Contents

List of Contributors xvii
Preface xix

I FUNDAMENTALS AND MICROBIOLOGICAL ASPECTS 1

1 Introduction to Air Pollution 3
Christian Kennes and Marí C. Veiga
1.1 Introduction 3
1.2 Types and sources of air pollutants 3
1.2.1 Particulate matter 5
1.2.2 Carbon monoxide and carbon dioxide 6
1.2.3 Sulphur oxides 7
1.2.4 Nitrogen oxides 7
1.2.5 Volatile organic compounds (VOCs) 9
1.2.6 Odours 10
1.2.7 Ozone 11
1.2.8 Calculating concentrations of gaseous pollutants 11
1.3 Air pollution control technologies 11
1.3.1 Particulate matter 11
1.3.2 Volatile organic and inorganic compounds 12
1.3.3 Environmentally friendly bioenergy 17
1.4 Conclusions 17
References 17

2 Biodegradation and Bioconversion of Volatile Pollutants 19
Christian Kennes, Haris N. Abubacker and Marí C. Veiga
2.1 Introduction 19
2.2 Biodegradation of volatile compounds 20
2.2.1 Inorganic compounds 20
2.2.2 Organic compounds 21
2.3 Mass balance calculations 24
2.4 Bioconversion of volatile compounds 25
2.4.1 Carbon monoxide and carbon dioxide 25
2.4.2 Volatile organic compounds (VOCs) 26
2.5 Conclusions 27
References 27
3 Identification and Characterization of Microbial Communities in Bioreactors 31
   Luc Malhautier, Léa Cabrol, Sandrine Bayle and Jean-Louis Fanlo
3.1 Introduction 31
3.2 Molecular techniques to characterize the microbial communities in bioreactors 32
   3.2.1 Quantification of the community members 32
   3.2.2 Assessment of microbial community diversity and structure 34
   3.2.3 Determination of the microbial community composition 39
   3.2.4 Techniques linking microbial identity to ecological function 40
   3.2.5 Microarray techniques 41
   3.2.6 Synthesis 42
3.3 The link of microbial community structure with ecological function in engineered ecosystems 42
   3.3.1 Introduction 42
   3.3.2 Temporal and spatial dynamics of the microbial community structure under stationary conditions in bioreactors 43
   3.3.3 Impact of environmental disturbances on the microbial community structure within bioreactors 45
3.4 Conclusions 47
References 47

II BIOREACTORS FOR AIR POLLUTION CONTROL 57

4 Biofilters 59
   Eldon R. Rene, María C. Veiga and Christian Kennes
4.1 Introduction 59
4.2 Historical perspective of biofilters 59
4.3 Process fundamentals 60
4.4 Operation parameters of biofilters 62
   4.4.1 Empty-bed residence time (EBRT) 62
   4.4.2 Volumetric loading rate (VLR) 63
   4.4.3 Mass loading rate (MLR) 63
   4.4.4 Elimination capacity (EC) 63
   4.4.5 Removal efficiency (RE) 63
   4.4.6 CO₂ production rate (P_CO₂) 63
4.5 Design considerations 64
   4.5.1 Reactor sizing 64
   4.5.2 Irrigation system 66
   4.5.3 Leachate collection and disposal 66
4.6 Start-up of biofilters 68
4.7 Parameters affecting biofilter performance 70
   4.7.1 Inlet concentrations and pollutant load 70
   4.7.2 Composition of waste gas and interaction patterns 71
   4.7.3 Biomass support medium 72
   4.7.4 Temperature 75
   4.7.5 pH 78
   4.7.6 Oxygen availability 79
   4.7.7 Nutrient availability 80
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.7.8</td>
<td>Moisture content and relative humidity</td>
<td>81</td>
</tr>
<tr>
<td>4.7.9</td>
<td>Polluted gas flow direction</td>
<td>83</td>
</tr>
<tr>
<td>4.7.10</td>
<td>Carbon dioxide generation rates</td>
<td>83</td>
</tr>
<tr>
<td>4.7.11</td>
<td>Pressure drop</td>
<td>85</td>
</tr>
<tr>
<td>4.8</td>
<td>Role of microorganisms and fungal growth in biofilters</td>
<td>87</td>
</tr>
<tr>
<td>4.9</td>
<td>Dynamic loading pattern and starvation conditions in biofilters</td>
<td>89</td>
</tr>
<tr>
<td>4.10</td>
<td>On-line monitoring and control (intelligent) systems for biofilters</td>
<td>93</td>
</tr>
<tr>
<td>4.10.1</td>
<td>On-line flame ionization detector (FID) and photo-ionization detector (PID) analysers</td>
<td>93</td>
</tr>
<tr>
<td>4.10.2</td>
<td>On-line proton transfer reaction–mass spectrometry (PTR-MS)</td>
<td>94</td>
</tr>
<tr>
<td>4.10.3</td>
<td>Intelligent moisture control systems</td>
<td>94</td>
</tr>
<tr>
<td>4.10.4</td>
<td>Differential neural network (DNN) sensor</td>
<td>95</td>
</tr>
<tr>
<td>4.11</td>
<td>Mathematical expressions for biofilters</td>
<td>95</td>
</tr>
<tr>
<td>4.12</td>
<td>Artificial neural network-based models</td>
<td>97</td>
</tr>
<tr>
<td>4.12.1</td>
<td>Back error propagation (BEP) algorithm</td>
<td>97</td>
</tr>
<tr>
<td>4.12.2</td>
<td>Important considerations during neural network modelling</td>
<td>99</td>
</tr>
<tr>
<td>4.12.3</td>
<td>Neural network model development for biofilters and specific examples</td>
<td>103</td>
</tr>
<tr>
<td>4.13</td>
<td>Fuzzy logic-based models</td>
<td>105</td>
</tr>
<tr>
<td>4.14</td>
<td>Adaptive neuro-fuzzy interference system-based models for biofilters</td>
<td>108</td>
</tr>
<tr>
<td>4.15</td>
<td>Conclusions</td>
<td>111</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>111</td>
</tr>
<tr>
<td>5</td>
<td>Biotrickling Filters</td>
<td>121</td>
</tr>
<tr>
<td></td>
<td>Christian Kennes and María C. Veiga</td>
<td>121</td>
</tr>
<tr>
<td>5.1</td>
<td>Introduction</td>
<td>122</td>
</tr>
<tr>
<td>5.2</td>
<td>Main characteristics of BTFs</td>
<td>122</td>
</tr>
<tr>
<td>5.2.1</td>
<td>General aspects</td>
<td>122</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Packing material</td>
<td>123</td>
</tr>
<tr>
<td>5.2.3</td>
<td>Biomass and biofilm</td>
<td>126</td>
</tr>
<tr>
<td>5.2.4</td>
<td>Trickling phase</td>
<td>126</td>
</tr>
<tr>
<td>5.2.5</td>
<td>Gas EBRT</td>
<td>128</td>
</tr>
<tr>
<td>5.2.6</td>
<td>Liquid and gas velocities</td>
<td>129</td>
</tr>
<tr>
<td>5.3</td>
<td>Pressure drop and clogging</td>
<td>130</td>
</tr>
<tr>
<td>5.3.1</td>
<td>Excess biomass accumulation</td>
<td>130</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Accumulation of solid chemicals</td>
<td>133</td>
</tr>
<tr>
<td>5.4</td>
<td>Full-scale applications and scaling up</td>
<td>134</td>
</tr>
<tr>
<td>5.5</td>
<td>Conclusions</td>
<td>135</td>
</tr>
<tr>
<td></td>
<td>References</td>
<td>135</td>
</tr>
<tr>
<td>6</td>
<td>Bioscrubbers</td>
<td>139</td>
</tr>
<tr>
<td></td>
<td>Pierre Le Cloirec and Philippe Humeau</td>
<td>139</td>
</tr>
<tr>
<td>6.1</td>
<td>Introduction</td>
<td>139</td>
</tr>
<tr>
<td>6.2</td>
<td>General approach of bioscrubbers</td>
<td>140</td>
</tr>
<tr>
<td>6.3</td>
<td>Operating conditions</td>
<td>141</td>
</tr>
<tr>
<td>6.3.1</td>
<td>Absorption column</td>
<td>142</td>
</tr>
<tr>
<td>6.3.2</td>
<td>Biodegradation step – activated sludge reactor</td>
<td>143</td>
</tr>
<tr>
<td>6.4</td>
<td>Removing families of pollutants</td>
<td>143</td>
</tr>
</tbody>
</table>
### Contents

6.4.1 Volatile organic compound (VOC) removal 144  
6.4.2 Odor control 146  
6.4.3 Sulfur compounds degradation 146  
6.5 Treatment of by-products generated by bioscrubbers 148  
6.6 Conclusions and trends 148  
References 149

7 Membrane Bioreactors 155  
Raquel Lebrero, Raúl Muñoz, Amit Kumar and Herman Van Langenhove  
7.1 Introduction 155  
7.2 Membrane basics 156  
7.2.1 Types of membranes 156  
7.2.2 Membrane materials 159  
7.2.3 Membrane characterization parameters 159  
7.2.4 Mass transport through the membrane 160  
7.3 Reactor configurations 163  
7.3.1 Flat-sheet membranes 164  
7.3.2 Tubular configuration membranes 165  
7.3.3 Membrane-based bioreactors 166  
7.4 Microbiology 166  
7.5 Performance of membrane bioreactors 168  
7.5.1 Membrane-based bioreactors 168  
7.5.2 Bioreactor operation: Influence of the operating parameters 169  
7.6 Membrane bioreactor modeling 170  
7.7 Applications of membrane bioreactors in biological waste-gas treatment 172  
7.7.1 Comparison with other technologies 172  
7.8 New applications: CO₂–NOₓ sequestration 172  
7.8.1 NOₓ removal 173  
7.8.2 CO₂ sequestration 176  
7.9 Future needs 177  
References 178

8 Two-Phase Partitioning Bioreactors 185  
Hala Fam and Andrew J. Daugulis  
8.1 Introduction 185  
8.2 Features of the sequestering phase – selection criteria 186  
8.3 Liquid two-phase partitioning bioreactors (TPPBs) 187  
8.3.1 Performance 187  
8.3.2 Mass transfer 189  
8.3.3 Modeling and design elements 194  
8.3.4 Limitations and research opportunities 196  
8.4 Solids as the partitioning phase 197  
8.4.1 Rationale 197  
8.4.2 Performance 197  
8.4.3 Mass transfer 198  
8.4.4 Modeling and design elements 199  
8.4.5 Limitations and research opportunities 200  
References 200
9  Rotating Biological Contactors

R. Ravi, K. Sarayu, S. Sandhya and T. Swaminathan

9.1 Introduction 207

9.1.1 Limitations of conventional gas-phase bioreactors 208

9.2 The rotating biological contactor 209

9.2.1 Modified RBCs for waste-gas treatment 210

9.3 Studies on removal of dichloromethane in modified RBCs 213

9.3.1 Comparison of different bioreactors (biofilters, biotrickling filters, and modified RBCs) 215

9.3.2 Studies on removal of benzene and xylene in modified RBCs 216

9.3.3 Microbiological studies of biofilms 217

References 219

10  Innovative Bioreactors and Two-Stage Systems

Eldon R. Rene, Maria C. Veiga and Christian Kennes

10.1 Introduction 221

10.2 Innovative bioreactor configurations 222

10.2.1 Planted biofilter 222

10.2.2 Rotatory-switching biofilter 223

10.2.3 Tubular biofilter 224

10.2.4 Fluidized-bed bioreactor 225

10.2.5 Airlift and bubble column bioreactors 227

10.2.6 Monolith bioreactor 229

10.2.7 Foam emulsion bioreactor 231

10.2.8 Fibrous bed bioreactor 233

10.2.9 Horizontal-flow biofilm reactor 234

10.3 Two-stage systems for waste gas treatment 235

10.3.1 Adsorption pre-treatment plus bioreactor 235

10.3.2 Bioreactor plus adsorption polishing 237

10.3.3 UV photocatalytic reactor plus bioreactor 237

10.3.4 Bioreactor plus bioreactor 240

10.4 Conclusions 242

References 243

III  BIOPROCESSES FOR SPECIFIC APPLICATIONS

11  Bioprocesses for the Removal of Volatile Sulfur Compounds from Gas Streams

Albert Janssen, Pim L.F. van den Bosch, Robert C. van Leerdam, and Marco de Graaff

11.1 Introduction 249

11.2 Toxicity of VOSCs to animals and humans 250

11.3 Biological formation of VOSCs 251

11.4 VOSC-producing and VOSC-emitting industries 252

11.4.1 VOSCs produced from biological processes 252

11.4.2 Chemical processes and industrial applications 252

11.4.3 Oil and gas 253

11.5 Microbial degradation of VOSCs 253
## ENVIRONMENTALLY-FRIENDLY BIOENERGY

### 14 Biogas

*Marta Ben, Christian Kennes and Marí̈a C. Veiga*

14.1 Introduction 321

14.2 Anaerobic digestion 321

14.2.1 A brief history 321

14.2.2 Overview of the anaerobic digestion process 323

14.3 Substrates 328

14.3.1 Agricultural and farming wastes 328

14.3.2 Industrial wastes 329

14.3.3 Urban wastes 333

14.3.4 Sewage sludge 333

14.4 Biogas 334

14.4.1 Biogas composition 334

14.4.2 Substrate influence on biogas composition 335

14.5 Bioreactors 335

14.5.1 Batch reactors 337

14.5.2 Continuously stirred tank reactor (CSTR) 337

14.5.3 Continuously stirred tank reactor with solids recycle (CSTR/SR) 337

14.5.4 Plug-flow reactor 337

14.5.5 Upflow anaerobic sludge blanket (UASB) 338

14.5.6 Attached film digester 338

14.5.7 Two-phase digester 338

14.6 Environmental impact of biogas 338

14.7 Conclusions 339

References 339

### 15 Biohydrogen

*Bikram K. Nayak, Soumya Pandit and Debabrata Das*

15.1 Introduction 345

15.1.1 Current status of hydrogen production and present use of hydrogen 346

15.1.2 Biohydrogen from biomass: present status 346

15.2 Environmental impacts of biohydrogen production 346

15.2.1 Air pollution due to conventional hydrocarbon-based fuel combustion 346

15.2.2 Biohydrogen, a zero-carbon fuel as a potential alternative 348

15.3 Properties and production of hydrogen 348

15.3.1 Properties of zero-carbon fuel 348

15.3.2 Biohydrogen production processes 350

15.4 Potential applications of hydrogen as a zero-carbon fuel 363

15.4.1 Transport sector 363

15.4.2 Fuel cells 366
15.5 Policies and economics of hydrogen production 371
  15.5.1 Economics of biohydrogen production 372
15.6 Issues and barriers 373
15.7 Future prospects 374
15.8 Conclusion 375
Acknowledgements 375
References 375

16 Catalytic Biodiesel Production 383
Zhenzhong Wen, Xinhai Yu, Shan-Tung Tu and Jinyue Yan
16.1 Introduction 383
16.2 Trends in biodiesel production 384
  16.2.1 Reactors 384
  16.2.2 Catalysts 389
16.3 Challenges for biodiesel production at industrial scale 393
  16.3.1 Economic analysis 393
  16.3.2 Ecological considerations 393
16.4 Recommendations 394
16.5 Conclusions 395
References 395

17 Microalgae Biodiesel 399
Hugo Pereira, Helena M. Amaro, Nadpi G. Katkam, Luísa Barreira,
A. Catarina Guedes, João Varela and F. Xavier Malcata
17.1 Introduction 399
17.2 Wild versus modified microalgae 402
17.3 Lipid extraction and purification 404
  17.3.1 Mechanical methods 405
  17.3.2 Chemical methods 406
17.4 Lipid transesterification 407
  17.4.1 Acid-catalyzed transesterification 408
  17.4.2 Base-catalyzed transesterification 408
  17.4.3 Heterogeneous acid/base-catalyzed transesterification 410
  17.4.4 Lipase-catalyzed transesterification 410
  17.4.5 Ionic liquid-catalyzed reactions 411
17.5 Economic considerations 412
  17.5.1 Competition between microalgal biodiesel and biofuels 412
  17.5.2 Main challenges to biodiesel production from microalgae 413
  17.5.3 Economics of biodiesel production 414
17.6 Environmental considerations 415
  17.6.1 Uptake of carbon dioxide 416
  17.6.2 Upgrade of wastewaters 416
  17.6.3 Management of microalgal biomass 417
17.7 Final considerations 418
18 Bioethanol

Johan W. van Groenestijn, Haris N. Abubacker, María C. Veiga and Christian Kennes

18.1 Introduction

18.2 Fermentation of lignocellulosic saccharides to ethanol
   18.2.1 Raw materials
   18.2.2 Pretreatment
   18.2.3 Production of inhibitors
   18.2.4 Hydrolysis
   18.2.5 Fermentation

18.3 Syngas conversion to ethanol – biological route
   18.3.1 Sources of carbon monoxide
   18.3.2 The Wood–Ljungdahl pathway involved in the bioconversion of carbon monoxide
   18.3.3 Parameters affecting the bioconversion of carbon monoxide to ethanol

18.4 Demonstration projects

18.5 Comparison of conventional fuels and bioethanol (corn, cellulosic, syngas) on air pollution

18.6 Key problems and future research needs

18.7 Conclusions

References
20 Biotrickling Filters for Removal of Volatile Organic Compounds from Air in the Coating Sector

Carlos Lafita, F. Javier Álvarez-Hornos, Carmen Gabaldón, Vicente Martínez-Soria and Josep-Manuel Penya-Roja

20.1 Introduction

20.2 Case study 1: VOC removal in a furniture facility

20.2.1 Characterization of the waste-gas sources

20.2.2 Design and operation of the system

20.2.3 Performance data

20.2.4 Economic aspects

20.3 Case study 2: VOC removal in a plastic coating facility

20.3.1 Characterization of the waste-gas sources

20.3.2 Design and operation of the system

20.3.3 Performance data

20.3.4 Economic aspects

Acknowledgements

References

21 Industrial Bioscrubbers for the Food and Waste Industries

Pierre Le Cloirec and Philippe Humeau

21.1 Introduction

21.2 Food industry emissions

21.2.1 Identification and quantification of waste-gas emissions

21.2.2 Choice of the technology

21.2.3 Design and operating conditions

21.2.4 Performance of the system

21.3 Bioscrubbing treatment of gaseous emissions from waste composting

21.3.1 Waste-gas emissions: nature, concentrations, and flow

21.3.2 Choice of the gas treatment process

21.3.3 Design and operating conditions

21.3.4 Gas collection system

21.3.5 Gas treatment system

21.3.6 Performance of the overall system

21.4 Conclusions and perspectives

References

22 Desulfurization of biogas in biotrickling filters

David Gabriel, Marc A. Deshusses and Xavier Gamisans

22.1 Introduction

22.2 Microbiology and stoichiometry of sulfide oxidation

22.2.1 Microbiology of sulfide oxidation

22.2.2 Stoichiometry of sulfide biological oxidation

22.3 Case study background and description of biotrickling filter