# Contents

*List of Contributors* *xix*
*Preface* *xxiii*

**PART I INTRODUCTION** **1**

**1 Overview of Biomass Conversion Processes and Separation and Purification Technologies in Biorefineries** **3**
*Hua-Jiang Huang and Shri Ramaswamy*

1.1 Introduction 3
1.2 Biochemical conversion biorefineries 4
1.3 Thermo-chemical and other chemical conversion biorefineries 8
1.3.1 Thermo-chemical conversion biorefineries 8
1.3.1.1 Example: Biomass to gasoline process 10
1.3.2 Other chemical conversion biorefineries 11
1.3.2.1 Levulinic acid 11
1.3.2.2 Glycerol 12
1.3.2.3 Sorbitol 12
1.3.2.4 Xylitol/Arabinitol 12
1.3.2.5 Example: Conversion of oil-containing biomass for biodiesel 12
1.4 Integrated lignocellulose biorefineries 14
1.5 Separation and purification processes 15
1.5.1 Equilibrium-based separation processes 15
1.5.1.1 Absorption 15
1.5.1.2 Distillation 16
1.5.1.3 Liquid-liquid extraction 16
1.5.1.4 Supercritical fluid extraction 17
1.5.2 Affinity-based separation 18
1.5.2.1 Simulated moving-bed chromatography 19
1.5.3 Membrane separation 20
1.5.4 Solid–liquid separation 23
1.5.4.1 Conventional filtration 23
1.5.4.2 Solid–liquid extraction 23
1.5.4.3 Precipitation and crystallization 24
1.5.5 Reaction-separation systems for process intensification 24
1.5.5.1 Reaction–membrane separation systems 25
1.5.5.2 Extractive fermentation (Reaction–LLE systems) 25
1.5.5.3 Reactive distillation 27
1.5.5.4 Reactive absorption 27

1.6 Summary 27
References 28

**PART II EQUILIBRIUM-BASED SEPARATION TECHNOLOGIES 37**

**2 Distillation 39**
*Zhigang Lei and Biaohua Chen*

2.1 Introduction 39
2.2 Ordinary distillation 40
2.2.1 Thermodynamic fundamental 40
2.2.2 Distillation equipment 41
2.2.3 Application in biorefineries 43
2.3 Azeotropic distillation 45
2.3.1 Introduction 45
2.3.2 Example in biorefineries 46
2.3.3 Industrial challenges 47
2.4 Extractive distillation 48
2.4.1 Introduction 48
2.4.2 Extractive distillation with liquid solvents 50
2.4.3 Extractive distillation with solid salts 50
2.4.4 Extractive distillation with the mixture of liquid solvent and solid salt 51
2.4.5 Extractive distillation with ionic liquids 52
2.4.6 Examples in biorefineries 54
2.5 Molecular distillation 54
2.5.1 Introduction 54
2.5.2 Examples in biorefineries 55
2.5.3 Mathematical models 55
2.6 Comparisons of different distillation processes 55
2.7 Conclusions and future trends 58
Acknowledgement 58
References 58

**3 Liquid-Liquid Extraction (LLE) 61**
*Jianguo Zhang and Bo Hu*

3.1 Introduction to LLE: Literature review and recent developments 61
3.2 Fundamental principles of LLE 62
3.3 Categories of LLE design 65
3.4 Equipment for the LLE process 67
3.4.1 Criteria 67
3.4.2 Types of extractors 68
3.4.3 Issues with current extractors 70
3.5 Applications in biorefineries 70
3.5.1 Ethanol 70
3.5.2 Biodiesel 72
3.5.3 Carboxylic acids 73

3.5.4 Other biorefinery processes 73
3.6 The future development of LLE for the biorefinery setting 74
References 75

**4 Supercritical Fluid Extraction** **79**
*Casimiro Mantell, Lourdes Casas, Miguel Rodríguez and Enrique Martínez de la Ossa*

4.1 Introduction 79
4.2 Principles of supercritical fluids 81
4.3 Market and industrial needs 83
4.4 Design and modeling of the process 84
4.4.1 Film theory 88
4.4.2 Penetration theory 88
4.5 Specific examples in biorefineries 89
4.5.1 Sugar/starch as a raw material 90
4.5.2 Supercritical extraction of vegetable oil 90
4.5.3 Supercritical extraction of lignocellulose biomass 91
4.5.4 Supercritical extraction of microalgae 92
4.6 Economic importance and industrial challenges 93
4.7 Conclusions and future trends 96
References 96

**PART III AFFINITY-BASED SEPARATION TECHNOLOGIES** **101**

**5 Adsorption** **103**
*Saravanan Venkatesan*

5.1 Introduction 103
5.2 Essential principles of adsorption 104
5.2.1 Adsorption isotherms 105
5.2.1.1 Freundlich isotherm 105
5.2.1.2 Langmuir isotherm 105
5.2.1.3 BET isotherm 107
5.2.1.4 Ideal adsorbed solution (IAS) theory 107
5.2.2 Types of adsorption isotherm 108
5.2.3 Adsorption hysteresis 109
5.2.4 Heat of adsorption 110
5.3 Adsorbent selection criteria 110
5.4 Commercial and new adsorbents and their properties 111
5.4.1 Activated carbon 112
5.4.2 Silica gel 113
5.4.3 Zeolites and molecular sieves 113
5.4.4 Activated alumina 114
5.4.5 Polymeric resins 114
5.4.6 Bio-based adsorbents 115
5.4.7 Metal organic frameworks (MOF) 116

5.5 Adsorption separation processes 116
5.5.1 Adsorbate concentration 116
5.5.2 Modes of adsorber operation 116
5.5.3 Adsorbent regeneration methods 117
5.5.3.1 Selection of regeneration method 117
5.5.3.2 Temperature swing adsorption (TSA) 117
5.5.3.3 Pressure swing adsorption (PSA) 120
5.6 Adsorber modeling 123
5.7 Application of adsorption in biorefineries 124
5.7.1 Examples of adsorption systems for removal of fermentation inhibitors from lignocellulosic biomass hydrolysate 125
5.7.2 Examples of adsorption systems for recovery of biofuels from dilute aqueous fermentation broth 129
5.7.2.1 *In situ* recovery of 1-butanol 129
5.7.2.2 Recovery of other prospective biofuel compounds 132
5.7.2.3 Ethanol dehydration 133
5.7.2.4 Biodiesel purification 135
5.8 A case study: Recovery of 1-butanol from ABE fermentation broth using TSA 136
5.8.1 Introduction 136
5.8.2 Adsorbent in extrudate form 136
5.8.3 Adsorption kinetics 136
5.8.4 Adsorption of 1-butanol by CBV28014 extrudates in a packed-bed column 136
5.8.5 Desorption 138
5.8.6 Equilibrium isotherms 139
5.8.7 Simulation of breakthrough curves 140
5.8.8 Summary from case study 140
5.9 Research needs and prospects 142
5.10 Conclusions 143
Acknowledgement 143
References 143

**6 Ion Exchange** **149**
*M. Berrios, J. A. Siles, M. A. Martín and A. Martín*

6.1 Introduction 149
6.1.1 Ion exchangers: Operational conditions—sorbent selection 150
6.2 Essential principles 151
6.2.1 Properties of ion exchangers 151
6.3 Ion-exchange market and industrial needs 153
6.4 Commercial ion-exchange resins 154
6.4.1 Strong acid cation resins 154
6.4.2 Weak acid cation resins 154
6.4.3 Strong base anion resins 155
6.4.4 Weak base anion resins 155
6.5 Specific examples in biorefineries 156
6.5.1 Water softening 156
6.5.2 Total removal of electrolytes from water 157

6.5.3 Removal of nitrates in water 157
6.5.4 Applications in the food industry 157
6.5.5 Applications in chromatography 158
6.5.6 Special applications in water treatment 159
6.5.7 Metal recovery 159
6.5.8 Separation of isotopes or ions 160
6.5.9 Applications of zeolites in ion-exchange processes 160
6.5.10 Applications of ion exchange in catalytic processes 161
6.5.11 Recent applications of ion exchange in lignocellulosic bioefineries 162
6.5.12 Recent applications of ion exchange in biodiesel bioefineries 162
6.6 Conclusions and future trends 164
References 164

**7 Simulated Moving-Bed Technology for Biorefinery Applications 167**
*Chim Yong Chin and Nien-Hwa Linda Wang*

7.1 Introduction 167
7.1.1 Principles of separations in batch chromatography and SMB 167
7.1.2 The advantages of SMB 169
7.1.3 A brief history of SMB and its applications 169
7.1.4 Barriers to SMB applications 171
7.2 Essential SMB design principles and tools 171
7.2.1 Knowledge-driven design 172
7.2.2 Design and optimization for multicomponent separation 173
7.2.2.1 Standing-wave analysis (SWA) 173
7.2.2.2 Splitting strategies for multicomponent SMB systems 178
7.2.2.3 Comprehensive optimization with standing-wave (COSW) 178
7.2.2.4 Other design methodologies 181
7.2.3 SMB chromatographic simulation 181
7.2.4 SMB equipment 184
7.2.5 Advanced SMB operations 188
7.2.5.1 Simulated moving-bed reactors 190
7.2.6 SMB commercial manufacturers 190
7.3 Simulated moving-bed technology in biorefineries 191
7.3.1 SMB separation of sugar hydrolysate and concentrated sulfuric acid 192
7.3.2 Five-zone SMB for sugar isolation from dilute-acid hydrolysate 193
7.3.3 Simulated moving-bed purification of lactic acid in fermentation broth 195
7.3.4 SMB purification of glycerol by-product from biodiesel processing 196
7.4 Conclusions and future trends 197
References 197

**PART IV MEMBRANE SEPARATION 203**

**8 Microfiltration, Ultrafiltration and Diafiltration 205**
*Ann-Sofi Jönsson*

8.1 Introduction 205
8.1.1 Applications of microfiltration 206

8.1.2 Applications of ultrafiltration 206
8.2 Membrane plant design 207
8.2.1 Single-stage membrane plants 208
8.2.2 Multistage membrane plants 208
8.2.3 Membranes 209
8.2.4 Membrane modules 209
8.2.5 Design and operation of membrane plants 210
8.3 Economic considerations 210
8.3.1 Capital cost 211
8.3.2 Operating costs 211
8.4 Process design 213
8.4.1 Flux during concentration 213
8.4.2 Retention 213
8.4.3 Recovery and purity 214
8.5 Operating parameters 216
8.5.1 Pressure 217
8.5.2 Cross-flow velocity 218
8.5.3 Temperature 219
8.5.4 Concentration 220
8.5.5 Influence of concentration polarization and critical flux on retention 220
8.6 Diafiltration 222
8.7 Fouling and cleaning 224
8.7.1 Fouling 224
8.7.2 Pretreatment 225
8.7.3 Cleaning 225
8.8 Conclusions and future trends 226
References 226

**9 Nanofiltration** **233**
*Mika Mänttäri, Bart Van der Bruggen and Marianne Nyström*

9.1 Introduction 233
9.2 Nanofiltration market and industrial needs 235
9.3 Fundamental principles 236
9.3.1 Pressure and flux 236
9.3.2 Retention and fractionation 236
9.3.3 Influence of filtration parameters 237
9.4 Design and simulation 238
9.4.1 Water permeation 238
9.4.2 Solute retention 238
9.4.2.1 Retention of organic components 239
9.4.2.2 Retention of inorganic components 240
9.5 Membrane materials and properties 241
9.5.1 Structure of NF membranes 242
9.5.2 Hydrophilic and hydrophobic characteristics 242
9.5.3 Charge characteristics 242
9.6 Commercial nanofiltration membranes 245

9.7 Nanofiltration examples in biorefineries 246
9.7.1 Recovery and purification of monomeric acids 246
9.7.1.1 Separation of lactic acid and amino acids in fermentation plants 247
9.7.1.2 Separation of lactic acid from cheese whey fermentation broth 247
9.7.2 Biorefineries connected to pulping processes 247
9.7.2.1 Valorization of black liquor compounds 248
9.7.2.2 Purification of pre-extraction liquors and hydrolysates 250
9.7.2.3 Examples of monosaccharides purification 251
9.7.2.4 Nanofiltration to treat sulfite pulp mill liquors 252
9.7.3 Miscellaneous studies on extraction of natural raw materials 253
9.7.4 Industrial examples of NF in biorefinery 254
9.7.4.1 Recovery and purification of sodium hydroxide in viscose production 254
9.7.4.2 Xylose recovery and purification into permeate 254
9.7.4.3 Purification of dextrose syrup 255
9.8 Conclusions and challenges 256
References 256

**10 Membrane Pervaporation** **259**
*Yan Wang, Natalia Widjojo, Panu Sukitpaneenit and Tai-Shung Chung*

10.1 Introduction 259
10.2 Membrane pervaporation market and industrial needs 260
10.3 Fundamental principles 261
10.3.1 Transport mechanisms 261
10.3.2 Evaluation of pervaporation membrane performance 264
10.4 Design principles of the pervaporation membrane 265
10.4.1 Membrane materials and selection 266
10.4.1.1 Polymeric pervaporation membranes for bioalcohol dehydration 267
10.4.1.2 Pervaporation membranes for biofuel recovery 271
10.4.2 Membrane morphology 281
10.4.3 Commercial pervaporation membranes 283
10.5 Pervaporation in the current integrated biorefinery system 283
10.6 Conclusions and future trends 288
Acknowledgements 289
References 289

**11 Membrane Distillation** **301**
*M. A. Izquierdo-Gil*

11.1 Introduction 301
11.1.1 Direct-contact membrane distillation (DCMD) 302
11.1.2 Air gap membrane distillation (AGMD) 303
11.1.3 Sweeping gas membrane distillation (SGMD) 303
11.1.4 Vacuum membrane distillation (VMD) 304
11.2 Membrane distillation market and industrial needs 304
11.2.1 Pure water production 305
11.2.2 Waste water treatment 306
11.2.3 Concentration of agro-food solutions 306

11.2.4 Concentration of organic and biological solutions 307
11.3 Basic principles of membrane distillation 308
11.3.1 Mass transfer 308
11.3.2 Concentration polarization phenomena 311
11.3.3 Heat transport 311
11.3.4 Liquid entry pressure 312
11.4 Design and simulation 313
11.5 Examples in biorefineries 315
11.6 Economic importance and industrial challenges 317
11.7 Comparisons with other membrane-separation technologies 319
11.8 Conclusions and future trends 321
References 322

**PART V SOLID-LIQUID SEPARATIONS 327**

**12 Filtration-Based Separations in the Biorefinery 329**
*Bhavin V. Bhayani and Bandaru V. Ramarao*

12.1 Introduction 329
12.2 Biorefinery 330
12.2.1 Pretreatment 330
12.2.2 Hydrolyzate separations 332
12.2.3 Downstream fermentation and separations 335
12.3 Solid–liquid separations in the biorefinery 335
12.4 Introduction to cake filtration 336
12.5 Basics of cake filtration 336
12.5.1 Application in biorefineries 339
12.5.2 Specific points of interest 340
12.6 Designing a dead-end filtration 340
12.6.1 Determination of specific resistance 340
12.6.2 Membrane fouling 340
12.6.3 The effect of pressure on specific resistance—cake compressibility 342
12.6.4 Relating cake compressibility to cake particles morphology 342
12.6.5 Effects of particles surface properties and the medium liquid 344
12.6.6 Fouling in filtration of lignocellulosic hydrolyzates 345
12.7 Model development 346
12.7.1 Requirements of a model 348
12.8 Conclusions 348
References 348

**13 Solid–Liquid Extraction in Biorefinery 351**
*Zurina Zainal Abidin, Dayang Radiah Awang Biak, Hamdan Mohamed Yusoff and Mohd Yusof Harun*

13.1 Introduction 351
13.2 Principles of solid–liquid extraction 352
13.2.1 Extraction mode 353
13.2.1.1 Single-stage, batch 354

13.2.1.2 Multistage crosscurrent flow 354
13.2.1.3 Multistage countercurrent flow 354
13.2.2 Solid–liquid extraction techniques 355
13.2.2.1 Solvent extraction 355
13.2.2.2 High-pressure extraction 355
13.2.2.3 Ultrasonic-assisted extraction 355
13.2.2.4 Microwave-assisted extraction 355
13.2.2.5 Heat reflux extraction 355
13.3 State of the art technology 356
13.4 Design and modeling of SLE process 357
13.4.1 Pretreatment of raw materials 357
13.4.2 Solid–liquid extraction 359
13.4.3 Equipment and operational setup 360
13.4.4 Process modeling 361
13.4.5 Scaling up 363
13.5 Industrial extractors 363
13.5.1 Batch extractors 364
13.5.2 Continuous extractors 366
13.5.3 Extraction of specialty chemicals 368
13.6 Economic importance and industrial challenges 368
13.7 Conclusions 371
References 371

**PART VI HYBRID/INTEGRATED REACTION-SEPARATION SYSTEMS—PROCESS INTENSIFICATION 375**

**14 Membrane Bioreactors for Biofuel Production 377**
*Sara M. Badenes, Frederico Castelo Ferreira and Joaquim M. S. Cabral*

14.1 Introduction 377
14.1.1 Opportunities for membrane bioreactor in biofuel production 378
14.1.2 The market and industry needs 379
14.2 Basic principles 381
14.2.1 Biofuels: Production principles and biological systems 381
14.2.2 Transport in membrane systems 386
14.2.3 Membrane modules and reactor operations 389
14.2.4 Membrane bioreactor 390
14.3 Examples of membrane bioreactors for biofuel production 390
14.3.1 Bioethanol production 390
14.3.1.1 Overview 390
14.3.1.2 Membrane bioreactors for cell retention and ethanol removal 392
14.3.1.3 Upstream saccharification stage: Retention of hydrolytic enzymes and sugar permeation 395
14.3.1.4 Downstream ethanol purification stage: Pervaporation 396
14.3.2 Biodiesel production 397
14.3.2.1 Overview 397
14.3.2.2 Membrane bioreactor for biodiesel production 398

14.3.3 Biogas production 399
14.3.3.1 Overview 399
14.3.3.2 Membrane bioreactor for biogas production 400
14.4 Conclusions and future trends 403
References 404

**15 Extraction-Fermentation Hybrid (Extractive Fermentation) 409**
*Shang-Tian Yang and Congcong Lu*

15.1 Introduction 409
15.2 The market and industrial needs 410
15.3 Basic principles of extractive fermentation 412
15.4 Separation technologies for integrated fermentation product recovery 413
15.4.1 Gas stripping 413
15.4.2 Pervaporation 416
15.4.3 Liquid–liquid extraction 419
15.4.4 Adsorption 422
15.4.5 Electrodialysis 424
15.5 Examples in biorefineries 426
15.5.1 Extractive ABE fermentation for enhanced butanol production 426
15.5.2 Extractive fermentation for organic acids production 428
15.6 Economic importance and industrial challenges 428
15.7 Conclusions and future trends 431
References 431

**16 Reactive Distillation for the Biorefinery 439**
*Aspi K. Kolah, Carl T. Lira and Dennis J. Miller*

16.1 Introduction 439
16.1.1 Reactive distillation process principles 439
16.1.2 Motives for application of reactive distillation 440
16.1.2.1 Reaction properties 440
16.1.2.2 Separation properties 440
16.1.3 Limitations and disadvantages of reactive distillation 440
16.1.4 Homogeneous and heterogeneous reactive distillation 441
16.2 Column internals for reactive distillation 441
16.2.1 Random or dumped catalyst packings 442
16.2.2 Catalytic distillation trays 442
16.2.3 Catalyst bales 443
16.2.4 Structured packings 443
16.2.5 Internally finned monoliths 446
16.3 Simulation of reactive distillation systems 446
16.3.1 Phase equilibria 446
16.3.2 Characterization of reaction kinetics 447
16.3.3 Calculation of residue curve maps 448
16.3.4 Simulation and design of reactive distillation systems 450
16.3.4.1 Equilibrium stage model 450

16.3.4.2 Rate-based model 450
16.3.4.3 Design of reactive distillation systems 451
16.4 Reactive distillation for the biorefinery 451
16.4.1 Esterification of carboxylic acids and transesterification of esters 451
16.4.1.1 Biodiesel production 452
16.4.1.2 Esterification of long-chain fatty acids 453
16.4.1.3 Lactate esterification 453
16.4.1.4 Short-chain organic acid esterification 454
16.4.1.5 Reactive distillation for glycerol esterification 455
16.4.2 Etherification 456
16.4.3 Acetal formation 457
16.4.4 Reactive distillation for thermochemical conversion pathways 457
16.5 Recently commercialized reactive distillation processes for the biorefinery 458
16.6 Conclusions 458
References 459

**17 Reactive Absorption 467**
*Anton A. Kiss and Costin Sorin Bildea*

17.1 Introduction 467
17.2 Market and industrial needs 468
17.3 Basic principles of reactive absorption 468
17.4 Modelling, design and simulation 469
17.5 Case study: Biodiesel production by catalytic reactive absorption 470
17.5.1 Problem statement 471
17.5.2 Heat-integrated process design 471
17.5.3 Property model and kinetics 473
17.5.4 Steady-state simulation results 474
17.5.5 Sensitivity analysis 476
17.5.6 Dynamics and plantwide control 478
17.6 Economic importance and industrial challenges 482
17.7 Conclusions and future trends 482
References 482

**PART VII CASE STUDIES OF SEPARATION AND PURIFICATION TECHNOLOGIES IN BIOREFINERIES 485**

**18 Cellulosic Bioethanol Production 487**
*Mats Galbe, Ola Wallberg and Guido Zacchi*

18.1 Introduction: The market and industrial needs 487
18.2 Separation procedures and their integration within a bioethanol plant 488
18.2.1 Process configurations 488
18.3 Importance and challenges of separation processes 490
18.3.1 Distillation 490
18.3.2 Dehydration of ethanol 493
18.3.2.1 Adsorption on zeolites 493

18.3.2.2 Pervaporation and vapor permeation 494
18.3.3 Evaporation 495
18.3.4 Liquid–solid separation 496
18.3.4.1 Filtration of solid residue (lignin) 496
18.3.4.2 Recovery of yeast 496
18.3.5 Drying of solids 497
18.3.5.1 Air dryer heated to low temperature by waste heat 497
18.3.5.2 Air dryer heated by back-pressure steam 498
18.3.5.3 Superheated steam dryer heated by high pressure steam 498
18.3.6 Upgrading of biogas 498
18.4 Pilot and demonstration scale 498
18.5 Conclusions and future trends 500
References 500

**19 Dehydration of Ethanol using Pressure Swing Adsorption 503**
*Marian Simo*

19.1 Introduction 503
19.2 Ethanol dehydration process using pressure swing adsorption 504
19.2.1 Adsorption equilibrium and kinetics 504
19.2.2 Principle of pressure swing adsorption 506
19.2.3 Ethanol PSA process cycle 506
19.2.3.1 Two-bed ethanol PSA cycle steps 506
19.2.4 Process performance and energy needs 507
19.3 Future trends and industrial challenges 510
19.4 Conclusions 511
References 511

**20 Separation and Purification of Lignocellulose Hydrolyzates 513**
*G. Peter van Walsum*

20.1 Introduction 513
20.1.1 Sugar platform 513
20.1.2 Biomass hydrolysis 513
20.1.3 Biomass pretreatment 514
20.1.4 Wood degradation products and potential biological inhibitors 515
20.1.5 Detoxification of wood hydrolysates 516
20.2 The market and industrial needs 516
20.2.1 Microbial inhibition by biomass degradation products 516
20.2.2 Enzyme inhibition by biomass degradation products 517
20.3 Operation variables and conditions 517
20.3.1 Effects of pretreatment conditions on enzymes and microbial cultures 517
20.3.2 Quantification of microbial inhibitors in pretreatment hydrolysates 518
20.3.3 Separations challenges posed by biomass degradation products 518
20.4 The hydrolyzates detoxification and separation processes 519
20.4.1 Evaporation, flashing 519
20.4.2 High pH treatment 519
20.4.2.1 Cation effects in overliming 519

20.4.2.2 pH and temperature effects 520
20.4.2.3 Different fermentative organisms 521
20.4.3 Adsorption 521
20.4.4 Liquid–liquid extraction 522
20.4.5 Ion exchange 522
20.4.6 Polymer-induced flocculation 523
20.4.7 Dialysis 523
20.4.8 Microbial detoxification 523
20.4.9 Enzyme detoxification 524
20.4.10 Microbial accommodation of inhibitors 524
20.5 Separation performances and results 524
20.6 Economic importance and industrial challenges 525
20.6.1 Cost of slow enzymes 525
20.6.2 Cost of slow fermentations 525
20.6.3 Benefits of co-products 526
20.6.4 Material consumption 526
20.6.5 Complexity: Capital and operating cost 527
20.6.6 Waste reduction 527
20.7 Conclusions 527
References 527

**21 Case Studies of Separation in Biorefineries—Extraction of Algae Oil from Microalgae 533**
*Michael Cooney*

21.1 Introduction 533
21.2 The market and industrial needs 534
21.2.1 Feedstock markets 534
21.2.2 Biodiesel markets 536
21.2.3 Algae products 537
21.2.4 Industrial needs 537
21.3 The algae oil extraction process 539
21.3.1 Harvesting/isolation 539
21.3.2 Drying 539
21.3.3 Cell wall lyses/disruption 539
21.4 Extraction 540
21.4.1 Organic-solvent based 540
21.4.2 Aqueous based 541
21.4.3 Combined aqueous and organic phases 543
21.4.4 Supercritical fluids 544
21.4.5 Solventless extraction 545
21.4.6 Emerging technologies 545
21.4.7 Refining lipids 546
21.5 Separation performance and results 546
21.6 Economic importance and industrial challenges 548
21.7 Conclusions and future trends 549
References 550

**22 Separation Processes in Biopolymer Production** **555**
*Sanjay P. Kamble, Prashant P. Barve, Imran Rahman and Bhaskar D. Kulkarni*

22.1 Introduction 555
22.2 The market and industrial needs 556
22.3 Lactic acid recovery processes 559
22.3.1 Electrodialysis 559
22.3.2 Adsorption 559
22.3.3 Reactive extraction 560
22.3.4 Reverse osmosis 560
22.3.5 Reactive distillation 561
22.4 Separation performance and results of autocatalytic counter current reactive distillation of lactic acid with methanol and hydrolysis of methyl lactate into highly pure lactic acid using 3-CSTRs in series 561
22.5 Economic importance and industrial challenges 564
22.6 Conclusions and future trends 565
Acknowledgements 566
References 566

**Index** **569**