

*Udo Wiesmann, In Su Choi,*  
*Eva-Maria Dombrowski*  
**Fundamentals of**  
**Biological Wastewater Treatment**

## 1807–2007 Knowledge for Generations

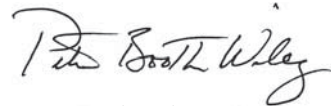
Each generation has its unique needs and aspirations. When Charles Wiley first opened his small printing shop in lower Manhattan in 1807, it was a generation of boundless potential searching for an identity. And we were there, helping to define a new American literary tradition. Over half a century later, in the midst of the Second Industrial Revolution, it was a generation focused on building the future. Once again, we were there, supplying the critical scientific, technical, and engineering knowledge that helped frame the world. Throughout the 20th Century, and into the new millennium, nations began to reach out beyond their own borders and a new international community was born. Wiley was there, expanding its operations around the world to enable a global exchange of ideas, opinions, and know-how.

For 200 years, Wiley has been an integral part of each generation's journey, enabling the flow of information and understanding necessary to meet their needs and fulfill their aspirations. Today, bold new technologies are changing the way we live and learn. Wiley will be there, providing you the must-have knowledge you need to imagine new worlds, new possibilities, and new opportunities.

Generations come and go, but you can always count on Wiley to provide you the knowledge you need, when and where you need it!



*William J. Pesce*  
President and Chief Executive Officer



*Peter Booth Wiley*  
Chairman of the Board

*Udo Wiesmann, In Su Choi,  
Eva-Maria Dombrowski*

# **Fundamentals of Biological Wastewater Treatment**



WILEY-VCH Verlag GmbH & Co. KGaA

#### The Authors

**Prof. Dr.-Ing. Udo Wiesmann**

Technische Universität Berlin  
Institut für Verfahrenstechnik  
Strasse des 17. Juni 135  
10623 Berlin  
Germany

**Dr.-Ing. In Su Choi**

Technische Universität Berlin  
Institut für Verfahrenstechnik  
Strasse des 17. Juni 135  
10623 Berlin  
Germany

**Prof. Dr.-Ing. Eva-Maria Dombrowski**

Technische Fachhochschule Berlin  
Fachgebiet Verfahrenstechnik  
und Biotechnologie  
Luxemburgerstraße 10  
13353 Berlin  
Germany

■ All books published by Wiley-VCH are carefully produced. Nevertheless, authors, editors, and publisher do not warrant the information contained in these books, including this book, to be free of errors. Readers are advised to keep in mind that statements, data, illustrations, procedural details or other items may inadvertently be inaccurate.

**Library of Congress Card No.: applied for**

**British Library Cataloguing-in-Publication Data**

A catalogue record for this book is available from the British Library.

**Bibliographic information published by the Deutsche Nationalbibliothek**

The Deutsche Nationalbibliothek lists this publication in the Deutsche Nationalbibliografie; detailed bibliographic data are available in the Internet at <http://dnb.d-nb.de>.

© 2007 WILEY-VCH Verlag GmbH & Co. KGaA, Weinheim

All rights reserved (including those of translation into other languages). No part of this book may be reproduced in any form – by photoprinting, microfilm, or any other means – nor transmitted or translated into a machine language without written permission from the publishers. Registered names, trademarks, etc. used in this book, even when not specifically marked as such, are not to be considered unprotected by law.

Printed in the Federal Republic of Germany  
Printed on acid-free paper

**Typesetting** Fotosatz Detzner, Speyer  
**Printing** betz-druck GmbH, Darmstadt  
**Bookbinding** Litges & Dopf Buchbinderei GmbH, Heppenheim

**ISBN** 978-3-527-31219-1

## 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 $K_{La}$	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>

## Preface

Clean water is an essential nutrient for humans, animals and plants. Because of its limited resources, especially in countries with low rainfall, little surface water, deep ground water levels and relatively high temperatures, careful use and frequent reuse after appropriate treatment are requirements for healthy life. This awareness is relatively new, because it was not until the late 19th century that the population of larger industrialized cities learned that wastewater must be treated to prevent disease. The reuse of treated water is still a topic of controversial discussions. However, the authors of this book are convinced both that we must learn to develop and continue to promote water recycling systems and also that biological wastewater treatment processes play a highly important role.

The modern concept of industrial wastewater treatment is moving away from the classic “end-of-pipe” technology towards “decentralized effluent treatment processes”, “process integrated water management” and ultimately in a number of cases being as close as possible to “fresh water-free processes”. The central concept is to save water. In the classic concept, the groups producing intermediate or finished products are relatively isolated from the group which treats the wastewater, frequently treating several different effluents mixed together. This situation characterizes the first period of industrial wastewater treatment. After sampling, the water quality is determined and compared with regulations and the treated water is discharged into surface water. In all but a few exceptional cases, municipal wastewater treatment is performed in this same manner. Frequently, it is more favorable and economical to treat some industrial effluents by using specialized processes (“decentralized effluent treatment”), giving a water quality which makes it possible to reuse one or more water streams and to save fresh water. The next phase of development is to combine production processes and wastewater treatment, often called “process-integrated water management” (sustainable water use, industrial water use, cleaner production, etc.).

Typically, the improvement comes about through a complete change of the production process paradigm to reduce water and energy consumption, as well as waste production. Here, productional and environmental engineers need to cooperate and build one team. In this book, the fundamentals are discussed which are needed to better understand the processes taking place in “end-of-pipe” and

“decentralized effluent treatment” plants. In the last chapter, examples of “process-integrated water management” and “decentralized treatment” are presented.

Two different wastewater treatment concepts can be followed: either the separation of impurities from water, or the partial or complete mineralization of impurities. Separation processes are based on fluid mechanics (sedimentation, centrifugation, filtration and flotation) or on synthetic membranes (micro-, ultra- and nanofiltration, as well as reverse osmosis). Additionally, physical–chemical processes can be used – like adsorption and coagulation – to separate dissolved or emulsified compounds from water. Impurities can be mineralized by biological and chemical processes (advanced oxidation with ozone,  $H_2O_2$ , UV, etc.). We want to concentrate our attention on biological processes. Other ones, such as sedimentation or membranes, will be discussed in connection with the activated sludge process and membrane bioreactors.

The main advantages of biological processes in comparison with chemical oxidation are: no need to separate colloids and dispersed solid particles before treatment, lower energy consumption, the use of open reactors, resulting in lower costs, and no need for waste gas treatment.

The advantages of chemical oxidation over biological processes are: no sludge production, mineralization of non-biodegradable compounds and smaller reactor volumes. If it is necessary to remove very large amounts of organics, both processes should be coupled if possible, first the biological step and then the chemical step. We will concentrate our discussion on the fundamentals of biodegradation.

Because of the early development of wastewater technology in industrialized countries, we frequently find “end-of-pipe” treatment plants in industry which simultaneously treat municipal wastewater and vice versa. “Decentralized effluent treatment” plants are initiated only if a large plant would be overloaded or the process would be negatively influenced by hazardous compounds. The main aim is then to optimize the treatment process by using process controls and thereby to reduce the cost of aeration and pumping.

In countries with rapidly growing industries and no municipal treatment plants, the construction and operation of a “decentralized effluent treatment” plant frequently has to be tested for each factory and realized as necessary. An appropriate treatment method should be applied rigorously to enable water reuse in regions with water scarceness or high water prices, for irrigation in agriculture, or as cooling water for power stations or industry. In addition, it is often very important to protect natural water systems used for drinking water supplies, recreation and conservation. Compared with “end-of-pipe” treatment, “decentralized treatment” is often the more economical process.

A better understanding is needed of the biological, physical, ecological, social and economical interactions surrounding water and wastewater. We cannot consider all these aspects, but this book provides important information about the fundamentals and engineering aspects of biological wastewater treatment. The methods used to describe and solve the problems presented are those used by biochemical engineers developing models based on mass balances which are valid for specific systems. The authors made every effort to present mathematical derivations

so comprehensively that at least graduate students can follow. The target group also includes all engineers, biologists and chemists working in the field of wastewater treatment who are interested in learning more about its fundamentals.

After a survey of the historical development of microbiology and wastewater treatment, we give a brief introduction to wastewater characteristics and relevant legislation as well as microbial metabolism and stoichiometry, which is of fundamental importance for mass balances with biological reactions. Gas/liquid oxygen transfer is discussed in detail because of its high importance for all aerobic processes in wastewater treatment. Anaerobic substrate degradation is discussed afterwards as a very interesting alternative for the treatment of high-load effluents. Persistent, industrially produced compounds are not easily treated in biological processes. Therefore, the results of several recent studies are summarized and discussed here. The great significance of nitrogen and phosphorus removal has led us to report about their stoichiometric and kinetic backgrounds individually. In the past two decades, discussions about modelling of the activated sludge process have increased. To gain a better understanding of activated sludge model number 1 (ASM 1) and its description of nitrogen removal, we give detailed explanations. We have dealt with the use of membranes in place of secondary clarifiers to emphasize that new possibilities exist for reusing and recycling water in the future. Therefore, they may be suitable in tandem with the topic of the previous chapters which discuss production-integrated water management and decentralized effluent treatment.

Mrs. Christine Heimerl-Rötsch transcribed our texts several times, as they were updated numerous times. She deserves our high recognition for her thoroughness and punctuality. Dr.-Ing. Gregory Morgan corrected our English. Although we made every effort to compose the text faultlessly, there was still need for improvement. We express our thanks to him.

It would not have been possible to write this book without the numerous discussions with students, graduate students, scientific and chemotechnical co-workers as well as assistants. Thank you all very much for your cooperation!

We realize that not all parts of this book are easy to read, because it was necessary to use a large number of different variables and complicated indices. It was our conviction, however, that this was necessary to avoid misunderstanding and confusion.

Over the past 25 years, many new processes have been tested successfully, a lot of them have gone into operation and a great number of papers have been published in this field. We hope that this book will help provide a better understanding and orientation in the important and interesting field of "Biological Wastewater Treatment".

*The Authors*





## List of Symbols and Abbreviations

Symbol	Explanation	Unit (example)	Basic unit
A	Surface	$m^2$	$L^2$
A	Membrane area	$m^2$	$L^2$
A	Membrane constant	$m\ h^{-1}\ bar^{-1}$	$L^2\ M^{-1}$
A*	Membrane constant	$g\ m^{-2}\ h^{-1}\ bar^{-1}$	$L^{-1}$
a	Volume specific surface	$m^2\ m^{-3}$	$L^2\ L^{-3}$
a	Activity	–	–
a	Coefficient	–	–
$a_1, a_2, a_3$	Constants	–	–
B	Membrane constant	$m\ h^{-1}$	$L\ T^{-1}$
Bi	Biot number	–	–
$B_v$	Loading per volume	$g\ m^{-3}\ d^{-1}$	$M\ L^3\ T^{-1}$
C	Dimensionless concentration	–	–
C	Integration constant	–	–
C*	Dimensionless dissolved concentration in equilibrium with gas concentration	–	–
C'	Dimensionless dissolved oxygen concentration	–	–
c	Concentration of special gas components in air	$g\ m^{-3}$	$M\ L^{-3}$
c'	Dissolved concentration	$g\ m^{-3}$	$M\ L^{-3}$
c*	Dissolved concentration in equilibrium with gas concentration	$g\ m^{-3}$	$M\ L^{-3}$
D	Dilution rate	$h^{-1}$	$T^{-1}$
$D_c$	Critical dilution rate	$h^{-1}$	$T^{-1}$
D	Diameter	m	L
D	Diffusion coefficient	$m^2\ h^{-1}$	$L^2\ T^{-1}$
DC	Desorption capacity	$g\ m^{-3}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
$D_x$	Dispersion coefficient in x direction	$m^2\ h^{-1}$	$L^3\ T^{-1}$

Symbol	Explanation	Unit (example)	Basic unit
$Da_{II}$	Damköhler number II ( $= \mu_{\max} t_v$ )	–	
$d$	Diameter	m	L
$d_h$	Hydraulic diameter	m	–
$E$	Efficiency	$\text{kg (kWh)}^{-1} \text{O}_2$	$\text{L}^{-2} \text{T}^2$
$E$	Density of residence time	–	
$E^*$	Dimensionless efficiency	–	–
$e_A$	Energy of activation	$\text{kJ mol}^{-1}$	$\text{M L}^2 \text{T}^{-2} \text{N}^{-1}$
$F$	Residence time distribution	–	
$F_{\text{O}_2}$	Power of resistance of oxygen molecules	–	
$f_i$	Portion of inert biomass related to the total biomass	–	
$f_p$	Portion of particulate products related to biomass	–	–
$\Delta G^0$	Difference of free reaction enthalpy	$\text{kJ mol}^{-1}$	$\text{M L}^2 \text{T}^{-2} \text{N}^{-1}$
$g$	Earth acceleration	$\text{m s}^{-2}$	$\text{L T}^{-2}$
$h$	Distance of the stirrer from the bottom	m	
$\Delta H^0$	Difference of enthalpy	$\text{kJ mol}^{-1}$	$\text{M L}^2 \text{T}^{-2} \text{N}^{-1}$
$H'$	Henry coefficient	$\text{g L}^{-1} \text{bar}^{-1}$	$\text{M L}^{-1} \text{T}^{-2}$
$H$	Henry coefficient	–	
$H_g$	Henry coefficient	$\text{atm (mol/l)}^{-1}$	$\text{N L}^{-2} \text{M}^{-1} \text{L}^{-3}$
$H$	“Height” of deep tanks		
$H$	Height	m	L
$I$	Strength of a electric current	A	S
$i$	Strength of electric current	A	
$i_{\text{XB}}$	Nitrogen in bacteria related to mass of bacteria and slowly biod. substrate	–	–
$i_{\text{XP}}$	Nitrogen in bacteria related to particular inert organic matter	–	–
$J$	Specific mass transfer rate (volume flux)	$\text{g m}^{-2} \text{s}^{-1}$ $\text{mol m}^{-2} \text{s}^{-1}$	$\text{M L}^{-2} \text{T}^{-1}$ $\text{N L}^{-2} \text{T}^{-1}$
$J_D$	Diffusion flux	$\text{g m}^{-2} \text{s}^{-1}$	$\text{M L}^{-2} \text{T}^{-1}$
$J_{D+C}$	Flux for diffusion and convection	$\text{g m}^{-2} \text{s}^{-1}$	$\text{M L}^{-2} \text{T}^{-1}$
$J_o$	Standard volume flux	$\text{L m}^{-2} \text{bar}^{-1} \text{s}^{-1}$	$\text{M T}^{-3}$
$K$	Total mass transfer coefficient	$\text{h}^{-1}$	$\text{T}^{-1}$
$K$	Boltzmann constant	$1.38 \times 10^{-23} \text{ J K}^{-1}$	$\text{M L}^2 \text{T}^{-2} \theta$
$K'$	Saturation coefficient for oxygen	$\text{mg L}^{-1}$	$\text{M L}^{-3}$
$K_D$	Dissoziation constant	–	–

Symbol	Explanation	Unit (example)	Basic unit
$K_e$	Equilibrium constant	–	–
$K'_e$	Equilibrium constant	$L\ mg^{-1}$	$L^3\ M^{-1}$
$K_{iH}, K_i$	Coefficients for excess substrate inhibition	$mg\ L^{-1}$	$M\ L^{-3}$
$K_{iN}$	Coefficient of non-competitive inhibition	$mg\ L^{-1}$	$M\ L^{-3}$
$K_L$	Overall mass transfer coefficient	$m\ h^{-1}$	$L\ T^{-1}$
$K_{La}$	Specific overall mass transfer coefficient	$h^{-1}$	$T^{-1}$
$K_m$	Michaelis–Menten coefficient	$mol\ L^{-1}$	$N\ L^{-3}$
$K_m$	Equilibrium constant	–	–
$K_{OH}$	Saturation coefficient for hydrolysis	$mg\ L^{-1}$	$M\ L^{-3}$
$K_p$	Henry coefficient	$bar\ L\ g^{-1}$	$M\ T\ L^{-1}$
$K_S$	Saturation coefficient for substrate	$mg\ L^{-1}$	$M\ L^{-3}$
$K_{SH}$	Saturation coefficient	–	–
$k$	Coefficient for dry air (= 0.2857)	–	–
$k$	Coefficient of reaction rate	$h^{-1}$	$T^{-1}$
$k_o$	Theoretical maximal value of reaction rate for $T \rightarrow \infty$	–	–
$k_L$	Mass transfer coefficient for liquid boundary	$m\ h^{-1}$	$L\ T^{-1}$
$k_{La}$	Specific mass transfer coefficient for liquid boundary	$h^{-1}$	$T^{-1}$
$k_G$	Mass transfer coefficient for gaseous boundary	$m\ h^{-1}$	$L\ T^{-1}$
$k_{Ga}$	Specific mass transfer coefficient for gaseous boundary	$h^{-1}$	$T^{-1}$
$k_d$	Decay coefficient	$h^{-1}$	$T^{-1}$
$k_s$	Coefficient of bacteria dying	$h^{-1}$	$T^{-1}$
$k_e$	Coefficient of endogeneous respiration	$h^{-1}$	$T^{-1}$
$L$	Length	$m$	$L$
$L$	Biofilm thickness	$m$	$L$
$LD_{50}$	Mass of a compound per mass of living test organism, fatal to one-half of population if delivered rapidly	$mg\ kg^{-1}$	–
$M$	Molmass	$g\ mol^{-1}$	$M\ N^{-1}$
$m$	Mass	$g$	$M$
$N$	Amount of moles	$mol$	$N$

Symbol	Explanation	Unit (example)	Basic unit
$n$	Speed of a stirrer	$s^{-1}$	$T^{-1}$
$n_i$	Number of droplets	–	–
$n_R$	Recycle ratio	–	–
$n_E$	Thickening degree	–	–
$n_{PHB}$	Fraction of PHB inside of bacteria	–	–
$n$	Number of stages of a cascade	–	–
OC	Specific oxygenation capacity	$mol\ L^{-1}\ h^{-1}$	$N\ L^{-3}\ T^{-1}$
OTR	Oxygen transfer rate	$g\ O_2\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
OTE	Oxygen transfer efficiency	–	–
P	Power demand	kW	$M\ L^2\ T^{-3}$
p	Pressure	bar	$M\ L^{-1}\ T^{-2}$
Q	Flow rate	$m^3\ h^{-1}$	$L^{-3}\ T^{-1}$
R	Radius	m	L
R	Gas constant [= 8.314 J (mol K) <sup>-1</sup> ]	J (mol K) <sup>-1</sup>	$M\ L^2\ T^{-2}\ N^{-1}\ \theta^{-1}$
R	Resistance	$m^{-1}$	$L^{-1}$
R	Retention coefficient	%	
$R_t$	True retention coefficient	%	
r	Reaction rate	$mg\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$ $N\ L^{-3}\ T^{-1}$
$r'$	Respiration rate	$g\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
$r_x$	Growth rate of bacteria	$g\ L^{-1}d^{-1}\ MLSS$	$M\ L^{-3}\ T^{-1}$
S	Concentration of substrates	$mg\ L^{-1})$ , $mol\ L^{-1}$	$M\ L^{-3}$ , $NL^{-3}$
SOTR	Standardized oxygen transfer rate	$mg\ L^{-1}\ h^{-1}$	$M\ L^{-3}\ T^{-1}$
$S^*$	Dimensionless dissolved oxygen concentration (= $S'/K'$ )	–	–
S	Selectivity	–	–
T	Temperature	K, °C	$\theta$
t	Time	h	T
$t_R$	Mean retention time	h	T
$t_{RC}$	Critical mean retention time	h	T
$t_{RX}$	Mean retention time of bacteria (= sludge age)	h	T
$t_{RXC}$	Critical sludge age	h	T
U	Voltage	V	$M\ L^2\ T\ A^{-1}$
V	Volume	$m^3$	$L^3$
v	Velocity	$m\ s^{-1}$	$L\ T^{-1}$
w	Flow rate	$m\ s^{-1}$	$L\ T^{-1}$

 1) BOD<sub>5</sub>, COD, DOC etc.

Symbol	Explanation	Unit (example)	Basic unit
$\bar{w}$	Gaging void velocity		
$\bar{w}$	Mean velocity	$\text{m s}^{-1}$	$\text{L T}^{-1}$
X	Concentration of bacteria	$\text{g L}^{-1}$ MLSS	$\text{M L}^{-3}$
$X^*$	Dimensionless bacteria concentration (= $X/K'$ )	–	–
x	Local coordinate	m	L
x	Mole fraction	–	–
y	Mole fraction	–	–
$y_{X-O/X-C}$	Mole fraction oxygen/carbon in bacteria	–	–
Y	Yield coefficient	–	–
$Y_{X/S}^o$	True yield coefficient growth of bacteria/used substrate	$\text{g MLSS (g COD)}^{-1}$	–
$Y_{X_C/S_C}^o$	True yield coefficient growth of bacteria carbon/used substrate	$\text{g C (g DOC)}^{-1}$	–
$Y_{X/S}$	Apparent yield coefficient growth of bacteria/used substrate	$\text{g MLSS (g COD)}^{-1}$	–
Z	Dimensionless local coordinate	–	–
z	Local coordinate	m	L
Bi	Biot number	(= $w d D^{-1}$ )	
Da	Damköhler number	(= $\mu_{\max} t_R$ )	
$Da_{II}$	Damköhler number II	(= $\mu_{\max} R^2 D^{-1}$ )	
Fr	Froude number	(= $n^2 d g^{-1}$ )	
Mo	Monod number	(= $S_o K_S^{-1}$ )	
$Mo'$	Modified Monod number	(= $c^* k'^{-1}$ )	
Ne	Newton number	(= $P d^{-5} n^{-3} g^{-1}$ )	
Pe	Peclet number	(= $w d D^{-1}$ )	
$Pe'$	Modified Peclet number	(= $\bar{w} L D_x^{-1}$ )	
Re	Reynolds number	(= $\bar{w} d v^{-1}$ )	
Sc	Schmidt number	(= $v D^{-1}$ )	
Sh	Sherwood number	(= $k_L d D^{-1}$ )	
Sm	Semenov number	(= $k_L a \mu_{\max}^{-1}$ )	
Y	Oxygen transfer number	$\left( \frac{K_L a V}{d^3} \left( \frac{v}{g^2} \right)^{1/3} \right)$	

---

Symbol	Explanation		
--------	-------------	--	--

---

**Greek Symbols**

$\alpha$	Conversion, removal ratio	–	–
$\alpha_w$	Relation of specific mass transfer coefficient wastewater/clean water	–	–
$\beta$	Separation coefficient of a settler	–	–
$\beta$	Osmotic coefficient	–	–
$\beta_w$	Relation dissolved oxygen concentration at 20 °C wastewater/clean water	–	–
$\gamma$	Activity coefficient	–	–
$\gamma_w$	$\alpha_w \beta_w$ relation maximal oxygen mass transfer rate at 20 °C wastewater/clean water	–	–
$\delta$	Boundary layer thickness	m	L
$\varepsilon$	Porosity	–	–
$\eta$	Rate of hydrolysis by anoxic bacteria related to rate of hydrolysis by aerobic bacteria	–	–
$\eta$	Efficiency coefficient	–	–
$\eta$	Dynamic viscosity	$\text{g m}^{-1} \text{s}^{-1}$	$\text{M L}^{-1} \text{T}^{-1}$
$\theta$	Coefficient, describing an influence of temperature	–	–
$\mu$	Specific growth rate	$\text{d}^{-1}$	$\text{T}^{-1}$
$\mu$	Tortousity	–	–
$\mu_{\text{O}_2}$	Velocity of diffusing oxygen molecules	$\text{m s}^{-1}$	$\text{L T}^{-1}$
$\nu$	Kinematic viscosity	$\text{m}^2 \text{s}^{-1}$	$\text{L}^2 \text{T}^{-1}$
$\xi$	Resistance coefficient	–	–
$\pi$	Number in analysis of dimensions	–	–
$\pi$	Osmotic pressure	bar	$\text{M L}^{-1} \text{T}^{-2}$
$\rho$	Density	$\text{g m}^{-3}$	$\text{M L}^{-3}$
$\Sigma$	Sum	–	–
$\sigma$	Surface tension	$\text{N m}^{-1}$	$\text{M T}^{-2}$
$\sigma$	Dimensionless variance	–	–
$\sigma^*$	Dimensionless surface tension	–	–
$\sigma_t$	Variance according time	s	T
$\tau$	Dimensionless time	–	–
$\varphi$	Phase angle of electric current	–	–

---

Symbol	Explanation
--------	-------------

---

**Indices**

arith	Arithmetic mean value
A	Active autotrophs
A	Air
Alk	Alkaline
a	Adsorption
a	Behind reactor
a	Air
ae	Aerobic
an	Anaerobic
ap	Apparent
ax	Anoxic
b	Back
b	Blower
c	Cake
cat	Catalyst
cf	Cross flow
C	Convective
CO <sub>2</sub> -O	CO <sub>2</sub> -oxygen
CO <sub>2</sub> -C	CO <sub>2</sub> -carbon
CO <sub>2</sub> -C/S-C	CO <sub>2</sub> -C/substrate-carbon
CO <sub>2</sub> -O/S-O	CO <sub>2</sub> -O/substrate-oxygen
CO <sub>2</sub> -N	CO <sub>2</sub> needed for neutralisation of H <sup>+</sup> formed by NH <sub>4</sub> -N oxidation
Σ	Summary
d	Daily
d	Decay
d	Diameter
d	Dissolved
D	Denitrifiers
D	Diffusion
DO	Dodecan
D+C	Diffusion and convection
e	Effluent
e	Endogenous
eff	Effective
ex	Excess
E	Enzyme
ES	Enzyme–substrate complex
ET5	Emulgin ET5

Symbol	Explanation
f	Fouling
f	Foreign
f	Free of oxygen
g	Gear
G	Gas
G	Generation
H	Active heterotrophs
H	Hydrolysis
i	Impuls
i	Inert
i	Inhibitor
i,j	Component
L	Liquid
max	Maximal
m	Membrane
m	Motor
M	After mixture
M	Mixing point
ML	Mixed liquid
MLSS	Mixed liquid suspended solids
N	Nitrogen
N	secondary materials
NB	<i>Nitrobacter</i>
ND	dissolved organic nitrogen
NH	Dissolved NH <sub>3</sub> and NH <sub>4</sub>
NH <sub>4</sub> -O <sub>2</sub>	Oxygen used for NH <sub>4</sub> oxydation
NH <sub>4</sub> -N	Nitrogen in ammonia
NS	<i>Nitrosomonas</i>
NO	Nitrate and nitrite nitrogen
NO <sub>2</sub>	Nitrite
NO <sub>3</sub>	Nitrate
NS	Nitrosomonas
o Influent	Standardized to $c' = 0 \text{ mg L}^{-1}$
org.P	Dissolved organic phosphorous
oTS	Organic dry matter
O <sub>2</sub>	Oxygen
p	Permeate
p	Particulate product
po	Pore
pw	Process water
P	Phosphorus



Symbol	Explanation
PM	Primary materials
PO <sub>4</sub>	Orthophosphate
P-P	Dissolved inorganic polyphosphate
rt	Rapid test
R	Reactor
R	Recycle
s	Substrate
spec	Specific
S	Sewage
SC	Substrate-carbon
SO	Substrate-oxygen
SS	Readily biodegradable substrate
St	Standard test
t	Total
th	Theoretical
T	Temperature
v	Related to volume
VOC	Volatile organic carbon
w	Water
XA	Biomass of autotrophs
XH	Biomass of heterotrophs
X	Local coordinate
XC	Bacteria mass-carbon
XO	Bacteria mass-oxygen
XC/XO	Carbon in bacteria mass/oxygen in bacteria mass
XC/SC	Carbon in bacteria mass/carbon in substrate
X/O <sub>2</sub>	Bacteria mass/oxygen
X/S	Bacteria mass/substrate
z	Local coordinate
0	Influent

### Numbers as Indices

20	Temperature of 20 °C
*	Saturation
–	Mean value
20	Applied to 20 °C
20,0	Applied to 20 °C and c' = 0 mg O <sub>2</sub> L <sup>-1</sup> dissolved oxygen

---

Symbol	Explanation
--------	-------------

---

**Abbreviations**

AAO	Anaerobic Anoxic Oxidation
ADP	Adenosin diphosphate
AO	Anaerobic Oxidation
ASM	Activated sludge model
ASCE	American Society of Civil Engineers
ATP	Adenosine triphosphate
ATV	Abwasser Technische Vereinigung
BOD	Biological oxygen demand
BWB	Berliner Wasserbetreiber
CA	Cellulose acetate
CFD	Computational fluid dynamics
COD	Chemical oxygen demand
CSTR	Completely stirred tank reactor
DNA	Deoxyribonucleic acid
DMSO	Dimethylsulfoxide
DOC	Dissolved organic carbon
DWA	Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V.
DVWK	Deutscher Verband für Wasserwirtschaft und Kulturbau e.V.
EDS	Endocrine disrupting substances
EPA	Environmental Protection Agency
EPS	Extracellular polymer substances
FM	Ratio of feed to biomass
LDS	Lignin degradation system
MAP	Magnesium ammonium phosphate
MBR	Membrane bioreactor
MLSS	Mixed liquor suspended solid
MLVSS	Mixed liquor volatile suspended solid
NDSA	Naphtalene disulfonic acid
NSA	Naphtalene sulfonic acid
PA	Polyamide
PAN	Polyacrylonitrile acid
PAO	Phosphate-accumulating organism
PES	Polyethersulphone
PFU	Plug-forming unit
PHB	Polyhydroxybutyrate
PP	Polypropylen
PSU	Polysulphone
PUDF	Polyvinylidenfluoride

---

Symbol	Explanation
RB5	Reactive black 5
RDR	Rotating disc reactor
RNA	Ribonucleic acid
SCP	Single-cell protein
SRB	Sulfur-reducing bacteria
SS	Suspended solid
UASB	Upflow anaerobic sludge blanket
VFA	Volatile fatty acid
VOC	Volatile organic compound
WWTP	Wastewater treatment plant

