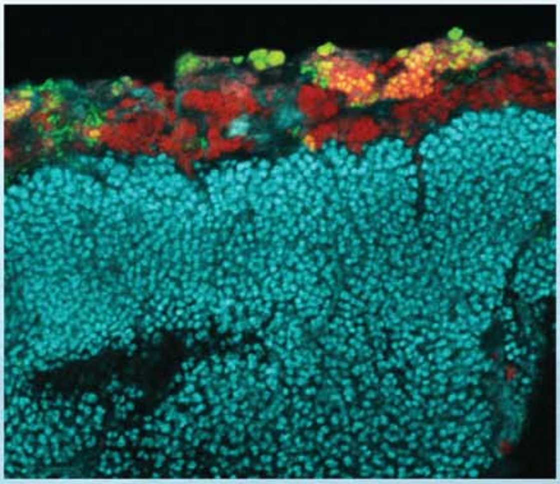
Environmental Biotechnology

PRINCIPLES AND APPLICATIONS

SECOND EDITION



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Environmental Biotechnology

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Environmental Biotechnology

Principles and Applications

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Second Edition

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Contents

The following electronic “bonus” Chapters B1 to B5 can be found at www.mhprofessional.com/rittmann2e.

Preface

Environmental biotechnology utilizes microorganisms to improve the sustainability of human society. These improvements include preventing the discharge of pollutants to the environment, cleaning up contaminated environments, generating valuable resources for human society, and improving human health. Environmental biotechnology is essential to society and truly unique as a technical discipline.

Environmental biotechnology is historic and eminently modern. Microbiological treatment technologies developed at the beginning of the twentieth century, such as activated sludge and anaerobic digestion, remain mainstays today. At the same time, new technologies constantly are being introduced to address very contemporary problems, such as detoxification of hazardous chemicals and recovery of valuable resources. Important tools used to characterize and control processes in environmental biotechnology also span the decades. For example, traditional measures of biomass, such as volatile suspended solids, have not lost their relevance, even though tools from molecular biology allow us to explore the diversity of the microbial communities.

Processes in environmental biotechnology work according to well-established principles of microbiology and engineering, but application of those principles normally requires some degree of empiricism. Although not a substitute for principles, empiricism must be embraced, because the materials treated with environmental biotechnology are inherently complex and varying in time and space.

The principles of engineering lead to quantitative tools, while the principles of microbiology often are more observational. Quantification is essential if processes are to be reliable and cost-effective. However, the complexity of the microbial communities involved in environmental biotechnology often is beyond quantitative description; unquantifiable observations are of the utmost value, too.

In *Environmental Biotechnology: Principles and Applications*, we connect these different facets of environmental biotechnology. Our strategy is to develop the basic concepts and quantitative tools in the first nine chapters, which comprise the principles part of this second edition. We consistently call upon those principles as we describe the applications in Chapters 10 through 15, as well as in five “bonus” chapters available electronically. Our theme is that *all microbiological processes behave in ways that are understandable, predictable, and unified*. At the same time, each application has its own special features that must be understood. The special features do not overturn or sidestep the common principles. Instead, they complement the principles and are most profitably understood in the light of the principles.

This book is targeted for graduate-level courses in curricula that exploit microbiological processes for environmental quality control. The book also is appropriate as a text for upper-level undergraduate courses and as a comprehensive resource for those engaged in professional practice and research involving environmental biotechnology.

The material in this second edition of *Environmental Biotechnology* can be used in one or several courses. For students not already having a solid background in microbiology, Chapters 1 to 4 provide a foundation in taxonomy, metabolism, genetics, and ecology. These chapters address the microbiology concepts that are most essential for understanding the principles and the applications that follow. They can serve as the text for a first course in environmental microbiology, or they can be used as a resource for students who need to refresh their knowledge in preparation for a more process-oriented course, research, or practice.

Chapters 5 through 9 provide the quantitative core of the principles. Chapter 5 develops quantitative tools for describing the stoichiometry and energetics of microbial reactions: what and how much the microorganisms consume and produce. Stoichiometry is the most fundamental of the quantitative tools. Chapters 6 and 7 systematically develop quantitative tools for kinetics: how fast are materials consumed and produced. Chapter 6 is for suspended-growth processes, while Chapter 7 is for biofilm processes. Described in Chapter 8 are some of the products that microorganisms make that affect process performance and ways to quantify them. The understanding expands the systematic tools of Chapters 6 and 7. Reliability and cost-effectiveness depend on applying kinetics properly. Chapter 9 describes how principles of mass balance and kinetics are used to apply stoichiometry and kinetics to the range of reactors used in environmental practice.

Chapters 10 through 15 comprise the applications section of the second edition. Each chapter includes information on the stoichiometry and kinetics of the key microorganisms, as well as features that are not easily captured by stoichiometric or kinetic parameters. Each chapter explains how processes are configured to achieve treatment objectives and what are the quantitative criteria for a good design. The objective is to link principles to practice as directly as possible.

We have reorganized the applications part to emphasize our goal of using environmental biotechnology to improve the sustainability of human society. Most prominently, we have made the first chapter of the applications part about methanogenesis, since it is the primary means to convert organic pollutants into a valuable energy form, methane gas. Methanogenic treatment can turn wastewater treatment into a net generator of renewable energy, instead of a major energy consumer.

Chapters 11 and 12 delve into the wide range of aerobic treatment processes for treating wastewater to remove biochemical oxygen demand (BOD). These processes are used worldwide and must be understood deeply to ensure that they perform well. Chapters 13 and 14 address the transformations, removal, and/or recovery of nitrogen and phosphorus. Many new developments have occurred in these areas since the first edition of *Environmental Biotechnology* was published. We describe the new advancements in science and technology in the second edition, and we give special attention to recovering valuable resources in wastewater while reducing the energy required to do so, rather than just removing polluting materials from wastewater, as commonly done in the past. Chapter 15 describes the use of biofilm processes to prepare safe and palatable drinking water, a topic whose acceptance has increased greatly since the first edition was published.

Those who have purchased the print textbook from McGraw-Hill also will gain access to five electronic "bonus" chapters: Chapter B1, Lagoons and Wetlands; Chapter B2, Microbiological Detoxification; Chapter B3, Microbial Electrochemical Cells; Chapter B4, Photosynthetic Biofactories; and Chapter B5, Complex Systems. These chapters can be found at www.mhprofessional.com/rittmann2e. They are being published electronically in order to lower the length and cost of the print book. That the bonus chapters are available only in electronic versions does not mean that they are of less importance. In fact, Chapters B2, B3, and B4 present information on some of the hottest new topics in environmental biotechnology. The bonus chapters are included in the ebook of this text.

One important feature of *Environmental Biotechnology* is that it contains many examples. These examples illustrate the step-by-step procedures for utilizing the tools needed to understand how microbial systems work or to design a treatment process. In most cases, learning by example is the most effective approach, and we give it strong emphasis.

The book also has extensive sets of problems at the ends of its chapters. The problems can be assigned as "homework," used as supplemental examples in class, or examined as study tools.

In an effort to promote uniformity in notation, we have elected to adapt the "Recommended Notation for Use in the Description of Biological Wastewater Treatment Processes," agreed upon internationally and as published in *Water Research* **16**, pp. 1501–1505 (1982). We hope this will encourage others to do the same, as this will facilitate much better communication among us.

We take this opportunity to thank our many wonderful students and colleagues, who have taught us new ideas, inspired us to look farther and deeper, and corrected our frequent errors. The numbers are too many to list by name, but you know who you are.

Finally, we thank Marylee and Martha for loving us, even when we became too preoccupied with the "book project."

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Environmental
Biotechnology

CHAPTER 1

Moving Toward Sustainability

In the 1970s, when the U.S. Environmental Protection Agency was first formed, the major environmental concern for water was pollution of rivers, streams, and lakes. Other major concerns were with air and land contamination. Since then, the world's population has more than doubled, and the availability of some of the world's natural resources (including water) to support human activities is shrinking toward unsustainable levels. Additionally, the release of greenhouse gases from the combustion of fossil fuels and from other sources has caused the Earth's temperature to rise, causing a host of significant and urgent environmental problems (IPCC, 2018; NAS, 2018; Reidmiller et al., 2018; U.S. EPA, 2018). Among the obvious are extraordinary storms and floods in some locations, greater droughts and extreme fires in others, melting of glaciers, a constant rise in sea levels, and the acidification of the oceans with an accompanying loss of sea life. These major problems, which have come to the fore relatively recently, require urgent attention and effective action. As environmental engineers and scientists, we must perform well our job of water-quality protection, but we must also address the growing need to preserve resources and reduce greenhouse gases as effectively as possible.

Environmental biotechnology is one of the powerful tools that we have for addressing the emerging and the long-standing challenges to sustainability. Environmental biotechnology can be defined as "managing microbial communities so that they provide services to society." The services include removing pollutants from water and other contaminated media, generating renewable resources, and improving human health. It is obvious that such services can address many of the pressing challenges facing human society. In Chapter 1, we begin by providing a framework for understanding the challenges that environmental engineers and scientists face, along with the opportunities for environmental biotechnology.

1.1 Water Uses and Resources

Beneficial uses of water require that the water have proper quality. Only a small portion of the total water available in the world has the quality suitable for most human needs, and difficulties are experienced in keeping the usable water free from contamination by human or industrial wastes. Environmental engineers have been given the responsibility to protect, store, and transport water; preserve its quality for aesthetic and environmental needs; and upgrade its quality for personal, agricultural, and industrial uses. These responsibilities present significant challenges.

Table 1.1 contains a summary of the global availability of water. Most of the world's water is contained in the ocean, where the salt content is about 3.4%, much too high for most human uses, including irrigation, drinking, and washing. The largest portion of freshwater, which makes up only 2.5% of the total, is locked in polar ice and glaciers. Liquid freshwater, the only water readily available with adequate quality to satisfy our greatest needs, represents less than 1% of the total water on Earth. In addition, most of this lies deep in the ground where it is difficult, if not impossible, to obtain.

While water is a renewable resource, our use of available freshwater is already high and growing so rapidly that it could exceed its rate of renewal in coming years. Solar radiation continually evaporates (mostly) seawater, leaving the salt and other chemicals behind. A portion of the resulting water vapor eventually condenses and falls on land as rain or snow to renew the supply of fresh and relatively clean water. It is the total rainfall of 119,000 km^3/year, rather than the Earth's total freshwater reservoir, that actually represents the sustainable supply, since it is new water each year. However, not all rainfall can be used. About two-thirds (74,200 km^3) evaporates before it can be captured; of the remainder that is stored or runs off the land (44,800 km^3), only about one-half can practically be captured for use.

1.2 Wastewater's Resources

Water is by far our most widely used natural resource. On a mass basis, water is used by the world's population at a rate more than 100-fold greater than for all other natural resources combined. Not only do we use water for drinking and washing, but we use it for agriculture to grow crops we eat, to generate electrical power and other forms of energy that run our society, for industry to produce the goods we use, for a broad range of municipal and commercial purposes, and for ecosystem preservation. Furthermore, water is used to carry away some of our wastes.

After we have used and dirtied water, we have commonly thought of it as *wastewater,* a term that is used throughout this book. Sewage is a term used to describe

TABLE 1.1 World Water Budget

Water Type and Location	Amount, km^3	Percentage of World's Total Water
Total water	1,386,000,000	100.0
Salt water	1,350,000,000	97.5
Freshwater	34,600,000	2.5
Ice	23,800,000	1.7
Liquid	10,800,000	0.8
Groundwater*	10,400,000	0.75
Surface water	90,000	0.007
Water vapor (atmosphere)	13,000	0.001
Yearly rainfall on land	119,000	–

*About one-half of the groundwater lies greater than 1.5 kilometers below the ground surface.
Source: Based upon information from Shiklomanov (1998).

wastewater coming directly from humans. Ironically, what we call wastewater is water that contains a wide range of resources, which we could term to be "used resources." For this reason, what was once viewed as waste is now being looked at as a resource, one that must not be wasted, but cleansed, captured in useful form, and used once again. For example, Singapore no longer uses the term wastewater; instead, they call it "used water." The needed degree of treatment for used water depends upon the purpose for which it is to be used. This is called "fit for use" treatment (Li et al., 2015).

Wastewaters contain important resources that can be captured and used to satisfy the basic needs of human society. The most important resource often is the water itself, once it has been cleaned to prevent harm to the consumer using fit-for-use treatment. Many wastewaters contain organic matter that contains energy, which, if captured, can be used to run our treatment systems and be sold on the market to generate income (Rittmann, 2013). Other commonly present resources are the fertilizing elements, nitrogen and phosphorus. Phosphorus is present in wastewater as simple phosphate or complex organic phosphate. If the simple phosphate is captured in a correct form, it can be removed, concentrated, and used once again as fertilizer (Rittmann et al., 2011). Nitrogen, generally in the form of ammonium or organic nitrogen in wastewater, also can be recovered and reused in agriculture. One key for reusing the phosphorus and nitrogen for agriculture is ensuring that treatment and recovery eliminate pathogens. A second key is that the recovered nutrient be in a form that can be available as a plant nutrient.

Important to realize is that, in order to feed the world's growing population, N_2 is now taken from the atmosphere and converted into ammonium for use as a crop fertilizer. The Haber–Bosch process, used for N_2 fixation to ammonium, consumes about 7% of the world's natural gas, one of the fossil fuels causing climate change (McCarty et al., 2011). The nitrogen in municipal wastewater comes from the food we eat, and the energy originally used to obtain that nitrogen from atmospheric N_2 represents as much energy as we currently use to run an aerobic wastewater treatment system. However, traditional wastewater treatment for nitrogen removal generally converts the ammonium back into N_2 gas. But instead of converting it back to N_2, we could reduce overall fossil fuel energy consumption if we recovered and used the ammonium directly as fertilizer.

A similar analysis can be made for phosphorus. Today, almost all phosphate is mined and used in agriculture. Most of that phosphate ends up in waterways due to run-off and wastewater discharges (Rittmann et al., 2011); this "lost phosphorus" spurs eutrophication and hypoxia. Traditional phosphate removal generates inorganic solids that are not usable in agriculture; that phosphate cannot be reused where it is needed. The greatest sustainability benefit comes from removing phosphate in a form that is readily useful in agriculture.

1.3 Climate Change

The processes used for transporting and cleaning water use energy, and this energy often comes from fossil-fuel combustion, thus adding to the rising problems from climate change. While the energy used for water represents only a modest fraction of the world's total fossil fuel use, it is a fraction that environmental engineers and scientists can address by finding ways to lower the amount of energy used for water transportation and for water and wastewater treatment.

Fossil-fuel combustion is not the only water-related factor contributing to greenhouse gases. Some of the byproducts emanating from treatment processes are greenhouse gases. For example, methane gas (CH_4) produced by anaerobic wastewater treatment is a good renewable energy resource that can help limit our use of fossil fuels; however, if CH_4 is allowed to escape to the atmosphere, the impact on climate change is large because methane has a greenhouse-gas warming potential 25 to 30 times that of CO_2 (U.S. EPA, 2018). Methane emissions from sewers and sanitary landfills, for which we are responsible, must also be reduced.

Another greenhouse gas that is produced through biological wastewater treatment is nitrous oxide (N_2O), and it has a warming potential nearly 300 times greater than that of carbon dioxide. If just a small fraction of the nitrogen entering wastewater treatment facilities is converted to N_2O and escapes to the atmosphere, efforts to reduce fossil fuel use would be overshadowed by the impact of the formation and release of N_2O.

In 2016, the total human global emission of greenhouse gases was estimated to be 42 billion tons of CO_2 equivalents (IPCC, 2018). The United States contributed 6.5 billion tons, or more than 15% of that (U.S. EPA, 2018). Of the U.S. contribution, 82% came from CO_2 emissions. While worldwide CH_4 and N_2O emissions are relatively small in mass terms compared with CO_2, their much larger global-warming potential means that their emissions in 2016 caused approximately 10% and 6%, respectively, of the overall climate-change impact.

The several human contributions of greenhouse gases are largely responsible for the Earth's temperature rise of about 1°C over the last 150 years, and the temperature will continue to rise if humans do not reduce their emissions of all the radiation-absorbing chemicals. The International Panel on Climate Change (IPCC, 2018) indicated that releases of fossil CO_2 will need to go to net zero by 2055, along with net zeroing of non-CO_2 greenhouse gases by 2030, if global temperature is not to rise by more than 2°C. Keeping the temperature rise to less than 2°C will require that greenhouse gases be net removed from the atmosphere! All economic sectors—worldwide—will need to make reduction of greenhouse gases a top priority, and this will include sectors involving environmental engineering and science professionals.

1.4 Sustainability

Today, a biological process must reliably achieve its effluent standards in a cost-effective manner, and it also must advance our society's sustainability needs for the future. As stated in the Brundtland Report (Brundtland, 1987) for the World Commission on Environment and Development, sustainable development "meets the needs of the present without compromising the ability of future generations to meet their own needs." The concept of sustainability was posited even earlier—in the 1970 U.S. National Environmental Policy Act—as a means to "create and maintain conditions, under which humans and nature can exist in productive harmony, that permit fulfilling the social, economic, and other requirements of present and future generations."

In general, sustainability represents a goal of balancing efforts to meet human needs today without destroying the natural environment upon which future generations will depend. Today, the concept of sustainability involves at least three interdependent pillars: economic development, social development, and environmental protection. They constitute the "triple bottom line" that accounts for social, environmental, and financial benefits and costs.

Table 1.2 The Three Pillars of Sustainability Together with Topics of Importance under Each as Defined by the U.S. Environmental Protection Agency

Environmental	Social	Economic
Ecosystem Services	Environmental Justice	Jobs
Green Engineering & Chemistry	Human Health	Incentives
Air Quality	Participation	Supply and Demand
Water Quality	Education	Natural Resource Accounting
Stressors	Resource Security	Costs
Resource Integrity	Sustainable Communities	Prices

To help advance sustainability goals, in 2015 the U.S. Environmental Protection Agency produced a Sustainability Primer that defines six broad topics atop each of the three pillars. The six topics for each pillar are listed in Table 1.2. For example, the environmental pillar includes *ecosystem services,* which emphasize efforts to protect, sustain, and restore the health of critical natural habitats and ecosystems. *Stressors,* including water pollutants and greenhouse gas emissions, are to be reduced. For *resource integrity,* waste generation is to be reduced to prevent accidental release and future cleanup liability. Within the social pillar, *environmental justice* calls for empowering communities overburdened by pollution to take action to improve their health and environment. *Resource security* means to protect, maintain, and restore access to basic resources. For the economic pillar, *supply and demand* uses accounting and market practices to promote environmental health and social prosperity, while *natural resource accounting* acts to improve understanding and accounting of ecosystem services using cost-benefit analysis. *Costs* is the example of striving to develop waste-free processes, thus minimizing the needs for regulation, treatment, and disposal costs, while *prices* refer to reducing risks for new technologies through demonstration and testing with community partners.

1.5 The Role of Environmental Biotechnology

Environmental biotechnology provides means to achieve many of the sustainability goals for water. Here are a few prominent examples:

- Anaerobic treatment can capture the energy value of organic matter found in many used waters. This can make the treatment process energy generating, which saves money for the operator and lowers society's use of fossil energy.
- Anaerobic treatment also converts nitrogen and phosphorus into inorganic forms (ammonium and phosphate) that can be recovered and used as feedstock for agricultural fertilizer.
- Anaerobic and aerobic treatment can detoxify harmful chemicals and make the water safe for various beneficial uses.

Although wastewater contains valuable resources, current treatment practices often discard them. Today, the choice of a biological treatment process must go beyond only meeting the immediate effluent standards. Instead, a well-chosen process should accomplish the basic mission of good effluent quality in ways that help achieve the long-term sustainable needs of society by viewing used waters as holders of resources. Modifications to existing processes and the development of new processes should be channeled toward meeting the needs for a sustainable future, an urgent goal for all of human society.

1.6 Organization of the Book

Attaining all of the good sustainability outcomes requires a firm understanding of the science and engineering fundamentals underlying environmental biotechnologies. Applying this understanding to design and operate facilities for improving water quality treatment is the major emphasis in this book.

Consistent with its title, this book is organized into two parts. The first part, comprising Chapters 2 to 9, lays out the principles underlying all microbiological processes: e.g., biochemistry, ecology, stoichiometry, and kinetics. These principles represent the essential knowledge for understanding, designing, and operating any environmental biotechnology.

The second part, Chapters 10 to 15, applies those principles to a wide range of applications. Consistent with our focus on sustainability, Chapter 10 is on methanogenesis, in which the energy embodied in organic compounds in used waters is converted to methane gas, a valuable fuel. Unlike the fossil methane in natural gas, methane coming from a methanogenic process is renewable and carbon-neutral if captured and used. Chapters 11 to 15 address aerobic treatment and removal and recovery of nutrients, including traditional approaches for improving water quality and emerging approaches for recovering valuable resources.

Those who purchase the textbook from McGraw-Hill also will gain access, at www.mhprofessional.com/rittmann2e, to five electronic “bonus” chapters: Lagoons and Wetlands, Microbiological Detoxification, Microbial Electrochemical Cells, Photosynthetic Biofactories, and Complex Systems. They are being made available in electronic versions in order to constrain the length and cost of the printed book.

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