

Vipin Chandra Kalia *Editor*

Polyhydroxyalkanoates: Sustainable Production and Biotechnological Applications II

Agriculture, Industry, and Environment

 Springer

Preface

Plastics, with their unique physical and chemical characteristics, can be molded into extensively used products. These have thus become an integral part of our daily lives. This uniqueness of plastics is what makes them so intriguing and interesting. Despite their extensive usage, the major limiting factor is their non-biodegradability, thus accumulating at an unprecedented rate. It is a significant cause of concern for administrators of the environmental and health sectors. An obvious solution to this environmental issue is to follow the principle of the 3Rs: Reduce, Reuse, and Recycle. This strategy to manage plastic waste has met with very little success, reducing waste quantum by around 10%. An alternative to non-biodegradable plastics was to look for biopolymers, which have the unique characteristics of degrading within a short span and under normal environmental conditions. At the beginning of the twentieth century, scientists found *Bacillus* species to possess intracellular bodies to contain biopolymers, which had properties quite like those of synthetic polymers. This fascinating scientific journey attracted many scientists who brought this field of biopolymers into global prominence. Around 300 species of bacteria have been identified with the potential to produce biopolymers, especially polyhydroxyalkanoates (PHAs) from biowastes as feed material. Bacteria preferentially produce polyhydroxybutyrates (PHBs), which can potentially replace plastics. PHBs, being homopolymers, have certain inherent shortcomings that limit their applications. In contrast, bacteria can be manipulated to produce copolymers of PHAs, which circumvent the limitations of the PHBs, and thus have been exploited for diverse biotechnological applications. Attempts have been made quite frequently to address the issues that need to be overcome, such as the difficulties encountered during the large-scale and sustainable production of PHAs. There is a need to search for robust organisms that can withstand adverse environmental conditions, channel carbon, and energy fluxes, inhibit competing pathways, produce copolymers, and improve downstream processing. Although books have been published on these themes, with the pace with which research and development activities are going on around the world, the need to update the information is required, especially for the benefit of young researchers who are fascinated by biopolymers. Most recent exhaustive review articles published in scientific journals of repute have been focusing on one or more of the following topics: biodiversity, feedstocks, PHA structures, metabolic engineering, manipulating morphology, enhancing biomass, and recovery. Thus, to switch from curiosity-driven research that is proving uneconomical to design and

device mechanisms for high-value processes and products, this book is targeted to present a comprehensive updated status of the R&D activities.

The book (Volume 1) focuses on microbial biodiversity and their metabolic potential to produce biopolymers. It provides opportunities to exploit wastes of biological origin to produce biopolymers and discusses the potential strategies for bioengineering of microbes for the sustainable production of bioplastics. The other two books focus on biotechnological applications of biopolymers in agriculture, industry, the environment (Volume II), and the biomedical sector (Volume III). It provides potential opportunities for environmental bioremediation and biotechnological bioprocesses for their potential translation into globally competent business proposals.

The book intends to help researchers channel their time, energy, and funds into areas with the greatest potential for achieving Sustainable Polyhydroxyalkanoate Production. Funding agencies will get information on prospective scientific R&D areas so that the researchers can develop globally competent business proposals. The most important component is the contributions made by well-established and reputed scientists. For society, it provides novel concepts about eco-friendly and economic benefits. The book would not have been published without the support and encouragement of Amita (my wife), Dr. Nivedita and Jolina (my daughters), and Daksh and Bhriгу (my sons). I must acknowledge the life bestowed upon me by my parents: Kanta and Ras Behari Kalia.

Seoul, Republic of Korea

Vipin Chandra Kalia

Contents

Life Cycle of Polyhydroxyalkanoates: The Journey from Cradle to Grave	1
Vipin Chandra Kalia	
1 Introduction	2
2 Life Cycle Assessment (LCA)	4
3 Conclusion and Perspective	8
References	8
Bioplastics for Combating Global Issues of Environmental Pollution	13
Sonam Dubey, Kashish Sharma, Bhawana Raikwar, and Sandhya Mishra	
1 Introduction	14
1.1 Synthetic Plastics	14
1.1.1 Collection and Sorting	14
1.1.2 Preparation	14
1.1.3 Incineration	14
1.1.4 Energy Recovery	14
1.1.5 Air Pollution Control	15
1.1.6 Waste Residue Management	15
2 COVID Era	16
2.1 Personal Protective Equipment (PPE) Usage	16
2.2 Packaging	16
2.3 Single-Use Plastics	16
2.4 Medical Waste	16
2.5 Sanitization Products	16
3 Microplastics a Global Concern	17
3.1 Primary Microplastics	18
3.2 Secondary Microplastics	18
4 Biodegradable Plastic Types	19
5 Impact of Synthetic Plastic on Human Health	21
5.1 Chemical Exposure	21
5.2 Microplastics and Nanoplastics	21
5.3 Food and Beverage Packaging	21

5.4	Air Pollution	22
5.5	Occupational Hazards	22
6	Polyhydroxyalkanoates (PHA)	22
6.1	Global Scenario of PHA	22
6.2	Key Properties of PHAs	26
6.3	Bioplastics Offer Several Advantages in Combating Global Environmental Pollution	26
7	PHA as Sustainable Alternate	33
8	Concluding Remarks	35
	References	36

Sustainable Production of Bioplastics (Polyhydroxyalkanoates)

via Co-digestion of Biowastes and Wastewaters 41

Chunjie Gong, Vipin Chandra Kalita, and Subhasree Ray

1	Introduction	42
2	Bioprocess for Producing PHAs from WW	45
3	Bacterial Diversity for Converting WW to PHA	46
3.1	Archaea	46
3.2	Gram-Positive Bacteria	47
3.3	Gram-Negative Bacteria	47
3.4	Mixed Bacterial Cultures	48
4	PHA Production from Biowastes Using Distilled Water for Preparing Feed	50
4.1	PHAs from Sugars	50
4.2	PHAs from Crude Glycerol	50
4.3	PHAs from Pea Shells	50
4.4	PHAs from Wastewater Treatment Plants	52
4.5	PHAs from Other Biowastes	52
5	Conclusion and Future Perspectives	53
	References	54

Polyhydroxyalkanoates: The Future of Sustainable

Denitrification for Wastewater Treatment 63

Summayya Batool and Si Ling Ng

1	Introduction	64
2	Nitrogen Pollution	65
2.1	Sources of Nitrogen Pollution in Water	66
2.1.1	Agricultural Runoff	66
2.1.2	Municipal and Industrial Wastewater	68
2.2	Environmental Impact of Nitrogen Pollution	68
2.3	Nitrogen Removal	69
2.4	Biological Denitrification	69
2.5	Denitrifying Bacteria	70
2.6	Chemistry of Denitrification	71
2.7	Environmental Factors Affecting Denitrification Process	72

2.7.1	Dissolved Oxygen Level	72
2.7.2	Heavy Metal Presence in Wastewater	72
2.7.3	Effects of Temperature and pH	72
2.7.4	External Carbon Source	73
2.8	Challenges in the Wastewater Denitrification	75
3	Polyhydroxyalkanoates (PHAs)	76
3.1	Introduction to PHAs	76
3.2	Production of PHA	77
3.3	PHAs as a Carbon Source for Biological Denitrification	78
3.4	Advantages of PHAs Over Conventional Electron Donors	81
4	Conclusions and Future Directions	83
	References	84

Polyhydroxyalkanoates as Potential Tools for Denitrification of Wastewater 91

Mridul Umesh, Adhithya Sankar Santhosh, Nilina James,
Sneha Grigary, Liya Merin Stanly, and Sreehari Suresh

1	Introduction	92
1.1	Polyhydroxyalkanoates	95
2	Denitrification Using PHA	97
2.1	Introduction of PHA Producing Microorganisms into Water	97
2.2	Uptake of PHA by Denitrifying Bacteria	98
2.3	Growth and Metabolism of Denitrifying Bacteria	98
3	Mechanism of PHA-Based Denitrification	99
4	Challenges Associated with Use of PHA for Denitrification	101
5	Conclusion	103
	References	104

Potential Perspectives of Microbial-PHA Biopolymers Produced by Using Agro-Wastes for Food Packaging Applications 111

Mohd Amir, Shareen Fatima, Gaurav Yadav, Ananya Bajpai,
Arooba Ilyas, Zeenat Khan, and Roohi

1	Introduction	112
2	PHA	113
2.1	Properties of PHAs	113
2.2	Structure of PHAs	114
2.3	Availability of PHAs	114
2.4	Applications of PHAs	115
3	Types of Packaging Materials	118
3.1	Plastics in Packaging Materials	119
3.2	Bioplastics in Packaging Materials	120
3.2.1	Starch-Based Bioplastics	121
3.2.2	Cellulose-Based Bioplastics	122
3.2.3	PHA-Based Bioplastics	123
4	Biosynthesis of PHA Using SSF and SmF	124

5	Extraction of PHA Polymer Using Different Methods	128
5.1	Solvent Extraction	128
5.2	Enzymatic Extraction	128
5.3	Microwave-Assisted Extraction	129
5.4	Supercritical Fluid Extraction	129
5.5	PHA Separation Using a Two-Phase Aqueous Solution	129
5.6	Sodium Dodecyl Sulfate (SDS) Sonication Extraction	130
5.7	Bioextraction	130
5.8	Exploring the Biodegradation of PHA in Various Environmental Settings	130
6	Promising Role of PHAs for Sustainable Biotechnological Applications	133
6.1	In Biofertilizers	133
6.1.1	Composites of BpF Biodegradation	134
6.2	As Nanodrug Carrier	135
7	Conclusion	137
	References	137

**Possibilities for Repurposing Organic Waste and Polyhydroxyalkanoate
into Sustainable, Intelligent Food Packaging Materials
by Microbial Valorization 145**

Nancy Rajgadia, Siddhi Joshi, Sylvia Parveen, Tanisha Singh,
and Mousumi Debnath

1	Introduction	146
2	Types of Packaging	147
2.1	Active Packaging	147
2.2	Antioxidant Food Packaging	147
2.3	Antimicrobial Packaging	148
3	Metal Oxides to Improve the Packaging Characteristics	148
3.1	Silver Nanoparticles	149
3.2	Zinc Oxide	149
3.3	Titanium Oxide	149
3.4	Palladium-Based Systems	149
4	Absorbers of Chemical, Physical, and Gases to Prevent Food Spoilage	150
4.1	CO ₂ Absorbers and Emitters	150
4.2	Physical Absorbers	150
4.3	Chemical Absorbers	151
5	Polymers Used in Food Packaging	151
5.1	Synthetic Polymers Used in Food Packaging	151
5.2	Biodegradable Polymers Used in Food Packaging	153
6	Polyhydroxyalkanoate as a Biodegradable Polymer for Food Packaging	154
6.1	Organic Waste in PHB Production	156
6.2	In Silico Analysis	156

6.3	Methods to Produce PHA for Food Packaging	159
6.3.1	Batch Fermentation.	160
6.3.2	Fed-Batch Fermentation	161
6.3.3	Continuous Fermentation	161
7	PHA-Based Biocomposites.	162
7.1	PHA/PVA PHA/PBAT Blends	164
7.2	PHB/Chitin Blends	164
7.3	PHA/PLA Blends.	165
7.4	PHBHV/Lignin Blends	166
7.5	PHB/Lignin Blends	167
7.6	PHB/Starch and PHB/Cellulose Blends	167
8	Characteristics of PHA to Be Used for Food Packaging	168
8.1	Oil Permeability	168
8.2	Flexibility and Water Solubility.	169
8.3	Antimicrobial Activity	169
8.4	Antioxidant Activity.	169
8.5	Composability of PHA Biopolymer	169
8.6	Mechanical Strength	170
9	Development of Biopolymer-Based Packaging Material	170
9.1	Wet Processing.	170
9.2	Dry Processing.	171
9.2.1	Extrusion.	171
9.2.2	Blow Molding	172
9.2.3	Thermoforming.	172
10	Market Study.	173
11	Applications of Food Packaging of PHA on Industrial Scale.	173
12	Conclusion	176
	References.	177

PHA Production from Food Waste with Their Applications as Antibacterial Agents in the Packaging Sector 187

Rajesh K. Srivastava, P. G. Swaroopa, K. S. Naidu,

D. Behera, and H. Tadi

1	Introduction.	188
2	Food Wastes	190
2.1	Milk Wastes/Whey.	191
2.2	Waste Oils	193
2.3	Spent Coffee Grounds	193
3	Polyhydroxyalkanoates (PHAs) Synthesis	194
3.1	PHA Production by Fermentation Process	194
4	Application of PHA Polymers in Packaging Industry	195
5	Conclusions.	201
	References.	201

Polyhydroxyalkanoates for Dye Removal: From Adsorption to Biodegradation	207
Sohana Malik, Sara Janiad, and Si Ling Ng	
1 Introduction	208
2 Characteristics of Wastewater Containing Dyes	209
3 Conventional Treatment Approaches and Challenges.	211
3.1 Challenges in Effective Dye Removal	213
4 Polyhydroxyalkanoates (PHAs)	213
5 Polyhydroxyalkanoates for Dye Treatment	215
5.1 PHAs as Adsorbent for Adsorptive Removal of Dyes	215
5.2 PHAs as Immobilization Media in Biological Dye Removal	218
5.3 Dye Wastewater Treatment Biomass for PHA Production	220
6 Conclusion	221
References.	222
Biodegradable PHA Plastics in Composting and Sewage Sludge Treatment Systems: A Green Revolution	225
Sabreen Aslam, Sarmila Gunasekaran, and Si Ling Ng	
1 Introduction	226
2 Microplastics (MPs)	229
2.1 Microplastics (MPs) in Various Environments	230
2.1.1 MPs in Terrestrial Environments: Their Impacts on Soil and Agriculture	230
2.1.2 MPs in Aquatic Environments: Sources, Presence and Ecological Impact.	230
2.1.3 Impact of MPs on the Atmospheric Environment.	231
2.2 Polyhydroxyalkanoates (PHAs).	231
2.2.1 Properties of Polyhydroxyalkanoates (PHAs)	231
2.2.2 Applications of Polyhydroxyalkanoates (PHAs)	234
3 Composting	234
4 Sewage Sludge Treatment.	235
4.1 Microplastics (MPs) in Sewage Sludge	236
4.2 Changes of Microplastics (MPs) in Sewage Sludge Treatment.	237
5 Effects of MPs on Sewage Sludge Treatments	238
5.1 Gas Emissions	239
5.2 Microbial Community	239
5.3 Compost Quality	240
6 Conclusion: Polyhydroxyalkanoates as a Sustainable Alternative to Combat Microplastic Pollution	241
References.	242

About the Editor



Vipin Chandra Kalia is presently working as a Professor at the National Research Foundation (Korea), Department of Chemical Engineering, Konkuk University, Seoul, Republic of Korea. Previously, he worked as an Emeritus Scientist at the Council of Scientific and Industrial Research (CSIR). He has been the Chief Scientist and the Deputy Director at Microbial Biotechnology and Genomics, CSIR-Institute of Genomics and Integrative Biology, Delhi. He is a Professor at the Academy of Scientific and Innovative Research (AcSIR), and he obtained his M.Sc. and Ph.D. in Genetics from the Indian Agricultural Research Institute, New Delhi. He has been elected as (1) Fellow of the National Academy of Sciences (FNASc), (2) Fellow of the National Academy of Agricultural Sciences (FNAAS), and (3) Fellow of the Association of Microbiologists of India (FAMSc). His main research areas are Microbial biodiversity, Bioenergy, Biopolymers, Genomics, Microbial evolution, Quorum sensing, Quorum quenching, Drug discovery, and Antimicrobials. He has published more than 200 papers in scientific journals such as *Nature Biotechnology*, *Biotechnology Advances*, *Trends in Biotechnology*, *Renewable and Sustainable Energy Reviews*, *Science of the Total Environment*, *Annual Review of Microbiology*, *Critical Reviews in Microbiology*, *Bioresource Technology*, *Seminars in Cancer Biology*, *BMC Genomics*, *Polymers*, and *Ecotoxicology and Environmental Safety*. He has authored 35 book chapters. His works have been cited 15179 times with an h-index of 68 and an i10 index of 184. He has edited 16 books published in Springer. He has been the Editor-in-Chief of the *Indian Journal of Microbiology* (2013

through 2023) and is still serving as the Editor/Academic Editor for multiple reputed journals. He has been a member of the American Society for Microbiology (2010–2015). He has been conferred the following awards: (i) Prof. S.R. Vyas Memorial Award, Association of Microbiologists of India (2016); (ii) American Society for Microbiology – Indo-US Science and Technology Forum (ASM-IUSSF)—Professorship Program, USA (2014); (iii) INSA Bilateral Exchange Programme, Indian National Science Academy, India (2006); (iv) DBT Overseas Associateship, Department of Biotechnology, Government of India (2005–2006); (v) Dr. J.V. Bhat Award, Association of Microbiologists of India (2012, 2015, 2016, 2017) and Faculty Research Award in Microbiology, 2018. He can be contacted at: vckaliaku@gmail.com.



Potential Perspectives of Microbial-PHA Biopolymers Produced by Using Agro-Wastes for Food Packaging Applications

Mohd Amir, Shareen Fatima, Gaurav Yadav, Ananya Bajpai, Arooba Ilyas, Zeenat Khan, and Roohi

Abstract

Fermentation processes such as solid-state fermentation and submerged fermentation are helpful for the production of PHA (polyhydroxyalkanoates) polymer at a large scale. These polymers have been extensively used in biotechnological applications, from medical implants to nanodrugs, agriculture mulch film, to heart valves. PHA-based bioplastic, when degraded in soil, can also be used as a biofertilizer. Bioplastic fertilizers, or BpF, have been used in farming and gardening for a long time. The best among them were PHAs utilized as a food packaging material. Traditionally food packaging systems were based on plastic food packaging cellulose-based, starch-based, protein-based, etc. Production of food packaging with the help of PHA polymer has become one of the most promising research, which also booms the bioplastic industries. The fermentation process maximizes PHA production and reduces the cost of PHA production using carbon-rich agro-wastes. These PHA biopolymers are produced from microbes and are extracted using different extraction methods; ATPS is the most promising extraction method for the maximum recovery of PHA. Besides having the properties of food packaging and disposable tableware, PHA biopolymer can also be used in numerous biotechnological applications. It can be used in agriculture as crop protection films, biofertilizers, therapeutic applications as a nanodrug carrier, tissue engineering, etc.

M. Amir · S. Fatima · G. Yadav · A. Bajpai · A. Ilyas · Z. Khan · Roohi (✉)
Department of Bioengineering, Protein Research Laboratory, Integral University,
Dashauli, Uttar Pradesh, India

© The Author(s), under exclusive license to Springer Nature Singapore Pte Ltd. 2025
V. C. Kalia (ed.), *Polyhydroxyalkanoates: Sustainable Production and Biotechnological Applications II*, https://doi.org/10.1007/978-981-96-1992-4_6

111