CONTENTS

Preface xiii
Acknowledgments xvii
List of Plastic Materials xix

1 The Anthropocene 1

  1.1 Energy Futures 6
    1.1.1 Fossil Fuel Energy 8
      1.1.1.1 Oil 8
      1.1.1.2 Coal 9
      1.1.1.3 Gas 10
      1.1.1.4 Nuclear Energy 11
    1.1.2 Renewable Energy 12
      1.1.2.1 Wind Energy 12
      1.1.2.2 Solar Energy 13
      1.1.2.3 Solar Biomass Energy 13
  1.2 Materials Demand in the Future 14
    1.2.1 Materials of Construction 15
    1.2.2 Metal Resources 16
    1.2.3 Critical Materials 18
    1.2.4 Plastic Materials 19
  1.3 Environmental Pollution 22
    1.3.1 Classifying Pollution Impacts 23
    1.3.2 Climate Change and Global Warming 24

References 27
# A Sustainability Primer

2.1 The Precautionary Principle

## 2.1.1 Objectives in Sustainability

2.2 Microeconomics of Sustainability: The Business Enterprise

2.3 Models on Implementing Sustainability

2.4 Life Cycle Analysis

2.5 The Emerging Paradigm and the Plastics Industry

### 2.5.1 Examples from Plastics Industry

- Using the Minimum Energy Needed to Manufacture Products
- Using the Energy Mix with a Minimal Environmental Footprint
- Recovering Waste Process Energy for Reuse
- Using Only as Much Material as Is Needed to Ensure Functionality
- Using More of Renewable and Recycled Raw Materials
- Reusing and Recycling Postuse Products
- Minimizing Externalities at Source: Green Chemistry
- Avoiding Toxic Components and Potential Hazards Associated with Products and Processes
- Converting the Pollutants into Resources

## References

# An Introduction to Plastics

3.1 Polymer Molecules

### 3.1.1 Size of Polymer Molecules

3.2 Consequences of Long-Chain Molecular Architecture

### 3.2.1 Molecular Weight of Chain Molecules

### 3.2.2 Tacticity

### 3.2.3 Partially Crystalline Plastics

### 3.2.4 Chain Branching and Cross-Linking

### 3.2.5 Glass Transition Temperature

3.3 Synthesis of Polymers

### 3.3.1 Addition or Chain Growth Reaction

### 3.3.2 Condensation or Step Growth Reaction

### 3.3.3 Copolymers

3.4 Testing of Polymers

### 3.4.1 Tensile Properties

### 3.4.2 Thermal Properties: DSC (Differential Scanning Calorimetry)

### 3.4.3 Thermal Properties: TGA

## References
3.5 Common Plastics 76
  3.5.1 Polyethylenes 77
  3.5.2 Polypropylenes 78
  3.5.3 Polystyrene 78
  3.5.4 Poly(vinyl chloride) 80
References 81

4 Plastic Products 83
  4.1 Plastics: The Miracle Material 84
  4.2 Plastic Production, Use, and Disposal 88
    4.2.1 From Resin to Products 90
      4.2.1.1 Resin Manufacture 90
      4.2.1.2 Compounding 90
      4.2.1.3 Processing into Product 91
  4.3 Processing Methods for Common Thermoplastics 91
    4.3.1 Injection Molding 91
    4.3.2 Extrusion 95
    4.3.3 Blow Molding 95
  4.4 The Environmental Footprint of Plastics 97
    4.4.1 Energy Considerations in Resin Manufacture 98
    4.4.2 Atmospheric Emissions from Plastics Industry 101
  4.5 Plastics Additives 103
    4.5.1 Fillers for Plastics 106
    4.5.2 Plasticizers in PVC 106
  4.6 Biopolymer or Bio-Derived Plastics 107
    4.6.1 Bio-Based Plastics and Sustainability 109
    4.6.2 Emerging Bio-Based Plastics 111
      4.6.2.1 Bio-PE 112
      4.6.2.2 Bio-PET 112
      4.6.2.3 PLA 113
      4.6.2.4 Poly(Hydroxyalkanoates) 115
      4.6.2.5 Bio-Based Thermosets: PU 116
References 116

5 Societal Benefits of Plastics 121
  5.1 Transportation Applications of Plastics 122
    5.1.1 Passenger Cars 122
    5.1.2 Air and Sea Transport 124
  5.2 Benefits from Plastic Packaging 126
    5.2.1 Waste Reduction 129
    5.2.2 Chemical and Microbial Protection 130
  5.3 Plastics in Agriculture 131
5.4 Building Industry Applications
  5.4.1 Pipes, Conduit, and Cladding 133
  5.4.2 Extruded PVC Cladding and Window Frames 134
  5.4.3 Foam Insulation 135
  5.4.4 Wood–Plastic Composites 137
5.5 Original Equipment Manufacture (OEM) 138
5.6 Using Plastics Sustainably 139
References 140

6 Degradation of Plastics in the Environment 145
  6.1 Defining Degradability 146
  6.2 Chemistry of Light-Induced Degradation 147
    6.2.1 Light-Initiated Photo-Oxidation in PE and PP 150
    6.2.2 Embrittlement and Fragmentation 152
    6.2.3 Temperature and Humidity Effects on Degradation 154
    6.2.4 Wavelength-Dependent Photodamage 155
    6.2.5 Testing Plastics for Photodegradability 157
  6.3 Enhanced Photodegradable Polyolefins 160
    6.3.1 Effects of Photodegradation on Biodegradation 162
  6.4 Biodegradation of Polymers 163
    6.4.1 Terminology and Definitions 165
    6.4.2 Biodegradable Plastics 168
    6.4.3 Testing Readily Biodegradable Plastics 170
  6.5 Biodegradability of Common Polymers 173
    6.5.1 Additives that Enhance Degradation in Common Polymers 175
    6.5.2 Degradable Plastics and Sustainable Development 176
References 178

7 Endocrine Disruptor Chemicals 185
  7.1 Endocrine Disruptor Chemicals Used in Plastics Industry 187
  7.2 BPA {2,2-Bis(4-Hydroxyphenyl)Propane} 187
    7.2.1 Exposure to BPA 190
    7.2.2 Effects of Exposure to BPA 192
    7.2.3 Dose–Response Relationships of BPA 194
    7.2.4 Safe Levels of BPA 194
    7.2.5 Contrary Viewpoint on BPA 196
    7.2.6 Environmental Sustainability and BPA 197
  7.3 Phthalate Plasticizers 198
    7.3.1 Exposure to Phthalates 201
    7.3.2 Toxicity of Phthalates 203
    7.3.3 Environmental Sustainability and Phthalates 203
  7.4 Polybrominated Diphenyl Ethers (PBDEs) 204
    7.4.1 Toxicity of PBDEs 207
    7.4.2 Environmental Sustainability and PBDE 208
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.5</td>
<td>Alkylphenols and Their Ethoxylates (APE)</td>
<td>209</td>
</tr>
<tr>
<td>7.6</td>
<td>EDCs and PET Bottles</td>
<td>209</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>212</td>
</tr>
<tr>
<td>8</td>
<td>Plastics and Health Impacts</td>
<td>227</td>
</tr>
<tr>
<td>8.1</td>
<td>Packaging versus the Contents</td>
<td>228</td>
</tr>
<tr>
<td>8.1.1</td>
<td>Packaging Milk in HDPE</td>
<td>230</td>
</tr>
<tr>
<td>8.1.2</td>
<td>Overpackaging</td>
<td>232</td>
</tr>
<tr>
<td>8.2</td>
<td>Package–Food Interactions</td>
<td>233</td>
</tr>
<tr>
<td>8.2.1</td>
<td>Oxygen and Water Permeability</td>
<td>234</td>
</tr>
<tr>
<td>8.2.2</td>
<td>Additive Migration and Toxicity</td>
<td>236</td>
</tr>
<tr>
<td>8.2.3</td>
<td>Residual Monomer in Packaging Resin</td>
<td>240</td>
</tr>
<tr>
<td>8.2.4</td>
<td>Scalping of Flavor Components</td>
<td>240</td>
</tr>
<tr>
<td>8.3</td>
<td>Styrene and Expanded Polystyrene Food Service Materials</td>
<td>242</td>
</tr>
<tr>
<td>8.3.1</td>
<td>Exposure to Styrene from Packaging</td>
<td>244</td>
</tr>
<tr>
<td>8.3.2</td>
<td>Leachate from PET Bottles</td>
<td>244</td>
</tr>
<tr>
<td>8.4</td>
<td>Ranking Common Plastics</td>
<td>245</td>
</tr>
<tr>
<td>8.4.1</td>
<td>PVC</td>
<td>248</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>249</td>
</tr>
<tr>
<td>9</td>
<td>Managing Plastic Waste</td>
<td>255</td>
</tr>
<tr>
<td>9.1</td>
<td>Recovery of Waste</td>
<td>258</td>
</tr>
<tr>
<td>9.1.1</td>
<td>Material Recycling</td>
<td>261</td>
</tr>
<tr>
<td>9.1.2</td>
<td>Feedstock Recovery</td>
<td>261</td>
</tr>
<tr>
<td>9.1.3</td>
<td>Energy Recovery</td>
<td>261</td>
</tr>
<tr>
<td>9.2</td>
<td>Pyrolysis of Plastic Waste for Feedstock Recovery</td>
<td>261</td>
</tr>
<tr>
<td>9.2.1</td>
<td>Direct Thermolysis</td>
<td>261</td>
</tr>
<tr>
<td>9.2.2</td>
<td>Hydrogenation or Hydrocracking</td>
<td>264</td>
</tr>
<tr>
<td>9.2.3</td>
<td>Gasification</td>
<td>265</td>
</tr>
<tr>
<td></td>
<td>9.2.3.1 Thermal Gasification</td>
<td>265</td>
</tr>
<tr>
<td></td>
<td>9.2.3.2 Plasma Arc Gasification</td>
<td>266</td>
</tr>
<tr>
<td>9.2.4</td>
<td>Feedstock Recycling</td>
<td>267</td>
</tr>
<tr>
<td>9.2.5</td>
<td>Landfilling</td>
<td>271</td>
</tr>
<tr>
<td>9.2.6</td>
<td>Plastics Waste Incineration</td>
<td>272</td>
</tr>
<tr>
<td>9.2.7</td>
<td>Biological Recovery Technologies</td>
<td>274</td>
</tr>
<tr>
<td>9.3</td>
<td>Sustainable Waste Management Choices</td>
<td>275</td>
</tr>
<tr>
<td>9.4</td>
<td>Mechanical Recycling of Plastics</td>
<td>278</td>
</tr>
<tr>
<td>9.4.1</td>
<td>Recycling: A Sustainable Choice</td>
<td>281</td>
</tr>
<tr>
<td>9.5</td>
<td>Recycling Bottles: Beverage Bottles and Jugs</td>
<td>282</td>
</tr>
<tr>
<td>9.5.1</td>
<td>Bottle-to-Bottle Recycling</td>
<td>282</td>
</tr>
<tr>
<td>9.5.2</td>
<td>Open-Loop Recycling</td>
<td>284</td>
</tr>
<tr>
<td>9.5.3</td>
<td>Recycling of HDPE</td>
<td>285</td>
</tr>
<tr>
<td>9.6</td>
<td>Designing for Recyclability</td>
<td>285</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>286</td>
</tr>
</tbody>
</table>
10 Plastics in the Oceans 295
  10.1 Origins of Plastics in the Ocean 297
  10.2 Weathering of Plastics in the Ocean Environment 299
    10.2.1 Beach (Supralittoral) Zone 300
    10.2.2 Surface Water Zone 301
    10.2.3 Deep Water and Sediment Zones 301
      10.2.3.1 Comparison of the Weathering Rates in Different Zones 301
  10.3 Microplastic Debris 304
    10.3.1 Primary and Secondary Microplastics 305
    10.3.2 Persistent Organic Pollutant in Microplastics 307
    10.3.3 Ingestion of Microplastics by Marine Species 309
  10.4 Ocean Litter and Sustainability 310
References 311

Index 319