



Biological Sludge Minimization and Biomaterials/Bioenergy Recovery Technologies

Edited by Etienne Paul and Yu Liu



BIOLOGICAL SLUDGE MINIMIZATION AND BIOMATERIALS/BIOENERGY RECOVERY TECHNOLOGIES

Edited by

**ETIENNE PAUL
YU LIU**

 **WILEY**

A JOHN WILEY & SONS, INC., PUBLICATION

Copyright © 2012 by John Wiley & Sons, Inc. All rights reserved.

Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of the Publisher, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at www.copyright.com. Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

Limit of Liability/Disclaimer of Warranty: While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

For general information on our other products and services or for technical support, please contact our Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

Wiley also publishes its books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit our web site at www.wiley.com.

Library of Congress Cataloging-in-Publication Data:

Biological sludge minimization and biomaterials/bioenergy recovery technologies / edited by Etienne Paul and Yu Liu.

p. cm.

Includes index

ISBN 978-0-470-76882-2 (cloth)

1. Water treatment plant residuals—Purification. 2. Waste products as fuel. 3. Water—Purification. 4. Biochemical engineering. I. Paul, Etienne, 1964- II. Liu, Yu, 1964- TD899.W3B56 2012
628.3—dc23

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

CONTENTS

Preface	xvii
Contributors	xxi
1 Fundamentals of Biological Processes for Wastewater Treatment	1
<i>Jianlong Wang</i>	
1.1 Introduction, 1	
1.2 Overview of Biological Wastewater Treatment, 2	
1.2.1 The Objective of Biological Wastewater Treatment, 2	
1.2.2 Roles of Microorganisms in Wastewater Treatment, 3	
1.2.3 Types of Biological Wastewater Treatment Processes, 4	
1.3 Classification of Microorganisms, 4	
1.3.1 By the Sources of Carbon and Energy, 4	
1.3.2 By Temperature Range, 6	
1.3.3 Microorganism Types in Biological Wastewater Treatment, 7	
1.4 Some Important Microorganisms in Wastewater Treatment, 8	
1.4.1 Bacteria, 8	
1.4.2 Fungi, 12	
1.4.3 Algae, 15	
1.4.4 Protozoans, 16	
1.4.5 Rotifers and Crustaceans, 18	
1.4.6 Viruses, 20	

- 1.5 Measurement of Microbial Biomass, 21
 - 1.5.1 Total Number of Microbial Cells, 21
 - 1.5.2 Measurement of Viable Microbes on Solid Growth Media, 22
 - 1.5.3 Measurement of Active Cells in Environmental Samples, 23
 - 1.5.4 Determination of Cellular Biochemical Compounds, 24
 - 1.5.5 Evaluation of Microbial Biodiversity by Molecular Techniques, 24
- 1.6 Microbial Nutrition, 24
 - 1.6.1 Microbial Chemical Composition, 25
 - 1.6.2 Macronutrients, 27
 - 1.6.3 Micronutrients, 28
 - 1.6.4 Growth Factor, 29
 - 1.6.5 Microbial Empirical Formula, 31
- 1.7 Microbial Metabolism, 31
 - 1.7.1 Catabolic Metabolic Pathways, 32
 - 1.7.2 Anabolic Metabolic Pathway, 38
 - 1.7.3 Biomass Synthesis Yields, 39
 - 1.7.4 Coupling Energy-Synthesis Metabolism, 41
- 1.8 Functions of Biological Wastewater Treatment, 42
 - 1.8.1 Aerobic Biological Oxidation, 42
 - 1.8.2 Biological Nutrients Removal, 45
 - 1.8.3 Anaerobic Biological Oxidation, 50
 - 1.8.4 Biological Removal of Toxic Organic Compounds and Heavy Metals, 55
 - 1.8.5 Removal of Pathogens and Parasites, 58
- 1.9 Activated Sludge Process, 59
 - 1.9.1 Basic Process, 60
 - 1.9.2 Microbiology of Activated Sludge, 61
 - 1.9.3 Biochemistry of Activated Sludge, 66
 - 1.9.4 Main Problems in the Activated Sludge Process, 67
- 1.10 Suspended- and Attached-Growth Processes, 69
 - 1.10.1 Suspended-Growth Processes, 69
 - 1.10.2 Attached-Growth Processes, 70
 - 1.10.3 Hybrid Systems, 71
 - 1.10.4 Comparison Between Suspended- and Attached-Growth Systems, 72
- 1.11 Sludge Production, Treatment and Disposal, 74
 - 1.11.1 Sludge Production, 74
 - 1.11.2 Sludge Treatment Processes, 76

1.1.1.3	Sludge Disposal and Application, 78	
	References, 79	
2	Sludge Production: Quantification and Prediction for Urban Treatment Plants and Assessment of Strategies for Sludge Reduction	81
	<i>Mathieu Spérandio, Etienne Paul, Yolaine Bessière, and Yu Liu</i>	
2.1	Introduction, 81	
2.2	Sludge Fractionation and Origin, 82	
2.2.1	Sludge Composition, 82	
2.2.2	Wastewater Characteristics, 83	
2.3	Quantification of Excess Sludge Production, 88	
2.3.1	Primary Treatment, 88	
2.3.2	Activated Sludge Process, 90	
2.3.3	Phosphorus Removal (Biological and Physicochemical), 97	
2.4	Practical Evaluation of Sludge Production, 99	
2.4.1	Sludge Production Yield Variability with Domestic Wastewater, 99	
2.4.2	Influence of Sludge Age: Experimental Data Versus Models, 100	
2.4.3	ISS Entrapment in the Sludge, 103	
2.4.4	Example of Sludge Production for a Different Case Study, 104	
2.5	Strategies for Excess Sludge Reduction, 106	
2.5.1	Classification of Strategies, 106	
2.5.2	Increasing the Sludge Age, 107	
2.5.3	Model-Based Evaluation of Advanced ESR Strategies, 109	
2.6	Conclusions, 111	
2.7	Nomenclature, 112	
	References, 114	
3	Characterization of Municipal Wastewater and Sludge	117
	<i>Etienne Paul, Xavier Lefebvre, Mathieu Spérandio, Dominique Lefebvre, and Yu Liu</i>	
3.1	Introduction, 117	
3.2	Definitions, 119	

- 3.3 Wastewater and Sludge Composition and Fractionation, 120
 - 3.3.1 Wastewater COD Fractions, 121
 - 3.3.2 WAS COD Fractions, 122
 - 3.3.3 ADS Organic Fractions, 122
- 3.4 Physical Fractionation, 123
 - 3.4.1 Physical State of Wastewater Organic Matter, 123
 - 3.4.2 Methods for Physical Fractionation of Wastewater Components, 123
- 3.5 Biodegradation Assays for Wastewater and Sludge Characterization, 124
 - 3.5.1 Background, 124
 - 3.5.2 Methods Based on Substrate Depletion, 125
 - 3.5.3 Methods Based on Respirometry, 125
 - 3.5.4 Anaerobic Biodegradation Assays, 128
- 3.6 Application to Wastewater COD Fractionation, 131
 - 3.6.1 Global Picture of Fractionation Methods and Wastewater COD Fractions, 131
 - 3.6.2 Application of Physical Separation for Characterization of Wastewater COD Fractions, 132
 - 3.6.3 Biodegradable COD Fraction, 133
 - 3.6.4 Relation Between Physical and Biological Properties of Organic Fractions, 136
 - 3.6.5 Unbiodegradable Particulate COD Fractions, 137
- 3.7 Assessment of the Characteristics of Sludge and Disintegrated Sludge, 143
 - 3.7.1 Physical Fractionation of COD Released from Sludge Disintegration Treatment, 143
 - 3.7.2 Biological Fractionation of COD Released from Sludge Disintegration Treatment, 145
 - 3.7.3 Biodegradability of WAS in Anaerobic Digestion, 145
 - 3.7.4 Unbiodegradable COD in Anaerobic Digestion, 146
- 3.8 Nomenclature, 147
- References, 149

4 Oxidic-Settling-Anaerobic Process for Enhanced Microbial Decay 155

Qingliang Zhao and Jianfang Wang

- 4.1 Introduction, 155
- 4.2 Description of the Oxidic-Settling-Anaerobic Process, 156
 - 4.2.1 Oxidic-Settling-Anaerobic Process, 156
 - 4.2.2 Characteristics of the OSA Process, 157

- 4.3 Effects of an Anaerobic Sludge Tank on the Performance of an OSA System, 158
 - 4.3.1 Fate of Sludge Anaerobic Exposure in an OSA System, 158
 - 4.3.2 Effect of Sludge Anaerobic Exposure on Biomass Activity, 160
- 4.4 Sludge Production in an OSA System, 161
- 4.5 Performance of an OSA System, 162
 - 4.5.1 Organic and Nutrient Removal, 162
 - 4.5.2 Sludge Settleability, 163
- 4.6 Important Influence Factors, 164
 - 4.6.1 Influence of the ORP on Sludge Production, 164
 - 4.6.2 Influence of the ORP on Performance of an OSA System, 164
 - 4.6.3 Influence of SAET on Sludge Production, 166
 - 4.6.4 Influence of SAET on the Performance of an OSA System, 166
- 4.7 Possible Sludge Reduction in the OSA Process, 166
 - 4.7.1 Slow Growers, 167
 - 4.7.2 Energy Uncoupling Metabolism, 167
 - 4.7.3 Sludge Endogenous Decay, 169
- 4.8 Microbial Community in an OSA System, 171
 - 4.8.1 Staining Analysis, 172
 - 4.8.2 FISH Analysis, 173
- 4.9 Cost and Energy Evaluation, 174
- 4.10 Evaluation of the OSA Process, 175
- 4.11 Process Development, 176
 - 4.11.1 Sludge Decay Combined with Other Sludge Reduction Mechanisms, 176
 - 4.11.2 Improved Efficiency in Sludge Anaerobic Digestion, 177
 - 4.11.3 Combined Minimization of Excess Sludge with Nutrient Removal, 178
- References, 179

5 Energy Uncoupling for Sludge Minimization: Pros and Cons

183

Bo Jiang, Yu Liu, and Etienne Paul

- 5.1 Introduction, 183
- 5.2 Overview of Adenosine Triphosphate Synthesis, 184
 - 5.2.1 Electron Transport System, 184

- 5.2.2 Mechanisms of Oxidative Phosphorylation, 185
- 5.3 Control of ATP Synthesis, 187
 - 5.3.1 Diversion of PMF from ATP Synthesis to Other Physiological Activities, 187
 - 5.3.2 Inhibition of Oxidative Phosphorylation, 187
 - 5.3.3 Uncoupling of Electron Transport and Oxidative Phosphorylation, 188
- 5.4 Energy Uncoupling for Sludge Reduction, 189
 - 5.4.1 Chemical Uncouplers Used for Sludge Reduction, 189
 - 5.4.2 Uncoupling Activity, 198
- 5.5 Modeling of Uncoupling Effect on Sludge Production, 200
- 5.6 Sideeffects of Chemical Uncouplers, 202
- 5.7 Full-Scale Application, 204
- References, 204

6 Reduction of Excess Sludge Production Using Ozonation or Chlorination: Performance and Mechanisms of Action **209**

Etienne Paul, Qi-Shan Liu, and Yu Liu

- 6.1 Introduction, 209
- 6.2 Significant Operational Results for ESP Reduction with Ozone, 210
 - 6.2.1 Options for Combining Ozonation and Biological Treatment, 210
 - 6.2.2 ESP Reduction Performance, 212
 - 6.2.3 Assessing Ozone Efficiency for Mineral ESP Reduction, 215
- 6.3 Side Effects of Sludge Ozonation, 216
 - 6.3.1 Outlet SS and COD, 216
 - 6.3.2 N Removal, 218
- 6.4 Cost Assessment, 221
- 6.5 Effect of Ozone on Sludge, 222
 - 6.5.1 Synergy Between Ozonation and Biological Treatment, 222
 - 6.5.2 Some Fundamentals of Ozone Transfer, 222
 - 6.5.3 Sludge Composition, 224
 - 6.5.4 Effect of Ozone on Activated Sludge: Batch Tests, 226
 - 6.5.5 Effect of Ozone on Biomass Activity, 228
 - 6.5.6 Competition for Ozone in Mixed Liquor, 231

6.6	Modeling Ozonation Effect, 233	
6.7	Remarks on Sludge Ozonation, 236	
6.8	Chlorination in Water and Wastewater Treatment, 236	
6.8.1	Introduction, 236	
6.8.2	Chlorination-Assisted Biological Processes for Sludge Reduction, 237	
6.8.3	Effect of Chlorine Dosage on Sludge Reduction, 239	
6.8.4	Chlorine Requirement, 240	
6.9	Nomenclature, 242	
	References, 244	
7	High-Dissolved-Oxygen Biological Process for Sludge Reduction	249
	<i>Zhi-Wu Wang</i>	
7.1	Introduction, 249	
7.2	Mechanism of High-Dissolved-Oxygen Reduced Sludge Production, 251	
7.2.1	High-Dissolved-Oxygen Decreased Specific Loading Rate, 251	
7.2.2	High-Dissolved-Oxygen Uncoupled Microbial Metabolism Pathway, 252	
7.2.3	High-Dissolved-Oxygen Shifted Microbial Population, 254	
7.3	Limits of High-Dissolved-Oxygen Process for Reduced Sludge Production, 255	
	References, 256	
8	Minimizing Excess Sludge Production Through Membrane Bioreactors and Integrated Processes	261
	<i>Philip Chuen-Yung Wong</i>	
8.1	Introduction, 261	
8.2	Mass Balances, 262	
8.3	Integrated Processes Based on Lysis-Cryptic Growth, 266	
8.3.1	Mass Balance Incorporating Sludge Disintegration and Solubilization, 268	
8.3.2	Thermal and Thermal-Alkaline Treatment, 274	
8.3.3	Ozonation, 276	
8.3.4	Sonication, 279	

- 8.4 Predation, 283
- 8.5 Summary and Concluding Remarks, 285
- References, 286

9 Microbial Fuel Cell Technology for Sustainable Treatment of Organic Wastes and Electrical Energy Recovery **291**

Shi-Jie You, Nan-Qi Ren, and Qing-Liang Zhao

- 9.1 Introduction, 291
- 9.2 Fundamentals, Evaluation, and Design of MFCs, 293
 - 9.2.1 Principles, 293
 - 9.2.2 Performance Evaluation, 293
 - 9.2.3 MFC Configurations, 294
- 9.3 Performance of Anodes, 295
 - 9.3.1 Electrode Materials, 295
 - 9.3.2 Microbial Electron Transfer, 296
 - 9.3.3 Electron Donors, 298
- 9.4 Cathode Performances, 299
 - 9.4.1 Electron Acceptors, 300
 - 9.4.2 Electrochemical Fundamentals of the Oxygen Reduction Reaction, 302
 - 9.4.3 Air-Cathode Structure and Function, 303
 - 9.4.4 Electrocatalyst, 304
- 9.5 Separator, 306
- 9.6 pH Gradient and Buffer, 307
- 9.7 Applications of MFC-Based Technology, 309
 - 9.7.1 Biosensors, 309
 - 9.7.2 Hydrogen Production, 310
 - 9.7.3 Desalination, 310
 - 9.7.4 Hydrogen Peroxide Synthesis, 312
 - 9.7.5 Environmental Remediation, 312
- 9.8 Conclusions and Remarks, 314
- References, 315

10 Anaerobic Digestion of Sewage Sludge **319**

Kuan-Yeow Show, Duu-Jong Lee, and Joo-Hwa Tay

- 10.1 Introduction, 319
- 10.2 Principles of Anaerobic Digestion, 320
 - 10.2.1 Hydrolysis and Acidogenesis, 321
 - 10.2.2 Methane Formation, 323

- 10.3 Environmental Requirements and Control, 324
 - 10.3.1 pH, 324
 - 10.3.2 Alkalinity, 325
 - 10.3.3 Temperature, 326
 - 10.3.4 Nutrients, 326
 - 10.3.5 Toxicity, 327
- 10.4 Design Considerations for Anaerobic Sludge Digestion, 329
 - 10.4.1 Hydraulic Detention Time, 329
 - 10.4.2 Solids Loading, 330
 - 10.4.3 Temperature, 331
 - 10.4.4 Mixing, 331
- 10.5 Component Design of Anaerobic Digester Systems, 331
 - 10.5.1 Tank Configurations, 331
 - 10.5.2 Temperature Control, 333
 - 10.5.3 Sludge Heating, 333
 - 10.5.4 Auxiliary Mixing, 334
- 10.6 Reactor Configurations, 336
 - 10.6.1 Conventional Anaerobic Digesters, 336
 - 10.6.2 Anaerobic Contact Processes, 338
 - 10.6.3 Other Types of Configurations, 340
- 10.7 Advantages and Limitations of Anaerobic Sludge Digestion, 343
- 10.8 Summary and New Horizons, 344
- References, 345

11 Mechanical Pretreatment-Assisted Biological Processes

349*Hélène Carrère, Damien J. Batstone, and Etienne Paul*

- 11.1 Introduction, 349
- 11.2 Mechanisms of Mechanical Pretreatment, 350
 - 11.2.1 From Sludge Disintegration to Cell Lysis and Chemical Transformation, 350
 - 11.2.2 Specific Energy, 350
 - 11.2.3 Sonication, 351
 - 11.2.4 Grinding, 353
 - 11.2.5 Shear-Based Methods: High-Pressure and Collision Plate Homogenization, 353
 - 11.2.6 Lysis Centrifuge, 353
- 11.3 Impacts of Treatment: Rate vs. Extent of Degradability, 353
 - 11.3.1 Grinding, 354
 - 11.3.2 Ultrasonication, 354

11.4	Equipment for Mechanical Pretreatment, 354	
11.4.1	Sonication, 355	
11.4.2	Grinding, 357	
11.4.3	Shear-Based Methods: High-Pressure and Collision Plate Homogenization, 358	
11.4.4	Lysis Centrifuge, 359	
11.5	Side Effects, 359	
11.6	Mechanical Treatment Combined with Activated Sludge, 360	
11.7	Mechanical Treatment Combined with Anaerobic Digestion, 361	
11.7.1	Performances, 361	
11.7.2	Dewaterability, 363	
11.7.3	Full-Scale Performance and Market Penetration, 364	
11.7.4	Energy Balance, 365	
11.7.5	Nutrient Release and Recovery/Removal, 366	
11.8	Conclusion, 367	
	References, 368	
12	Thermal Methods to Enhance Biological Treatment Processes	373
	<i>Etienne Paul, H�el�ene Carr�ere, and Damien J. Batstone</i>	
12.1	Introduction, 373	
12.2	Mechanisms, 374	
12.2.1	Effects of Heating on Cells, 374	
12.2.2	Effect of Heating on Sludge, 376	
12.2.3	Mechanisms of Thermal Pretreatment, 388	
12.3	Devices for Thermal Treatment, 388	
12.3.1	Low-Temperature Pretreatment, 389	
12.3.2	High-Temperature Pretreatment, 390	
12.4	Applications of Thermal Treatment, 390	
12.4.1	Thermal Treatment Combined with Activated Sludge, 390	
12.4.2	Thermal Pretreatment to Anaerobic Digestion, 394	
12.5	Conclusions, 398	
	References, 399	
13	Combustion, Pyrolysis, and Gasification of Sewage Sludge for Energy Recovery	405
	<i>Yong-Qiang Liu, Joo-Hwa Tay, and Yu Liu</i>	
13.1	Introduction, 405	
13.2	Characteristics and Dewatering of Sewage Sludge, 406	

13.3	Energy Recovery from Sludge, 408	
13.3.1	Incineration, 408	
13.3.2	Pyrolysis and Gasification, 416	
13.3.3	Wet Oxidation, 419	
13.3.4	Thermal Plasma Pyrolysis and Gasification, 420	
	References, 421	
14	Aerobic Granular Sludge Technology for Wastewater Treatment	429
	<i>Bing-Jie Ni and Han-Qing Yu</i>	
14.1	Introduction, 429	
14.2	Technological Starting Points: Cultivating Aerobic Granules, 431	
14.2.1	Substrate Composition, 431	
14.2.2	Organic Loading Rate, 433	
14.2.3	Seed Sludge, 433	
14.2.4	Reactor Configuration, 433	
14.2.5	Operational Parameters, 434	
14.3	Mechanisms of the Aerobic Granulation Process, 436	
14.3.1	Granulation Steps, 436	
14.3.2	Selective Pressure, 437	
14.4	Characterization of Aerobic Granular Sludge, 438	
14.4.1	Biomass Yield and Sludge Reduction, 438	
14.4.2	Formation and Consumption of Microbial Products, 440	
14.4.3	Microbial Structure and Diversity, 441	
14.4.4	Physicochemical Characteristics, 442	
14.5	Modeling Granule-Based SBR for Wastewater Treatment, 447	
14.5.1	Nutrient Removal in Granule-Based SBRs, 447	
14.5.2	Multiscale Modeling of Granule-Based SBR, 450	
14.6	Bioremediation of Wastewaters with Aerobic Granular Sludge Technology, 452	
14.6.1	Organic Wastewater Treatment, 452	
14.6.2	Biological Nutrient Removal, 452	
14.6.3	Domestic Wastewater Treatment, 454	
14.6.4	Xenobiotic Contaminant Bioremediation, 454	
14.6.5	Removal of Heavy Metals or Dyes, 455	
14.7	Remarks, 456	
	References, 457	

15 Biodegradable Bioplastics from Fermented Sludge, Wastes, and Effluents	465
<i>Etienne Paul, Elisabeth Neuhauser, and Yu Liu</i>	
15.1 Introduction, 465	
15.1.1 Context of Poly(hydroxyalkanoate) Production from Sludge and Effluents, 465	
15.1.2 Industrial Context for PHA Production, 467	
15.2 PHA Structure, 469	
15.3 Microbiology for PHA Production, 469	
15.4 Metabolism of PHA Production, 471	
15.4.1 PHB Metabolism, 472	
15.4.2 Metabolism for Other PHA Production, 475	
15.4.3 Nutrient Limitations, 476	
15.4.4 PHA Metabolism in Mixed Cultures, 477	
15.4.5 Effect of Substrate in Mixed Cultures, 478	
15.5 PHA Kinetics, 479	
15.6 PHA Storage to Minimize Excess Sludge Production in Wastewater Treatment Plants, 481	
15.7 Choice of Process and Reactor Design for PHA Production, 482	
15.7.1 Criteria, 482	
15.7.2 Anaerobic–Aerobic Process, 483	
15.7.3 Aerobic Dynamic Feeding Process, 485	
15.7.4 Fed-Batch Process Under Nutrient Growth Limitation, 486	
15.8 Culture Selection and Enrichment Strategies, 487	
15.9 PHA Quality and Recovery, 489	
15.10 Industrial Developments, 490	
References, 492	
Index	499