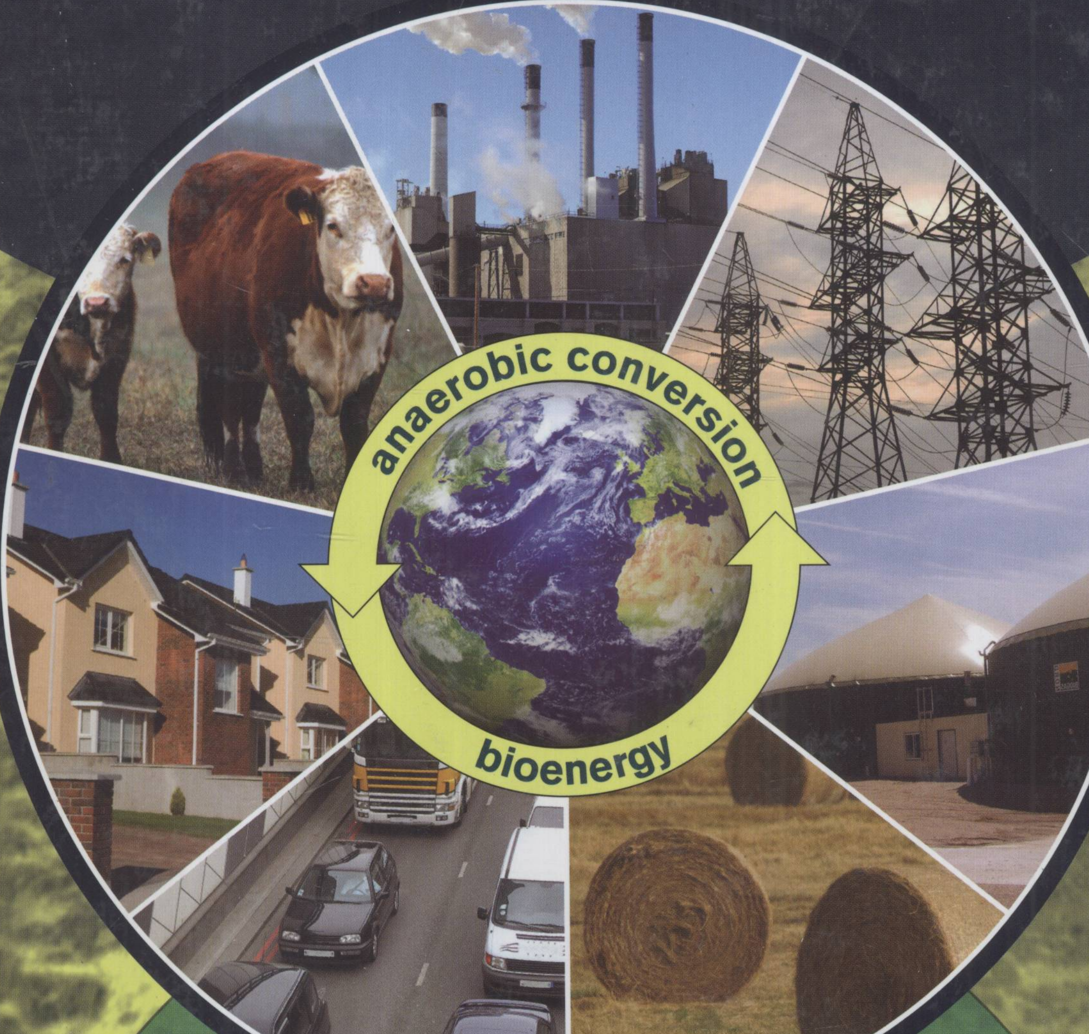
# Anaerobic Biotechnology for Bioenergy Production

## PRINCIPLES AND APPLICATIONS

Samir Kumar Khanal




WILEY-BLACKWELL

# ANAEROBIC BIOTECHNOLOGY FOR BIOENERGY PRODUCTION

## Principles and Applications



**SAMIR KUMAR KHANAL**
University of Hawai'i at Mānoa



WILEY-BLACKWELL
A John Wiley & Sons, Ltd., Publication

Edition first published 2008


Blackwell Publishing was acquired by John Wiley & Sons in February 2007. Blackwell's publishing program has been merged with Wiley's global Scientific, Technical, and Medical business to form Wiley-Blackwell.

*Editorial Office*
2121 State Avenue, Ames, Iowa 50014-8300, USA

For details of our global editorial offices, for customer services, and for information about how to apply for permission to reuse the copyright material in this book, please see our website at www.wiley.com/wiley-blackwell.



*Library of Congress Cataloging-in-Publication Data*
Anaerobic biotechnology for bioenergy production : principles and applications / Samir Kumar Khanal [contributor and editor].
p. cm.
Includes bibliographical references and index.
ISBN-13: 978-0-8138-2346-1 (alk. paper)
ISBN-10: 0-8138-2346-3 (alk. paper)
1. Alcohol–Synthesis. 2. Biomass energy. 3. Anaerobic bacteria. 4. Industrial microbiology. 5. Sewage sludge digestion. 6. Refuse and refuse disposal–Biodegredation. I. Khanal, Samir Kumar.
TP358.A55 2008
662′.88–dc22

2008013128

A catalogue record for this book is available from the U.S. Library of Congress.
Set in 11.5/13.5pt Adobe Garmound by Aptara Inc., New Delhi, India
Printed in Singapore by Fabulous Printers Pte Ltd

# ANAEROBIC BIOTECHNOLOGY FOR BIOENERGY PRODUCTION

## Principles and Applications

# Contents

# Contributors

**Srisuda Dhamwichukorn** is President and Chief Scientist of Pacific Time Co. Ltd. and Universe and Science Co. Ltd., Bangkok, Thailand. She received her Ph.D. in environmental biotechnology from Michigan Technological University, Michigan, and was Postdoctoral Research Associate at the University of Notre Dame, Indiana. Dr Dhamwichukorn's research interests are in microbial community analysis using molecular techniques, bioremediation, applications of DNA microarrays, and bioinformatics.

**Santha Harikishan** is a Process Engineer at Black and Veatch, Kansas City, Missouri. He obtained his M.S. in environmental engineering from Iowa State University. Santha has extensive practical experience with biosolids processing and bioenergy production. He is actively involved in process and facility design for wastewater treatment plants, and evaluation and development of residuals management schemes for treatment facilities.

**Hong Liu** is an Assistant Professor of Biological and Ecological Engineering at Oregon State University. She obtained her Ph.D. in environmental engineering from the University of Hong Kong and received postdoctoral training at Pennsylvania State University. Dr Liu has published over 30 research papers, mainly in the areas of microbial fuel cell and biohydrogen production. She and her coworkers at Pennsylvania State University won *Popular Mechanics 2005 Breakthrough Award* for their invention of a bioelectrochemically assisted process for hydrogen generation. Her current research interests are in the areas of environmental biotechnology, microbial fuel cell, and bioenergy production.

**Keshab Raj Sharma** is a Research Fellow in Advanced Water Management Center at the University of Queensland, Australia. He received Ph.D. in environmental engineering from the Hong Kong University of Science and Technology, Hong Kong. Dr Sharma's research focuses on biofilm processes, and process modeling and simulation of biological systems.

## Illustrator

**Prachand Shrestha** is a Ph.D. candidate in Biorenewable Resources Program at Iowa State University. He obtained his M.S. in environmental engineering from Iowa State University. His research interests are in the area of renewable energy and biobased products.

## Technical Editor

**Christopher S. Jones** is Laboratory Supervisor at Des Moines Water Works, Des Moines, Iowa. He holds Ph.D. in analytical chemistry from Montana State University, Bozeman, Montana. He has over a decade of technical writing experience.

# Preface

Technological advances have improved the quality of life throughout the twentieth century. Although we have been quick to enjoy the benefits of our technological prowess, we have been slow to acknowledge its negative consequences. Increasingly, we are forced to confront these negative consequences: climate change, increased global demand for energy, growing energy insecurity, and continuous exploitation of limited natural resources. World energy demand is expected to grow by as much as 50% by 2025, mainly due to increasing demand from rapidly growing Asian countries such as China and India.

Sustainability must be the foundation for economic growth in the twenty-first century. We need to redirect our efforts toward bioenergy production from renewable, low-cost, and locally available feedstocks such as biowastes and agri-residues. Such efforts will not only alleviate environmental pollution, but also reduce energy insecurity and demand for declining natural resources. The most cost-effective and sustainable approach is to employ a biotechnology option. Anaerobic biotechnology is a sustainable technology that generates renewable bioenergy and biofuels and helps us achieve our environmental and energy objectives. This book is a result of fine contribution made by several distinguished researchers, and inspiration by King *Bhumibol Adulyadej*'s (Thailand) self-sufficiency economy concept.

Information on this subject is limited, and this textbook will be a first reference for both undergraduate and graduate students, researchers, instructors, consulting engineers, and others interested in bioenergy. The book is intended to be a useful resource to both engineering and science students in agricultural, biological, chemical, and environmental engineering, renewable energy, and bioresource technology.

The book does not assume a previous background in anaerobic biotechnology, although most readers should have a good working knowledge of science or engineering. The first six chapters cover the fundamental aspects of anaerobic processes. The remaining six chapters focus on applications with an emphasis on bioenergy production from wastes and agri-residues. Pertinent calculations and design examples are included in each chapter.

Chapter 1 presents an overview of anaerobic fermentation, including definitions, biochemical reactions, major considerations in an anaerobic system, benefits, limitations, and calculations of the energy generation from various feedstocks.

Chapter 2 covers the common metabolic stages of the anaerobic fermentation of organics and microbiological processes, and aims to provide readers with the necessary basics of microbiology, biochemistry, and stoichiometry involved in an anaerobic system. Chapter 3 focuses on the effect of environmental factors such as temperature, pH, nutrients, and toxicity on the growth of key microbial groups involved in bioenergy production. Chapter 4 describes the biokinetics of anaerobic systems and application of mathematical modeling (e.g., anaerobic digestion model 1 (ADM1)) as a tool in design, operation, and optimization of anaerobic processes for bioenergy production. Chapter 5 covers bioreactor configurations and growth systems (e.g., attached, granular, and suspended) used in anaerobic processes. Appropriate reactor selection and design for bioenergy production are also addressed.

The modern molecular techniques in anaerobic fermentation and their application for the generation of methane, hydrogen, ethanol, and butanol are presented in Chapter 6. Chapter 7 outlines the selection of a suitable reactor design and operating conditions for bioenergy production from a sulfate-rich feedstock without sulfide inhibition. Strategies for sulfide control by converting aqueous and gaseous sulfides to elemental sulfur are also discussed. The next chapter covers bioenergy production from residues of emerging biofuel industries, including feedstocks, biofuel production processes from these feedstocks, stillage and glycerin generation, and anaerobic digestion of these residues. Also covered are water reclamation/reuse and biosolids disposal issues in biofuel industries. Chapter 9 describes the fundamentals of fermentative hydrogen production, including the hydrogen production pathway, strategies of obtaining enriched cultures, factors affecting hydrogen yield, process engineering, and microbiology. In addition, the concept of a bioelectrochemical-based microbial reactor for hydrogen production is also covered. The focus of Chapter 10 is development of the microbial fuel cell (MFC), with emphasis on principles, stoichiometry, energetics, microbiology, design, and operation. Different pretreatment technologies to enhance hydrolysis of high-solids feedstocks are discussed in Chapter 11. The last chapter provides an overview of digester gas production from various feedstocks along with a discussion of the cleaning requirements and energy use options.

I acknowledge several people whose selfless guidance and inspiration positively impacted my career path and preparation of this book. Bhoj Raj Bhattarai, Dhruba Narayan Pathak, and Ram Charan Chauhan were my early mentors who introduced me to science. My advisors Akhilendra Bhusan Gupta, Heinz Eckhardt, and Ju-Chang Huang taught me the art of waste treatment. Shihwu Sung, J. (Hans) van Leeuwen, Robert Brown, and Anthony L. Pometto III at Iowa State University provided an opportunity to work on bioenergy-related research projects for nearly 6 years. Chettiyapan Visvanathan, Chongrak Polprasert, and Preeda Parkpian at Asian Institute of Technology, Thailand, graciously offered me a home to work on the book project during the past three summers. Several of my graduate students at Iowa State University assisted me with workout examples and suggestions.

I am thankful to my contributing authors Harikishan Santha, Hong Liu, Keshab Sharma, and Srisuda Dhamwichukorn for their timely help in providing excellent write-ups in their respective areas of expertise. I am indebted to Christopher Jones for critically reviewing the manuscript. I am grateful to my graduate student Prachand Shrestha at Iowa State University for transforming my poor handwritten sketches into beautiful drawings for the completed book. I also acknowledge his help in formatting chapters. I am thankful to Justin Jeffryes of Wiley-Blackwell for his encouragement in preparing a book in the bioenergy area. Shelby Hayes at Wiley-Blackwell provided administrative assistance and kept me on schedule with her frequent reminder e-mails. Funds from United States Department of Agriculture (USDA), through the Biotechnology Bioproducts Consortium and Subvention Grant at Iowa State University, and the University of Hawaiʻi at Mānoa partially supported the book project.

Last but not the least, I extend my sincere gratitude, love, and appreciation to my family members, especially my mom, Uma Devi, my three loving sisters, Mala, Malati, and Parbati, and my brother Barma for their support throughout the years. I am also indebted to Saranya for her support and encouragement. And especially my young son Sivarat (Irwin), who missed my company in the many evenings, holidays, and weekends I was working on this book. I hope he will appreciate this effort when he grows up. This book is dedicated to my late father, Shri Lok Bahadur Khanal.

Samir Kumar Khanal, Ph.D., P.E.
University of Hawaiʻi at Mānoa

# Contents

CHAPTER

# 1

# Overview of Anaerobic Biotechnology

*Samir Kumar Khanal*

> We are convinced . . . that socially compatible and environmentally sound economic development is possible only by charting a course that makes full use of environmentally advantageous technologies. By this, we mean technologies that utilize resources as efficiently as possible and minimize environmental harm while increasing industrial productivity and improving quality of life (United States National Research Council Committee, 1995).

## 1.1 Anaerobic Biotechnology and Bioenergy Recovery

Environmental pollution is one of the greatest challenges human beings face in the twenty-first century. We are also faced with the consequences of climate change, increased global demand on fossil fuels, energy insecurity, and continuous exploitation of limited natural resources. The traditional approach of pollution control, which focuses on ridding pollutants from a single medium, that is, transformation of pollutants from liquid to solid or gas phases and vice versa, is no longer a desirable option. It has become enormously important to direct research efforts toward sustainable methods that not only alleviate environmental pollution, but also ease the stress on depleted natural resources and growing energy insecurity. The most cost-effective and sustainable approach is to employ a biotechnology option. Anaerobic biotechnology is a sustainable approach that combines waste treatment with the recovery of useful byproducts and renewable biofuels. Widespread application of anaerobic technology could ease increasing energy insecurity and limit the emission of toxic air pollutants, including green house gases to the atmosphere.

Figure 1.1 illustrates the potentials of anaerobic biotechnology in recovery of value-added products and biofuels from waste streams. Carbon, nitrogen, hydrogen, and sulfur from municipal, industrial, and agricultural solid and liquid wastes are converted into value-added resources. These include biofuels (hydrogen, butanol, and methane), electricity from microbial fuel cells (MFCs), fertilizers (biosolids), and useful chemicals (sulfur, organic acids, etc.). The sulfur can be used

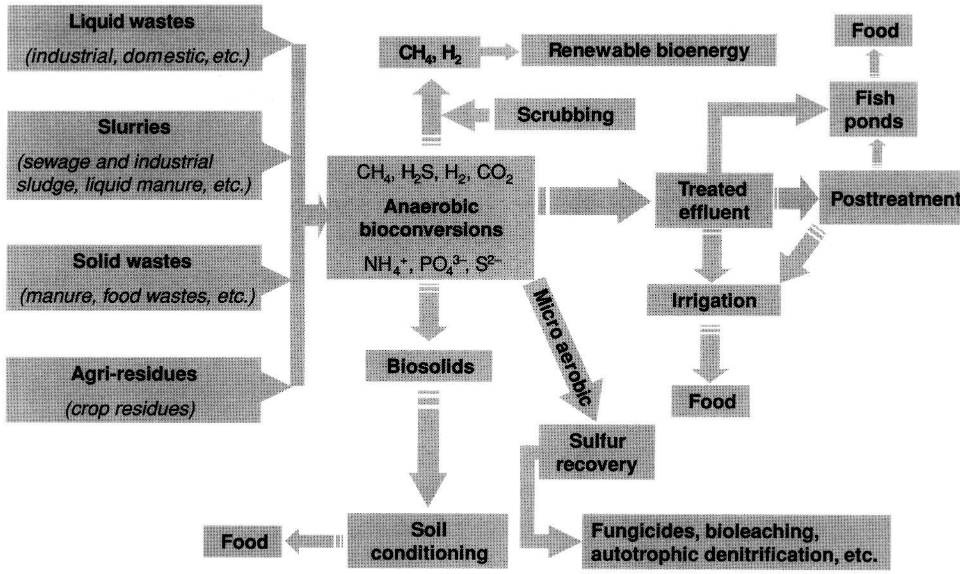



**FIG. 1.1.** Integrated anaerobic bioconversion processes in recovery of resources from wastes.

as an electron donor for bioleaching of heavy metals or removal of nitrate through autotrophic denitrification. Posttreatment effluent can be lagooned or reused for fish farming, algal production, and irrigation (see Box 1.1).

> **Box 1.1**
>
> **Research Need**
> Due to the concern of endocrine disrupting chemicals (EDCs), e.g., natural steroidal hormones, pharmaceuticals, and personal care products in human/livestock wastes, growing fish, and algae for protein in effluent for human consumption could become a major heath issue. More research is needed to examine the residual levels of EDCs in the effluent and their potential impact on aquatic species.

From the perspective of developing and underdeveloped nations, a wider application of anaerobic biotechnology has even larger implications, as it would fulfill three basic needs: (a) improvement in health and sanitation through pollution control; (b) generation of renewable energy for household activities, such as cooking, lighting, and heating, and running small-scale businesses, for example, poultry farming and silkworm raising; and (c) supply of digested materials (biosolids) as a biofertilizer for crop production. Thus, anaerobic biotechnology