	343
15.6.6	Biohydrogen	344
15.6.7	Biomethane	344
15.7	Biomass Supply	344
15.7.1	Biomass from Dedicated Energy Crops	345
15.7.2	Biomass Debris and Waste	345
15.8	Organic Material-Based Energy: CO ₂ Impartiality and Its Effects on Carbon Pools	346
15.9	Non-CO ₂ GHG Emissions in Bioenergy Systems	347
15.9.1	N ₂ O Emissions	347
15.9.2	CH ₄ Emanations	347
15.10	Microalgae for Biodiesel Production	348

15.10.1 Biodiesel Production	349
15.11 Futurity Progression in Bioenergy	349
15.11.1 Second Generation Biofuels	349
15.11.2 Biorefinery	350
15.12 Conclusion	351
References	351
Index	361

Preface

The global population is projected to reach 9 billion by the year 2050. It is imperative to begin preparing for the challenges that come with accommodating this rapidly growing population. One of the most significant challenges will be to ensure that we can provide adequate food and nutritious diets to this growing population, as well as a healthy environment. The orthodox agricultural practice has depended heavily on non-renewable inputs such as pesticides, fertilizers, herbicides, and insecticides. Due to the rapid pace of industrialization and the continuous growth of human population, we are witnessing an alarming increase in environmental pollution caused by various anthropogenic and industrial activities. This has resulted in extensive damage to our environment. The majority of these pollutants are derived from inappropriate utilization and discharge of industrial effluents, fertilizers, pesticides, smelting and mining of ores, as well as the release of automobile exhaust and effluent from storage batteries. Additionally, the release of metalloids, heavy metals, petrochemicals, and petroleum hydrocarbons also contribute significantly to the problem. However, their introduction has led to increased agricultural production and significant advancements for humankind, but the application of agrochemicals has also resulted in numerous environmental and health hazards. Algae have been identified as a sustainable biotechnological resource that could help in resolving several of these problems.

This book provides up-to-date and cutting-edge information on the application of algae in producing sustainable solutions to various challenges that arise from an increase in agricultural production, as well as its utilization in bioremediation of industrial wastewater. Moreover, this book provides detailed information about the recent advancements in smart microalgae wastewater treatment using Internet of Things (IoT) and edge computing applications. Other topics covered include the use of microalgae in various applications (with past, present and future projections); the use of algae to remove arsenic; algae's role in plastic biodegradation, heavy metal bioremediation, and toxicity removal from industrial

wastewater; the application of DNA transfer techniques in algae; the use of algae as food and in the production of food, ascorbic acid, health food, supplements, and food surrogates; relevant biostimulants and biofertilizers that could be derived from cyanobacterials and their role in sustainable agriculture; and algae's application in the effective production of biofuels and bioenergy.

This book is aimed at a diverse audience, including global leaders, industrialists, individuals in the food industry, agriculturists, the fishery sector, animal husbandry practitioners, investors, innovators, farmers, policy makers, extension workers, educators, researchers, and those in other interdisciplinary fields of science. It also serves as an educational resource manual and project guide for undergraduate and postgraduate students, as well as for educational institutions that seek to carry out research in the field of algae. Additionally, this book unites experts in relevant fields to describe the successful application of algae and its derivatives for bioremediation of extremely polluted environments, especially in water, air and soil. This book is highly recommended to a diverse community of professionals, scientists, environmentalists, industrialists, researchers, students in higher education, innovators, and policy makers who have an interest in bioremediation technologies and sustainable development.

I want to express my deepest appreciation to all the contributors who have dedicated their time and efforts to make this book a success. Furthermore, I want thank my coeditors for their effort and dedication during this project. Moreover, I wish to gratefully acknowledge the suggestions, help, and support of Martin Scrivener and others from Scrivener Publishing.

Charles Oluwaseun Adetunji

(Ph.D, AAS affiliate MNYA; MBSN; MNSM, MNBGN)

Dean Faculty of Science, Edo State University, Uzairue, Nigeria

March 2023

Smart Microalgae Wastewater Treatment: IoT and Edge Computing Applications with LCA and Technoeconomic Analysis

Mohd. Zafar^{1*}, Avnish Pareek¹, Taqi Ahmed Khan¹,
Ramkumar Lakshminarayanan² and Naveen Dwivedi³

¹*Department of Applied Biotechnology, College of Applied Sciences & Pharmacy,
University of Technology and Applied Sciences - Sur, Sultanate of Oman*

²*Department of Information Technology, College of Computing & Information
Sciences, University of Technology and Applied Sciences - Sur, Sultanate of Oman*

³*Department of Biotechnology, S. D. College of Engineering and Technology,
Muzaffarnagar, India*

Abstract

The application of microalgae in applied biotechnological studies for different bio-materials, such as biodiesel, bioethanol, and other high-value bioproducts, has been gaining attention in recent years. Large-scale integrated microalgae-wastewater treatment facilities have emerged as a promising technology. Technoeconomic and life cycle analyses of integrated algae technology in municipal wastewater treatment plants (WWTPs) can reveal its potential as a viable market technology. Thus, integrated microalgae WWTPs is seen as a promising field and is getting attention from the scientific community due to its multifold benefits in terms of nitrogen and phosphorous removal with reduction of organic load, accumulation of heavy metals, and simultaneous production of value-added biomaterials.

This chapter was designed to provide concise details on recent advancements in biological and technological approaches, LCA studies, and IoT and edge computing-based modeling and monitoring of integrated microalgae WWTPs with a technoeconomic feasibility analysis for its assessment as a promising market technology. It is noteworthy that stakeholders have an interest in integrated microalgae WWTPs, but are looking for a standardized process, including design,

*Corresponding author: mohdz.sur@cas.edu.om

Charles Oluwaseun Adetunji, Julius Kola Oloke, Naveen Dwivedi, Sabeela Beevi Ummalyma, Shubha Dwivedi, Daniel Ingo Hefft and Juliana Bunmi Adetunji (eds.) Next-Generation Algae: Volume I: Applications in Agriculture, Food and Environment, (1–48) © 2023 Scrivener Publishing LLC

data availability, and management aspects, along with a legislative framework that makes it simple to implement.

Keywords: Microalgae biorefinery, wastewater treatment, life cycle assessment, energy analysis, IoT and edge computing

1.1 Introduction

It is noteworthy that global warming is considered a major issue for many countries around the world. Due to the recent pace of industrialization and urbanization, the emission of different greenhouse gases (GHGs), such as carbon dioxide (CO_2), has led to climate change. Thus, the agreement between world nations known as the Kyoto Protocol was enforced in 1997 to ensure the specific reduction of GHGs by countries. Among the different GHGs, CO_2 is considered to be the largest contributor to the greenhouse effect, and CO_2 mitigation strategies will directly affect the total GHGs emissions. In order to remove the excess atmospheric CO_2 emission, the following methods have been adopted worldwide: (i) Physicochemical processes, including solvent scrubbing, adsorption, absorption, cryogenics and membranes, (ii) Ocean storage of CO_2 and (iii) Biological transformation and mitigation of CO_2 to organic matter using a biological system [1].

Globally, about a 40% water deficit is predicted by 2030, along with several unavoidable challenges associated with societal and economic development in view of current perspectives on the increasing demand for water and lack of water reclamation technology [2]. The conventional wastewater treatment processes, viz. aerobic activated sludge-based process, nitrification-denitrification, and phosphorous removal, are facing challenges to meet the stringent nutrients discharge standards and a large amount of wastewater effluent is still being discharged with nutrients contents, resulting in eutrophication in the aquatic environment [2]. In addition, there are several other disadvantages, such as the high energy consumption, carbon emission, additional sludge discharge, and instability associated with these conventional processes, which can hinder the sustainability-based low carbon, low energy consumption, and resource recycling associated wastewater treatment [1].

Thus, the microalgae-related wastewater treatment (MBWT) process has been gaining attention in recent years and is considered as one of the most promising advanced technologies for sustainable wastewater treatment and efficient nutrient recovery from wastewater. The feasibility

of microalgae-related treatment of wastewater generated from different sources, such as municipal, agricultural, and industrial, is being exploited as a tertiary wastewater treatment by many researchers because of its advantages as a highly efficient process for nutrient removal [3–7]. A symbiotic relationship between microalgae and the bacterial population of wastewater was reported by Oswald *et al.*, who observed the efficiency of microalgae in the enhancement of hazardous compounds removal with protection of the bacterial population [8]. Under symbiotic relationship, microalgae utilize CO_2 (produced through aerobic metabolism of bacteria) through the process of photosynthesis and generated O_2 could be utilized by the heterotrophic bacterial population for the assimilation of waste organic compounds. This created the idea of utilizing microalgae for wastewater treatment for the removal of excess nutrients of wastewater effluent and to reduce the risk of the eutrophication threat to natural water bodies. Furthermore, the microalgal biomass produced in wastewater treatment could be considered for “value-added product from waste” as a feedstock in further biorefinery processes [9–11] (Figure 1.1).

In this chapter, recent advancements with respect to diversity of microalgae, process system, internet of things (IoT) and edge computing-based process monitoring and control, and life cycle assessment (LCA)-based techno-economic feasibility analysis of microalgae-based wastewater treatment process are discussed. The details of psychrophilic, thermophilic and acidophilic microalgae and their roles in high-tech, low-cost, and environmentally friendly wastewater treatment process are discussed. Also, the different process systems associated with CO_2 bio-fixation with simultaneous

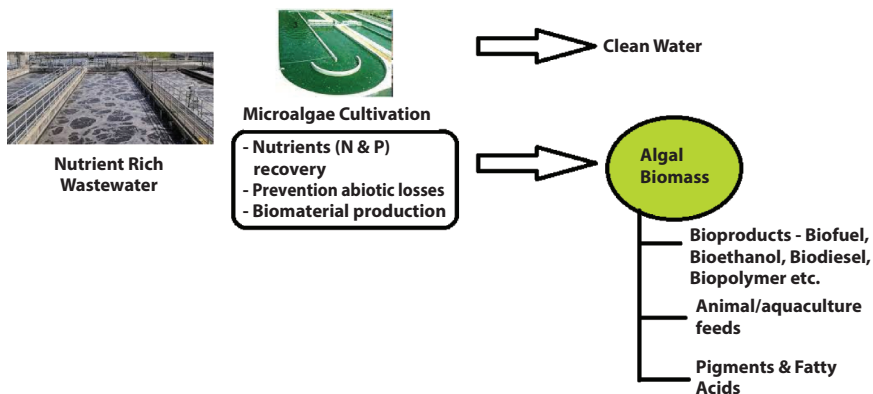


Figure 1.1 Resource recovery from microalgae-based wastewater treatment system for circular bioeconomy.

wastewater treatment are discussed. In addition, the application of emerging technologies, such as IoT automation, to microalgae-related technologies and machine learning approaches for data acquisition, monitoring and analysis of microalgae-based wastewater treatment system is discussed in view of the establishment of an integrated microalgae-wastewater treatment-based biorefinery and bioeconomy. Finally, the evaluation of microalgae-based carbon capture technology associated with wastewater is provided in terms of life cycle assessment, emergy analysis, and material flow analysis.

1.2 Importance and Potential of Extremophilic Microalgae-Based Wastewater Treatment (WWT) Plant

The essential importance of water to life on Earth is threatened by water pollution, which is a significant environmental concern [12]. Water contamination may be caused by anthropogenic or natural activity. The most important causes of human-made water pollution are harmful products from manufacturing processing and effluent making from businesses such as petrochemical plants and pulp and paper mills [13]. The hazardous and carcinogenic organic pollution emitted by crude oil, pharma, petrochemical and coal industries is recognized as being phenol and phenol compounds [14, 15]. Several research studies have examined the biological removal by microalgae of carbonate, nitrogen, and phosphorus through wastewater fluids. Different microalgal species are used in diverse types of wastewaters, including municipal, farming, brewery, refineries and industrial effluents with different efficiencies of treatment and microalgal growth [16–18].

There are numerous benefits to biological approaches, with certain microorganisms reporting degradation of phenols and phenolic compounds up to 1 g/L [15, 19]. The focus on harsh conditions has grown throughout the last few decades, resulting in a pure culture being obtained of unidentified extremophilic microorganisms and their associated metabolites [20]. Such extremophilic bacteria can provide crucial knowledge about ecological and biochemical responses and can lead to biotechnology or commercial uses [21, 22]. Extreme thermophiles currently have great potential and, while utilizing a contemporary understanding of genetics of these microbes, their application in renewable feedstock production by means of metabolic engineering will further increase [23]. Thermophilic

microalgae are also used to find enough enzymes that then are integrated into plant genomes to increase their output and resistance to production [15]. Micro-algae separation and selection allow high quantities of biomass and important chemicals such as lipids to be produced in an industrial way [22, 24, 25]. The capacity to extract ammonium from wastewater at temperatures of 40-42 °C and light intensities of 2,500 $\mu\text{mol m}^2/\text{s}$ for 5 h in a day was studied using a green microalga *Chlorella sorokiniana* isolated from a wastewater stabilization pond at La Paz, Baja California Sur, Mexico [15, 26]. Thermophilic microalgae may obviously be utilized as a gene pool to identify thermostable enzymes which can be employed in dry locations for improved stability and culture in such settings [27]. Thermophilic microalgae are becoming increasingly more important since they can live at high CO_2 levels. This characteristic makes them attractive candidates for CO_2 emissions from industrial flue gases and adds a step towards global warming reduction. Thermophilic microalgae are efficiently employed to bioremediate harmful industrial effluents and wastewater regardless of origin [15].

1.3 Status of Microalgae-Based WWT Plants

1.3.1 Conditions and Requirements (Abiotic and Biotic Requirements, Nutrients Requirement)

Wastewater remediation is required for preventing pollution and contamination of freshwater bodies as well as for effective reuse of the treated wastewater for sustainability. An ever-increasing population, reduction of freshwater availability, expanding industrialization, and growing human development index (HDI) has increased the demand for wastewater recycling and its sustainable utilization to help manage the precious potable water resources globally in the 21st century [28].

Wastewater is treated conventionally using four types of treatment methods based on the technology used or the category of inflow water. The different treatment plant types are sewage treatment plants (STPs), effluent treatment plants (ETPs), activated sludge plants (ASPs), and common and combined effluent treatment plants (CETPs). Most of the resultant treated water is used for non-potable applications after secondary treatments itself because of technological and/or logistical limitations [29, 30] and non-mandatory status of the tertiary treatment. However, this type of treated water often does not meet the minimum quality standards of water reuse and once released into water bodies it rapidly brings down

the dissolved oxygen (DO) and causes pH fluctuation, resulting in the creation of dead aquatic zones and an increase in the overall toxicity [31, 32]. Moreover, these conventional wastewater treatment plants (CWWTPs) are energy intensive and require high operational and maintenance cost [33, 34]. In such a scenario, where the conventional systems are already posing challenges, an ever-increasing population will further stress the global wastewater treatment and reuse scenario as the nutrient load of nitrogen and phosphorus will increase, which will further call for a mandatory tertiary treatment [35–38]. Studies have shown that microalgae are excellent candidates for nitrogen and phosphorus removal and are better than other classes of microorganisms. Being photosynthetic and highly adaptive in their environment, microalgae are also considered the best candidates for tertiary treatment systems. The autotrophic nature of these organisms reduces the system's energy footprint and atmospheric carbon sequestering along with N and PO_4^- removal, which is an added bonus to the environment [39–44].

Wastewaters are complex systems, their treatment is not as straightforward as often understood in terms of biochemical oxygen demand (BOD), chemical oxygen demand (COD) and sludge. Their temporal and spatial characteristics depend on their source, geophysical conditions, factors such as temperature and pH, effluent and nutrient load, physical and chemical impurities, biotic load and flow regime, treatment system size, treatment protocol, transformation products and treatment technology, etc. Besides the composition of the wastewater, wastewater treatment at a national/regional level also depends upon the environmental policy, water resource availability, water withdrawn and water stress [45]. Nevertheless, the present discussion is focused on microalgae-based wastewater treatment plants and only the factors that directly affect these plants will be discussed in this section. The following table shows some of the recent works on biotic and abiotic factors of microalgae-based WWT. This will help to develop more clarity on biotic-abiotic factors and growth conditions for microalgae as well as its potential as a wastewater treatment candidate. From Table 1.1 it can be clearly understood that microalgae are a good candidate for nitrogen and phosphorus removal under all different system configurations. They are even effective in untreated wastewaters and can be employed along with conventional treatment methods. It can be further observed from the literature cited in the table that the best results are obtained with natural consortia instead of using a single isolated species [39]. In addition to the use of natural consortia, a combination with aerobic bacteria seems to give better results as has been suggested in many studies in the literature cited in this table. It is also proved that aerobic

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement.

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Lighting, pH Temperature CO ₂ Total Nitrogen (TN) Total Phosphorus (TP)	Species of microalgae and bacterial consortia, cell density, cell size and biovolume <i>Franceia amphitricha</i> <i>Scenedesmus</i> sp. <i>Chlorella</i> sp. <i>Chlorellaceae</i> <i>Chlamydomonas</i> sp. <i>Desmodesmus</i> sp.	New isolated species	Anaerobic digested (AD) effluent sample	600-L horizontal tubular photo-bioreactors	- 99% removal of (TN) and Total Phosphorus (TP).	[40]

(Continued)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. (Continued)

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Irradiance Temperature Orbital Shaking	3 fluoroquinolones- ofloxacin, ciprofloxacin, norfloxacin; 3 macrolides - azithromycin, erythromycin, clarithromycin; and 3 antibiotics - trimethoprim, piperimidic acid, sulfapyridine	<i>Chlamydomonas reinhardtii</i> (UTEX ID 2243), <i>Chlorella sorokiniana</i> (UTEX ID 1663), <i>Dunaliella tertiolecta</i> (UTEX ID LB999) and <i>Pseudokirchneriella subcapitata</i> (UTEX ID 1648)	Direct toilet water	1200L Photobioreactor and a suspect screening methodology for assessment of the transformation products (TPs) generated from 9 antibiotics	- Microalgae ability for macrolide biotransformation. -40 different TPs were identified.	[53]
COD, TSS, Total nitrogen (TN), Total Phosphorus (TP) pH, Temp Total solar irradiance	Interaction of several species	<i>Leptolyngbya</i> sp. <i>Synechococcus</i> sp. <i>Chlorella</i> sp. <i>Parachlorella</i> sp. <i>Dictyosphaerium</i> sp. <i>Scenedesmus</i> sp. <i>Desmodesmus</i> sp. <i>Pediastrum</i> sp. <i>Zooplankton Daphnia</i> sp.	Untreated influent wastewater	High-rate algal ponds (HRAPs)	- Microalgae biodiversity plays critically essential role in high productivity of HRAPs treating municipal wastewater.	[54]

(Continued)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. (Continued)

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
CO ₂ , NO ₃ ⁻ , SO ₄ ²⁻ , pH, Light, temperature, wind (m/s), precipitation (mm), relative humidity (%) DO	Consortium of local freshwater green algae	<i>Chlorella</i> sp., <i>Scenedesmus</i> <i>dimorphus</i> , <i>Scenedesmus</i> <i>quadricauda</i> , and <i>Desmodesmus</i> <i>armatus</i> , <i>Coelastrum</i> <i>microporum</i>	Municipal untreated wastewater and CO ₂ from CHP plant	Raceway pond systems	- In wastewater treatment process, the interaction between bacteria and microalgae plays a crucial role.	[55]
nitrogen (N), phosphorus (P), magnesium (Mg), carbonate (CO ₃) and gamma radiation	-	<i>Chlorella vulgaris</i>	Synthetic media	Lab-scale setup	- Biomass increase with high N and P and low Mg and CO ₃ , Lipid accumulation increase with low N and P and high Mg and CO ₃ . - Gamma radiation has negative effect on biomass and lipid accumulation.	[56]

(Continued)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. *(Continued)*

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Autotrophic and heterotrophic growth conditions	-	<i>Auxenochlorella protothecoides</i>	Synthetic media	Lab-scale setup	- Hub genes defined	[57]
Ammonium urea, and Nitrate as nitrogen source	Algal consortium	<i>Tetraselmis</i> sp. (UTEX LB 2767), <i>Raphidocelis subcapitata</i> (UTEX 1648), <i>Chlamydomonas reinhardtii</i> (UTEX 2243), and <i>Scenedesmus obliquus</i> (UTEX 393) <i>Navicula</i> sp.	Wastewater as a feedstock	Lab-scale setup	- In heterogeneous nitrogen environments, functional diversity increases with species complementarity and productivity	[58]

(Continued)

Table 1.1 Microalgae-based WWT abiotic and biotic requirements, nutrients requirement. (*Continued*)

Abiotic factor	Biotic factor	Organism used	Treatment level/ sampling	Treatment system	Findings	Reference
Ammonium as Nitrogen source	Bacteria derived from the AD effluents interactions with the <i>Chlorella</i> species	<i>Chlorella vulgaris</i> (KCTC AG10002) and <i>Chlorella protothecoides</i> (UTEX 1806)	AD effluents from four different lab-scale anaerobic digesters	Lab-scale setup	- A viable way to treat and value-add the wastewater effluents by <i>Chlorella</i> cultured on AD effluents	[59]
pH, EC, TS, TDS, TSS, DO, COD, Ammonia, Nitrate, Phosphate	Varying concentrations of same algal species at different HRT	<i>Chlorella vulgaris</i>	Raw domestic wastewater	Lab-scale setup	- Addition of microalgae to CWWTs can be a solution for pollution control	[32]
pH Nitrogen and phosphorus	Microalgae consortia	Different naturally occurring sewage algal species	Comparative study on wastewater and artificial media	Lab-scale setup	- Microalgae consortia has effectively removed phosphate and nitrogen with real wastewater instead of from synthetic media	[44]

bacteria support microalgal photosynthetic rates by reducing the micro-environments around the microalga and thereby help faster, better, energy smart and sustainable treatment of wastewater; whereas the conventional wastewater treatment is both oxygen and energy intensive, and thus less environmentally friendly and less sustainable [46]. Moreover, from Table 1.1, it can be further observed that if the microalgae are autotrophic there are fewer requirements on the surrounding media and the biomass produced can be further utilized or valorized, unlike the CWWTs [30, 42, 47, 48]. Microalgae has proven to be good in most of the wastewater treatment studies, except for complex wastes like phenols [49] and hydrocarbons [40, 50–52].

1.3.2 Microalgae-Based WWT System – Photobioreactor System in Suspension and Immobilized Model

Microalgae culture systems are vast. In wastewater treatment, local consortia of microalgae is preferably cultured in open raceway ponds or high-rate algal ponds (HRAPs). However, algae cultivation is done in a photobioreactor (PBR) either for culture valorization, biomaterial production or for high lipid production as well as to study the finer nuances of R&D on a specific species or an improved strain [60–62]. Nevertheless, the use of a photobioreactor for treatment of wastewater could undermine the overall cost and energy efficiency [63].

Microalgae is adventitious over filamentous as well as macroalgae in terms of its feasibility of culture in suspension as well as in immobilized forms [64]. With the advancement of information technology, control and feedback loops, automation, etc., PBR has gone from lab scale to pilot scale in the last two decades. Although giving a complete overview of the two decades of PBR algal cultivation is difficult and beyond the scope here, a few suspensions and immobilized algal culture studies are presented in Table 1.2.

1.3.3 Evaluation of Treatment Performance

Performance evaluation (PE) of a system is important for optimization of a process and is extensively applied in wastewater treatment processes. It is reported that the PE data do not provide suitable operational information for the optimization of individual units involved in a WWTP; however, they are important indicators for the overall performance of the system [78]. A good system performance can significantly reduce the operation