

## Contents

**Preface** XIII

**List of Symbols and Abbreviations** XVII

<b>1</b>	<b>Historical Development of Wastewater Collection and Treatment</b>	<b>1</b>
1.1	Water Supply and Wastewater Management in Antiquity	1
1.2	Water Supply and Wastewater Management in the Medieval Age	4
1.3	First Studies in Microbiology	7
1.4	Wastewater Management by Direct Discharge into Soil and Bodies of Water – The First Studies	11
1.5	Mineralization of Organics in Rivers, Soils or by Experiment – A Chemical or Biological Process?	12
1.6	Early Biological Wastewater Treatment Processes	14
1.7	The Cholera Epidemics – Were They Caused by Bacteria Living in the Soil or Water?	16
1.8	Early Experiments with the Activated Sludge Process	16
1.9	Taking Samples and Measuring Pollutants	18
1.10	Early Regulations for the Control of Wastewater Discharge	19
	<i>References</i>	20
<b>2</b>	<b>Wastewater Characterization and Regulations</b>	<b>25</b>
2.1	Volumetric Wastewater Production and Daily Changes	25
2.2	Pollutants	27
2.2.1	Survey	27
2.2.2	Dissolved Substances	28
2.2.2.1	Organic Substances	28
2.2.2.2	Inorganic Substances	30
2.2.3	Colloids	32
2.2.3.1	Oil-In-Water Emulsions	32
2.2.3.2	Solid-In-Water Colloids	33
2.2.4	Suspended Solids	34
2.3	Methods for Measuring Dissolved Organic Substances as Total Parameters	34

2.3.1	Biochemical Oxygen Demand	34
2.3.2	Chemical Oxygen Demand	36
2.3.3	Total and Dissolved Organic Carbon	37
2.4	Legislation	38
2.4.1	Preface	38
2.4.2	German Legislation	38
2.4.2.1	Legislation Concerning Discharge into Public Sewers	38
2.4.2.2	Legislation Concerning Discharge into Waters	39
2.4.3	EU Guidelines	41
	<i>References</i>	42
<b>3</b>	<b>Microbial Metabolism</b>	<b>43</b>
3.1	Some Remarks on the Composition and Morphology of Bacteria (Eubacteria)	43
3.2	Proteins and Nucleic Acids	45
3.2.1	Proteins	45
3.2.1.1	Amino Acids	45
3.2.1.2	Structure of Proteins	46
3.2.1.3	Proteins for Special Purposes	47
3.2.1.4	Enzymes	47
3.2.2	Nucleic Acids	50
3.2.2.1	Desoxyribonucleic Acid	50
3.2.2.2	Ribonucleic Acid	54
3.2.2.3	DNA Replication	57
3.2.2.4	Mutations	58
3.3	Catabolism and Anabolism	59
3.3.1	ADP and ATP	59
3.3.2	Transport of Protons	59
3.3.3	Catabolism of Using Glucose	60
3.3.3.1	Aerobic Conversion by Prokaryotic Cells	60
3.3.3.2	Anaerobic Conversion by Prokaryotic Cells	65
3.3.4	Anabolism	66
	<i>References</i>	67
<b>4</b>	<b>Determination of Stoichiometric Equations for Catabolism and Anabolism</b>	<b>69</b>
4.1	Introduction	69
4.2	Aerobic Degradation of Organic Substances	70
4.2.1	Degradation of Hydrocarbons Without Bacterial Decay	70
4.2.2	Mineralization of 2,4-Dinitrophenol	71
4.2.3	Degradation of Hydrocarbons with Bacterial Decay	74
4.3	Measurement of O <sub>2</sub> Consumption Rate $r_{O_2,S}$ and CO <sub>2</sub> Production Rate $r_{CO_2,S}$	76
	<i>Problems</i>	78
	<i>References</i>	81

<b>5</b>	<b>Gas/Liquid Oxygen Transfer and Stripping</b>	<b>83</b>
5.1	Transport by Diffusion	83
5.2	Mass Transfer Coefficients	86
5.2.1	Definition of Specific Mass Transfer Coefficients	86
5.2.2	Two Film Theory	87
5.3	Measurement of Specific Overall Mass Transfer Coefficients $K_{L,a}$	90
5.3.1	Absorption of Oxygen During Aeration	90
5.3.1.1	Steady State Method	90
5.3.1.2	Non-steady State Method	91
5.3.1.3	Dynamic Method in Wastewater Mixed with Activated Sludge	92
5.3.2	Desorption of Volatile Components During Aeration	93
5.4	Oxygen Transfer Rate, Energy Consumption and Efficiency in Large-scale Plants	95
5.4.1	Surface Aeration	95
5.4.1.1	Oxygen Transfer Rate	95
5.4.1.2	Power Consumption and Efficiency	96
5.4.2	Deep Tank Aeration	98
5.4.2.1	Preliminary Remarks	98
5.4.2.2	The Simple Plug Flow Model	99
5.4.2.3	Proposed Model of the American Society of Civil Engineers	101
5.4.2.4	Further Models	103
5.4.2.5	Oxygen Transfer Rate	103
5.4.2.6	Power Consumption and Efficiency	106
5.4.2.7	Monitoring of Deep Tanks	106
5.5	Dimensional Analysis and Transfer of Models	108
5.5.1	Introduction	108
5.5.2	Power Consumption of a Stirred, Non-aerated Tank – A Simple Example	109
5.5.3	Description of Oxygen Transfer, Power Consumption and Efficiency by Surface Aerators Using Dimensionless Numbers	112
5.5.4	Application of Dimensionless Numbers for Surface Aeration	113
	<i>Problem</i>	115
	<i>References</i>	117
<b>6</b>	<b>Aerobic Wastewater Treatment in Activated Sludge Systems</b>	<b>119</b>
6.1	Introduction	119
6.2	Kinetic and Reaction Engineering Models With and Without Oxygen Limitation	119
6.2.1	Batch Reactors	119
6.2.1.1	With High Initial Concentration of Bacteria	119
6.2.1.2	With Low Initial Concentration of Bacteria	122
6.2.2	Chemostat	122
6.2.3	Completely Mixed Activated Sludge Reactor	125
6.2.3.1	Preliminary Remarks	125
6.2.3.2	Mean Retention Time, Recycle Ratio and Thickening Ratio as Process Parameters	126

6.2.3.3	Sludge Age as Parameter	128
6.2.4	Plug Flow Reactor	130
6.2.5	Completely Mixed Tank Cascades With Sludge Recycle	132
6.2.6	Flow Reactor With Axial Dispersion	134
6.2.7	Stoichiometric and Kinetic Coefficients	136
6.2.8	Comparison of Reactors	137
6.3	Retention Time Distribution in Activated Sludge Reactors	138
6.3.1	Retention Time Distribution	138
6.3.2	Completely Mixed Tank	140
6.3.3	Completely Mixed Tank Cascade	140
6.3.4	Tube Flow Reactor With Axial Dispersion	141
6.3.5	Comparison Between Tank Cascades and Tube Flow Reactors	142
6.4	Technical Scale Activated Sludge Systems for Carbon Removal	144
	<i>Problems</i>	146
	<i>References</i>	149
<b>7</b>	<b>Aerobic Treatment with Biofilm Systems</b>	<b>151</b>
7.1	Biofilms	151
7.2	Biofilm Reactors for Wastewater Treatment	152
7.2.1	Trickling Filters	152
7.2.2	Submerged and Aerated Fixed Bed Reactors	154
7.2.3	Rotating Disc Reactors	156
7.3	Mechanisms for Oxygen Mass Transfer in Biofilm Systems	158
7.4	Models for Oxygen Mass Transfer Rates in Biofilm Systems	159
7.4.1	Assumptions	159
7.4.2	Mass Transfer Gas/Liquid is Rate-limiting	159
7.4.3	Mass Transfer Liquid/Solid is Rate-limiting	160
7.4.4	Biological Reaction is Rate-limiting	160
7.4.5	Diffusion and Reaction Inside the Biofilm	160
7.4.6	Influence of Diffusion and Reaction Inside the Biofilm and of Mass Transfer Liquid/Solid	163
7.4.7	Influence of Mass Transfer Rates at Gas Bubble and Biofilm Surfaces	164
	<i>Problems</i>	164
	<i>References</i>	166
<b>8</b>	<b>Anaerobic Degradation of Organics</b>	<b>169</b>
8.1	Catabolic Reactions – Cooperation of Different Groups of Bacteria	169
8.1.1	Survey	169
8.1.2	Anaerobic Bacteria	169
8.1.2.1	Acidogenic Bacteria	169
8.1.2.2	Acetogenic Bacteria	171
8.1.2.3	Methanogenic Bacteria	171
8.1.3	Regulation of Acetogenics by Methanogenics	173

8.1.4	Sulfate and Nitrate Reduction	175
8.2	Kinetics – Models and Coefficients	176
8.2.1	Preface	176
8.2.2	Hydrolysis and Formation of Lower Fatty Acids by Acidogenic Bacteria	176
8.2.3	Transformation of Lower Fatty Acids by Acetogenic Bacteria	177
8.2.4	Transformation of Acetate and Hydrogen into Methane	179
8.2.5	Conclusions	180
8.3	Catabolism and Anabolism	182
8.4	High-rate Processes	184
8.4.1	Introduction	184
8.4.2	Contact Processes	185
8.4.3	Upflow Anaerobic Sludge Blanket	187
8.4.4	Anaerobic Fixed Bed Reactor	188
8.4.5	Anaerobic Rotating Disc Reactor	190
8.4.6	Anaerobic Expanded and Fluidized Bed Reactors	191
	<i>Problem</i>	192
	<i>References</i>	193
<b>9</b>	<b>Biodegradation of Special Organic Compounds</b>	<b>195</b>
9.1	Introduction	195
9.2	Chlorinated Compounds	196
9.2.1	Chlorinated n-Alkanes, Particularly Dichloromethane and 1,2-Dichloroethane	196
9.2.1.1	Properties, Use, Environmental Problems and Kinetics	196
9.2.1.2	Treatment of Wastewater Containing DCM or DCA	198
9.2.2	Chlorobenzene	200
9.2.2.1	Properties, Use and Environmental Problems	200
9.2.2.2	Principles of Biological Degradation	200
9.2.2.3	Treatment of Wastewater Containing Chlorobenzenes	202
9.2.3	Chlorophenols	203
9.3	Nitroaromatics	204
9.3.1	Properties, Use, Environmental Problems and Kinetics	204
9.3.2	Treatment of Wastewater Containing 4-NP or 2,4-DNT	206
9.4	Polycyclic Aromatic Hydrocarbons and Mineral Oils	206
9.4.1	Properties, Use and Environmental Problems	206
9.4.2	Mineral Oils	207
9.4.3	Biodegradation of PAHs	209
9.4.3.1	PAHs Dissolved in Water	209
9.4.3.2	PAHs Dissolved in n-Dodecane Standard Emulsion	211
9.5	Azo Reactive Dyes	211
9.5.1	Properties, Use and Environmental Problems	211
9.5.2	Production of Azo Dyes in the Chemical Industry – Biodegradability of Naphthalene Sulfonic Acids	213
9.5.3	Biodegradation of Azo Dyes	215

9.5.3.1	Direct Aerobic Degradation	215
9.5.3.2	Anaerobic Reduction of Azo Dyes	215
9.5.3.3	Aerobic Degradation of Metabolites	216
9.5.4	Treatment of Wastewater Containing the Azo Dye Reactive Black 5	216
9.6	Final Remarks	217
	<i>References</i>	218
<b>10</b>	<b>Biological Nutrient Removal</b>	<b>223</b>
10.1	Introduction	223
10.2	Biological Nitrogen Removal	227
10.2.1	The Nitrogen Cycle and the Technical Removal Process	227
10.2.2	Nitrification	228
10.2.2.1	Nitrifying Bacteria and Stoichiometry	228
10.2.2.2	Stoichiometry and Kinetics of Nitrification	231
10.2.2.3	Parameters Influencing Nitrification	235
10.2.3	Denitrification	237
10.2.3.1	Denitrifying Bacteria and Stoichiometry	237
10.2.3.2	Stoichiometry and Kinetics of Denitrification	239
10.2.3.3	Parameters Influencing Denitrification	240
10.2.4	Nitrite Accumulation During Nitrification	242
10.2.5	New Microbial Processes for Nitrogen Removal	243
10.3	Biological Phosphorus Removal	244
10.3.1	Enhanced Biological Phosphorus Removal	244
10.3.2	Kinetic Model for Biological Phosphorus Removal	245
10.3.2.1	Preliminary Remarks	245
10.3.2.2	Anaerobic Zone	246
10.3.2.3	Aerobic Zone	247
10.3.3	Results of a Batch Experiment	248
10.3.4	Parameters Affecting Biological Phosphorus Removal	249
10.4	Biological Nutrient Removal Processes	250
10.4.1	Preliminary Remarks	250
10.4.2	Nitrogen Removal Processes	250
10.4.3	Chemical and Biological Phosphorus Removal	252
10.4.4	Processes for Nitrogen and Phosphorus Removal	253
10.4.4.1	Different Levels of Performance	253
10.4.4.2	WWTP Waßmannsdorf	255
10.4.4.3	Membrane Bioreactors (MBR)	257
10.5	Phosphorus and Nitrogen Recycle	257
10.5.1	Recycling of Phosphorus	257
10.5.2	Recycling of Nitrogen	258
	<i>Problems</i>	259
	<i>References</i>	262

<b>11</b>	<b>Modelling of the Activated Sludge Process</b>	<b>267</b>
11.1	Why We Need Mathematical Models	267
11.2	Models Describing Carbon and Nitrogen Removal	268
11.2.1	Carbon Removal	268
11.2.2	Carbon Removal and Bacterial Decay	269
11.2.3	Carbon Removal and Nitrification Without Bacterial Decay	270
11.3	Models for Optimizing the Activated Sludge Process	271
11.3.1	Preface	271
11.3.2	Modelling the Influence of Aeration on Carbon Removal	272
11.3.3	Activated Sludge Model 1 (ASM 1)	275
11.3.4	Application of ASM 1	283
11.3.5	More Complicated Models and Conclusions	285
	<i>Problems</i>	286
	<i>References</i>	288
<b>12</b>	<b>Membrane Technology in Biological Wastewater Treatment</b>	<b>291</b>
12.1	Introduction	291
12.2	Mass Transport Mechanism	293
12.2.1	Membrane Characteristics and Definitions	293
12.2.2	Mass Transport Through Non-porous Membranes	296
12.2.3	Mass Transport Through Porous Membranes	300
12.3	Mass Transfer Resistance Mechanisms	301
12.3.1	Preface	301
12.3.2	Mass Transfer Resistances	302
12.3.3	Concentration Polarization Model	303
12.3.4	Solution–diffusion Model and Concentration Polarization	306
12.3.5	The Pore Model and Concentration Polarization	308
12.4	Performance and Module Design	308
12.4.1	Membrane Materials	308
12.4.2	Design and Configuration of Membrane Modules	309
12.4.2.1	Preliminary Remarks	309
12.4.2.2	Dead-end Configuration	313
12.4.2.3	Submerged Configuration	314
12.4.2.4	Cross-flow Configuration	314
12.4.3	Membrane Fouling and Cleaning Management	315
12.4.3.1	Types of Fouling Processes	315
12.4.3.2	Membrane Cleaning Strategies	316
12.5	Membrane Bioreactors	318
12.5.1	Final Treatment (Behind the Secondary Clarifier)	318
12.5.2	Membrane Bioreactors in Aerobic Wastewater Treatment	319
12.5.3	Membrane Bioreactors and Nutrient Removal	323
	<i>Problems</i>	324
	<i>References</i>	327

<b>13</b>	<b>Production Integrated Water Management and Decentralized Effluent Treatment</b>	<b>331</b>
13.1	Introduction	331
13.2	Production Integrated Water Management in the Chemical Industry	333
13.2.1	Sustainable Development and Process Optimization	333
13.2.1.1	Primary Points of View	333
13.2.1.2	Material Flow Management	334
13.2.1.3	Production of Naphthalenedisulfonic Acid	336
13.2.1.4	Methodology of Process Improvement	338
13.2.2	Minimization of Fresh Water Use	339
13.2.2.1	Description of the Problem	339
13.2.2.2	The Concentration/Mass Flow Rate Diagram and the Graphical Solution	340
13.2.3	The Network Design Method	344
13.3	Decentralized Effluent Treatment	346
13.3.1	Minimization of Treated Wastewater	346
13.3.1.1	Description of the Problem	346
13.3.1.2	Representation of Treatment Processes in a Concentration/Mass Flow Rate Diagram	347
13.3.1.3	The Lowest Wastewater Flow Rate to Treat	349
13.3.2	Processes for Decentralized Effluent Treatment	349
	<i>Problems</i>	350
	<i>References</i>	354
	<b>Subject Index</b>	<b>355</b>