Contents

Part I Introduction and Basic Theory

1 Biotechnology for Air Pollution Control – an Overview
Zarook Shareefdeen, Brian Herner, Ajay Singh 3
1.1 Introduction 3
1.2 Methods of Odor and VOC Control 3
1.3 Biological Reactors 4
1.3.1 Bioreactor Media 4
1.3.2 Microbiology 5
1.3.3 Types of Bioreactors 7
1.4 Modeling and Design of Bioreactors 8
1.4.1 Modeling of Bioreactors 8
1.4.2 Design of Bioreactors 9
1.5 Types of Contaminants 10
1.6 Case Studies 11
1.7 Conclusion 12
References 12

2 Environmental Laws and Regulations Related to Odor and Waste Gas Contaminants
Rodney L. Aldrich 17
2.1 Introduction 17
2.2 Control of VOCs 18
2.3 Control of Odor-Causing Chemicals 20
2.4 Brief Overview of Odor Restrictions Around the World 21
2.4.1 The United States of America 21
2.4.2 Japan 24
2.4.3 China 24
2.4.4 The United Kingdom 24
2.4.5 Canada 25
2.5 Conclusions 26
References 28

3 Methods of Odor and VOC Control
Sergio Revah, Juan M. Morgan-Sagastume 29
3.1 VOCs and Odor Definition 29
3.2 Methods for VOCs and Odor Control 30
3.3 Physical-chemical Methods 35
3.3.1 Dilution 35
3.3.2 Condensation 35
3.3.3 Membranes 36
3.3.4 UV Oxidation 36
3.3.5 Plasma 37
3.3.6 Adsorption 38
3.3.7 Combustion (Flares, Thermal and Catalytic Incinerators) 38
3.3.8 Masking 40
3.3.9 Caustic Scrubbing 40
3.3.10 Regenerative Gas Scrubbing 41
3.3.11 Chemical Precipitation 42
3.3.12 Chlorine Oxidation 42
3.3.13 Ozone Oxidation 42
3.3.14 Potassium Permanganate Oxidation 42
3.3.15 Catalytic Oxidation with Fe^{3+} (LO-CAT Process) 43
3.3.16 Hydrogen Peroxide Oxidation 43
3.3.17 Oxidation with FeO 43
3.4 Biological Methods 43
3.4.1 Terminology 45
3.4.2 Mechanisms 47
3.4.3 The Biological Phase 48
3.5 Types of Bioreactors 53
3.5.1 Biofilter 54
3.5.2 Biotrickling Filters 55
3.5.3 Rotating Biological Contactors 56
3.5.4 Bioscrubbers 56
3.5.5 Membrane Bioreactors 57
3.5.6 Suspended Cell Bioreactor 58
3.6 Conclusions 59
References 60

4 Selection of Bioreactor Media for Odor Control
Rakesh Govind, Sandeep Narayan 65
4.1 Introduction 65
4.2 Diffusive Versus Convective Media 66
4.3 Naturally Bioactive Media 68
4.4 Synthetic Media 71
4.5 Randomly Packed Versus Structured Biomedia 83
4.6 Biofilter Versus Biotrickling Filter 85

4.7 Experimental Studies on Diffusive Biofilter Media 86
4.7.1 Experimental Setup 86
4.7.2 Analytical Procedure 87
4.7.3 Results and Discussion 88
4.8 Experimental Studies on Convective Biofilter Media 90
4.9 Studies on Encapsulated Biomass and Membrane Biofilters 92
4.10 Conclusions 94
Appendix 95
References 99

5 Microbiology of Bioreactors for Waste Gas Treatment
Ajay Singh, Owen Ward 101
5.1 Introduction 101
5.2 Microbial Communities Involved in Waste Gas Treatment 102
5.3 The Nature of Microbial Biofilms 104
5.4 Biodegradation of Air Pollutants 106
5.4.1 Biokinetics 106
5.4.2 Biodegradation of Organic Compounds 107
5.4.3 Biodegradation of Inorganic Compounds 108
5.5 Factors Affecting Microbial Degradation of Air Contaminants 110
5.5.1 Bioavailability 110
5.5.2 Nutritional 111
5.5.3 Environmental 113
5.6 Genetic Approaches for Improved Microorganisms 114
5.7 Monitoring of Microbial Processes 115
5.8 Conclusions 116
References 116

Part II Biological Reactor Technologies

6 Biofilter Technology
Indrani Datta, D. Grant Allen 125
6.1 Introduction 125
6.2 Overall Process Description 125
6.3 Biofiltration Terminology 126
6.3.1 Empty Bed Residence Time 127
6.3.2 Surface (or Volumetric) and Mass Loading Rate 127
6.4 Mechanism of Operation 128
6.4.1 Transfer and Partitioning of Contaminants to the Biofilm 128
6.4.2 Biodegradation 129
6.5 Characterizing Biofilter Performance 129
6.5.1 Removal Efficiency 129
6.5.2 Elimination Capacity 130
6.5.3 Maximum Elimination Capacity 130

6.6 Factors Affecting Biofilter Performance 131
6.6.1 Packing Media 131
6.6.2 Moisture Content 131
6.6.3 Temperature 132
6.6.4 Oxygen Content 132
6.6.5 pH 133
6.6.6 Nutrients 133
6.6.7 Pressure Drop 133
6.6.8 Medium Depth 134
6.6.9 Waste Gas Pretreatment 135
6.6.10 Maintenance 135
6.7 Microbiology of Biofilters 135
6.8 Advantages and Disadvantages 136
6.9 Applications of Biofilters 137
6.10 Conclusions 139
References 140

7 Biotrickling Filter Technology
Marc A. Deshusses, David Gabriel 147

7.1 Introduction 147
7.2 Biotrickling Filter Design and Operation 150
7.3 Conversion of Chemical Scrubbers to Biotrickling Filters 152
7.3.1 First Approach to the Conversion 153
7.3.2 General Procedure to Convert Full-Scale Chemical Scrubbers 155
7.3.3 H_2S Treatment of Converted Chemical Scrubbers at OCSD 161
7.4 Conclusions 166
References 166

8 Bioscrubber Technology
Ajay Singh, Zarook Shareefdeen, Owen P. Ward 169

8.1 Introduction 169
8.2 Bioscrubbers 170
8.3 Bioscrubber Design 173
8.3.1 Mechanism for Odorous Gas Treatment by Bioscrubbers 173
8.3.2 The Absorber 174
8.3.3 The Bioreactor 177
8.3.4 Variations in Bioscrubber Designs 178
8.4 Bioprocess Control in Bioscrubbers 180
8.4.1 Microbiology 180
8.4.2 Nutrients 182
8.4.3 Oxygen 182
8.4.4 pH and Temperature 183
8.4.5 Sludge Accumulation and Disposal 183

8.5 Application of Bioscrubbers 184
8.5.1 Waste Gases from Wastewater Treatment Plant 184
8.5.2 Aerobic and Anaerobic Gas Treatment 187
8.5.3 Treatment of Flue Gases 187
8.5.4 Treatment of Waste Gas from Fish Feed Factory 188
8.5.5 Treatment of Waste Gas Containing VOCs 188
8.6 Conclusion and Future Directions 189
References 190

9 Membrane Bioreactor Technology
Mark W. Fitch 195

9.1 Introduction 195
9.2 Membrane Bioreactor Design 195
9.2.1 Mechanism 197
9.2.2 Membranes 198
9.2.3 Materials 199
9.3 Reactor Configuration 201
9.4 Operating Results 201
9.4.1 Loading and Elimination Capacity 201
9.4.2 Transient Loads and Aging 205
9.4.3 Biofilm Thickness 206
9.4.4 Heat 206
9.5 Models of Membrane Biofiltration 206
9.5.1 Mass Transfer 206
9.5.2 Biodegradation 208
9.5.3 Model Results 209
9.6 Conclusions 209
References 209

10 Modeling of Biofilters and Biotrickling Filters for Odor and VOC Control Applications
Marc A. Deshusses, Zarook Shareefdeen 213

10.1 Introduction to Modeling 213
10.1.1 General Model Concepts 214
10.1.2 Importance of Modeling in Design and Operation 215
10.2 A Review of Biofilter Models 215
10.2.1 Steady-State Models 215
10.2.2 Transient Models 217
10.2.3 Critical Parameters 218
10.3 Uses of Biofilter Models in Full-Scale Designs 219
10.3.1 Wastewater Treatment Applications 219
10.3.2 Rendering Applications 221
10.4 A Review of Biotrickling Filter Models 222
10.5 Conclusions and Future Work 228
References 229

Part III Biological Reactors – Applications

11 Biofilter Design and Operation for Odor Control – The New Zealand Experience
Roger Cudmore, Peter Gostomski 235

11.1 Introduction 235
11.2 Stream Characterization 236
11.2.1 Composition 236
11.2.2 Process Knowledge 237
11.2.3 Temperature and Relative Humidity 238
11.2.4 Particulates 238
11.2.5 Odor Chemistry 239
11.3 Pretreatment|Conditioning of Airstream 239
11.3.1 Particulates 240
11.3.2 Temperature 240
11.3.3 Relative Humidity 241
11.3.4 Bed Design 242
11.3.5 Air Distribution 242
11.3.6 Bed Media 243
11.3.7 Specification of Soil and Bark 243
11.4 Operation and Monitoring 246
11.4.1 General Operation and Maintenance 246
11.4.2 Pressure Drop 247
11.4.3 Moisture 247
11.4.4 Temperature 248
11.4.5 pH 248
11.4.6 Emission Monitoring 248
11.4.7 Biofilter Maintenance 248
11.4.8 Common Failures 249
11.5 Conclusions 250
References 250

12 Biological Treatment of Waste Gases Containing Inorganic Compounds
Madjid Mohseni 253

12.1 Introduction 253
12.2 Common Inorganic Air Pollutants 253
12.2.1 Ammonia 254
12.2.2 Amines 254
12.2.3 Nitrogen Oxides (NO_x) 254
12.2.4 Sulfur Oxides (SO_x) 255
12.3 Treatment Technologies for Inorganic Air Pollutants 255
12.4 Biological Technologies for Inorganic Air Pollutants 259
12.4.1 Biodegradation of Ammonia 259
12.4.2 Biodegradation of NO_x 261
12.5 Biofiltration 262
12.5.1 Biofiltration of Ammonia 262

12.5.2 Biofiltration of Mixtures of Ammonia and Hydrogen Sulfide ... 265
12.5.3 Biofiltration of Nitrogen Oxides ... 265
12.6 Biotrickling Filtration ... 267
12.7 Bioscrubbing ... 269
12.8 Photobiodegradation ... 269
12.9 Other Biological Processes ... 270
12.9.1 Membrane Bioreactors ... 271
12.9.2 Fluidized|Spouted Bed Bioreactors ... 271
12.9.3 Phytoremediation ... 272
12.10 Conclusions and Further Research Needs ... 272
References ... 274

13 Biological Treatment of Waste Gases Containing Volatile Organic Compounds
Pierre Le Cloirec, Yves Andrès, Claire Gérente, Pascaline Pré ... 281

13.1 Introduction ... 281
13.2 Biodegradation of Volatile Organic Compounds ... 282
13.2.1 Microbial Growth ... 282
13.2.2 Microorganisms and Pollutants ... 284
13.3 Applications of Biological Processes ... 286
13.3.1 General Operating Conditions ... 286
13.3.2 Biofilters ... 287
13.3.3 Biotrickling Filters ... 292
13.3.4 Bioscrubbers ... 292
13.4 By-Products Generated During Biological Treatments of VOCs ... 296
13.4.1 Overview of Wastes and By-Products Generated ... 296
13.4.2 Energy Recovery ... 297
13.5 Conclusions ... 300
References ... 300

Part IV Biological Reactors – Case Studies

14 Odor Removal in Industrial Facilities
Vladimir Popov, Vitaliy Zhukov ... 305

14.1 Introduction ... 305
14.2 Substrate Composition and Concentration ... 306
14.3 Biomass Control ... 307
14.4 Compliance ... 308
14.5 Modern Trends in Biofilter Development ... 309
14.6 Case Studies ... 315
14.6.1 Odorous VOC: Formaldehyde Removal ... 315
14.6.2 High-Performance|Enhanced Removal of Sulfur Compounds ... 317

14.7 Conclusions 324
References 325

15 Odor Removal in Municipal Wastewater Treatment Plants – Case Studies
Todd S. Webster 327
15.1 Introduction 327
15.2 An Odor Control Biofilter Located Within a Sewer Manhole Cover 327
15.2.1 Design 328
15.2.2 Operation 329
15.2.3 Performance 329
15.3 Multiple Biofilter Application Treating Odors from a Headworks Operation 329
15.3.1 Design 331
15.3.2 Operation and Performance 332
15.4 Multiple Biofilter Application (High Flow) at a Wastewater Pumping Station 332
15.4.1 Design and Operation 332
15.4.2 Performance 332
15.5 A Single Biofilter Application (Low Flow) at a Wastewater Pumping Station 334
15.5.1 Design and Operation 335
15.5.2 Performance 336
15.6 Single Biofilter at a Wastewater Pumping Station Operated Under Varying Air Temperatures 338
15.6.1 Design and Operation 338
15.6.2 Performance 339
15.7 Biofiltration of Odors at a Biosolids Handling Facility 341
15.7.1 Design and Operation 342
15.7.2 Performance 344
15.8 An Intermittent Water Addition Biotrickling Filter Reactor 345
15.8.1 Design 345
15.8.2 Operation 346
15.8.3 Performance 348
15.9 Long-Term Operation of a Biotrickling Filter Reactor 350
15.9.1 Design 350
15.9.2 Operation and Performance 351
15.10 Conclusions 353
References 353

16 Biotrickling and Bioscrubber Applications to Control Odor and Air Pollutants: Developments, Implementation Issues and Case Studies
Bart Kraakman 355
16.1 Introduction 355
16.2 Definitions, Advantages and Limitations 356
16.2.1 Definitions 356

16.2.2 Advantages of Biotrickling Filters and Bioscrubbers versus Biofilters 356
16.2.3 Disadvantage 357
16.3 Recent Developments 357
16.4 Robustness 362
16.5 Missing Gaps for Future Developments 363
16.6 Case Studies 364
16.6.1 Odor Removal from Waste Gas Emissions at an Anaerobic Wastewater Treatment Plant with a Purspring Bioreactor 364
16.6.2 H_2S Removal from Stripped Groundwater with a Purspring Bioreactor 368
16.6.3 V-Spring Bioreactor System Treating CS_2 Emissions at a Fungicide Manufacturing Plant 371
16.7 Conclusions 373
References 375

Part V Future of Biotechnology

17 Future Prospects of Biotechnology for Odor Control
Fethiye Ozis, Arash Bina, Joseph S. Devinny 383
17.1 The Growing Need for Odor Control 383
17.2 Biotechnology is an Important Alternative 384
17.3 Possible Obstacles 386
17.4 Current Successes 387
17.4.1 Wastewater Treatment Plant Odor Control 388
17.4.2 Swine Industry 390
17.5 Technology Developments 391
17.5.1 Rational Design 391
17.5.2 Reliability 391
17.5.3 Inert Packing 393
17.5.4 Biomass Control 394
17.5.5 Inoculation 395
17.5.6 Standards 396
17.5.7 Sensing and Automation 396
17.5.8 Increasing Size 397
17.5.9 Wastewater Will Lead the Way 397
17.5.10 Application to New Effluents 398
17.5.11 Development of Green Manufacturing-Biosystem Combinations 398
17.6 Conclusions 399
References 399

Subject Index **403**