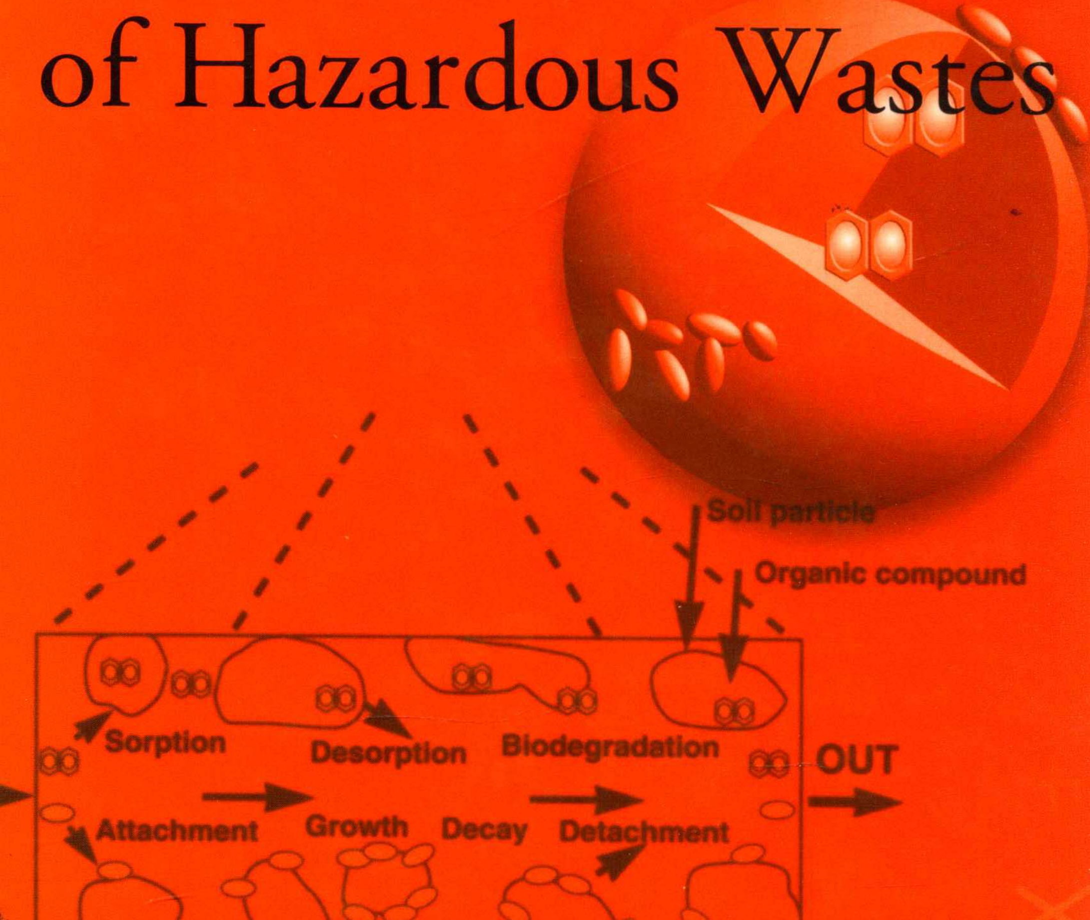
Biological Treatment of Hazardous Wastes



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A Wiley-Interscience Publication
JOHN WILEY & SONS, INC.
New York • Chichester • Weinheim • Brisbane • Singapore • Toronto

This book is printed on acid-free paper. ♾

Library of Congress Cataloging in Publication Data

Lewandowski, Gordon A.
Biological treatment of hazardous wastes/Gordon A. Lewandowski, Louis J. DeFilippi.
p. cm.
Includes index.
ISBN 0-471-04861-5 (cloth: alk. paper)
1. Hazardous wastes—Biodegradation. I. DeFilippi, Louis J. II. Title.
TD1061.L48 1998
628.4'2-dc21 97-10384

Printed in the United States of America

10 9 8 7 6 5 4 3 2 1

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PREFACE

Our purpose in putting this book together is to provide a combination of both fundamental principles and practical applications for the biological treatment of hazardous wastes that goes beyond a formularized exposition of specific solutions for particular pollutants. We hope to accomplish this by including hydrogeological, engineering, and microbiological fundamentals in the context of biotreatment applications. Some of the chapters will appeal to readers interested in the application of mathematics to engineering design considerations, while other readers will be more interested in chapters dealing with microbiology and the like.

We are inclined in favor of the use of biological systems for many aspects of waste treatment. Unlike physical approaches, biotreatment has the potential to transform organic pollutants into innocuous products rather than merely transferring the pollutant to another medium. Furthermore, by comparison to other chemical transformation techniques, such as incineration, biotreatment is generally cheaper and enjoys a greater degree of public acceptance.

Microorganisms can transform virtually any organic compound, whether man-made or naturally occurring. It is up to engineers and scientists using biotreatment techniques to manipulate, whenever possible, environmental conditions (oxygen content, chemical composition, temperature, etc.) in order to effect complete transformation to acceptable products in the most cost-effective manner.

The media in which pollutants occur can be aqueous, gaseous, or associated with sediments and soils, with the possibility of pollutant transfer between these media. In fact, soil-bound pollutants must often be transferred to an aqueous or gaseous phase in order to effect their treatment.

Pollutants can be treated ex situ (which requires design of an engineered reactor in which the biological reactions take place) or in situ (which requires manipulation of the conditions in a naturally occurring subsurface 'reactor'). In situ methodologies are particularly complex, dealing as they do with a hydrogeology that is preexisting and that often presents severe constraints on the treatment process. Both ex situ and in situ reactors can involve microorganisms in a suspended or attached (fixed-film) state. These states may be physiologically different and are treated differently in methods used for engineering analysis and design.

Another critical factor in biological treatment is the presence (or absence) of oxygen or other oxidizing agent (such as nitrate or sulfate). In many fixed-film systems, both aerobic (oxygen-rich) and anaerobic (oxygen-poor) regions can occur in close proximity, relative to the surface of the biofilm.

We hope that the reader will obtain an appreciation of these factors in designing biotreatment processes. All too often, the failure of such processes has been ascribed to the serendipity of living organisms, when in fact such failures are the product of a lack of basic understanding of the complex factors involved.

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ACKNOWLEDGMENTS

Dr. Lewandowski would particularly like to thank graduate student Dilip Mandal (and his forbearing wife, Aparna) for his invaluable assistance in correcting manuscripts and transferring them in a uniform manner to disk. Dr. Lewandowski would also like to thank the New Jersey Institute of Technology for granting him a sabbatical, during which (among other tasks) he was able to initiate this book.

Dr. DeFilippi would like to thank his wife, Dr. Irene DeFilippi, for all of her support and suggestions during the editing of this book, and his good friend, F. Stephen Lupton, who has immeasurably enhanced his understanding of microbial processes.

Both editors would like to thank the contributing authors for the high quality of their chapters, their diligence, and their patience.

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CONTENTS

CHAPTER 1

Suspended-Biomass and Fixed-Film Reactors

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CLASSIFICATION OF REACTORS FOR BIOLOGICAL TREATMENT

A large number of reactor configurations exist as a consequence of the many parameters involved in any biotreatment process and the possibility of optimizing different aspects of the process. The following is a review of bioreactor classification according to the way in which:

- Mechanical energy is delivered to the reactor's contents
- Gas is sparged and off-gases are collected
- The reactor is operated (continuously, batchwise, or sequencing batch)
- The desired degree of homogeneity is achieved
- High biomass concentration is maintained

Mechanical Energy Delivery Systems

A biological reactor must be able to satisfy a number of different and sometimes contrasting requirements in order to operate properly. Examples of such requirements include the maximization of the microbial concentration in the entire volume of the reactor, the achievement (as much as possible) of good internal homogenization to make the nutrients available to the entire biomass, the dispersion of a sparged gas phase (typically in aerated reactors) to generate a large gas–liquid interfacial area, and the enhancement of mass transfer from air bubbles to microorganisms through sufficiently high turbulence intensity.

Biological Treatment of Hazardous Wastes, Edited by Gordon A. Lewandowski and Louis J. DeFilippi
ISBN 0-471-04861-5

In order to accomplish all this, mechanical energy must be supplied to the reactor in one or more of the following ways:

- By mechanical agitators (e.g., stirred reactors)
- By a moving liquid (e.g., jet reactors with a recirculation pump)
- By an expanding gas (e.g., airlift reactors)

In general, mechanically agitated reactors are able to deliver the greatest amount of power per unit liquid mass in the reactor, typically resulting in high gas–liquid mass-transfer rates. The pumping action of many impellers can also provide a good level of homogeneity within the reactor. However, the efficiency of mechanical agitation systems (expressed as amount of oxygen transferred per unit energy delivered) is also much lower than the other two reactor types (especially the expanding gas system).

Gas Sparging and Off-Gas Collection Requirements

Depending on the type of microorganisms used, biotreatment processes can be classified into aerobic or anaerobic. Aerobic processes require that oxygen be supplied to the microorganisms in the bioreactor, typically by sparging air into the liquid waste. Unfortunately, the saturation concentration of oxygen in water is quite small (of the order of 8 mg/L at room temperature). Therefore, aerobic reactors usually have some provisions for dispersing air (or sometimes oxygen-enriched air) through the waste to form small bubbles with a large interfacial area. The transfer of oxygen to the biomass is also enhanced by the turbulence that results from the input of mechanical energy.

Anaerobic reactors do not typically require that any gas be dispersed into the reactor contents (although in some reactor configurations the off-gas is reinjected into the liquid to mix the reactor contents). Therefore the external mechanical energy input they require is typically quite small and limited to that necessary for the generation of a recirculation flow capable of maintaining uniformity of the reactor contents. Since anaerobic metabolism is slower than aerobic metabolism, anaerobic reactors typically require longer retention times (or bigger reactor volumes) than aerobic reactors. In addition, the growth rate of anaerobes is slower than aerobes, which makes continuous anaerobic reactors more susceptible to hydraulic overloading than aerobic reactors. One way in which this problem can be minimized is by immobilizing the microorganisms inside the reactor (Aivasidis and Wandrey, 1988).

Most anaerobic organisms are poisoned by oxygen. In addition, anaerobiosis typically results in the generation of compounds that present an odor problem. Therefore, whereas many aerobic reactors are often open to the atmosphere, anaerobic reactors are not. Closed reactors offer the further advantage of facilitating the collection of anaerobic off-gases that may be rich in methane and can be used as an energy source.

Continuous and Batch Reactor Operations

In *continuous operation* the reactor is continuously fed with the waste stream, while the treated stream is continuously removed from the reactor. Alternatively, a reactor can be operated in a *batch mode* in which the waste material is charged to the reactor, the degradation reaction is allowed to proceed until completion, and the treated waste is discharged.

In *semibatch processes*, the waste material is continuously fed to an otherwise batch-operated reactor. In some applications (e.g., in *sequencing batch reactors*, or SBRs) the reactor is sequentially operated in a batch or semibatch mode by loading the waste to be treated, allowing the biomass to grow and treat the waste, and finally discharging the treated effluent. All these phases of the process are carried out in single reactors, as shown in Figure 1.1. If several such reactors are operated in parallel with a staggered time sequence, the overall process is practically continuous, from a user point of view. SBRs have found applications in a number of treatment processes (Irvine and Busch, 1979; Baltzis et al., 1991).

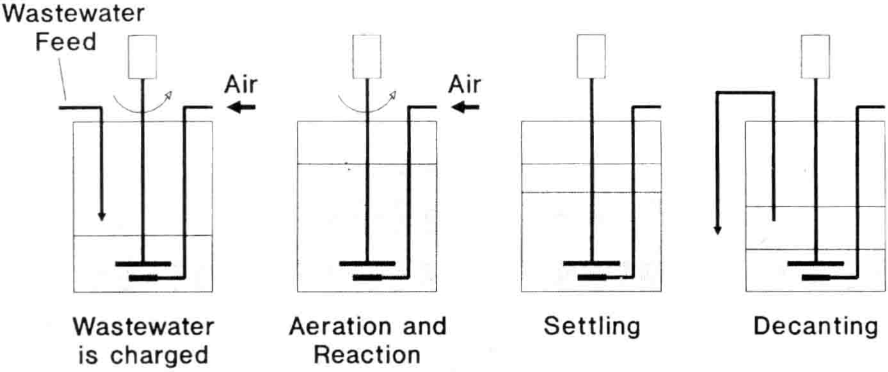

Figure 1.1 Operation of a sequencing batch reactor (after Armenante, 1993).

In continuous reactor operation, the *residence* or *detention time*, θ, defined as the ratio of the reactor volume, *V*, to the volumetric flow rate, *Q*:

$$\theta = \frac{V}{Q} \tag{1}$$

is a measure of the average amount of time spent in the reactor by the waste being processed (Levenspiel, 1972). Consequently, the longer the residence time, the larger the reactor volume will be for a given flow rate. Continuous operation is quite common in large-scale operation, especially if the waste is being produced at a uniform rate. However, the ability of a continuous flow reactor to accommodate fluctuations in flow or waste concentration is generally less than that of a sequencing batch reactor.

Batch operation is more common when the amount of waste is small or when the time required for the degradation process is too long for effective continuous treatment. Batch biotreatment is more flexible than continuous treatment since the treatment time can be shortened or lengthened depending on how fast the degradation process proceeds. A drawback of many batch processes is that they are labor intensive (although this limitation is being ameliorated with the advent of advanced microprocessors). In addition, storage of the waste between batches is necessary.

Degree of Homogeneity in Reactors: Well-Mixed vs. Plug-Flow Reactors

Although perfect mixing of reactor contents is only theoretically possible, continuous reactors or batch reactors in which a gas is continuously sparged are often designed as, and often resemble, *well-mixed* systems (Fig. 1.2*a*). In such

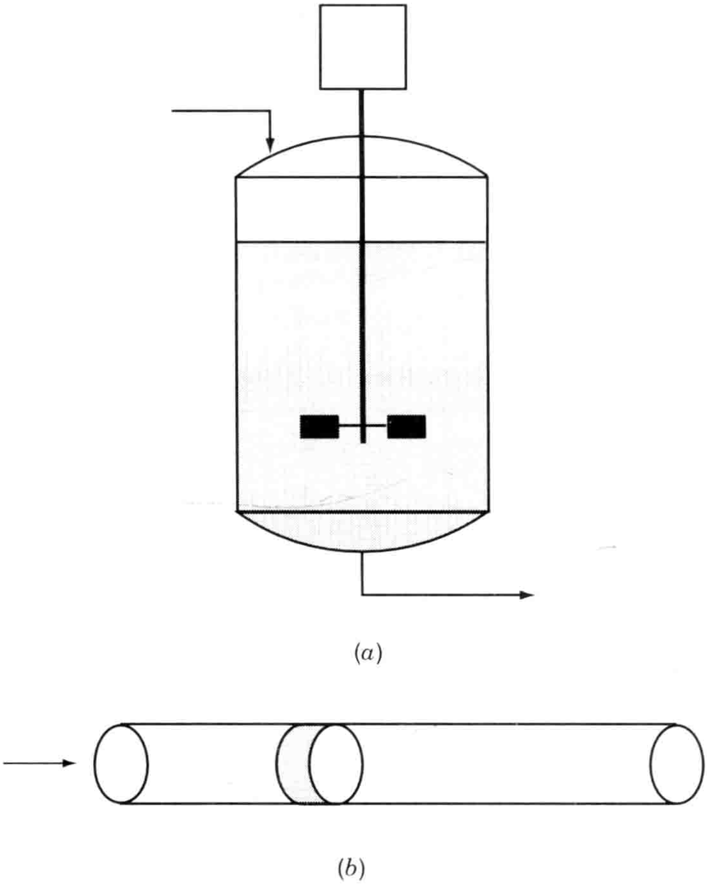

Figure 1.2 (*a*) Well-mixed reactor (CSTR). (*b*) Plug-flow reactor.

cases, the concentration inside the reactor is assumed to be homogeneous because of the presence of a mixing device (e.g., an impeller) or good internal recirculation. This assumption is often made in the design of bioreactors because most biodegradation reactions are typically much slower than the reactor's blending time, that is, the average time required for the homogenization of the reactor contents. This simplifies the modeling of well-mixed batch reactors. For example, if a pollutant does not inhibit growth of the microorganisms, and is furthermore the limiting growth nutrient (as opposed to oxygen, nitrogen, or phosphorous), the unsteady state mass balances for the biomass and the pollutant in a batch reactor can be written, respectively, as (Sundstrom and Klei, 1979; Horan, 1990; Metcalf & Eddy, 1991):

$$\frac{dX}{dt} = \frac{\mu_m C}{K_m + C} X - k_d X \tag{2}$$

$$-\frac{dC}{dt} = \frac{1}{Y} \frac{\mu_m C}{K_m + C} X \tag{3}$$

where X is the biomass concentration, C is the pollutant concentration, μ_m and K_m are the Monod kinetic parameters, k_d is the cell death/endogenous respiration constant, and Y is the yield coefficient (biomass formed per unit of substrate utilized). These equations can be easily integrated if the initial conditions are known.

By contrast, for a well-mixed continuous-flow reactor [also referred to as a *continuous stirred-tank reactor* (CSTR)], the corresponding steady-state mass-balance equations are (Bailey and Ollis; 1986; Horan, 1990; Metcalf & Eddy, 1991; Sundstrom and Klei, 1979):

$$\frac{X - X_{\text{in}}}{\theta} + \frac{\mu_m C}{K_m + C} X - k_d X = 0 \tag{4}$$

$$\frac{C_{\text{in}} - C}{\theta} - \frac{1}{Y} \frac{\mu_m C}{K_m + C} X = 0 \tag{5}$$

where the subscript '*in*' denotes the concentration in the incoming stream, θ is the residence time, and C is the pollutant concentration in the effluent (which is equal to the concentration in a perfectly mixed reactor). More complicated equations can be developed for the case in which a recycle is present (Metcalf & Eddy, 1991; Sundstrom and Klei, 1979).

At the other extreme of the operating spectrum a reactor can be operated as a *plug-flow* system in which the liquid moves through the reactor as it would ideally in a narrow pipe, that is, without any mixing fluid elements with those preceding or following it in the pipe (Fig. 1.2*b*). The mathematical representation of such a