stewater Microbiology Series

The Microbiology of Anaerobic Digesters

MICHAEL H. GERARDI

The Microbiology of Anaerobic Digesters

Michael H. Gerardi

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Preface

Completely mixed anaerobic digesters are the most commonly used treatment system in North America for the degradation of municipal sludges. Although these suspended-growth systems are not used as commonly at industrial wastewater treatment plants, more and more industrial plants are using fixed-film anaerobic digesters for the treatment of soluble organic compounds in their wastewaters.

Anaerobic digesters perform most of the degradation of organic compounds at wastewater treatment plants. However, digesters often experience operational problems that result in process upsets and increased operational costs. Examples of process upsets and operational problems include foam and scum production, decanting and dewatering difficulties, loss of treatment efficiency, toxic upsets, and "souring" of the digester. Poorly operating anaerobic digesters often contribute to operational problems in other treatment units such as the activated sludge process, gravity thickener, clarifiers, and sludge dewatering facilities.

Because of the importance of anaerobic digesters in wastewater treatment processes, a review of the microbiology of the bacteria and the operational conditions that affect their activity is of value in addressing successful and cost-effective operation. This book provides an in-depth review of the bacteria, their activity, and the operational conditions that affect anaerobic digester performance. The identification of operational problems and troubleshooting and corrective measures for process control are presented.

This book is prepared for an audience of operators and technicians who are responsible for the daily operation of anaerobic digesters. It presents troubleshooting and process control measures to reduce operational costs, maintain treatment efficiency, and prevent system upsets.

The Microbiology of Anaerobic Digesters is the third book in the Wastewater Microbiology Series by John Wiley & Sons. This series is designed for operators and technicians, and it presents a microbiological review of the organisms involved in wastewater treatment processes and provides biological techniques for monitoring and regulating these processes.

Michael H. Gerardi
Linden, Pennsylvania

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Part I

Overview

1

Introduction

The organic content of sludges and soluble wastes can be reduced by controlled bacterial activity. If the bacterial activity is anaerobic, the reduction in organic content is achieved through sludge digestion. If the bacterial activity is aerobic, the reduction in organic content is achieved through sludge stabilization.

Anaerobic digesters having suspended bacterial growth are commonly used at municipal wastewater treatment plants to degrade (digest) sludges (Figure 1.1). With the development of anaerobic digesters having fixed-film bacterial growth (Figure 1.2), more and more industrial wastewater treatment plants are using anaerobic digesters to degrade soluble organic wastes. Anaerobic digesters represent catabolic (destructive) processes that occur in the absence of free molecular oxygen (O_2).

The goals of anaerobic digesters are to biologically destroy a significant portion of the volatile solids in sludge and to minimize the putrescibility of sludge. The main products of anaerobic digesters are biogas and innocuous digested sludge solids. Biogas consists mostly of methane (CH_4) and carbon dioxide (CO_2).

Primary and secondary sludges are degraded in anaerobic digesters (Figure 1.3). Primary sludge consists of the settled solids from primary clarifiers and any colloidal wastes associated with the solids. Secondary sludge consists mostly of waste-activated sludge or the humus from trickling filters. The mixture of primary and secondary sludges contains 60% to 80% organic matter (dry weight) in the forms of carbohydrates, fats, and proteins.

The mixture of primary and secondary sludges is an ideal medium for bacterial growth. The sludges are rich in substrates (food) and nutrients and contain a large number and diversity of bacteria required for anaerobic digestion.

The anaerobic digester is well known as a treatment process for sludges that contain large amounts of solids (particulate and colloidal wastes). These solids

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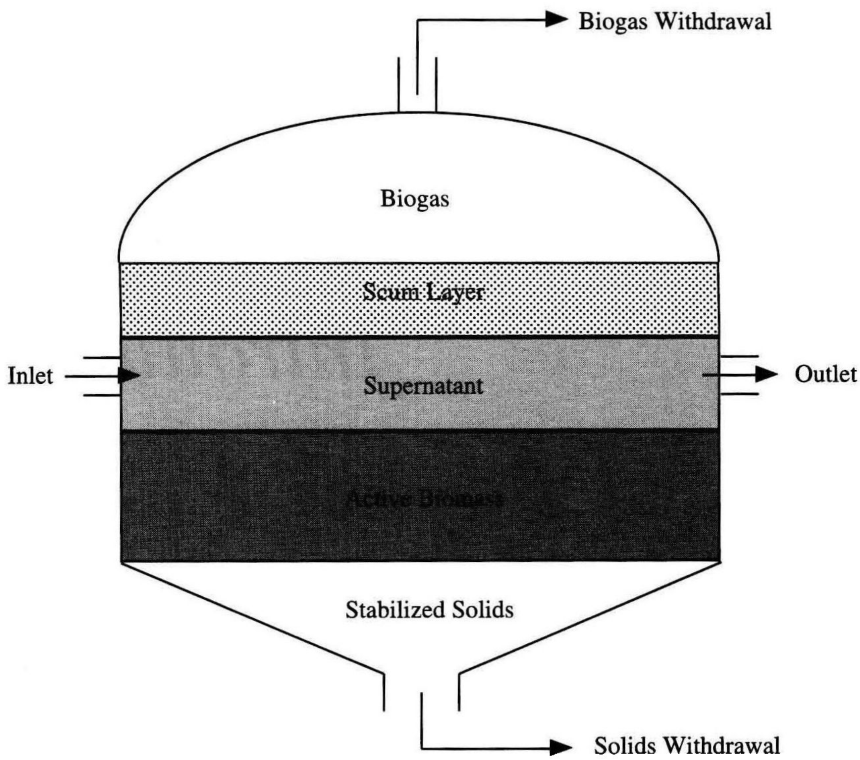

***Figure 1.1** Suspended growth anaerobic digesters are commonly used at municipal wastewater treatment plants for the degradation of primary and secondary sludges. These digesters produce several layers as a result of sludge degradation. These layers are from top to bottom: biogas, scum, supernatant, active biomass or sludge, and stabilized solids.*

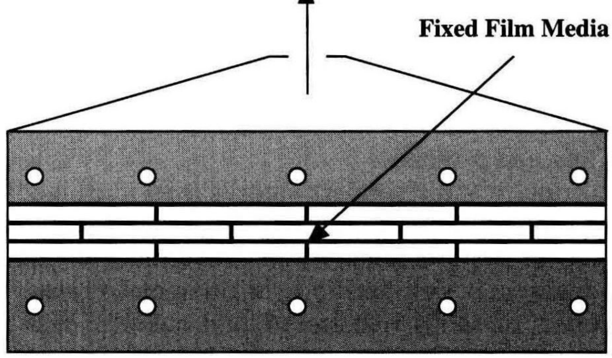

***Figure 1.2** Fixed film anaerobic digesters employ the use of a medium such as plastic or rocks on which bacteria grow as a biofilm. Wastewater passing over the medium is absorbed and adsorbed by the biofilm and degraded.*

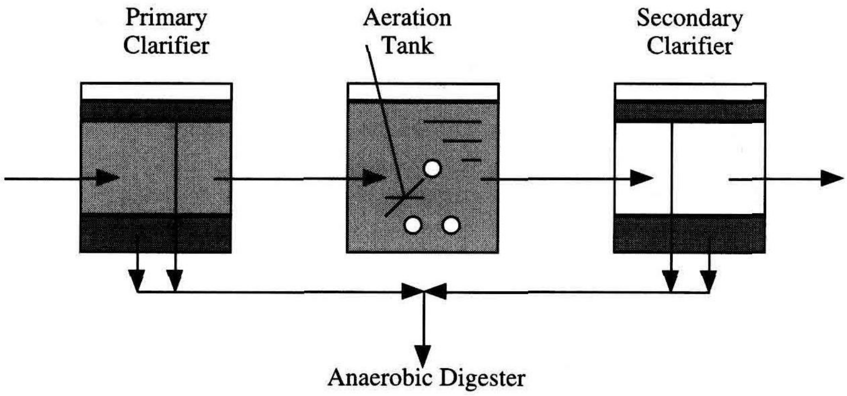

Figure 1.3 *Primary and secondary sludges typically are degraded in suspended growth anaerobic digesters at municipal wastewater treatment plants. The sludges contain relatively large quantities of particulate and colloidal wastes.*

require relatively long digestion periods (10–20 days) to allow for the slow bacterial processes of hydrolysis and solubilization of the solids. Once solubilized, the resulting complex organic compounds are degraded to simplistic organic compounds, mostly volatile acids and alcohols, methane, new bacterial cells ($C_5H_7O_2N$), and a variety of simplistic inorganic compounds such as carbon dioxide and hydrogen gas (H_2).

With the development of fixed-film bacterial growth in anaerobic digesters, many soluble organic wastes can be digested quickly and efficiently. Because the wastes are soluble, time is not required for hydrolysis and solubilization of the wastes.

When sludges are digested, the organic content of the sludges is decreased as volatile materials within the sludges are destroyed, that is, the volume and weight of the solids are reduced. The volatile content for most anaerobic digested sludges is 45%–55% (Figure 1.4).

Anaerobic digesters (Figure 1.5) degrade approximately 80% of the influent organic waste of a conventional municipal wastewater treatment plant. Nearly 30% of the waste is removed by primary clarifiers and transferred to anaerobic digesters, and approximately 50% of the waste is synthesized or transformed into new bacterial cells or solids [mixed-liquor volatile suspended solids (MLVSS) or trickling filter humus]. These synthesized solids also are transferred to anaerobic digesters through the wasting of secondary solids.

Because of the relatively large quantity of organic wastes placed on the anaerobic digestion process, a review of the bacteria, their activity, and the operational factors that influence their activity are critical. This review provides for proper maintenance of digester performance and cost-effective operation and helps to ensure adequate monitoring, troubleshooting, and process control of anaerobic digesters.

Anaerobic sludge digestion consists of a series of bacterial events that convert organic compounds to methane, carbon dioxide, and new bacterial cells. These events are commonly considered as a three-stage process.

The first stage of the process involves the hydrolysis of solids (particulate and colloidal wastes). The hydrolysis of these wastes results in the production of

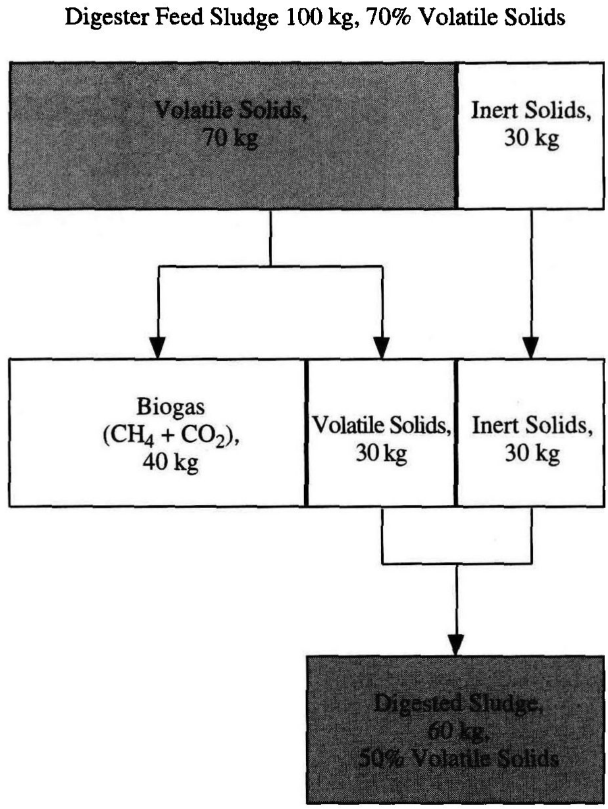

***Figure 1.4** The digestion of sludges in anaerobic digesters results in significant reduction in the volatile content of the sludges as well as the volume and weight of the sludges.*

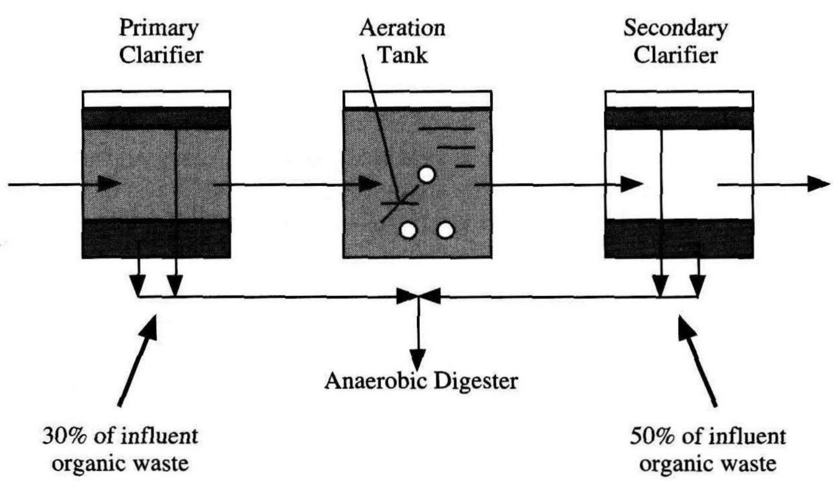

***Figure 1.5** Most of the influent organic wastes of a wastewater treatment plant are degraded in an anaerobic digester. Settled solids in the primary clarifier represent approximately 30% of the influent organic wastes, while secondary solids represent approximately 50% of the influent organic wastes. In the activated sludge process much of the organic waste is converted to bacterial cells. These cells represent organic wastes, i.e., upon their death; they serve as a substrate for surviving bacteria.*

simplistic, soluble organic compounds (volatile acids and alcohols). The second stage of the process, acetogenesis, involves the conversion of the volatile acids and alcohols to substrates such as acetic acid or acetate (CH_3COOH) and hydrogen gas that can be used by methane-forming bacteria. The third and final stage of the process, methanogenesis, involves the production of methane and carbon dioxide.

Hydrolysis is the solubilization of particulate organic compounds such as cellulose (Equation 1.1) and colloidal organic compounds such as proteins (Equation 1.2) into simple soluble compounds that can be absorbed by bacterial cells. Once absorbed, these compounds undergo bacterial degradation that results in the production of volatile acids and alcohols such as ethanol (CH_3CH_2OH) and propionate (CH_3CH_2COOH). The volatile acids are converted to acetate and hydrogen gas. Methane production occurs from the degradation of acetate (Equation 1.3) and the reduction of carbon dioxide by hydrogen gas (Equation 1.4).

$$\text{cellulose} + H_2O \text{ —hydrolysis} \rightarrow \text{soluble sugars} \quad (1.1)$$

$$\text{proteins} + H_2O \text{ —hydrolysis} \rightarrow \text{soluble amino acids} \quad (1.2)$$

$$CH_3COOH \rightarrow CH_4 + CO_2 \quad (1.3)$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O \quad (1.4)$$

In addition to the reduction in volume and weight of sludges, anaerobic digesters provide many attractive features including decreased sludge handling and disposal costs and reductions in numbers of pathogens (Table 1.1). The relatively high temperatures and long detention times of anaerobic digesters significantly reduce the numbers of viruses, pathogenic bacteria and fungi, and parasitic worms. This reduction in numbers of pathogens is an extremely attractive feature in light of the increased attention given by regulatory agencies and the general public with respect to health risks represented by the use of digested sludges (biosolids) for agricultural and land reclamation purposes.

Although anaerobic digesters offer many attractive features, anaerobic digestion of sludges unfortunately has an unwarranted reputation as an unstable and difficult-to-control process. This unwarranted reputation is due to several reasons, including a lack of adequate knowledge of anaerobic digester microbiology and proper operational data (Table 1.2).

TABLE 1.1 Attractive Features of Anaerobic Digesters

Able to degrade recalcitrant natural compounds, e.g., lignin
Able to degrade xenobiotic compounds, e.g., chlorinated aliphatic hydrocarbons
Control of some filamentous organisms through recycling of sludge and supernatant
Improved dewaterability of sludge
Production of methane
Use of biosolids as a soil additive or conditioner
Suitable for high-strength industrial wastewater
Reduction in malodors
Reduction in numbers of pathogens
Reduction in sludge handling and disposal costs
Reduction in volatile content of sludge

TABLE 1.2 Reasons Contributing to the Unwarranted Reputation of the Anaerobic Digester as an Unstable Process

Lack of adequate knowledge of anaerobic digester microbiology
Lack of commercial interest
Lack of operator training
Lack of proper operational performance data for installed digesters
Lack of research and academic status
Regrowth needed for industrial toxicity episodes

TABLE 1.3 Examples of Significant Differences Between Aerobic Stabilization and Anaerobic Digestion of Wastes

Feature	Anaerobic Digestion	Aerobic Stabilization
Process rate	Slower	Faster
Sensitivity to toxicants	Higher	Lower
Start-up time	Slower	Faster

Until recently, little information was available that reviewed the bacteria and their requirements for anaerobic digestion of solids. The difficulty in obtaining adequate data was caused by the overall complex anaerobic digestion process, the very slow generation time of methane-forming bacteria, and the extreme "sensitivity" of methane-forming bacteria to oxygen. Therefore, it was not uncommon for operators to have problems with digester performance.

These problems, the development and use of aerobic "digesters," and the use of relatively cheap energy for aerobic stabilization of wastes contributed to the lack of interest in anaerobic digesters. Although aerobic stabilization, that is, the use of aerobic digesters, and anaerobic digestion of wastes are commonly used at wastewater treatment process, significant differences exist between these biological processes (Table 1.3).

Methane production under anaerobic conditions has been occurring naturally for millions of years in such diverse habitats as benthic deposits, hot springs, deep ocean trenches, and the intestinal tract of cattle, pigs, termites, and humans. Methane production also occurs in rice paddies.

More than 100 years ago, anaerobic digesters were first used in Vesoul, France to degrade domestic sludge. Until recently, anaerobic digesters were used mostly to degrade municipal sludges and food-processing wastewater. Municipal sludges and food-processing wastewater favor the use of anaerobic digesters, because the sludges and wastewater contain a large diversity of easily degradable organics and a large complement of inorganics that provide adequate nutrients and alkalinity that are needed in the anaerobic digestion process.

TABLE 1.4 Chemical Wastes Amenable to Anaerobic Digestion

Acetone	Formate
Acrylates	Glycerol
Alcohols	Glycols
Aldehydes	Ketones
Amino acids	Methyl acetate
Anilines	Nitrobenzene
Catechols	Organic acids
Cresol	Phenols
Formaldehyde	Quinones

TABLE 1.5 Industrial Wastes Amenable to Anaerobic Digestion

Alcohol stillage	Pectin
Bean	Petroleum
Beverage production	Pharmaceutical
Brewery	Potato
Canning	Pulp and paper
Cheese	Seafood and shellfish
Chemical	Slaughterhouse and meat packing
Corn	Sugar
Dairy	Vegetable
Distillery	Wheat and grain
Egg	Winery
Fruit	Wool scouring
Leachate	Yeast

A better understanding of the microbiology of anaerobic digesters and process modifications, particularly fixed-film processes, have permitted the use of anaerobic digesters for dilute wastewaters and a large variety of industrial wastes (Tables 1.4 and 1.5). This understanding and these process modifications, together with the need to pretreat industrial wastewaters and sludges and the attractive features of anaerobic digesters, have generated renewed interest in their use in degrading not only municipal sludges but also industrial wastewaters.

The number of wastes that are amenable to anaerobic digestion is quite large. Examples of industrial wastes include acetone, butanol, cresol, ethanol, ethyl acetate, formaldehyde, formate, glutamate, glycerol, isopropanol, methanol, methyl acetate, nitrobenzene, pentanol, phenol, propanol, isopropyl alcohol, sorbic acid, *tert*-butanol, and vinyl acetate. Because many industrial wastes can be treated anaerobically, the feasibility of anaerobic digestion of an industrial waste is determined by several factors. These factors include the concentration of the waste, the temperature of the waste stream, the presence of toxicants, biogas and sludge production, and expected treatment efficiency.

The development of the fixed film filter was a significant achievement in anaerobic technology (Figure 1.6). The filter provides relatively long solids retention time (SRT). Increased retention time makes it possible to treat moderately low-strength

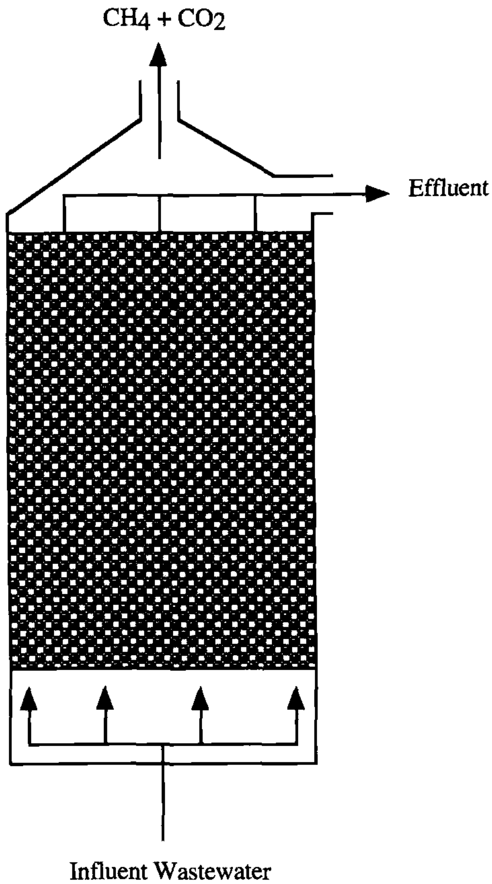

Figure 1.6 In an anaerobic filter, wastewater flows from bottom to top or top to bottom of the treatment unit. The wastewater passes over media that contains a fixed film of bacteria growth that degrades the organic wastes in the wastewater.

[2000–20,000 mg/l chemical oxygen demand (COD)] soluble organic industrial waste. Because of the highly concentrated bacterial population of the filter, a highly stable digestion process can be achieved even during significant variations in operating conditions and loadings. Therefore, interest in anaerobic biotechnology for treating industrial waste streams has grown considerably.

2

Bacteria

At least 300 different species of bacteria are found in the feces of a single individual. Most of these bacteria are strict anaerobes. The majority of the remaining bacteria are facultative anaerobes. *Escherichia coli* is a common facultative anaerobe in feces.

Bacteria from fecal wastes as well as hundreds of soil and water bacteria that enter a conveyance system through inflow and infiltration (I/I) are found in the influent of municipal wastewater treatment processes. For the purpose of this text, bacteria that are commonly found in wastewater treatment processes are divided into groups according to 1) their response to free molecular oxygen (O_2) and 2) their enzymatic ability to degrade substrate in the anaerobic digester.

RESPONSE TO FREE MOLECULAR OXYGEN

Bacteria may be divided further into three groups according to their response to free molecular oxygen (Table 2.1). These groups are 1) strict aerobes, 2) facultative anaerobes, and 3) anaerobes, including the methane-forming bacteria.

Strict aerobes are active and degrade substrate only in the presence of free molecular oxygen. These organisms are present in relatively large numbers in aerobic fixed-film processes, for example, trickling filters, and aerobic suspended-growth processes, for example, activated sludge. In the presence of free molecular oxygen they perform significant roles in the degradation of wastes. However, strict aerobes die in an anaerobic digester in which free molecular oxygen is absent.

Facultative anaerobes are active in the presence or absence of free molecular oxygen. If present, free molecular oxygen is used for enzymatic activity and the

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