

Contents

The Editors XIX

List of Contributors XXI

- 1 Advances in Polymer Composites: Biocomposites –State of the Art, New Challenges, and Opportunities** 1
Koichi Goda, Meyyarappallil Sadasivan Sreekala, Sant Kumar Malhotra, Kuruvilla Joseph, and Sabu Thomas
- 1.1 Introduction 1
- 1.2 Development of Biocomposite Engineering 3
- 1.3 Classification of Biocomposites 5
- References 8
- 2 Synthesis, Structure, and Properties of Biopolymers (Natural and Synthetic)** 11
Raju Francis, Soumya Sasikumar, and Geethy P. Gopalan
- 2.1 Introduction 11
- 2.2 Classification 13
- 2.3 Natural Biopolymers 13
- 2.3.1 Proteins 14
- 2.3.1.1 Collagen 15
- 2.3.1.2 Elastin 18
- 2.3.1.3 Albumin 19
- 2.3.1.4 Fibrin 19
- 2.3.1.5 Fibronectin 20
- 2.3.1.6 Zein 20
- 2.3.1.7 Gluten 21
- 2.3.1.8 Gelatin 22
- 2.3.1.9 Soy Protein 23
- 2.3.1.10 Whey Protein 24
- 2.3.1.11 Casein 24
- 2.3.2 Polysaccharides 27
- 2.3.2.1 Cellulose 27
- 2.3.2.2 Starch 28

2.3.2.3	Chitosan	30
2.3.2.4	Chitin	31
2.3.2.5	Hyaluronic Acid (HA)	32
2.3.2.6	Alginic Acid	32
2.3.2.7	Pectin	33
2.3.3	Polysaccharides from Marine Sources	34
2.3.3.1	Agar	34
2.3.3.2	Agarose	34
2.3.3.3	Alginic Acid/Alginate	35
2.3.3.4	Carrageenan	36
2.3.3.5	Cutan	36
2.3.3.6	Cutin	38
2.3.4	Low Molecular Weight Biopolymers	39
2.3.4.1	Guar Gum	39
2.3.4.2	Rosin	40
2.3.4.3	Chondroitin Sulfate	41
2.3.4.4	Gum Copal	41
2.3.4.5	Gum Damar	42
2.3.5	Microbial Synthesized Biopolymers	42
2.3.5.1	Pullulan	42
2.3.5.2	Dextran	43
2.3.5.3	Curdlan	44
2.3.5.4	Xanthan	45
2.3.5.5	Bacterial Cellulose	46
2.3.6	Natural Poly(Amino Acids)	46
2.3.6.1	Jute	49
2.3.6.2	Coir	49
2.3.6.3	Yarn	49
2.3.6.4	Silk	49
2.3.7	Nucleic Acids	50
2.3.7.1	Natural Nucleic Acids	50
2.3.7.2	Synthetic Nucleic Acids (SNA)	51
2.4	Synthetic Biopolymers	54
2.4.1	Poly(Glycolide) PGA or Poly(Glycolic Acid)	55
2.4.2	Poly(Lactic Acid) (PLA)	55
2.4.3	Poly(Lactide-co-Glycolide)	56
2.4.4	Polycaprolactone (PCL)	57
2.4.5	Poly(<i>p</i> -Dioxanone) (PDO)	57
2.4.6	Poly(Trimethylene Carbonate) (PTMC)	58
2.4.7	Poly- β -Hydroxybutyrate (PHB)	58
2.4.8	Poly(Glycerol Sebacic Acid) (PGS)	58
2.4.9	Poly(Propylene Fumarate) (PPF)	59
2.4.10	Poly(Anhydrides) (PAs)	60
2.4.11	Poly(Orthoesters) (POEs)	60
2.4.12	Poly(Phosphazene)	61

2.4.13	Poly(Vinyl Alcohol) (PVA)	62
2.4.14	Poly(Hydroxyalkanoates) (PHAs)	63
2.4.15	Poly(Ester Amides) (PEAs)	63
2.5	Need for Biopolymers	64
2.6	Exceptional Properties of Biopolymers	65
2.7	Biomedical Polymers	65
2.7.1	Chitosan	66
2.7.2	Poly(Lactic Acid) (PLA)	67
2.7.3	Collagen	67
2.7.4	Polycaprolactone (PCL)	68
2.7.5	Poly(2-Hydroxyethyl Methacrylate) (PHEMA)	68
2.7.6	Carbohydrate-Based Vaccines	69
2.7.7	Chitin	69
2.7.8	Albumin	69
2.7.9	Fibrin	70
2.7.10	Hyaluronic Acid (HA)	70
2.7.11	Chondroitin Sulfate (CS)	70
2.7.12	Alginic Acid	70
2.7.13	Poly(Anhydrides)	70
2.8	Composite Material	71
2.9	Blends	71
2.10	Applications of Biopolymers	72
2.10.1	Medical Applications	72
2.10.1.1	Surgical Sutures	72
2.10.1.2	Bone Fixation Devices	73
2.10.1.3	Vascular Grafts	73
2.10.1.4	Adhesion Prevention	74
2.10.1.5	Artificial Skin	74
2.10.1.6	Drug Delivery Systems	74
2.10.1.7	Artificial Corneas	75
2.10.1.8	Artificial Blood Vessels	75
2.10.2	Agricultural Applications	76
2.10.2.1	Agricultural Mulches	76
2.10.2.2	Controlled Release of Agricultural Chemicals	77
2.10.2.3	Agricultural Planting Containers	77
2.10.3	Packaging	77
2.10.3.1	Starch-Based Packaging Materials	78
2.10.3.2	PLA-Based Packaging Materials	78
2.10.3.3	Cellulose-Based Packaging Materials	79
2.10.3.4	Pullulan-Based Packaging Materials	79
2.10.3.5	Other Biopackaging Solution	80
2.11	Partially Biodegradable Packaging Materials	80
2.12	Nonbiodegradable Biopolymers	80
2.12.1	Poly(Thioesters)	80
2.12.1.1	Poly(3-Mercaptopropionate) (Poly(3MP))	81

2.13	Conversion of Nonbiodegradable to Biodegradable Polymers	82
2.14	Current Research Areas in Biopolymers and Bioplastics	82
2.15	General Findings and Future Prospects	83
	Acknowledgments	83
	Abbreviations	84
	References	84
3	Preparation, Microstructure, and Properties of Biofibers	109
	<i>Takashi Nishino</i>	
3.1	Introduction	109
3.2	Structure of Natural Plant Fibers	110
3.2.1	Microstructure	110
3.2.2	Crystal Structure	114
3.3	Ultimate Properties of Natural Fibers	117
3.3.1	Elastic Modulus	117
3.3.2	Tensile Strength	120
3.4	Mechanical and Thermal Properties of Cellulose Microfibrils and Macrofibrils	121
3.5	All-Cellulose Composites and Nanocomposites	126
3.6	Conclusions	129
	References	129
4	Surface Treatment and Characterization of Natural Fibers: Effects on the Properties of Biocomposites	133
	<i>Donghwan Cho, Hyun-Joong Kim, and Lawrence T. Drzal</i>	
4.1	Introduction	133
4.2	Why Is Surface Treatment of Natural Fibers Important in Biocomposites?	134
4.3	What Are the Surface Treatment Methods of Natural Fibers?	137
4.3.1	Chemical Treatment Methods	138
4.3.1.1	Alkali Treatment	138
4.3.1.2	Silane Treatment	139
4.3.1.3	Acetylation Treatment	143
4.3.1.4	Benzoylation and Benzylation Treatments	143
4.3.1.5	MAPP Treatment	143
4.3.1.6	Peroxide Treatment	144
4.3.2	Physical Treatment Methods	145
4.3.2.1	Plasma Treatment	145
4.3.2.2	Corona Treatment	146
4.3.2.3	Electron Beam Treatment	147
4.3.2.4	Ultraviolet Treatment	147
4.3.2.5	Ultrasonic Treatment	148
4.4	How Does the Surface Treatment Influence the Properties of Biocomposites?	149
4.4.1	Chemical Changes of Natural Fibers	149

4.4.2	Morphological and Structural Changes of Natural Fibers	150
4.4.3	Mechanical Changes of Natural Fibers	151
4.4.4	Interfacial Properties of Biocomposites	153
4.4.5	Mechanical Properties of Biocomposites	157
4.4.6	Impact Properties of Biocomposites	160
4.4.7	Dynamic Mechanical Properties of Biocomposites	161
4.4.8	Thermal Properties of Biocomposites	164
4.4.9	Water Absorption Behavior of Biocomposites	166
4.5	Concluding Remarks	168
	References	169
5	Manufacturing and Processing Methods of Biocomposites	179
5.1	Processing Technology of Natural Fiber-Reinforced Thermoplastic Composite	179
	<i>Tatsuya Tanaka</i>	
5.1.1	Background	179
5.1.2	NF- Reinforced PLA Resin Composite Material	181
5.1.3	Pellet Production Technology of Continuation Fiber-Reinforced Thermoplastic Resin Composite Material	181
5.1.4	Pellet Manufacturing Technology of the Continuous Natural Fiber-Reinforced Thermoplastic Resin Composite Material	183
5.1.4.1	Process Outline	183
5.1.4.2	Review of Mechanical Apparatus	183
5.1.4.3	Main Equipment	185
5.1.4.4	Process Features	186
5.1.4.5	Mechanical Properties of NF-LFP	188
5.1.5	Pellet Manufacturing Technology of the Distributed Type Natural Fiber-Reinforced Thermoplastic Resin Composites	189
5.1.5.1	Process Development	189
5.1.5.2	Automatic Material-Supplying System	191
5.1.5.3	Optimal Screw Configuration and Influence of BF Fiber Diameter	193
5.1.5.4	Influence of BF Content	195
5.1.6	Future Outlook	197
5.2	Processing Technology of Wood Plastic Composite (WPC)	197
	<i>Hirokazu Ito</i>	
5.2.1	Raw Materials	198
5.2.1.1	Manufacture of Woody Materials	198
5.2.1.2	Plastic	201
5.2.1.3	Compatibilizer	202
5.2.2	Compounding Process	203
5.2.2.1	Compounding Using an Extrusion Machine	203
5.2.2.2	Compounding Using a Henschel Type Mixer	204
5.2.2.3	Evaluation of Compounds	205
5.2.3	Molding Process	207

5.2.3.1	Extrusion Molding	207
5.2.3.2	Injection Molding	208
5.2.4	The Future Outlook for WPC in Industry	209
	References	209
6	Biofiber-Reinforced Thermoset Composites	213
	<i>Masatoshi Kubouchi, Terence P. Tumulva, and Yoshinobu Shimamura</i>	
6.1	Introduction	213
6.2	Materials and Fabrication Techniques	213
6.2.1	Thermosetting Resins	213
6.2.1.1	Synthetic Thermosets	214
6.2.1.2	Biosynthetic Thermosets	215
6.2.2	Natural Fibers	215
6.2.3	Fabrication Techniques	217
6.2.3.1	Hand Layup	218
6.2.3.2	Compression Molding	219
6.2.3.3	Filament Winding	219
6.2.3.4	Pultrusion	219
6.2.3.5	Resin Transfer Molding	220
6.3	Biofiber-Reinforced Synthetic Thermoset Composites	220
6.3.1	Polyester-Based Composites	220
6.3.2	Epoxy-Based Composites	222
6.3.3	Vinyl Ester-Based Composites	223
6.3.4	Phenolic Resin-Based Composites	224
6.3.5	Other Thermoset-Based Composites	225
6.4	Biofiber-Reinforced Biosynthetic Thermoset Composites	225
6.4.1	Lignin-Based Composites	225
6.4.2	Protein-Based Composites	226
6.4.3	Tannin-Based Composites	227
6.4.4	Triglyceride-Based Composites	228
6.4.5	Other Thermoset-Based Composites	229
6.5	End-of-Life Treatment of NFR Thermoset Composites	231
6.5.1	Recycling as Composite Fillers	231
6.5.2	Pyrolysis	232
6.5.3	Chemical Recycling	232
6.5.4	Energy Recovery	233
6.6	Conclusions	233
	References	234
7	Biofiber-Reinforced Thermoplastic Composites	239
	<i>Susheel Kalia, Balbir Singh Kaith, Inderjeet Kaur, and James Njuguna</i>	
7.1	Introduction	239
7.2	Source of Biofibers	240
7.3	Types of Biofibers	241
7.3.1	Annual Biofibers	241

7.3.1.1	Straw	242
7.3.1.2	Bast Fiber	242
7.3.1.3	Grasses	244
7.3.1.4	Residues	244
7.3.2	Perennial Biofibers (Wood Fibers)	245
7.3.2.1	Tree Plantation Products	245
7.3.2.2	Forest Plant Products	246
7.3.2.3	Agro-Forestry Products	246
7.4	Advantages of Biofibers	248
7.5	Disadvantages of Biofibers	248
7.6	Graft Copolymerization of Biofibers	250
7.7	Surface Modifications of Biofibers Using Bacterial Cellulose	252
7.8	Applications of Biofibers as Reinforcement	255
7.8.1	Composite Boards	256
7.8.1.1	Particleboards	256
7.8.1.2	Fiberboards	258
7.8.2	Biofiber-Reinforced Thermoplastic Composites	259
7.8.2.1	Bamboo Fiber-Reinforced Thermoplastics	259
7.8.2.2	Ramie Fiber-Reinforced Thermoplastics	260
7.8.2.3	Flax Fiber-Reinforced Thermoplastics	261
7.8.2.4	Sisal Fiber-Reinforced Thermoplastics	264
7.8.2.5	Jute Fiber Reinforced-Thermoplastics	266
7.8.2.6	Hemp Fiber-Reinforced Thermoplastics	269
7.9	Biofiber Graft Copolymers Reinforced Thermoplastic Composites	271
7.10	Bacterial Cellulose and Bacterial Cellulose-Coated, Biofiber-Reinforced, Thermoplastic Composites	274
7.11	Applications of Biofiber-Reinforced Thermoplastic Composites	277
7.12	Conclusions	278
	References	279
8	Biofiber-Reinforced Natural Rubber Composites	289
	<i>Parambath Madhom Sreekumar, Preetha Gopalakrishnan, and Jean Marc Saiter</i>	
8.1	Introduction	289
8.2	Natural Rubber (NR)	289
8.3	Biofibers	290
8.4	Processing	292
8.5	Biofiber-Reinforced Rubber Composites	292
8.5.1	Cure Characteristics	293
8.5.2	Mechanical Properties	294
8.5.2.1	Effect of Fiber Length	294
8.5.2.2	Effect of Fiber Orientation	295
8.5.2.3	Effect of Fiber Loading	296
8.5.3	Viscoelastic Properties	300

8.5.4	Diffusion and Swelling Properties	302
8.5.5	Dielectric Properties	304
8.5.6	Rheological and Aging Characteristics	305
8.6	Approaches to Improve Fiber–Matrix Adhesion	307
8.6.1	Mercerization	307
8.6.2	Benzoylation	308
8.6.3	Coupling Agents	308
8.6.4	Bonding Agents	309
8.7	Applications	312
8.8	Conclusions	312
	References	312
9	Improvement of Interfacial Adhesion in Bamboo Polymer Composite Enhanced with Microfibrillated Cellulose	317
	<i>Kazuya Okubo and Toru Fujii</i>	
9.1	Introduction	317
9.2	Materials	318
9.2.1	Matrix	318
9.2.2	Bamboo Fibers	318
9.2.3	Microfibrillated cellulose (MFC)	319
9.3	Experiments	320
9.3.1	Fabrication Procedure of Developed Composite Using PLA, BF, and MFC (PLA/BF/MFC Composite)	320
9.3.2	Three-Point Bending Test	321
9.3.3	Microdrop Test	321
9.3.4	Fracture Toughness Test	321
9.3.5	Bamboo Fiber Embedded Test	322
9.4	Results and Discussion	322
9.4.1	Internal State of PLA/BF/MFC Composite	322
9.4.2	Bending Strength of PLA/BF/MFC Composite	322
9.4.3	Fracture Toughness of PLA/BF/MFC Composite	325
9.4.4	Crack Propagation Behavior	325
9.5	Conclusion	328
	Acknowledgments	328
	References	328
10	Textile Biocomposites	331
10.1	Elastic Properties of Twisted Yarn Biocomposites	331
	<i>Koichi Goda and Rie Nakamura</i>	
10.1.1	Introduction	331
10.1.2	Classical Theories of Yarn Elastic Modulus	332
10.1.3	Orthotropic Theory for Twisted Yarn-Reinforced Composites	335
10.1.3.1	Yarn Modulus Based on Orthotropic Theory	335
10.1.3.2	Relation between Mechanical Properties and Twist Angle	338
10.1.3.3	Extension of Theory to Off-Axis Loading	341

10.1.4	Conclusion	344
10.2	Fabrication Process for Textile Biocomposites	345
	<i>Asami Nakai and Louis Laberge Lebel</i>	
10.2.1	Introduction	345
10.2.2	Intermediate Materials for Continuous Natural Fiber-Reinforced Thermoplastic Composites	345
10.2.3	Braid-Trusion of Jute/Polylactic Acid Composites	349
10.2.3.1	Braid Geometry	349
10.2.3.2	Experiments	353
10.2.3.3	Results and Discussion	356
10.2.4	Conclusion	358
	References	358
11	Bionanocomposites	361
	<i>Eliton S. Medeiros, Amélia S.F. Santos, Alain Dufresne, William J. Orts, and Luiz H. C. Mattoso</i>	
11.1	Introduction	361
11.2	Bionanocomposites	362
11.2.1	Bionanocomposite Classification	362
11.2.1.1	Particulate Bionanocomposites	363
11.2.1.2	Elongated Particle Bionanocomposites	363
11.2.1.3	Layered Particle-Reinforced Bionanocomposites	363
11.2.2	Reinforcements Used in Bionanocomposites	364
11.2.2.1	Nanoclays	365
11.2.2.2	Cellulose	365
11.2.2.3	Chitin and Chitosan	368
11.2.3	Matrices for Bionanocomposites	369
11.2.3.1	Polysaccharides	370
11.2.3.2	Biodegradable Polymers from Microorganisms and Biotechnology	375
11.2.3.3	Biodegradable Polymers from Petrochemical Products	377
11.2.4	Mixing, Processing, and Characterization of Bionanocomposites	380
11.2.4.1	Mixing	380
11.2.4.2	Processing	381
11.2.4.3	Characterization	382
11.2.5	Polysaccharide Bionanocomposites	383
11.2.5.1	Starch Bionanocomposites	383
11.2.5.2	Chitin Bionanocomposites	387
11.2.5.3	Chitosan Bionanocomposites	388
11.2.6	Protein Bionanocomposites	391
11.2.6.1	Soy Protein Isolate	392
11.2.6.2	Gelatin	395
11.2.6.3	Collagen	397
11.2.6.4	Other Protein-Based Bionanocomposites	398

- 11.2.7 Bionanocomposites Using Biodegradable Polymers from Microorganisms and Biotechnology 399
 - 11.2.7.1 Polyhydroxyalkanoates 399
 - 11.2.7.2 Polylactides 404
- 11.2.8 Bionanocomposites Using Biodegradable Polymers from Petrochemical Products 406
 - 11.2.8.1 Poly(ϵ -Caprolactone) 406
 - 11.2.8.2 Polyesteramides 411
 - 11.2.8.3 Aliphatic and Aromatic Polyesters and Their Copolymers 412
- 11.2.9 Other Biodegradable Polymers 416
 - 11.2.9.1 Poly(Vinyl Alcohol) 416
 - 11.2.9.2 Poly(Vinyl Acetate) 417
 - 11.2.9.3 Poly(Glycolic Acid) 418
- 11.3 Final Remarks 419
 - References 420
- 12 Fully Biodegradable “Green” Composites 431**
Rie Nakamura and Anil N. Netravali
 - 12.1 Introduction 431
 - 12.2 Soy Protein-Based Green Composites 434
 - 12.2.1 Introduction 434
 - 12.2.2 Fiber/Soy Protein Interfacial Properties 435
 - 12.2.3 Effect of Soy Protein Modification on the Properties of Resins and Composites 437
 - 12.2.3.1 Effect of Phytigel[®] Addition 437
 - 12.2.3.2 Effect of Stearic Acid Modification 439
 - 12.3 Starch-Based Green Composites 441
 - 12.3.1 Introduction 441
 - 12.3.2 Fiber Treatments 442
 - 12.3.2.1 Studies on Fiber Treatment 442
 - 12.3.2.2 Relationship between NaOH Concentration and Cellulose 442
 - 12.3.2.3 Effect of NaOH Treatment of Ramie Yarns on the Tensile Properties of Starch-Based Green Composites 444
 - 12.3.3 Cellulose Nanofiber-Reinforced “Green” Composites 446
 - 12.3.4 Evaluation of Mechanical Properties of Green Composites 447
 - 12.4 Biodegradation of “Green” Composites 450
 - 12.4.1 Biodegradation of PHBV 451
 - 12.4.2 Effect of Soy Protein Modification on Its Biodegradation 455
 - 12.4.3 Biodegradation of Starch-Based Green Composites 458
 - References 460

13	Applications and Future Scope of “Green” Composites	465
	<i>Hyun-Joong Kim, Hyun-Ji Lee, Taek-Jun Chung, Hyeok-Jin Kwon, Donghwan Cho, and William Tai Yin Tze</i>	
13.1	Introduction	465
13.1.1	Biodegradable Plastics versus Traditional Plastics	466
13.2	Applications of Biocomposites (Products/Applications/Market)	467
13.2.1	Survey of Technical Applications of Natural Fiber Composites	467
13.2.1.1	The International Trend in Biocomposites	468
13.2.2	Automotive Applications	469
13.2.2.1	Materials	469
13.2.2.2	Requirements	470
13.2.2.3	Market and Products	471
13.2.3	Structural Applications	472
13.2.3.1	Materials for Structural Applications of Green Composites	473
13.2.3.2	Requirements	473
13.3	Future Scope	476
13.3.1	Choice of Materials and Processing Methods	477
13.4	Conclusion	478
	References	479
14	Biomedical Polymer Composites and Applications	483
	<i>Dionysis E. Mouzakis</i>	
14.1	Introduction	483
14.2	Biocompatibility Issues	485
14.3	Natural Matrix Based Polymer Composites	488
14.3.1	Silk Biocomposites	488
14.3.2	Chitin and Chitosan as Matrices	489
14.3.3	Mammal Protein-Based Biocomposites	490
14.3.4	Hyaluronic Acid Composites	491
14.3.5	Other Natural Polymer Matrices	493
14.4	Synthetic Polymer Matrix Biomedical Composites	494
14.4.1	Biodegradable Polymer Matrices	495
14.4.2	Synthetic Polymer Composites	499
14.4.2.1	Orthopedic Applications	499
14.4.2.2	Dental Applications	500
14.4.2.3	Other Tissue Engineering Applications	502
14.5	Smart Polymers and Biocomposites	502
14.6	Polymer-Nanosystems and Nanocomposites in Medicine	504
14.7	Conclusions	506
14.8	Outlook	507
	References	507

15	Environmental Effects, Biodegradation, and Life Cycle Analysis of Fully Biodegradable “Green” Composites 515
	<i>Ajalesh Balachandran Nair, Palanisamy Sivasubramanian, Preetha Balakrishnan, Kurungattu Arjunan Nair Ajith Kumar, and Meyyarappallil Sadasivan Sreekala</i>
15.1	Introduction 515
15.2	Environmental Aspects 518
15.3	Environmental Impacts of Green Composite Materials 520
15.4	Choice of Impact Categories 521
15.4.1	Global Warming 521
15.4.2	Acidification 521
15.4.3	Abiotic Depletion 521
15.5	Environmental Impact of Polylactide 522
15.6	Environmental Effect of Polyvinyl Alcohol (PVA) 523
15.7	Potential Positive Environmental Impacts 526
15.7.1	Composting 526
15.7.2	Landfill Degradation 526
15.7.3	Energy Use 526
15.8	Potential Negative Environmental Impacts 526
15.8.1	Pollution of Aquatic Environments 527
15.8.1.1	Increased Aquatic BOD 527
15.8.1.2	Water Transportable Degradation Products 527
15.8.1.3	Risk to Marine Species 528
15.8.2	Litter 528
15.8.2.1	Determination of Appropriate Disposal Environments 528
15.8.2.2	Role of the Built Environment 529
15.9	Biodegradation 529
15.9.1	Biodegradability Test 530
15.9.1.1	Natural Soil Burial Test and Simulated Municipal Solid Waste (MSW) Aerobic Compost Test 530
15.9.1.2	Mechanical Property and Weight Loss Tests after Biodegradability 530
15.9.1.3	Microbial Counts in Natural and Compost Soil 531
15.9.1.4	Molecular Weight after Biodegradability 531
15.9.1.5	Differential Scanning Calorimetry (DSC) Analysis 531
15.9.1.6	FTIR-ATR Analysis 532
15.9.1.7	Morphological Test 532
15.10	Advantages of Green Composites over Traditional Composites 532
15.11	Disadvantages of Green Composites 532
15.12	Application and End-Uses 532
15.12.1	Automobiles 533
15.12.2	Aircrafts and Ships 533
15.12.3	Mobile Phones 533
15.12.4	Decorative Purposes 534
15.12.5	Uses 534

15.13	Biodegradation of Polyvinyl Alcohol (PVA) under Different Environmental Conditions	534
15.13.1	Biodegradation of Polyvinyl Alcohol under Composting Conditions	535
15.13.2	Biodegradation of Polyvinyl Alcohol in Soil Environment	535
15.13.3	Anaerobic Biodegradation of Polyvinyl Alcohol in Aqueous Environments	536
15.14	Biodegradation of Polylactic Acid	536
15.15	Biodegradation of Polylactic Acid and Its Composites	537
15.16	Biodegradation of Cellulose	539
15.17	Cellulose Fiber-Reinforced Starch Biocomposites	539
15.18	Life Cycle Assessment (LCA)	541
15.18.1	Methods	542
15.18.2	Green Design Metrics	543
15.18.3	Decision Matrix	545
15.19	Life Cycle Assessment Results	546
15.20	Green Principles Assessment Results	548
15.21	Comparison	548
15.22	Life Cycle Inventory Analysis of Green Composites	551
15.22.1	Fiber Composites	551
15.22.2	Natural Fibers	552
15.22.3	Life Cycle Analysis of Polylactide (PLA)	552
15.23	Life Cycle Analysis of Poly(hydroxybutyrate)	556
15.24	Life Cycle Analysis of Cellulose Fibers	556
15.25	Conclusions	558
	Abbreviations	559
	References	561

Index	569
--------------	-----

