

## Contents

**Foreword** *xxvii*

**Preface** *xxix*

### **Part I Modern Perspective of Zero Waste Drives 1**

- 1 Anaerobic Co-digestion as a Smart Approach for Enhanced Biogas Production and Simultaneous Treatment of Different Wastes 3**  
*S. Bharathi and B. J. Yogesh*
- 1.1 Introduction 3
- 1.1.1 Biodegradation – Nature’s Art of Recycling 3
- 1.1.2 Anaerobic Digestion (AD) 4
- 1.1.3 Sustainable Biomethanation 5
- 1.2 Anaerobic Co-digestion (AcD) 5
- 1.2.1 Zero Waste to Zero Carbon Emission Technology 6
- 1.2.2 Alternative Feedstocks 6
- 1.2.3 Microbiological Aspects 8
- 1.2.4 Strategies for Inoculum Development 8
- 1.2.5 Real-Time Monitoring of AcD 9
- 1.2.5.1 The pH Fluctuations 10
- 1.2.5.2 Carbon–Nitrogen Content 11
- 1.2.5.3 Temperature 11
- 1.2.5.4 Volatile Fatty Acids 12
- 1.2.5.5 Ammonia 12
- 1.2.5.6 Organic Loading Rate 12
- 1.3 Digester Designs 13
- 1.4 Digestate/Spent Slurry 14
- 1.5 Conclusion 15
- References 15

<b>2</b>	<b>Integrated Approaches for the Production of Biodegradable Plastics and Bioenergy from Waste</b>	<b>19</b>
	<i>Chandan Kumar Sahu, Mukta Hugar, and Ravi Kumar Kadeppagari</i>	
2.1	Introduction	19
2.2	Food Waste for the Production of Biodegradable Plastics and Biogas	19
2.2.1	Biodegradable Plastics from Food Waste	20
2.2.2	Food Waste and Bioenergy	21
2.2.2.1	Ethanol from Food Waste	21
2.2.2.2	Food Waste to Biohydrogen	21
2.2.2.3	Production of Biogas from Food Waste	21
2.3	Dairy and Milk Waste for the Production of Biodegradable Plastics and Biogas	22
2.3.1	Biodegradable Plastics and Dairy Waste	22
2.3.2	PHB Production in Fermenter	22
2.3.3	Bioenergy from Dairy and Milk Waste	22
2.4	Sugar and Starch Waste for the Production of Biodegradable Plastics and Biogas	23
2.4.1	Sugar Waste	23
2.4.1.1	Sugar Waste and PHA	23
2.4.1.2	Bioenergy from Sugar Waste	24
2.4.2	Starch Waste	24
2.4.2.1	Biodegradable Plastics and Starch Waste	25
2.4.2.2	Bioenergy from Starch Waste	25
2.5	Wastewater for the Production of Biodegradable Plastics and Bioenergy	25
2.5.1	Biodegradable Plastics from Wastewater	26
2.5.1.1	Production of PHA from Wastewater	26
2.5.1.2	Production of PHB	26
2.5.2	Production of Bioenergy	26
2.6	Integrated Approaches for the Production of Biodegradable Plastics and Bioenergy from Waste	27
2.7	Conclusions	28
	References	28
<b>3</b>	<b>Immobilized Enzymes for Bioconversion of Waste to Wealth</b>	<b>33</b>
	<i>Angitha Balan, Vaisiri V. Murthy, and Ravi Kumar Kadeppagari</i>	
3.1	Introduction	33
3.2	Enzymes as Biocatalysts	34
3.3	Immobilization of Enzymes	35
3.3.1	Enzyme Immobilization Methods	35
3.3.1.1	Adsorption	35
3.3.1.2	Covalent Bonding	36
3.3.1.3	Affinity Immobilization	36
3.3.1.4	Entrapment	36

3.3.2	Advantages of Immobilizing Enzymes	37
3.3.2.1	Stabilization	37
3.3.2.2	Flexibility of Bioreactor Design	37
3.3.2.3	Reusability and Recovery	38
3.4	Bioconversion of Waste to Useful Products by Immobilized Enzymes	38
3.4.1	Utilization of Protein Wastes	39
3.4.2	Carbohydrates as Feedstock	39
3.4.3	Utilization of Polysaccharides	40
3.4.4	Lipids as Substrates	41
3.5	Applications of Nanotechnology for the Immobilization of Enzymes and Bioconversion	41
3.6	Challenges and Opportunities	43
	Acknowledgments	43
	References	44

## **Part II Bioremediation for Zero Waste 47**

<b>4</b>	<b>Bioremediation of Toxic Dyes for Zero Waste</b>	<b>49</b>
	<i>Venkata Krishna Bayineni</i>	
4.1	Introduction	49
4.2	Background to Dye(s)	50
4.3	The Toxicity of Dye(s)	50
4.4	Bioremediation Methods	51
4.4.1	Types of Approaches: <i>Ex situ</i> and <i>In situ</i>	51
4.4.2	Microbial Remediation	52
4.4.2.1	Aerobic Treatment	52
4.4.2.2	Anaerobic Treatment	52
4.4.2.3	Aerobic–Anaerobic Treatment	52
4.4.3	Decolorization and Degradation of Dyes by Fungi	53
4.4.4	Decolorization and Degradation of Dyes by Yeast	53
4.4.5	Decolorization and Degradation of Dyes by Algae	53
4.4.6	Bacterial Decolorization and Degradation of Dyes	54
4.4.6.1	Factors Affecting Dye Decolorization and Degradation	54
4.4.7	Microbial Decolorization and Degradation Mechanisms	58
4.4.7.1	Biosorption	58
4.4.7.2	Enzymatic Degradation	58
4.4.8	Decolorization and Degradation of Dyes by Plants (Phytoremediation)	58
4.4.8.1	Plant Mechanism for Treating Textile Dyes and Wastewater	60
4.4.8.2	Advantages of Phytoremediation	60
4.4.9	Integrated Biological, Physical, and Chemical Treatment Methods	60
4.4.10	rDNA Technology	60
4.4.11	Enzyme-Mediated Dye Removal	62
4.4.12	Immobilization Techniques	62

4.5	Conclusion	63
	References	63
<b>5</b>	<b>Bioremediation of Heavy Metals</b>	<b>67</b>
	<i>Tanmoy Paul and Nimai C. Saha</i>	
5.1	Introduction	67
5.2	Ubiquitous Heavy Metal Contamination – The Global Scenario	68
5.3	Health Hazards from Heavy Metal Pollution	69
5.4	Decontaminating Heavy Metals – The Conventional Strategies	71
5.5	Bioremediation – The Emerging Sustainable Strategy	72
5.5.1	Intervention of Metal Contamination by Microbial Adaptation	72
5.5.1.1	Genetic Circuitry Involved in Microbial Bioremediation	74
5.5.1.2	Different Heavy Metal–Resistant Mechanisms	74
5.5.2	Plant-Assisted Bioremediation (Phytoremediation)	75
5.5.3	Algae-Assisted Bioremediation (Phycoremediation)	77
5.5.4	Fungi-Assisted Bioremediation (Mycoremediation)	77
5.6	Conclusion	78
	References	79
<b>6</b>	<b>Bioremediation of Pesticides Containing Soil and Water</b>	<b>83</b>
	<i>Veena S. More, Allwin Ebinesar Jacob Samuel Sehar, Anagha P. Sheshadri, Sangeetha Rajanna, Anantharaju Kurupalya Shivram, Aneesa Fasim, Archana Rao, Prakruthi Acharya, Sikandar Mulla, and Sunil S. More</i>	
6.1	Introduction	83
6.2	Pesticide Biomagnification and Consequences	84
6.3	Ill Effects of Biomagnification	84
6.4	Bioremediation	85
6.5	Methods Used in Bioremediation Process	86
6.5.1	<i>In Situ</i> Method	87
6.5.1.1	Bioaugmentation	87
6.5.1.2	Bioventing	87
6.5.1.3	Biosparging	87
6.5.1.4	Biostimulation	87
6.5.2	<i>Ex Situ</i> Methods	87
6.5.2.1	Composting	87
6.5.2.2	Land farming	88
6.5.2.3	Biopiles	88
6.5.2.4	Bioreactors	88
6.6	Bioremediation Process Using Biological Mediators	88
6.6.1	Bacterial Remediation	88
6.6.2	Fungal Remediation	89
6.6.3	Phytoremediation	89
6.7	Factors Affecting Bioremediation	90
6.7.1	Soil Type and Soil Moisture	90
6.7.2	Oxygen and Nutrients	90

- 6.7.3 Temperature and pH 90
- 6.7.4 Organic Matter 91
- 6.8 Future Perspectives 91
- References 91

## **7 Bioremediation of Plastics and Polythene in Marine Water 95**

*Tarun Gangar and Sanjukta Patra*

- 7.1 Introduction 95
- 7.2 Plastic Pollution: A Threat to the Marine Ecosystem 96
- 7.3 Micro- and Nanoplastics 96
  - 7.3.1 Microplastics 97
    - 7.3.1.1 Toxicity of Microplastics 98
    - 7.3.2 Nanoplastics 99
  - 7.4 Microbes Involved in the Degradation of Plastic and Related Polymers 99
    - 7.4.1 Biodegradation of Plastic 99
      - 7.4.1.1 Polyethylene (PE) 100
      - 7.4.1.2 Polyethylene Terephthalate (PET) 101
      - 7.4.1.3 Polystyrene (PS) 101
    - 7.5 Enzymes Responsible for Biodegradation 101
    - 7.6 Mechanism of Biodegradation 102
      - 7.6.1 Formation of Biofilm 102
      - 7.6.2 Biodeterioration 103
      - 7.6.3 Biofragmentation 103
      - 7.6.4 Assimilation 103
      - 7.6.5 Mineralization 104
  - 7.7 Biotechnology in Plastic Bioremediation 104
  - 7.8 Future Perspectives: Development of More Refined Bioremediation Technologies as a Step Toward Zero Waste Strategy 106
  - Acknowledgment 106
  - Conflict of Interest 107
  - References 107

## **Part III Biological Degradation Systems 111**

### **8 Microbes and their Consortia as Essential Additives for the Composting of Solid Waste 113**

*Mansi Rastogi and Sheetal Barapatre*

- 8.1 Introduction 113
- 8.2 Classification of Solid Waste 113
- 8.3 Role of Microbes in Composting 114
- 8.4 Effect of Microbial Consortia on Solid Waste Composting 116
- 8.5 Benefits of Microbe-Amended Compost 119
- References 119

<b>9</b>	<b>Biodegradation of Plastics by Microorganisms</b>	<b>123</b>
	<i>Md. Anisur R. Mazumder, Md. Fahad Jubayer, and Thottiam V. Ranganathan</i>	
9.1	Introduction	123
9.2	Definition and Classification of Plastics	124
9.2.1	Definition of Plastic	124
9.2.2	Classification	125
9.2.2.1	Based on Biodegradability	125
9.2.2.2	Based on Structure and Thermal Properties	126
9.2.2.3	Characteristics of Different Biodegradable Plastics	126
9.3	Biodegradation of Plastics	128
9.3.1	General Outline	128
9.3.2	Biodegradation Phases and End Products	129
9.3.2.1	Aerobic Biodegradation	129
9.3.2.2	Anaerobic Biodegradation	130
9.3.3	Mechanism of Microbial Degradation of Plastic	130
9.3.4	Factors Affecting Biodegradation of Plastics	131
9.3.5	Microorganisms Involved in the Biodegradation Process	132
9.3.6	Enzymes Involved in the Plastic Biodegradation	133
9.3.6.1	Cutinases (EC 3.1.1.74)	135
9.3.6.2	Lipases (EC 3.1.1.3)	135
9.3.6.3	Carboxylesterases (EC 3.1.1.1)	135
9.3.6.4	Proteases	135
9.3.6.5	Lignin Modifying Enzymes	136
9.4	Current Trends and Future Prospects	136
	List of Abbreviations	137
	References	138
<b>10</b>	<b>Enzyme Technology for the Degradation of Lignocellulosic Waste</b>	<b>143</b>
	<i>Swarna Haldar and Soumitra Banerjee</i>	
10.1	Introduction	143
10.2	Enzymes Required for the Degradation of Lignocellulosic Waste	144
10.2.1	Degradation of Cellulose	144
10.2.1.1	Microbial Production of Cellulase	144
10.2.1.2	Enzymes Responsible for Cellulose Degradation	145
10.2.1.3	Physical Pre-treatments to Break down Cellulose	145
10.2.2	Degradation of Hemicellulose	146
10.2.2.1	Enzymes Responsible for Degradation of Hemicellulose	146
10.2.2.2	Microbial Production of Hemicellulases	147
10.2.2.3	Physical Pre-treatments to Break down Hemicellulose	147
10.2.3	Degradation of Lignin	148
10.2.3.1	Microbial Production of Lignin Degrading Enzymes	148
10.2.3.2	Enzymes Responsible for the Degradation of Lignin	148
10.2.4	Degradation of Pectin	149
10.3	Utilizing Enzymes for the Degradation of Lignocellulosic Waste	150

- 10.4 Conclusion 150  
References 150

**11 Usage of Microalgae: A Sustainable Approach to Wastewater Treatment 155**

*Kumudini B. Satyan, Michael V. L. Chhandama, and Dhanya V. Ranjit*

- 11.1 Introduction 155
- 11.1.1 Microalgae 156
- 11.1.2 Composition of Wastewater 157
- 11.2 Microalgae for Wastewater Treatment 158
- 11.2.1 Biological Oxygen Demand (BOD) 159
- 11.2.2 Chemical Oxygen Demand (COD) 159
- 11.2.3 Nutrients (Nitrogen and Phosphorus) 160
- 11.2.4 Heavy Metals 160
- 11.2.5 Xenobiotic Compounds 161
- 11.3 Cultivation of Microalgae in Wastewater 162
- 11.3.1 Factors Affecting the Growth of Microalgae 162
- 11.3.1.1 TN:TP Ratio 162
- 11.3.1.2 pH 162
- 11.3.1.3 Light 162
- 11.3.2 Algal Culture Systems 163
- 11.3.2.1 Open Systems 163
- 11.3.2.2 Closed Systems 164
- 11.4 Algae as a Source of Bioenergy 164
- 11.4.1 Biodiesel from Microalgae 165
- 11.4.2 Bioethanol from Microalgae 165
- 11.4.3 Biomethane from Microalgae 165
- 11.4.4 Hydrogen Production 165
- 11.4.5 Microbial Fuel Cells 166
- 11.5 Conclusion 166  
References 166

**Part IV Bioleaching and Biosorption of Waste: Approaches and Utilization 171**

**12 Microbes and Agri-Food Waste as Novel Sources of Biosorbents 173**

*Simranjeet Singh, Praveen C. Ramamurthy, Vijay Kumar, Dhriti Kapoor, Vaishali Dhaka, and Joginder Singh*

- 12.1 Introduction 173
- 12.2 Conventional Methods for Agri-Food Waste Treatment 175
- 12.3 Application of the Biosorption Processes 176
- 12.3.1 Removal of Inorganic Pollutants 176
- 12.3.2 Removal of Organic Pollutants 177

12.4	Use of Genetically Engineered Microorganisms and Agri-Food Waste	178
12.5	Biosorption Potential of Microbes and Agri-Food Waste	179
12.6	Modification, Parameter Optimization, and Recovery	180
12.6.1	Modification	181
12.6.2	Parameters	182
12.6.3	Recovery	182
12.7	Immobilization of Biosorbent	182
12.8	Conclusions	183
	References	185
<b>13</b>	<b>Biosorption of Heavy Metals and Metal-Complexed Dyes Under the Influence of Various Physicochemical Parameters</b>	<b>189</b>
	<i>Allwin Ebinesar Jacob Samuel Sehar, Veena S. More, Amrutha Gudibanda Ramesh, and Sunil S. More</i>	
13.1	Introduction	189
13.2	Mechanisms Involved in Biosorption of Toxic Heavy Metal Ions and Dyes	191
13.3	Chemistry of Heavy Metals in Water	191
13.4	Chemistry of Metal-Complexed Dyes	192
13.5	Microbial Species Used for the Removal of Metals and Metal-Complexed Dyes	192
13.5.1	Biosorption of Zinc Using Bacteria	192
13.5.2	Biosorption of Heavy Metals by Algae	193
13.5.3	Removal of Toxic Heavy Metals by Fungi	194
13.5.4	Biosorption of Heavy Metals Using Yeast	194
13.6	Industrial Application on the Biosorption of Heavy Metals	195
13.6.1	Biosorption of Heavy Metals Using Fluidized Bed Reactor	195
13.6.2	Biosorption of Heavy Metals by Using Packed Bed Reactors	197
13.7	Biosorption of Reactive Dyes	198
13.8	Metal-Complexed Dyes	199
13.9	Biosorption of Metal-Complexed Dyes	200
13.10	Conclusion	203
	References	203
<b>14</b>	<b>Recovery of Precious Metals from Electronic and Other Secondary Solid Waste by Bioleaching Approach</b>	<b>207</b>
	<i>Dayanand Peter, Leonard Shruti Arputha Sakayaraj, and Thottiam Vasudevan Ranganathan</i>	
14.1	Introduction	207
14.2	What Is Bioleaching?	208
14.2.1	Mechanism of Bioleaching	208
14.2.2	Industrial Processes of Bioleaching	209
14.2.3	Factors Affecting Bioleaching	209



- 14.2.4 Advantages of Bioleaching Over Other Methods 210
- 14.2.5 Limitation of Bioleaching Over Other Methods 210
- 14.3 E-Waste, What Are They? 210
  - 14.3.1 E-Waste Production Scale 211
  - 14.3.2 Pollution Caused by E-Waste 211
  - 14.3.3 General Methods of E-Waste Treatment 212
- 14.4 Role of Microbes in Bioleaching of E-Waste 212
  - 14.4.1 Bacteria 212
  - 14.4.2 Fungi 213
  - 14.4.3 Actinobacteria and Cyanogenic Organisms 213
- 14.5 Application of Bioleaching for Recovery of Individual Metals 214
  - 14.5.1 Gold 214
  - 14.5.2 Silver 215
  - 14.5.3 Copper 215
  - 14.5.4 Nickel 215
- 14.6 Large-Scale Bioleaching of E-Waste 215
- 14.7 Future Aspects 215
  - List of Abbreviations 216
  - References 216

## Part V Bioreactors for Zero Waste 219

- 15 Photobiological Reactors for the Degradation of Harmful Compounds in Wastewaters 221**
  - Naveen B. Kilaru, Nelluri K. Durga Devi, and Kondepati Haritha*
  - 15.1 Introduction 221
  - 15.2 Photobiological Agents and Methods Used in PhotoBiological Reactors 222
    - 15.2.1 Microbes Acting as Photobiological Agents in Various Photobiological Reactors for the Remediation of Wastewater 222
      - 15.2.1.1 Olive Mill Wastewater Treatment by Immobilized Cells of *Aspergillus niger* 222
      - 15.2.1.2 Isolation of Alkane-Degrading Bacteria from Petroleum Tank Wastewater 224
      - 15.2.1.3 Development of Microbubble Aerator for Wastewater Treatment by Means of Aerobic Activated Sludge 224
      - 15.2.1.4 Wastewater Produced from an Oilfield and Incessant Treatment with an Oil-Degrading Bacterium 225
      - 15.2.1.5 Pepper Mild Mottle Virus (a Plant Pathogen) as an Apt to Enteric Virus 225
      - 15.2.1.6 Cyanobacteria as a Bio-resource in Making of Bio-fertilizer and Biofuel from Wastewaters 226
      - 15.2.1.7 Bio-sorption of Copper and Lead Ions by Surplus Beer Yeast 226

- 15.2.1.8 Organization of Lipid-Based Biofuel Production with Waste Treatment Using Oleaginous Bacteria 227
- 15.2.1.9 Anaerobic Degradation of Textile Dye Bath Effluent Using *Halomonas* Species 228
- 15.2.1.10 Laccase Production on *Eichhornia crassipes* Biomass 229
- 15.2.1.11 Algae–Bacteria Interaction in Photo-Bioreactors 230
- 15.2.1.12 Photo Sequence Batch Reactor 230
- 15.2.1.13 Detection of *su11* and *su12* Genes in Sulfonamide-Resistant Bacteria (SRB) from Sewage, Aquaculture Sources, Animal Wastes, and Hospital Wastewater 231
- 15.2.1.14 Photosynthetic Bacteria as a Potential Alternative to Meet Sustainable Wastewater Treatment Requirement 231
- 15.2.1.15 Anaerobic Fermentation for the Production of Short-Chain Fatty Acids by Acidogenic Bacteria 232
- 15.2.2 Use of Photolytic and Photochemical Methods in Various Photobiological Reactors for Treatment of Wastewater 233
- 15.2.2.1 Photo-Enhanced Degradation of Contaminants of Emerging Concern in Wastewater 233
- 15.2.2.2 Pond Reactors (Photo-Fenton Process) 233
- 15.2.2.3 Photochemical Approaches in the Treatment of Wastewater 235
- 15.2.3 Membrane Bioreactor 237
- 15.2.4 Nanotechnology in Photobiological Reactors for the Treatment of Wastewater 238
- 15.2.4.1 Potential of Nanotechnology in the Treatment of Wastewater 238
- 15.2.4.2 Moving Bed Biofilm Reactor 238
- 15.3 Conclusion 238
- Acknowledgment 238
- References 239

## **16 Bioreactors for the Production of Industrial Chemicals and Bioenergy Recovery from Waste 241**

*Gargi Ghoshal*

- 16.1 Introduction 241
- 16.1.1 Biogas Production 241
- 16.1.2 Biohydrogen Production 243
- 16.2 Basic Biohydrogen-Manufacturing Technologies and their Deficiency 244
- 16.2.1 Direct Biophotolysis 244
- 16.2.2 Photofermentation 245
- 16.2.3 Dark Fermentation 245
- 16.3 Overview of Anaerobic Membrane Bioreactors 246
- 16.3.1 Challenges and Opportunities 246
- 16.3.1.1 Membrane Fouling and Energy Demands 246
- 16.3.1.2 Biohydrogen Generation Rate and Yield 248
- 16.4 Factors Affecting Biohydrogen Production in AnMBRs 248

- 16.4.1 Nutrients Availability 248
- 16.4.2 Hydraulic Retention Time (HRT) and Solid Retention Time (SRT) 250
- 16.4.3 Design of Biohydrogen-Producing Reactor 250
- 16.4.4 Substrate Concentration 250
- 16.4.5 Temperature and pH 251
- 16.4.6 Seed Culture 251
- 16.4.7 Hydrogen Partial Pressure 251
- 16.5 Techniques to Improve Biohydrogen Production 252
- 16.5.1 Reactor Design and Configuration 252
- 16.5.2 Microbial Consortia 252
- 16.6 Environmental and Economic Assessment of BioHydrogen Production in AnMBRs 253
- 16.7 Future Perspectives of Biohydrogen Production 253
- 16.8 Products Based on Solid-State Fermenter 253
- 16.8.1 Bioactive Products 253
- 16.8.2 Enzymes 254
- 16.8.3 Organic Acids 255
- 16.8.4 Biopesticides 256
- 16.8.5 Aroma Compounds 256
- 16.8.6 Bio-Pigment Production 257
- 16.8.7 Miscellaneous Compounds 257
- 16.9 Koji Fermenters for SSF for Production of Different Chemicals 257
- 16.10 Recent Research on Biofuel Manufacturing in Bioreactors Other than Biohydrogen 258
- References 259

## **Part VI Waste2Energy with Biotechnology: Feasibilities and Challenges 263**

### **17 Utilization of Microbial Potential for Bioethanol Production from Lignocellulosic Waste 265**

*Manisha Rout, Bithika Sardar, Puneet K. Singh, Ritesh Pattnaik, and Snehasish Mishra*

- 17.1 Introduction 265
- 17.1.1 Bioethanol from Different Feed Stocks 265
- 17.1.2 Sources of Lignocellulosic Biomass 266
- 17.1.3 Structure and Composition of Lignocellulose 266
- 17.1.4 Challenges in Bioethanol Production from LCB 267
- 17.2 Processing of Lignocellulosic Biomass to Ethanol 268
- 17.3 Biological Pretreatment 271
- 17.3.1 Potential Microorganisms Involved in Lignin Degradation 272
- 17.3.1.1 Lignin Degrading Fungi 272
- 17.3.1.2 Lignin-Degrading Bacteria 274
- 17.3.2 Mechanism Involved in Delignification 274

17.3.3	Enzymes Involved Biological Pretreatment	274
17.3.3.1	Lignin Peroxidase	275
17.3.3.2	Manganese Peroxidase	275
17.3.3.3	Laccases	275
17.3.3.4	Versatile Peroxidase (VP)	276
17.4	Enzymatic Hydrolysis	276
17.4.1	Hydrolysis of Polysaccharides	277
17.4.1.1	Cellulose and Hemicellulose Degrading Enzymes and Mechanisms	277
17.5	Fermentation	277
17.5.1	Microorganisms Involved in Fermentation	277
17.5.2	Fermentation Process	278
17.5.3	Product Recovery of Bioethanol Post Fermentation	278
17.6	Conclusion and Future Prospects	279
	References	280
<b>18</b>	<b>Advancements in Bio-hydrogen Production from Waste Biomass</b>	<b>283</b>
	<i>Shyamali Sarma and Sankar Chakma</i>	
18.1	Introduction	283
18.2	Routes of Production	285
18.2.1	Biophotolysis	285
18.2.2	Dark Fermentation	286
18.2.3	Photo-Fermentation	286
18.3	Biomass as Feedstock for Biohydrogen	286
18.4	Factors Affecting Biohydrogen	288
18.4.1	Influence of pH	288
18.4.2	System Temperature	288
18.4.3	Inoculum	289
18.4.4	Substrates	291
18.4.5	Type of Reactor	291
18.4.5.1	Batch Mode	291
18.4.5.2	Continuous Mode	292
18.4.5.3	Fed Batch	292
18.5	Strategies to Enhance Microbial Hydrogen Production	292
18.5.1	Integrative Process	293
18.5.2	Medium and Process Optimization	293
18.5.3	Metabolic Flux Analysis	294
18.5.4	Application of Ultrasonication	295
18.5.5	Strain Development	295
18.6	Future Perspectives and Conclusion	297
	References	297

<b>19</b>	<b>Reaping of Bio-Energy from Waste Using Microbial Fuel Cell Technology</b>	<b>303</b>
	<i>Senthilkumar Kandasamy, Naveenkumar Manickam, and Samraj Sadhappa</i>	
19.1	Introduction	303
19.1.1	Effects of Industrial Wastes on Environment	304
19.1.1.1	MFC as Energy Source	304
19.1.1.2	Theory of Microbial Fuel Cell	305
19.2	Microbial Fuel Cell Components and Process	306
19.2.1	Mechanism Behind MFC	306
19.2.1.1	Electrode Materials in MFC	308
19.2.1.2	Proton Exchange Membrane	309
19.3	Application of Microbial Fuel Cell to the Social Relevance	309
19.3.1	Electricity Generation	309
19.3.1.1	Bio Hydrogen	310
19.3.2	Wastewater Treatment	310
19.3.3	Biosensor	310
19.4	Conclusion and Future Perspectives	311
	References	311
<b>20</b>	<b>Application of Sustainable Micro-Algal Species in the Production of Bioenergy for Environmental Sustainability</b>	<b>315</b>
	<i>Senthilkumar Kandasamy, Jayabharathi Jayabalan, and Balaji Dhandapani</i>	
20.1	Introduction	315
20.1.1	Classification of Biofuels	315
20.1.2	Microalgae and Bioenergy	316
20.2	Cultivation and Processing of Microalgae	317
20.2.1	Cultivation of Microalgae	319
20.2.1.1	Isolation of Cell Cultures	319
20.2.1.2	Single-Cell Isolation	319
20.2.2	Techniques	319
20.2.2.1	Filtration	319
20.2.2.2	Autoclaving	320
20.2.2.3	Dry Heat	320
20.2.2.4	Pasteurization	320
20.2.3	Culture Conditions	320
20.2.3.1	Temperature	320
20.2.3.2	Lighting	321
20.2.3.3	Culture Media	321
20.2.3.4	pH	321
20.2.3.5	Aeration	321

20.2.4	Culture Methods	321
20.2.4.1	Batch Culture	321
20.2.4.2	Continuous Culture	322
20.2.5	Harvesting Cultures	322
20.2.6	Bioenergy Production Process from Microalgae	322
20.2.6.1	Production Processes	322
20.2.6.2	Biomass Production from Marine Water Algae	322
20.2.7	Large-Scale Production and Processing of Microalgae	324
20.2.7.1	Biomethane Production by Anaerobic Digestion	324
20.2.7.2	Liquid Oil Production by Thermal Liquefaction Process	325
20.2.7.3	Transesterification Process	325
20.2.7.4	Nano-Catalyzed Transesterification Process	325
20.2.7.5	Biohydrogen Production by Photobiological Process	326
20.3	Genetic Engineering for the Improvement of Microalgae	326
20.4	Conclusion and Challenges in Commercializing Microalgae	327
	References	327

## **Part VII Emerging Technologies (Nano Biotechnology) for Zero Waste 329**

<b>21</b>	<b>Nanomaterials and Biopolymers for the Remediation of Polluted Sites 331</b>	<i>Minchitha K. Umesh, Sadhana Venkatesh, and Swetha Seshagiri</i>
21.1	Introduction	331
21.2	Water Remediation	332
21.2.1	Application of Nanotechnology for Water Disinfection and Textile Dye Degradation	332
21.2.2	Nanobiopolymers for Water Disinfection and Textile Dye Degradation	334
21.3	Soil Remediation	336
21.3.1	Application of Nanotechnology for Soil Remediation	337
	References	339
<b>22</b>	<b>Biofunctionalized Nanomaterials for Sensing and Bioremediation of Pollutants 343</b>	<i>Satyam and S. Patra</i>
22.1	Introduction	343
22.2	Synthesis and Surface Modification Strategies for Nanoparticles	345
22.3	Binding Techniques for Biofunctionalization of Nanoparticles	345
22.3.1	Covalent Functionalization	346
22.3.2	Non-Covalent Functionalization	346
22.3.3	Encapsulation	347
22.3.4	Adsorption	348

- 22.4 Commonly Functionalized Biomaterials and Their Role in Remediation 348
  - 22.4.1 Biopolymers 348
  - 22.4.2 Surfactants 351
  - 22.4.3 Nucleic Acid 352
  - 22.4.4 Proteins and Peptides 352
  - 22.4.5 Enzymes 353
- 22.5 Biofunctionalized Nanoparticle-Based Sensors for Environmental Application 354
- 22.6 Limitation of Biofunctionalized Nanoparticles for Environmental Application 355
- 22.7 Future Perspective 356
- 22.8 Conclusion 356
  - Acknowledgment 357
  - References 357
- 23 Biogeneration of Valuable Nanomaterials from Food and Other Wastes 361**  
*Amrutha B. Mahanthesh, Swarna Halda, and Soumitra Banerjee*
  - 23.1 Introduction 361
  - 23.2 Green Synthesis of Nanomaterials by Using Food and Agricultural Waste 362
  - 23.3 Synthesis of Bionanoparticles from Food and Agricultural Waste 362
    - 23.3.1 Cellulose Nanomaterials 363
    - 23.3.2 Protein Nanoparticles 364
  - 23.4 Conclusion 365
    - Acknowledgments 365
    - References 365
- 24 Biosynthesis of Nanoparticles Using Agriculture and Horticulture Waste 369**  
*Vinayaka B. Shet, Keshava Joshi, Lokeshwari Navalgund, and Ujwal Puttur*
  - 24.1 Introduction 369
  - 24.2 Agricultural and Horticultural Waste 370
  - 24.3 Biosynthesis of Nanoparticle 370
    - 24.3.1 Processing of Agriculture and Horticulture Waste 370
    - 24.3.2 Synthesis of Nanoparticles 372
    - 24.3.3 Separation of Nanoparticles 372
  - 24.4 Characterization of Biosynthesized Nanoparticles 373
    - 24.4.1 UV Spectrophotometer 373
    - 24.4.2 Fourier-Transform Infrared Spectroscopy (FTIR) 374
    - 24.4.3 Dynamic Light Scattering (DLS) and Zeta Potential 374
    - 24.4.4 Scanning Electron Microscope (SEM) and Transmission Electron Microscope (TEM) with Energy-Dispersive X-ray (EDX) 374

24.4.5	X-ray Diffraction (XRD)	375
24.5	Applications of Biosynthesized Nanoparticles	375
24.5.1	Antimicrobial Activity	375
24.5.2	Photocatalysis	375
24.5.3	Removal of Antibiotic from Water	376
24.5.4	Effect on Enzyme Activity	376
24.5.5	Nanofertilizer	376
24.5.6	Radical Scavenging Activity	376
24.5.7	Nano Additives for Fuel	377
	References	377
<b>25</b>	<b>Nanobiotechnology – A Green Solution</b>	<b>379</b>
	<i>Baishakhi De and Tridib K. Goswami</i>	
25.1	Introduction	379
25.2	Nanotechnology and Nanobiotechnology – The Green Processes and Technologies	381
25.2.1	Green Chemistry	382
25.2.1.1	Advantages and Challenges	384
25.3	The Versatile Role of Nanotechnology and Nanobiotechnology	385
25.3.1	Agriculture, Potable Water, and Food Processing	385
25.3.2	Health, Medicine, Drug Delivery, and Pharmaceuticals	388
25.3.3	Automobile, Aircraft, Space Travel	389
25.3.4	Sustainable Energy, Building Technology	389
25.3.5	Society and Education	390
25.4	Nanotechnologies in Waste Reduction and Management	390
25.5	Conclusion	393
	References	393
<b>26</b>	<b>Novel Biotechnological Approaches for Removal of Emerging Contaminants</b>	<b>397</b>
	<i>Sangeetha Gandhi Sivasubramaniyan, Senthilkumar Kandasamy, and Naveen kumar Manickam</i>	
26.1	Introduction	397
26.2	Classification of Emerging Contaminants	397
26.2.1	Microfibers and Microplastics	398
26.2.2	Pharmaceutical Contaminants	398
26.2.3	Personal Care Products and Its Contaminants	398
26.2.4	Inorganic Metals in Foods and Water	399
26.2.5	Perfluorinated Compounds	399
26.2.6	Disinfection Byproducts	399
26.3	Various Sources of ECs	399
26.3.1	Deposition of Solid and Liquid Waste on Land	399
26.3.2	Deposition of Solid and Liquid Waste into the Water Sources	400
26.4	Need of Removal of ECs	400
26.5	Methods of Treatment of EC	400



26.5.1	Physical Methods	400
26.5.2	Chemical Methods	401
26.5.3	Biotechnological Approach	401
26.6	Biotechnological Approaches for the Removal of ECs	401
26.6.1	Digestion by Membrane Bioreactor	401
26.6.2	Enzymatic Treatment	401
26.6.3	Biofiltration	402
26.6.4	Bioremediation	402
26.6.4.1	Bioaugmentation	403
26.6.4.2	Bioreactors	403
26.6.4.3	Biostimulation	404
26.6.4.4	Bioventing	404
26.6.4.5	Composting	404
26.6.4.6	Land Farming/Land Treatment	405
26.6.4.7	Biopiling	405
26.6.5	Phytoremediation	405
26.6.5.1	Phytoextraction and Phytoaccumulation	406
26.6.5.2	Phytostabilization	406
26.6.5.3	Phytovolatilization	406
26.6.5.4	Phytofiltration	406
26.6.5.5	Phytodegradation	406
26.7	Conclusion	406
	References	407

## **Part VIII Economics and Commercialization of Zero Waste Biotechnologies 409**

<b>27</b>	<b>Bioconversion of Waste to Wealth as Circular Bioeconomy Approach</b>	<b>411</b>
	<i>Dayanand Peter, Jaya Rathinam, and Ranganathan T. Vasudevan</i>	
27.1	Introduction	411
27.1.1	Circular Economy	411
27.1.2	Bioeconomy	412
27.1.3	Circular Bioeconomy	412
27.2	Biovalorization of Organic Waste	413
27.2.1	Extraction of Bioactives	413
27.2.2	Bioenergy Production	413
27.3	Bioeconomy Waste Production and Management	414
27.4	Concerns About Managing Food Waste in Achieving Circular Bioeconomy Policies	416
27.5	Economics of Bioeconomy	417
27.6	Entrepreneurship in Bioeconomy	417
27.6.1	Current Trends in Bioeconomy	418
27.7	Conclusion	418

List of Abbreviations 418  
References 418

**28 Bioconversion of Food Waste to Wealth – Circular Bioeconomy Approach 421**

*Rajam Ramasamy and Parthasarathi Subramanian*

- 28.1 Introduction 421
- 28.2 Circular Bioeconomy 422
- 28.3 Food Waste Management Current Practices 424
- 28.4 Techniques for Bioconversion of Food Waste Toward Circular Bioeconomy Approach 425
  - 28.4.1 Anaerobic Digestion 425
    - 28.4.1.1 Factors Influencing Anaerobic Digestion 427
    - 28.4.2 Microbial Fermentation 429
    - 28.4.3 Enzymatic Treatment 431
      - 28.4.3.1 Enzyme Immobilization Technology 434
  - 28.5 Conclusion 435
  - References 435

**29 Zero-Waste Biorefineries for Circular Economy 439**

*Puneet K. Singh, Pooja Shukla, Sunil K. Verma, Snehasish Mishra, and Pankaj K. Parhi*

- 29.1 Introduction 439
- 29.2 Bioenergy, Bioeconomy, and Biorefineries 440
- 29.3 Bioeconomic Strategies Around the World 443
  - 29.3.1 Malaysia 444
  - 29.3.2 Brazil 444
  - 29.3.3 United States 444
  - 29.3.4 Canada 444
  - 29.3.5 Germany 444
  - 29.3.6 European Union 445
  - 29.3.7 Scenario of Bioeconomy in India 445
- 29.4 Challenging Factors and Impact on Bioeconomy 445
- 29.5 Effect of Increased CO<sub>2</sub> Concentration, Sequestration, and Circular Economy 447
- 29.6 Carbon Sequestration in India 447
- 29.7 Methods for CO<sub>2</sub> Capture 448
  - 29.7.1 Scenario 1. Photosynthetic Bacterial Model for CO<sub>2</sub> Sequestration 448
  - 29.7.2 Scenario 2. Biochar Model for CO<sub>2</sub> Sequestration 448
  - 29.7.3 Scenario 3. Biofuels 449
  - 29.7.4 Biological-Based Methods to Capture CO<sub>2</sub> 449
    - 29.7.4.1 Photosynthetic Model 449
    - 29.7.4.2 Substrate in Biorefinery and Carbon Management 449
- 29.8 Conclusion and Future Approach 451
- References 452

<b>30</b>	<b>Feasibility and Economics of Biobutanol from Lignocellulosic and Starchy Residues</b>	<b>457</b>
	<i>Sandesh Kanthakere</i>	
30.1	Introduction	457
30.2	Opportunities and Future of Zero Waste Biobutanol	458
30.3	Generation of Lignocellulosic and Starchy Wastes	459
30.3.1	Types and Sources of Waste Generation	460
30.3.2	Composition of Lignocellulose and Starchy Residues	461
30.4	Value Added Products from Lignocellulose and Starchy Residues	462
30.4.1	Feasibility of Biobutanol Production from Lignocellulose and Starchy Residues	463
30.4.2	Pretreatment	463
30.4.3	Economics of Biobutanol Production	465
30.5	Conclusion	468
	References	468
<b>31</b>	<b>Critical Issues That Can Underpin the Drive for Sustainable Anaerobic Biorefinery</b>	<b>473</b>
	<i>Spyridon Achinas</i>	
31.1	Introduction	473
31.2	Biogas – An Energy Vector	474
31.3	Anaerobic Biorefinery Approach	475
31.4	Technological Trends and Challenges in the Anaerobic Biorefinery	477
31.4.1	Pretreatment	477
31.4.2	Multistage AD Process	480
31.4.3	Dynamics of Methanogenic Communities	480
31.5	Perspectives Toward the Revitalization of the Anaerobic Biorefineries	482
31.5.1	Reciprocity Between Research, Industry, and Government	482
31.5.2	Transition to the Biogas-based Green Economy	483
31.6	Conclusion	485
	Conflict of Interest	485
	References	485
<b>32</b>	<b>Microbiology of Biogas Production from Food Waste: Current Status, Challenges, and Future Needs</b>	<b>491</b>
	<i>Vanajakshi Vasudeva, Inchara Crasta, and Sandeep N. Mudliar</i>	
32.1	Introduction	491
32.2	Fundamentals for Accomplishing National Biofuel Policy	492
32.3	Significances of Anaerobic Microbiology in Biogas Process	493
32.4	Microbiology and Physico-Chemical Process in AD	493
32.4.1	Hydrolysis and Acidogenesis	493
32.4.2	Acetogenesis	494
32.4.3	Methanogenesis and the Essential Microbial Consortia	495
32.5	Pretreatment	496

32.6	Variations in Anaerobic Digestion	496
32.7	Factors Influencing Biogas Production	497
32.7.1	Temperature	497
32.7.2	pH	497
32.7.3	VFA	498
32.7.4	Microbial Consortia in AD	498
32.7.5	Recirculation of Leachate	499
32.7.6	Ammonia	499
32.7.7	Feedstock Composition	500
32.7.7.1	Protein-Rich Substrate	500
32.7.7.2	Lipid-Rich Substrate	500
32.7.7.3	Carbohydrate-Rich Substrate	500
32.7.8	Trace Element Supplementation	500
32.7.9	Environment/Alkalinity	501
32.7.10	Toxicity	501
32.8	Application of Metagenomics	502
32.9	Conclusions and Future Needs	504
	List of Abbreviations	504
	References	505

## **Part IX Green and Sustainable future (Zero Waste and Zero Emissions) 507**

<b>33</b>	<b>Valorization of Waste Cooking Oil into Biodiesel, Biolubricants, and Other Products</b>	<b>509</b>
	<i>Murlidhar Meghwal, Harita Desai, Sanchita Baisya, Arpita Das, Sanghmitra Gade, Rekha Rani, Kalyan Das, and Ravi Kumar Kadeppagari</i>	
33.1	Introduction	509
33.2	Treatment	510
33.2.1	Chemical Treatment	510
33.2.2	Microbiological and Biotechnological Treatment	511
33.3	Evaluation of Waste Cooking Oil and Valorized Cooking Oil	511
33.4	Versatile Products as an Outcome of Valorized Waste Cooking Oil	512
33.4.1	Biosurfactants and Liquid Detergents	512
33.4.2	Green Chemical Lubricants	513
33.4.3	Biodiesel Production	513
33.4.4	Microbial Lipids	513
33.4.5	Vitamins and Nutraceuticals	514
33.4.6	Biopolymer Synthesis	514
33.4.7	Polyhydroxyalkanoates	515
33.4.8	Feedstock for Microbial Processes	515
33.4.9	Bioasphalt	516
33.4.10	Bioplasticizers	516
33.4.11	Biosolvent	516

- 33.5 Conclusion 516
- References 517

## **34 Agri and Food Waste Valorization Through the Production of Biochemicals and Packaging Materials 521**

*A. Jagannath and Pooja J. Rao*

- 34.1 Introduction 521
- 34.2 Importance 522
- 34.3 Worldwide Initiatives 522
- 34.4 Composition-Based Solutions and Approaches 523
- 34.5 Biochemicals 523
  - 34.5.1 Functional Phytochemicals 524
  - 34.5.2 Industrial-Relevant Biochemicals 524
  - 34.5.3 Enzymes 525
  - 34.5.4 Foods/Feeds/Supplements 525
- 34.6 Biofuels 526
- 34.7 Packaging Materials and Bioplastics 526
  - 34.7.1 Scope and Features 527
  - 34.7.2 Polylactic Acid (PLA) 527
  - 34.7.3 Polyhydroxyalkanoates (PHAs) 529
  - 34.7.4 Reinforcement in Bioplastic Properties 529
    - 34.7.4.1 Natural Extract 529
    - 34.7.4.2 Copolymerization 530
    - 34.7.4.3 Green Composites 530
- 34.8 Green Valorization 531
- 34.9 Conclusion 531
- References 532

## **35 Edible Coatings and Films from Agricultural and Marine Food Wastes 543**

*C. Naga Deepika, Murlidhar Meghwal, Pramod K. Prabhakar, Anurag Singh, Rekha Rani, and Ravi Kumar Kadeppagari*

- 35.1 Introduction 543
- 35.2 Sources of Food Waste 544
- 35.3 Film/Coating Made from Agri-Food Waste 545
  - 35.3.1 Biopolymers from Fruits and Vegetables Waste 545
  - 35.3.2 Biopolymers from Grain Wastage 546
  - 35.3.3 Bioactive Compounds from Plant Residues 547
- 35.4 Film/Coating Materials from Marine Biowaste 548
  - 35.4.1 Fish Processing By-products 549
  - 35.4.2 Crustacean By-Products 549
- 35.5 Film/Coating Formation Methods 550
  - 35.5.1 Solvent Casting 550
  - 35.5.2 Extrusion 551
  - 35.5.3 Dipping Method 552

- 35.5.4 Spraying Method 552
- 35.5.5 Spreading Method 552
- 35.6 Conclusion 552
- References 553

**36 Valorization of By-Products of Milk Fat Processing 557**

*Menon R. Ravindra, Monika Sharma, Rajesh Krishnegowda, and Amanchi Sangma*

- 36.1 Introduction 557
- 36.2 Processing of Milk Fat and Its By-Products 558
- 36.3 Valorization of Buttermilk 558
  - 36.3.1 Buttermilk as an Ingredient in Food and Dairy Products 559
    - 36.3.1.1 Market Milk 559
    - 36.3.1.2 Dahi 559
    - 36.3.1.3 Yoghurt 559
    - 36.3.1.4 Cheeses 560
    - 36.3.1.5 Indian Traditional Dairy Products 560
    - 36.3.1.6 Buttermilk Ice Cream 560
    - 36.3.1.7 Dairy-Based Beverages 560
    - 36.3.1.8 Probiotic Drinks 561
    - 36.3.1.9 Dried Buttermilk 561
  - 36.3.2 Buttermilk as Encapsulating Agent 561
  - 36.3.3 Buttermilk as a Source of Phospholipids 562
- 36.4 Valorization of Ghee Residue 562
  - 36.4.1 Utilization of Ghee Residue for Value-Added Products 563
  - 36.4.2 Ghee Residue as an Ingredient in Dairy and Food Industry 563
    - 36.4.2.1 Baked Products 563
    - 36.4.2.2 Chocolate and Confectionery 563
    - 36.4.2.3 Ghee-Residue-Based Flavor Enhancer 564
    - 36.4.2.4 Indian Traditional Sweetmeat 564
  - 36.4.3 Ghee Residue as Animal Feed 564
  - 36.4.4 Ghee Residue as Source of Phospholipids 564
- 36.5 Conclusion 565
- References 565

**Index 569**