CHAPTER XI. BIOGASIFICATION

A. Introduction

The possibility of biologically recovering energy in the form of the combustible gas, methane, has prompted an interest in applying biogasification to waste treatment in developed and developing countries alike. The attraction to the concept arises from the fact that biogasification of solid waste serves a twofold function -- namely, waste treatment and energy production. If viewed solely as a solid waste treatment method, biogasification probably does not rank with composting in terms of technical and economic practicality and feasibility in most economically developing countries. Biogasification plant design and operation are more expensive and allow much less latitude of scale and level of technology than composting. Equipment needs are more rigorous, and maintenance and processing demand a higher level of personnel competence. However, biogasification is more practical than composting for treating readily degradable wastes (such as some food wastes), nightsoil, and body wastes. Moreover, it can be very practical when used in conjunction with sanitary landfilling.

In the 1970s and in much of the 1980s, the hope of realising the great potential attributed to biogasification led to a proliferation of a variety of biogasification schemes, particularly in economically developing countries for the treatment of nightsoil and animal manures. The schemes were designed to carry out the process with a minimum of, or even without, sophisticated equipment. Moreover, they called for native raw materials to be used for constructing the digesters and gas collectors. Inevitably, only a very few of the proposed schemes proved to be sufficiently realistic to have survived. The surviving systems are those that adhere to realism and to principles of biology and good engineering.

During the mid-1990s and continuing as of this writing, substantial research, development, and commercialisation of solid waste biogasification systems has occurred in Europe in response to the promulgation of the Landfill Directive by the European Union [25]. In brief, the Directive specifies the maximum biodegradable content of wastes that are destined for land disposal, and aggressive material recycling goals. Also, in response to the Directive, the designers and system suppliers are integrating waste pre-processing, biogasification, and composting technologies in order to simultaneously decrease the organic content and quantities of waste requiring land disposal.

A presentation dealing with biogasification systems that are biologically and economically sound and realistic is made in this chapter. Thus, basic principles of biogasification are the first subjects to be covered. Specifically, basic principles that receive attention are biogasification biology and related construction design, and pertinent design and operation factors. The chapter is concluded with a discussion of the advantages and disadvantages of the biogasification option and an evaluation of its present status.

B. Principles

B1. DEFINITIONS

Among the terms frequently used as synonyms for biogasification are “methane fermentation”, “methane production”, and “anaerobic digestion”. All are suitable, despite the fact that they also are applied to processes that may have no bearing on methane production. Gases generated in the alternative processes usually include only carbon dioxide and occasionally a trace gas. (It should be noted that in microbiology taxonomy, “methane fermentation” refers to the fermentation, i.e.,
the decomposition of methane.) Anaerobic digestion is not necessarily attended by methane production. Nevertheless, the three terms are justified by common usage, and especially for want of a better term. In this chapter, the three terms are used interchangeably.

As popularly accepted and for the purposes of this book, biogasification is defined as being the biological decomposition of organic matter of biological origin under anaerobic conditions with an accompanying production primarily of methane (CH\textsubscript{4}) and secondarily of other gases, chief of which is carbon dioxide (CO\textsubscript{2}). The two features that distinguish the process as defined from other forms of biological decomposition are “under anaerobic conditions” and “the production of methane”.

### C. Process description

A feature that has a major influence on the application of biogasification in waste treatment is the fact that, conventionally, the process takes place in more or less distinct stages or phases. The stages are distinct in that they can be separated from each other with respect to reactions, reaction products, and microflora. Generally, it is held that the number of stages is two -- namely, acid stage followed by a methane forming stage. However, some researchers hold that three stages are involved when the substrate is a waste [9]. In that view, the two conventional steps are preceded by a “polymer breakdown” step when a waste is the substrate.

A division of the process into three stages probably more accurately reflects the microbiology of the overall process than does the two-stage division. However, consideration of biogasification as a two-stage process makes for simplicity of description and reference, and is the one commonly used in the technical literature. Moreover, the two-stage division is justified if one thinks of the process in terms of pre-methane activity and of methane forming activity. The traditional division into two phases is more readily apparent in practice than a three-phase division would be.

The process is sequential in that the acid stage precedes the methane forming stage regardless of whether the culture (i.e., digester) is operated on a batch or a continuous basis. In a continuous type of operation, all stages may be encountered at any time. This is true because all input must pass through the sequence. Therefore, if the operation is on a continuous basis, all stages would be represented at any point in time, and newly introduced material would be going through the acid stage; whereas, simultaneously, material previously introduced may already be in the methane-forming stage.

Assuming the three-stage division, the entire process begins with the polymer stage. In the polymer stage, organic wastes are acted upon by a group of facultative microorganisms that enzymatically hydrolyse the polymers of the raw waste into soluble monomers. The monomers (short-chain organic acids, acetic acid, etc.) become the substrate for the next stage (acid stage). Some carbon dioxide also is formed. The organic acids form the substrate for the bacteria active in the final methane-production stage. In this stage, the methane producers (methanogens) break down the organic acids into, primarily, methane. Methanogens are strict anaerobes, and as such do not tolerate free oxygen, i.e., atmospheric oxygen (O\textsubscript{2}). Methanogens produce methane in two ways: 1) they can ferment an organic acid (e.g., acetic acid) to methane and carbon dioxide; and 2) they can reduce carbon dioxide to methane through the use of hydrogen or formate produced by other bacteria. The interrelationship of the three steps is diagrammed in Figure XI-1.

The overall process rests upon the maintenance of a relatively critical balance between the respective activities of the three stages. An imbalance reduces the efficiency of the overall process and may lead to the complete cessation of all microbial activity and, hence, no methane production would occur.
Immediately after its initiation, the sequence of readily observable reactions in a continuous culture is a gradual decline in pH level (the acid stage), followed by a similarly gradual rise in pH level, and eventually by the production of a gas rich in methane (the methane production stage).

The end products of the final stage are methane, carbon dioxide, trace gases, and a satisfactorily stable residue.

![Figure XI-1. Relationship of three stages in biogasification](image)

C1. MICROBIAL ecology of the stages

Over the past four or five decades and continuing today, many competent scientists have thoroughly investigated the bacteriology of methane production. The investigations have mainly been focused on the isolation, identification, and population size of the methane producers.

Some research has been conducted on identifying and quantifying the representative species of the microflora involved in the biogasification of sewage sludge, organic municipal solid waste, and some agricultural residues [15-20]. The acidogenic population, consisting of about 90% of the total digester population, is the largest of all the groups [21]. However, relatively little is known about the number and physiological activities of the acidogenic microorganisms [22].

Although constituent population sizes may be modest, the variety of the microorganisms that make up the microflora of biogasification is relatively extensive. The bacterial populations involved in the polymer stage are primarily those that have enzymatic systems capable of hydrolysing the complex molecules of the intact waste particles. Molecules to be hydrolysed are mainly those of carbohydrates. Others, in lesser amounts, are those of lipids and proteins.

The carbohydrates are represented chiefly by cellulose and other components of plant fibre, such as lignin and hemicellulose. The presence of cellulytic enzymes is particularly important because the greater fraction of municipal wastes and many agricultural wastes is cellulosic.

Generally, biogasification proceeds more rapidly with a mixed collection of hydrolytic microbes than with a single (pure) culture. The faster pace is partly due to the synergistic action resulting from the interaction of several types of microbes. A likely outcome of the synergism is the destruction of potentially inhibitory byproducts.

C1.1. Acid stage

The role of acid forming bacteria is to convert polymer stage breakdown products into organic acids (straight-chain fatty acids) that can be utilised by methane-formers. Among the acids
formed in the stage, acetic acid is the most abundant. Among the lesser abundant are formic, propionic, valeric, butyric, and trace amounts of other acids. Characteristically, the acid-formers grow vigorously and tolerate a wide variety of environmental conditions. Because of the vigorous growth and wide tolerance, the acid stage rarely is the rate-limiting factor in biogasification. However, conditions can and do arise under which the intensity of the acid stage can inhibit biogasification. Such conditions develop when the activity of the acid-formers is not counterbalanced by the utilisation of the acids by methanogens, and to some extent by other organisms. In the absence of such utilisation, acid buildup occurs to such an extent that the pH of the culture drops to an inhibitory level. The tolerance exhibited by the acid stage to environmental conditions probably arises from the diversity of its microbial composition. Consequently, slow growth seldom is a problem of the acid stage.

C1.2. Methane stage

In the methane stage, decomposition products from the acid stage (short-chain fatty acids, CO₂, and H₂) are converted into CO₂, CH₄, and an assortment of trace gases. Methane producing bacteria (methanogens) accomplish the transformation by way of two types of reactions: 1) fermentation of short-chain fatty acids and some alcohols; and 2) a respiration in which H₂, CO₂, and certain simple organic compounds are oxidised anaerobically, coupled with the reduction of CO₂ to CH₄. The following two reactions typify the fermentation reactions in the conversion of the acids and alcohols.

Acetic acid:

\[ CH₃COOH \rightarrow CH₄ + CO₂. \]

Methyl alcohol:

\[ 4CH₃OH \rightarrow 3CH₄ + CO₂ + 2H₂O. \]

The production of CH₄ through respiration involving the incomplete oxidation of alcohol to acetic acid, coupled with the reduction of CO₂ to CH₄, can be exemplified by the reaction by Methanobacterium omelianski. The reaction is as follows:

\[ 2CH₃CH₂OH + CO₂ \rightarrow 2CH₃COOH + CH₄ \]

The reduction of CO₂ with molecular hydrogen is:

\[ 4H₂ + CO₂ \rightarrow CH₄ + 2H₂O. \]

Unlike the acid-formers, the methanogens grow slowly and show very little latitude regarding nutritional and environmental requirements. In terms of nutrition, they are restricted to simple organic compounds. Therefore, in the biogasification of wastes, they must rely upon the polymer and acid stages to meet their carbon and acid needs. Moreover, they must depend upon the nitrogen in the ammonia produced by the breakdown of organic nitrogen compounds.

A distinctive and very practical characteristic of the methane stage is a relatively intensive sensitivity to certain environmental factors. Chief among these factors is atmospheric oxygen. Methanogens are obligate anaerobes and, hence, atmospheric oxygen becomes inhibitory to them even at exceedingly low concentrations. This sensitivity extends to some degree with respect to highly oxidised compounds. Thus, nitrites and nitrates can inhibit the growth of the methanogens.
Unlike methanogens, most acid-formers are facultative anaerobes, i.e., O\textsubscript{2} is not inhibitory to their growth.

Another restrictive factor is pH level. Whereas for the acid stage, the tolerated pH range is as wide as pH 4.5 or 5.0, to 7.5 or even 8.0, the permissible range for the methane stage is only pH 6.0 to 7.5. The optimum level is pH 7.0.

D. Process rate limitation factors

Potential limitations imposed by each of the three stages on the rate of the biogasification (digestion) process as a whole have practical effects on equipment design and specifications, and on operation. The rate limitation imposed by the polymer stage originates in its role of rendering essential nutrients bound in the raw feedstock (waste) available to bacteria involved in the second and third stages of the biogasification process. The stage is rate limiting because it is needed for solubilizing insoluble cellulose and complex organic nitrogenous compounds. The cellulose is converted into soluble carbohydrates by way of extra cellulases. As stated earlier, acid-forming bacteria convert the soluble carbohydrates to low molecular weight fatty acids in the second stage. The third stage is the final rate determinant. In fact, it often is regarded as the rate-limiting stage for the process as a whole, because it is the final step and because the methanogens are basically slow growing. In the third stage, acids and certain other intermediate decomposition products are converted into CH\textsubscript{4} and CO\textsubscript{2}.

D1. ENVIRONMENTAL factors

Key environmental factors (i.e., those that relate to culture and growth conditions) are oxidation-reduction level, hydrogen ion concentration (pH), temperature, and substrate. The importance of having a low oxidation-reduction level and a restricted pH range was discussed previously. Hence, the focus of the paragraphs that follow is on temperature and substrate.

D1.1. Temperature

A direct relation exists between extent and intensity of microbial activity and temperature level within a temperature range tolerated by the organisms. Each range characteristically has a minimum level below which no activity occurs and a maximum level above which all activity ceases and the microbes do not survive. Within the survival range, activity and growth increases with rise in temperature until an optimum level is reached, and decreases after the optimum level is reached. In the biogasification process, this influence is manifested by changes in rate and volume of gas production, and rate and amount of volatile solids destroyed.

In practice, temperature ranges have been grouped into two broad classes or types -- namely, mesophilic and thermophilic. Correspondingly, the microorganisms that have mesophilic ranges are termed mesophiles; those having a thermophilic range are termed thermophiles. The mesophilic range begins at about 10° to 15°C, peaks or plateaus at about 35° to 38°C, and ends at about 45°C. The thermophilic range begins at 45° to 50°C, peaks at 50° to 55°C, and ends at 70° to 75°C.

Some types of microorganisms can survive and perhaps thrive under both temperature regimens. Mesophilic microorganisms that can tolerate thermophilic conditions are termed facultative thermophiles; equally tolerant thermophiles are termed facultative mesophiles. Microorganisms lacking such tolerance are designated obligate mesophiles or thermophiles, as the case may be. A mesophilic culture can be adapted to thermophilic conditions. However, as will be explained later, there is considerable reason for attributing the so-called adaptation to enrichment. Consequently, to operate a digester under thermophilic conditions, either an existing culture of
thermophiles must be used, or one must be developed. Development, whether it be adaptation or enrichment, is a slow process. Most likely, successful development will be the result of a chance occurrence of a “wild” strain of thermophiles in the “starting culture”.

D1.1.1. Developing a thermophilic culture

Two of the procedures or methods for developing a thermophilic digester culture are discussed.

D1.1.1.1. First method

A digester culture is set up and its temperature is adjusted to 35°C. Within a 30-day period thereafter, the temperature is elevated gradually until the culture temperature reaches 50° to 55°C.

D1.1.1.2. Second method

Directly after it has been set up, the temperature of the culture is elevated to the thermophilic level (50° to 55°C). The immediate response of the culture is an apparent cessation of all activity and growth such that the culture seemingly has been “killed”. Nevertheless, if the culture is not disturbed and the temperature is maintained at 50° to 55°C, eventually it will exhibit indications of activity, and in time will have become fully adapted to thermophilic conditions. In effect, the culture was transformed into an enrichment culture for thermophiles.

D1.1.2. Thermophilic vs. mesophilic - decision factors

Generally, thermophilic cultures are more sensitive than are mesophilic cultures. For example, a thermophilic culture does not thrive under mesophilic conditions. Their sensitivity is an important decision factor because restoring a failed thermophilic culture or replacing it with a new culture is a time-consuming process. The situation is far less serious when a mesophilic culture fails (e.g., unplanned exposure to thermophilic temperatures). Development of a replacement culture can be accomplished in a much shorter time.

It is very likely that gain, if any, in pathogen destruction, gas production, and in rate and extent of volatile solids destruction and resultant shortening of detention period in a thermophilic system would be offset by the added expenditure of energy that would necessarily be involved. In short, the cost-benefit ratio would surpass that for a mesophilic system.

D1.2. Substrate

In this book, “substrate”, “feedstock”, and “digester input” are used interchangeably.

As is true with most biotreatment systems, the waste to be treated serves as the substrate and feedstock for the microbial populations that are active in the biological phases of the treatment. The suitability of a waste as a substrate depends upon three characteristics -- namely, physical properties, chemical composition, and biodegradability. Actually, biodegradability is determined in large part by the physical properties and chemical composition of a waste. With respect to chemical composition, possession of nutrient (fertiliser) elements and molecular structure of the compounds that contain them are the pertinent characteristics.

D1.2.1. Physical properties

An advantageous feature of physical properties in general is relative ease of changing or adjusting them to improve their utility as a feedstock. Two such properties are particle size and moisture content.
D1.2.1.1. Particle size

The influence of particle size is the relation of particle size to the ratio of mass-to-surface area -- the smaller the particle size, the greater is the ratio. The influence of the ratio is primarily by way of its bearing on ease and degree of accessibility by active microbes to nutrient elements in the waste mass. Secondary effects are breaching of barriers in the form of “protective” coatings (e.g., waxes, lignaceous sheathes), exposure to moisture and gases, and potentially inhibitory metabolic products. Inasmuch as extent of accessibility is a function of particle surface area exposed to microbial action, the greater the ratio of particle surface area to mass, the more intensive becomes the microbial activity and, hence, the rate of decomposition is accelerated.

The bearing of the magnitude of the surface area-to-mass ratio varies according to the type and nature of wastes. Thus, with municipal organic waste and fibrous agricultural wastes, digestibility increases with increase in size of the ratio. The ratio is not so critical where highly putrescible wastes are concerned (i.e., particle size can be larger). Examples of such wastes are food wastes, yard wastes, and some market wastes. Unless they contain bedding, cattle and poultry manure may be fed directly into a digester without having been size reduced.

D1.2.1.2. Moisture content

The appropriate and permissible moisture content depends upon the type of biogasification system intended and designed. Within the past three decades, two broad classes of municipal waste digestion systems based on moisture content have come into vogue -- namely, conventional (“low solids”, “slurry”) and “high solids”. Chronologically, the conventional form is the original form; whereas the high solids form did not reach significant acceptance until the 1980s. Both high- and low-solids digestion systems are being extensively researched and implemented in Europe as of this writing [26].

Experience indicates that for conventional (low solids) systems, a solids content of 5% to 10% (i.e., moisture content, 90% to 95%) is appropriate for the digester culture and feed. In conventional systems, too high of a solids content leads to inadequate mixing, with the objectionable consequences to be described later. Too low of a solids content necessitates a larger than necessary digester volume. Because of the expense involved, digester size can be the deciding factor for economic feasibility.

D1.2.1.3. Chemical composition

With regard to chemical composition of substrate and feed, elemental composition and the structure of the molecules that contain essential elements are main considerations. Essential nutrient and metabolic elements are conventionally arranged into two groups -- namely, “macronutrients” and “micronutrients”. However, this arrangement neglects essential elements that do not fit within these two groups; among them are calcium and magnesium. The micronutrients (“trace elements”) include sodium, cobalt, manganese, and a number of other metallic elements. Most wastes contain the full array of essential trace elements.

Macronutrients include nitrogen, phosphorus, and potassium (“NPK”). Not only are these elements essential, they must also be present in an appropriate ratio, i.e., a certain balance must exist between the three elements. An appropriate carbon-to-nitrogen ratio (C:N) is a requisite for the continued successful functioning of a digester. An excessively high C:N promotes acid formation and accumulation. The accumulation retards methanogen activity and, hence, methane production ceases. On the other hand, when the C:N is too low, nitrogen is converted to ammonium-N at a faster rate than can be assimilated by the methanogens. As a consequence, ammonia reaches concentrations that are toxic to the microbes.
The physical and chemical natures of the waste are among the more important factors that determine the level at which C:N is optimum; hence, the range above and below which it is inhibitory. For readily degradable substrates, the optimum C:N is on the order of 20:1 to 25:1. However, for materials that are resistant to microbial attack, the C:N can be as high as 35:1, or even 40:1. Common examples of resistant, i.e., refractory, wastes are wood and other lignaceous wastes, rice hulls, and straw. Because it breaks down extremely slowly, wood is not amenable to conventional low-solids digestion. However, its digestibility can be increased somewhat by way of pre-treatment involving exposure to heat, pressure, and acid or alkali.

Nutrient deficiencies in the waste are remedied either by adding a waste that contains the missing nutrients, or by enriching the deficient substrate with appropriate chemical fertiliser elements. The monetary costs of chemical fertiliser elements usually discourage their use in a developing country. The nitrogen content and carbon-to-nitrogen ratios of several wastes are presented in Table XI-1.

In Table XI-2 are listed chemical and other characteristics of some representative wastes. A comparison of the ratio of water-soluble constituents with combined lignin-cellulose contents can serve as a means of gauging the degradability of the listed wastes. The higher the ratio, the greater is the degree of degradability.

Because of a tendency to float, wood, straw, rice hulls, and other wastes of low density do not constitute suitable materials for low-solids digestion systems. The unsuitability is due to the propensity of low-density wastes to intensify scum formation. Consequently, it becomes necessary to control the more or less thick surface layer of scum that characterises conventional anaerobic digestion.
<table>
<thead>
<tr>
<th>Material</th>
<th>Total-N (% dry wt)</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Animal Wastes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Urine</td>
<td>15 to 18</td>
<td>0.8</td>
</tr>
<tr>
<td>Blood</td>
<td>10 to 14</td>
<td>3</td>
</tr>
<tr>
<td>Fish scraps</td>
<td>6.5 to 10</td>
<td>5.1</td>
</tr>
<tr>
<td>Mixed slaughterhouse wastes</td>
<td>7 to 10</td>
<td>2</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>6.3</td>
<td>--</td>
</tr>
<tr>
<td>Sheep manure</td>
<td>3.8</td>
<td>--</td>
</tr>
<tr>
<td>Pig manure</td>
<td>3.8</td>
<td>--</td>
</tr>
<tr>
<td>Horse manure</td>
<td>2.3</td>
<td>25</td>
</tr>
<tr>
<td>Cow manure</td>
<td>1.7</td>
<td>18</td>
</tr>
<tr>
<td>Farmyard manure (average)</td>
<td>2.15</td>
<td>14</td>
</tr>
<tr>
<td><strong>Nightsoil</strong></td>
<td>5.5 to 6.5</td>
<td>6 to 10</td>
</tr>
<tr>
<td><strong>Plant Wastes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Young grass clippings (hay)</td>
<td>4.0</td>
<td>12</td>
</tr>
<tr>
<td>Grass clippings (average mixed)</td>
<td>2.4</td>
<td>19</td>
</tr>
<tr>
<td>Purslane</td>
<td>4.5</td>
<td>8</td>
</tr>
<tr>
<td>Amaranthus</td>
<td>3.6</td>
<td>11</td>
</tr>
<tr>
<td>Cocksfoot</td>
<td>2.6</td>
<td>19</td>
</tr>
<tr>
<td>Lucerne</td>
<td>2.4 to 3.0</td>
<td>16 to 20</td>
</tr>
<tr>
<td>Seaweed</td>
<td>1.9</td>
<td>19</td>
</tr>
<tr>
<td>Cut straw</td>
<td>1.1</td>
<td>48</td>
</tr>
<tr>
<td>Flax waste (phormium)</td>
<td>1.0</td>
<td>58</td>
</tr>
<tr>
<td>Wheat straw</td>
<td>0.3</td>
<td>128</td>
</tr>
<tr>
<td>Rotted sawdust</td>
<td>0.25</td>
<td>208</td>
</tr>
<tr>
<td>Raw sawdust</td>
<td>0.1</td>
<td>511</td>
</tr>
<tr>
<td><strong>Household Wastes</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Raw garbage</td>
<td>2.2</td>
<td>25</td>
</tr>
<tr>
<td>Bread</td>
<td>2.1</td>
<td>--</td>
</tr>
<tr>
<td>Potato tops</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td>Paper</td>
<td>nil</td>
<td>--</td>
</tr>
<tr>
<td><strong>Refuse</strong></td>
<td>0.8 to 2.0</td>
<td>25 to 60</td>
</tr>
</tbody>
</table>

Sources: References 4, 5.
Table XI-2. Chemical composition of major crop and forest wastes (% of air-dry material)

<table>
<thead>
<tr>
<th>Constituent</th>
<th>Mature Wheat Straw</th>
<th>Soybean Tops</th>
<th>Alfalfa Tops</th>
<th>Young Cornstalks</th>
<th>More Mature Cornstalks</th>
<th>Young Pine Needles</th>
<th>Old Pine Needles</th>
<th>Mature Oak Leaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fats and waxes</td>
<td>1.10</td>
<td>3.80</td>
<td>10.41</td>
<td>3.42</td>
<td>5.94</td>
<td>7.65</td>
<td>23.92</td>
<td>4.01</td>
</tr>
<tr>
<td>Water-soluble constituents</td>
<td>5.57</td>
<td>22.09</td>
<td>17.24</td>
<td>28.27</td>
<td>14.14</td>
<td>13.02</td>
<td>7.29</td>
<td>15.32</td>
</tr>
<tr>
<td>Hemicelluloses</td>
<td>26.35</td>
<td>11.08</td>
<td>13.14</td>
<td>20.38</td>
<td>21.91</td>
<td>14.68</td>
<td>18.98</td>
<td>15.60</td>
</tr>
<tr>
<td>Cellulose</td>
<td>39.10</td>
<td>28.53</td>
<td>23.65</td>
<td>23.05</td>
<td>28.67</td>
<td>18.26</td>
<td>16.43</td>
<td>17.18</td>
</tr>
<tr>
<td>Lignin</td>
<td>21.60</td>
<td>13.84</td>
<td>8.95</td>
<td>9.68</td>
<td>9.46</td>
<td>27.63(^a)</td>
<td>22.68(^a)</td>
<td>29.66(^a)</td>
</tr>
<tr>
<td>Protein</td>
<td>2.10</td>
<td>11.04</td>
<td>12.81</td>
<td>2.61</td>
<td>2.44</td>
<td>8.53</td>
<td>2.19</td>
<td>3.47</td>
</tr>
<tr>
<td>Ash</td>
<td>3.53</td>
<td>9.14</td>
<td>10.30</td>
<td>7.40</td>
<td>7.54</td>
<td>3.08</td>
<td>2.51</td>
<td>4.68</td>
</tr>
</tbody>
</table>

\(^a\) The high lignin content is partially an artefact due to the analytical procedure used in its determining.

D2. PERFORMANCE factors

The factors of principal interest are those that are related in some way to the substrate, and which either stimulate or inhibit digester performance. These factors usually are in the form of substances either present in or added to the substrate.

D2.1. Transfer of metabolic products

The rate of transfer of dissolved metabolic and other products from the liquid to the gaseous phase can be a limiting factor due to the need to remove these products from the vicinity of individual cells. Inhibition arising from an inadequate transfer from the liquid to the gaseous phase may occur when the bacteria individually are completely surrounded by a wall of bubbles, as would occur at a very high substrate concentration. The envelope of bubbles interferes with diffusion of substrate into intercellular spaces. A solution to the problem is to vigorously agitate the culture, as for example, by thoroughly mixing on a continuous basis.

D3. FACTORS in the form of elements or compounds

Certain substances, either inherently or in combination with another substance, adversely affect the growth and activities of microorganisms involved in biogasification. The effect ranges from mild inhibition to destruction. The extent of inhibition depends upon the concentration of the toxic substance. Some substances become lethal at very low concentrations; whereas others become inhibitory only after a critical concentration has been passed. Paradoxically, the essential trace elements are of the first type.

When the concentration of inhibitory substances is lower than critical, inhibition may or may not be immediately apparent during the polymer and acid-forming stages. On the other hand, inhibition is almost immediately apparent during the methane stage, and is manifested by a drop in methane production. Methanogens are particularly sensitive to ammonia and ammonium ions, soluble sulphides, and soluble heavy metal salts (e.g., copper, cadmium, nickel). For example, soluble sulphides are toxic at concentrations beginning at 50 to 100 mg/L. Soluble metals salts become toxic when concentrations exceed a few ppm.
Ammonia and ammonium-ion toxicity depends upon pH level. Thus, when the pH level is higher than 7.4, ammonia is toxic at concentrations greater than 1,500 to 3,000 mg/L of total ammonia-N. On the other hand, the ammonium ion is toxic at any pH level when its concentration is greater than 3,000 mg/L of total ammonium-N. The influence of pH is largely due to its effect on the equilibrium that exists between dissolved ammonia gas and ammonium ions. The equilibrium shifts towards the ammonium ion at low pH levels, and inhibition begins at 3,000 mg/L. Conversely, the shift is toward ammonia gas at the higher pH levels, and inhibition may begin at 1,500 mg/L. The potential inhibitory effects of the ammonium ion at high concentrations do not nullify its utility nor its role as a key source of nitrogen.

The salts of alkaline-earth metals (sodium (Na), potassium (K), calcium (Ca), magnesium (Mg)) are stimulatory at concentrations below a critical level and inhibitory at concentrations above that level. The concentrations are determined by the cation portion of the salt. Sodium is stimulatory at 100 to 200 mg/L; K, at 200 to 400 mg/L; Ca, at 100 to 200 mg/L; and Mg, at 75 to 150 mg/L. The critical level for Na is about 3,500 mg/L; for K and Ca, about 2,500 mg/L; and for Mg, about 1,000 mg/L. In other words, these are the concentrations at which the named elements become inhibitory.

These and any other elements can exert their stimulatory and inhibitory influences only when they are in solution. Harmful and inhibitory effects can be avoided by rendering the compounds insoluble. Thus, an inhibitive concentration of dissolved sulphide can be reduced or eliminated by adjusting the pH level such that the compound becomes insoluble and is precipitated. An alternative recourse would be to add a heavy metal to act as a precipitant. A disadvantage of the latter approach is an increase in the heavy metal content of the sludge and, thereby, a magnification of the constraints on its disposal or utilisation. Incidentally, a soluble sulphide can serve as an antidote for heavy metal poisoning of a digester culture. The antidotal effect is the result of the formation of an insoluble heavy metal/sulphide complex. A disadvantage of such an approach is an increase in the heavy metal content of the sludge and, hence, a lowering of its agricultural utility.

Although this section deals primarily with the low-solids type of digester, the basic principles discussed are applicable both to low-solids and high-solids digesters.

E. Parameters

Regardless of type of digestion (i.e., low vs. high solids), parameters fall into two broad groups -- namely, those pertinent to the cultural environment that affects digester performance and those used for judging digester performance. Values assigned to environmental parameters are based on those environmental conditions that promote optimum digester performance and, conversely, those that lead to destruction of the culture and, thus, to “zero” digester performance. Examples of types of environmental parameters are hydrogen ion level and alkalinity. The principal parameters on which digester performance is judged are gas production and composition, rate and extent of volatile solids destruction, volatile acid content, pH level, and buffering capacity.

A range of values for key environmental and performance parameters has been developed for sewage sludge digestion. Unfortunately, because of chemical and physical structure differences, this range is not necessarily applicable to the digestion of other types of solids.

E1. Gas production and composition

Gas production ranks highest among the parameters commonly used to judge cultural performance and guide digester operation. It is a direct measure of overall microbial activity. In combination with the parameter, composition, it is a measure of the activities of the methanogens.
The combination of the two parameters is a measure of energy recovery efficiency and economic practicality.

Gas production usually is expressed in terms of volume of gas produced per unit of mass of total solids and of volatile solids introduced. Gas production per unit of total solids depends both on the volatile solids content of the total solids and on the extent to which the volatile (organic) solids are converted into gas. Gas production per unit of volatile solids may be expressed either as volume of gas produced per unit mass of volatile solids introduced or as volume of gas per unit mass of volatile solids destroyed. Gas production in terms of volatile solids introduced is a particularly useful parameter, because it is a measure of the efficiency of the utilisation of volatile (i.e., organic) solids by the culture.

Gas volume per unit of volatile matter depends both upon the detention period and other operational features, and upon the nature of the waste. For example, in one study, gas production amounted to 0.374 to 0.454 m$^3$/kg of raw sewage solids introduced. Examples of gas production in the digestion of other types of wastes are listed in Tables XI-3 and XI-4. The yields listed in the two tables are in terms of volume of gas per unit mass of total solids introduced. It is highly likely that yields obtained with municipal wastes generated in a developing country would be roughly comparable to the yield obtained with raw sewage sludge in the United States.

**Table XI-3. Biogas production from digestion of common sludges**

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Biogas/Unit Wt of Dry Solids (m$^3$/kg)</th>
<th>Temperature (°C)</th>
<th>Methane Content of Gas (%)</th>
<th>Detention Time (days)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cattle manure</td>
<td>0.20 to 0.33</td>
<td>11.1 to 31.1</td>
<td>--</td>
<td>--</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>0.46 to 0.56</td>
<td>32.6 to 50.6</td>
<td>58 to 60</td>
<td>9 to 30</td>
</tr>
<tr>
<td>Swine manure</td>
<td>0.49 to 0.76</td>
<td>32.6 to 32.9</td>
<td>58 to 61</td>
<td>10 to 15</td>
</tr>
<tr>
<td>Sheep manure</td>
<td>0.37 to 0.61</td>
<td>--</td>
<td>64</td>
<td>20</td>
</tr>
<tr>
<td>Forage leaves</td>
<td>0.5</td>
<td>--</td>
<td>--</td>
<td>29</td>
</tr>
<tr>
<td>Sugarbeet leaves</td>
<td>0.5</td>
<td>--</td>
<td>--</td>
<td>11 to 20</td>
</tr>
<tr>
<td>Algae</td>
<td>0.32</td>
<td>45 to 50</td>
<td>55</td>
<td>11 to 20</td>
</tr>
<tr>
<td>Nightsoil</td>
<td>0.38</td>
<td>20 to 26</td>
<td>--</td>
<td>21</td>
</tr>
<tr>
<td>Municipal refuse (USA)</td>
<td>0.31 to 0.35</td>
<td>35 to 40</td>
<td>55 to 60</td>
<td>15 to 30</td>
</tr>
</tbody>
</table>

Sources: References 9, 23.
Table XI-4. Bovine, swine, poultry, and horse manure NPK equivalents and potential methane yields

<table>
<thead>
<tr>
<th>Animal</th>
<th>Waste Production (kg/day/animal)</th>
<th>Methane (m³/day/animal)</th>
<th>N (kg/yr/animal)</th>
<th>P (kg/yr/animal)</th>
<th>K (kg/yr/animal)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bovine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beef</td>
<td>38</td>
<td>11.9</td>
<td>32</td>
<td>15</td>
<td>40</td>
</tr>
<tr>
<td>Dairy</td>
<td>52</td>
<td>15.8</td>
<td>64</td>
<td>29</td>
<td>79</td>
</tr>
<tr>
<td>Replacement</td>
<td>34</td>
<td>10.2</td>
<td>21</td>
<td>10</td>
<td>27</td>
</tr>
<tr>
<td>Swine</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sows (136 kg)</td>
<td>14</td>
<td>5.1</td>
<td>15</td>
<td>8</td>
<td>5.4</td>
</tr>
<tr>
<td>Hogs (68 kg)</td>
<td>7.3</td>
<td>2.5</td>
<td>7.7</td>
<td>4.1</td>
<td>2.7</td>
</tr>
<tr>
<td>Weaners (27 kg)</td>
<td>3.6</td>
<td>1.4</td>
<td>4.1</td>
<td>1.8</td>
<td>1.4</td>
</tr>
<tr>
<td>Poultry (per 1,000)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Broilers</td>
<td>28</td>
<td>7.4</td>
<td>64</td>
<td>27</td>
<td>23</td>
</tr>
<tr>
<td>Layers</td>
<td>118</td>
<td>31.1</td>
<td>499</td>
<td>403</td>
<td>222</td>
</tr>
<tr>
<td>Turkeys</td>
<td>134</td>
<td>34.2</td>
<td>245</td>
<td>195</td>
<td>109</td>
</tr>
<tr>
<td>Horses</td>
<td>17</td>
<td>4.8</td>
<td>45</td>
<td>17</td>
<td>35</td>
</tr>
</tbody>
</table>

Source: Reference 14.

The parameter for estimating the rate of gas from the digestion of a given waste should be based only on data obtained after the digester culture has reached steady-state conditions. Yields obtained before steady-state is reached or after it has passed are lower than the maximum potential yields. Thus, yield steadily progresses from almost zero at the start of the culture until it reaches the rate characteristic of steady-state. Conversely, after steady-state begins to deteriorate, yields correspondingly decline.

The great utility of gas production as a parameter is largely due to its ease of recognition. For example, an unexpected deviation from a prevailing rate of gas production is a symptom of culture malfunction. Nevertheless, some deviation is inevitable even during steady-state, inasmuch as almost every biological system is characterised by a daily fluctuation. However, the fluctuations are only slight and a given deviation is not persistent. The practical impossibility of maintaining all operational and environmental conditions at a constant level renders some deviation inevitable. Nevertheless, a consistent decline for longer than four or five days could be taken as an indication of trouble. A sudden, sharp decline in yield bespeaks imminent danger to the culture.

The use of gas production as a parameter depends not only upon the volume of gas produced, but also upon its composition. In waste treatment, the components of interest are carbon dioxide and methane. Methane is the more useful of the two and, hence, significant. Two factors determine the magnitude of the methane content -- namely, substrate and the methanogen population, i.e., the density and intensity of activity of the latter. With regard to the substrate, a predominance of carbohydrates usually results in a 1:1 ratio of methane to carbon dioxide. Accordingly, 50% of the gas produced is methane. Conversely, the use of a highly nitrogenous substrate (e.g., raw sewage sludge) may result in a gaseous product that is 65% methane.

The continuing increase in methane percentage that lasts until steady-state is reached is the reason why only steady-state gas composition data should be used as operational and performance parameters. As was stated earlier, the rate of the development of the methanogen population is slower than that of most of the other microorganisms involved in biogasification.
Consequently, the methane content of gas produced initially is negligible. Eventually, however, traces of methane begin to be detected. Provided that conditions remain appropriate, methane production increases until it levels off at a steady-state.

E2. DESTRUCTION of volatile matter

Destruction of volatile matter is a performance and operational parameter because only the volatile (organic) fraction of a waste is biodegradable and, hence, is subject to anaerobic digestion. Therefore, rate and extent of destruction are measures of rate and extent of microbial conversion of organic solids into gas and stable or inert matter. Destruction can be as high as 60% to 70% with food preparation wastes and as low as 30% to 40% with newsprint as the principal carbon source.

Several factors exert a significant influence on the parameter, rate, and destruction of volatile matter. Among them are particle size distribution, degradability, temperature, and detention period. The four factors must be taken into consideration when evaluating changes in rate of destruction of volatile matter.

E3. VOLATILE acid content

Volatile acid concentration becomes a key parameter only when it is in a state of flux. A state of flux indicates an imbalance between proliferation and activities of acid formers and those of methanogens. The imbalance becomes a problem when the acid concentration is at a limiting, i.e., inhibitory, level. The occurrence of an inhibitory level is a function of a number of variables, including organic mass loading rate [27]. Limiting levels are those at which the accompanying pH level is inhibitory to methanogens. This relation between pH level and buffering capacity renders impractical any attempt to designate a particular total organic acid concentration as being inevitably lethal. The reason is that resulting pH changes are functions of the buffering capacity of the culture medium and adaptation of the microbial complex. Thus, it has been amply demonstrated that suitably adapted methanogens flourish at volatile acid concentrations of 10,000 mg/L. (Volatile acids concentration is expressed as mg/L acetic acid.) Chances are that they could be adapted to concentrations higher than that level. In contrast, with a poorly buffered culture, the inhibitory concentration could be as low as 200 or 300 mg/L. In summary, the significance of volatile acid concentration as a parameter depends upon the constancy of concentration rather than upon a specific concentration.

Constancy of volatile acid concentration can serve as an operational parameter, in that the presence of an inhibitory condition is manifested by a gain in the amount of volatile acids. The gain would be the result of the resistance of the acid-formers to unfavourable conditions being superior to that of the methanogens. Any progressive gain in acid concentration after steady-state has been reached is an indication of impending difficulty, even though concentration may be as low as 200 mg/L.

E4. HYDROGEN ion concentration

The pH range tolerated by methanogens is very narrow -- namely, 6.0 to 7.5. Hydrogen ion concentration could be regarded as an operational parameter because it is a manifestation of volatile acid formation. However, its utility as a parameter is lessened because the pH level also depends upon the buffering capacity of the culture. For example, the culture could be well on the way to complete inhibition before a substantial change could be noted in the pH level. The utility of the parameter depends to a large extent upon the immediacy with which it responds to significant changes in the overall conditions of the culture.
E5. BUFFERING capacity

In practice, alkalinity is a measure of the buffering capacity of the culture medium within the neutral pH range. Thus, the capacity of the medium to accept protons is its alkalinity. The alkalinity of the medium is a function of its bicarbonate, carbonate, and hydroxide components [1]. Of the three components, bicarbonate is the most important; the reason is that it is responsible for the neutral buffering capacity.

A failing of the routine analysis currently practiced is that it does not provide all of the information essential for satisfactory digester performance, because it determines alkalinity only to pH 4.0. Therefore, it accounts for only about 80% of the acetate alkalinity and pertinent bicarbonate alkalinity. (Bicarbonate alkalinity is total alkalinity minus acetic alkalinity.) The buffering range of acetate is effective only from pH 3.75 to pH 5.75. Moreover, this range is much lower than that tolerated by the methanogens. The bicarbonate alkalinity required to maintain pH level at 7.0 depends upon the carbon dioxide content of the digester gas. For example, with the CO_2 of the gas at 25%, the required bicarbonate alkalinity would be on the order of 2,000 mg/L. The needed alkalinity would be 4,000 mg/L, if the carbon dioxide concentration were from 50% to 53%. Generally, satisfactory performance is obtained within the broad range of 1,500 to 5,000 mg/L as acetic acid.

E6. REMEDIAL measures

Appropriate remedial measures must be taken when parameter values indicate the approach or actual existence of an inhibitory situation and, thereby, a likely deterioration in digester performance. The causes should determine the remedial measures. Thus, simply adding lime or buffer to raise an unfavourably low pH may raise the pH level, but it does nothing to alleviate the problem responsible for the pH drop. Moreover, in low-solids digestion, the lime may become a cement-like precipitate upon the bottom of the digester unless precautions are taken.

Although ammonia would effectively raise the pH, its use is attended by a danger to the culture because ammonia becomes toxic to the culture microorganisms even at very low concentrations. Cost and uncertain availability at the concentrations needed militate against the use of sodium bicarbonate to enhance the bicarbonate concentration.

As soon as digester malfunction becomes apparent, “feeding” should be discontinued because continued feeding most likely would magnify the problem. Unfortunately, no clear-cut, reliable remedy is available at present. Feasibility permitting, the best recourse is to dispose of the digester contents and then develop a new culture. Except for a very small operation, such recourse is not feasible because of the severe and rigid constraints placed by regulatory agencies on the dumping of incompletely treated material on the environment. The constraints are justifiable because of the unfavourable impact of the material on the quality of the environment.

F. Operational procedures

F1. MIXING

The usual rationale for mixing is that it enhances digestion efficiency regardless of type of digestion system. In high-solids digestion and in low-solids digestion, mixing serves several important functions. Two such functions are the removal of metabolic waste products accumulated in the culture's interstitial voids and simultaneous replacement with additional nutrients. Additionally, mixing is a critical feature in the digestion of some types of substrates, e.g., fibrous materials. With respect to low-solids digestion, rate and frequency of mixing or
agitation of the digester contents distinguishes conventional systems from high-rate digestion systems. The two systems are diagrammed in Figures XI-2 and XI-3.

**Figure XI-2. Conventional digestion (low solids)**

Reduction of sedimentation layering is an important function of mixing in low-solids digestion. Usually, the contents of an unmixed low-solids digester separate into the following four layers: scum layer, supernatant, actively digesting sludge layer, and stabilised sludge (see Figure XI-2).
F1.1. Problems associated with scum formation

The scum layer is the uppermost layer. It is a froth consisting of bubbles formed by the rising of gases released in the supernatant layer. Because of the high surface tension of the supernatant, the bubbles are long-lasting and tend to accumulate and, as a result, the layer tends to increase in thickness. Because of its buoyancy, the froth collects low-density materials such as wood, straw, chaff, hair, and feathers. If the organic fraction of solid waste is part of the feedstock, small particles of paper (especially newsprint) may also become part of the scum layer. Generally, some inert fines may be found distributed throughout the froth.

Depending upon a number of factors, the thickness of the layer may be as little as 5 cm to as much as 30 cm. Digestion efficiency is adversely affected by the scum layer because the layer collects degradable material and, thereby, keeps it from entering the active zone of digestion. The extent of the isolation may be substantial if the substrate contains a large percentage of fibrous material. The exclusion of biodegradable mass from the active zone obviously decreases overall efficiency because the energy content of excluded material remains untapped.

A thick scum layer can interfere with the operation of a digester. Interference can be with operational procedures such as gas collection, medium and gas recirculation, and the lesser mixing systems. A further unfavourable result of a thick layer is that a portion of the reactor volume serves no purpose -- thereby diminishing the effective capacity of the reactor.

F1.2. Control of scum formation

Inasmuch as scum formation is minimised, if not avoided completely through proper mixing, scum formation can be controlled through the application of an appropriate mixing program. Regarding intensity, the required vigour of the mixing action, as well as the frequency needed, increases with an increase in the tendency to form scum.

Mixing can be accomplished in low-solids digestion either by recirculating liquid medium and/or gas, by mechanical mixing, or by a combination of recirculation and mechanical mixing. Recirculation usually would be sufficient when the supernatant is moderately viscous, and the digesting solids are low in fibrous content and bulk density. Recirculation of liquid medium is accomplished by taking liquid from the bottom of the digester and re-introducing it by way of discharging it above the culture through one or more jets. The approach with gas recirculation is to remove gas from the gas plenum and inject it at the bottom of the culture. The mixing action is supplied by the ascent of the resulting bubbles through the culture.

If scum formation cannot be controlled by way of recirculation, it becomes necessary to resort to mechanical mixing. The several available mechanical mixer designs basically involve the rotation of a paddle or paddles in the culture suspension. Variation generally is in the arrangement and location of the paddles. (Manual rotation of the paddle device is feasible only with cultures less than about 500 L in volume.) Continuous mixing is required only when large digester volumes are involved. For the smaller applications, mixing need be done only once or twice each day. A balance must be struck between the ability of the mixing system to break up the scum layer and its innate tendency to promote the formation of scum.

For many reasons, accomplishing mixing in high-solids digestion is much more complicated than it is in low-solids digestion. The injection operation provides some mixing in a “plug-flow” system. Tumbling the material in an airtight, rotating horizontal drum might be another approach.
F2. LOADING

Loading parameters are functions of the nature of the substrate and the degree to which operating conditions approximate the optimum. With low-solids digesters operated on a continuous basis, the extent of energy recovery from wastes and the efficiency at which digester capacity is utilised are determined by rate and amount of loading. Overloading not only leads to a decline in amount of energy recovery but also eventually results in the demise of the microorganisms -- a situation often referred to as “stuck digester”. The consequence of not loading at full capacity is inefficient utilisation of digester volume and imposition of the economic penalty associated with an unnecessarily large unit. Questionable benefits of underloading might be a higher percentage of energy recovery and a greater safety factor.

Loading may be expressed either in terms of units of volatile solids introduced per unit of digester capacity per unit of time, or of total solids per unit of digester capacity per unit of time. The use of volatile solids in expressing loading promotes uniformity and a certain degree of universality, because the percentage of volatile solids varies with type of waste. Accordingly, loading is expressed in terms of volatile solids in this discussion. Moreover, all loading rates are on the basis of dry weight of the solids.

The nature of a waste determines the suitability, i.e., “permissibility”, of a loading rate. Generally, if the waste is readily biodegradable (e.g., manure, green plants, meat), the recommended volatile solids loading is less, because the amount of material directly available to the organisms, especially the acid-formers, is greater. Because the carbon in refractory organic materials (straw, paper, dry leaves) is difficultly available to the microorganisms, the loadings can be somewhat larger without leading to adverse results. For example, at a 20- to 30-day detention period, the loading rate with raw sewage sludge could be on the order of 1.4 to 2.6 kg/m$^3$ digester volume/day. However, the permissible loading could range from 1.0 to 2.2 kg/m$^3$/day, with a 1:1 mixture of raw sewage sludge and organic refuse rich in paper (e.g., MSW). The breadth of the range is due to that of the temperature range, in that the lower end applies to temperate climates and the upper applies to tropical climates. A likely compromise with nightsoil can be about 1.0 to 2.2 kg/m$^3$/day [9]. Such a loading rate would accommodate the excrement from about 28 individuals. If cow dung is the substrate, the loading rate could range from 1.17 to 5.29 kg/m$^3$ digester volume/day.

F3. DETENTION time (period)

Alternative terms for “detention” are “retention” and “residence”. Although the terms may on occasion be used in reference to batch cultures, usually they are applied only to the continuous type of culture. In practice, the solid and liquid phases of the digester contents may have a common detention time. If they have different periods, the liquid phase has one period and the solids phase has another period. The solids phase includes both the microflora and the suspended solids. The designation “hydraulic detention time” applies to the culture as a whole. The hydraulic detention time is either the common detention time or the liquid detention time. The hydraulic detention time is conventionally used in the operation of large-scale, low-solids digesters. It can be expressed as:

$$t = \frac{V}{q}$$

where:
• \( t \) = the detention time;
• \( V \) = the culture volume; and
• \( q \) = the throughput per unit of time.

Although the use of the dual detention approach is quite common in the aerobic treatment of wastewaters, its application in anaerobic waste treatment is relatively limited, albeit slowly increasing. Examples of dual detention periods in aerobic wastewater treatment are activated sludge, trickling filter, the rotating disk, and fixed-bed adaptations. Dual detention periods by way of fixed-bed adaptations have advantageous potential in anaerobic digestion practice. Two examples of situations where it is especially appropriate are: 1) a situation in which the microbial mass constitutes the bulk of the settleable solids, or the microbial growth rate is so rapid that the water consumption would be excessive if a hydraulic detention time were the only one applied; or 2) one in which the rapidity of the rate of nutrient depletion with a rapidly growing culture may be such that an abbreviated detention period would be suitable. The additional handling involved is a disadvantage of a dual detention period, as is the possibility of exposing the methanogens to atmospheric oxygen. Yet another disadvantage would be poor settling characteristics and a substantial concentration of inert fines. With such a combination, the net effect would be a gradual accumulation of inert fines without an accompanying recirculation of microbes.

Because of the difficulties associated with the dual detention approach, the subsequent discussion is principally concerned with the common (or single) type of hydraulic detention period. For several reasons, appropriate detention time is a requisite for digester efficiency.

• An unnecessarily long detention period could result in the construction of an unnecessarily large digester or in the inefficient use of existing digester capacity.

• With an unnecessarily long detention period, there is the strong possibility that the average age of the microbial populations may be beyond that of peak productivity, i.e., beyond the phase of exponential multiplication.

• The hydraulic detention period must be long enough to allow the culture to continue at peak activity. Otherwise, the population would be less than adequate for accomplishing the required energy conversion and, in effect, the full amount of potentially available energy would not be recovered.

• If the detention period is not long enough to accommodate a rate of bacterial multiplication great enough to compensate for the numbers of bacteria discharged in the digester effluent, the active microbial population would disappear -- the culture would be “washed out”.

In summary, the optimum detention time is one in which: 1) the microbial population, particularly that of the methanogens, is maintained in the exponential growth phase; and 2) the greater part of the reclaimable energy in the waste is converted to the chemical energy of methane. Nevertheless, the proper length of the detention period is determined by a collection of environmental and operational conditions and of the composition of the substrate. The more closely that conditions approach optimum and the more decomposable the waste, the shorter can be the detention period. When all environmental and operational conditions are maintained at optimum, the ultimate limitation is the genetic makeup of the bacteria. In anaerobic digestion, it is the genetic makeup of the methanogens that makes it necessary to apply detention periods in terms of weeks rather than of hours. The minimum penalty for failure to account for this limitation is incomplete recovery of energy bound in the waste. The maximum penalty is the destruction or loss of the active microbial population and, eventually, a “stuck” digester.
Obviously, the suitability of a particular length of detention period varies with the nature of the substrate. For example, a satisfactory detention time for the digestion of municipal refuse in the United States probably would be about 15 days under appropriate conditions; whereas a 30-day period might be unnecessarily long. In a developing nation, the detention time would likely be 10 to 15 days. Researchers have found that a 5-day detention period was sufficient for the digestion of pure cellulose (reagent grade) that had been fortified with nutrients [3].

F4. STARTING a digester

“Starting a digester” may be loosely defined as “the establishment of culture and environmental conditions conducive to the proliferation of both indigenous and introduced methanogens”. In effect, it is the establishment of an enrichment culture for the organisms. The emphasis is on methanogens because usually the necessary populations of hydrolyzers and acid-formers are developed without difficulty. In fact, care must be taken to counteract the drop in pH level caused by acid that is generated by the acid-formers. The drop persists until the population of the slow-growing methanogens reaches a level at which it utilises all of the acids produced by the acid-formers.

Examples of situations that could make it necessary to “start a digester” are: 1) initiation of a biogasification project or expansion of an ongoing one, and 2) replacement of a “stuck” culture.

Volumetric capacity of the intended digester is one of the determinants of the method to be followed in starting a digester. A second basic determinant is type of digestion system, i.e., low-solids vs. high-solids. Unless otherwise specified, this section deals with low-solids digestion.

F4.1. Small digester (1 to 2 m$^3$)

The digester is loaded with the waste “starter”, that could consists of 5 to 10 kg of highly organic loam. An alternative starter could be 15 to 20 L of bottom mud from a stagnant pond or swampland. A third alternative is sludge from an existing, satisfactorily functioning digester. The sludge should be diluted to about 5% solids and added in an amount sufficient to account for approximately 10% of the designed full volume of the digester. (With a high-solids digester, the sludge should be dewatered to about 85% total solids and should constitute about 10% of the waste mass.)

If a starter cannot be obtained, it would be necessary to resort to enrichment based on indigenous methanogens. The time involved would be longer than that when a starter is used.

F4.2. Large-scale digester

In general, methods of starting a small-scale and a large-scale digester are comparable. With low-solids digestion, an exception occurs when sewage is available. In a developing nation, sewage probably would be available in the country’s highly urbanised regions. The procedure for starting would be as follows: 1) the digester is filled to capacity with sewage and is allowed to remain undisturbed; and 2) after the passage of one or two weeks, a 30-day program of “feeding” is begun. The duration of the program is flexible in that it can be extended until a sufficiently large population of methanogens has developed -- as would be indicated by the production of methane. Thereafter, the loading could be gradually increased until the designed loading capacity is reached.

An alternative method is as follows: the digester is loaded with digesting sludge (obtained from an active digester) to about 10% of the designed final volume. The remaining 90% of the volume is filled with sewage. A loading based on the volume of the “starter” sludge is initiated.
immediately. Thereafter, the loading is gradually increased at increments that reflect the resulting expansion of the starter volume.

G. Digester construction design principles

Although construction design principles in a developing country setting do not materially differ from those in an industrialised country, construction practice does differ.

Low-solids digestion systems currently in vogue are strongly based on those practiced in conventional treatment of wastewater solids. The designs fall into three main groups -- namely, “conventional”, “high-rate”, and “contact” (“fixed-bed”).

G1. CONVENTIONAL digestion systems

The dimensions of the biogasification reactor (digester) constitute the first design consideration to be discussed. The required dimensions vary with type of system and digester culture, i.e., high-solids vs. low-solids digestion, and batch culture vs. continuous culture. The reactor volume involved either in batch or in continuous high-solids systems is that of the total volume of the waste to be digested. Continuity is achieved in a continuous culture by the imposition of a loading program that involves the periodic removal of an amount (volume) of culture equal to the volume of the waste to be introduced.

The situation is more complex with low-solids continuous cultures. The dimensions are functions of the amount of waste to be processed. Therefore, the dimensions depend upon the total amount of waste that must be digested, and the loading and withdrawal regimen. Regimen pertains to volume of slurried waste to be added each day, as well as the average time a given load will be in the digester (detention time), and the volumes of gaseous, liquid, and solids produced each day and their management. If the temperature of the culture is controlled, the volume of the system for heating and circulating the water used in elevating and maintaining the temperature of the digester culture also must be taken into consideration. In most situations in economically developing countries, the reactors are not heated.

In summary, the necessary digester volume is determined by the amount of wastes to be processed each day, the moisture content of the waste, the volatile solids concentration, the loading rate, solids content of the slurry, and detention time. The theoretical minimum volume of the digester can be calculated by dividing the amount of volatile solids to be added each day by the imposed loading rate. Thus, if the amount of volatile solids (VS) to be disposed each day were 1,200 kg and the loading rate were 3 kg VS/m$^3$/day, the theoretically required digester size would be at least 400 m$^3$. In practice, the size actually needed would be larger, because allowances must be made for “freeboard” and adjustments involved in the reconciliation of dilution requirements with intended detention times. The volume of the gas holder depends upon the amount of waste processed per day multiplied by the amount of gas produced per unit of waste introduced into the digester. Gas produced per unit of volatile solids introduced is determined by the many factors previously mentioned. As a rule, the actual size of the gas holder can be smaller than the calculated theoretical size, because some or all of the gas will be utilised on a regular basis as soon as, or shortly after, it is generated.

G2. HIGH-RATE digestion systems

The high-rate system is best suited to large-scale operations in urbanised situations. High-rate digestion is a two-stage operation in which the two stages are in series, and each stage takes place in a separate digester (cf. Figure XI-3). The first stage is the active stage. Two distinguishing characteristic of this stage are: 1) the fact that the digesting waste is thoroughly agitated, and
2) the detention period is only a few days. Effluent from digester-1 (first stage) is discharged into the second digester (second stage). In this stage, the digesting material is allowed to remain quiescent. The principal function of the second digester is to serve as a settling chamber in which the digester’s contents separate into two layers -- namely, digested sludge and supernatant. The supernatant is topped by a gas plenum.

G3. “CONTACT” digestion systems

A version of the contact approach that has gained considerable attention is the “fixed-bed” system. In this system, the fixed-bed aspect is attained by providing a surface on which the microorganisms can become attached and form a film that consists mostly of active microorganisms. The surface on which the film develops is that of a solid, in a configuration conducive to film formation. The film is bathed by the waste. Periodically, either the entire film or only the film's outer layer sloughs off. The sloughing provides a detention period for the microorganisms. Examples of contact systems in wastewater treatment are the trickling filter and the rotating disk(s).

A major problem with contact systems is the maintenance of the anaerobic conditions that are essential in biogasification. Practical constraints on the adoption of contact and fixed-bed treatment in developing countries are technological and financial in nature.

G4. HEATING the digester

The practical feasibility of the application of the digestion process in cold and temperate climates demands that the temperature of the digester culture be maintained at a level sufficiently high to ensure maximum microbiological activity, or at least at a level that permits the minimum required degree of activity.

A digester culture is easily heated by circulating hot water through a coil immersed in the digester’s contents. Among the variety of sources of the energy needed to elevate the temperature of the circulating water, solar energy is an interesting possibility. The key element of the system is a solar panel that has a black backing and over which water is trickled. (The face of the panel is oriented to receive maximum exposure to the sun.) In its passage over the “face” of the panel, the trickling water becomes increasingly warmer. The heated water collects in a reservoir positioned at the base of the panel. The heated water can be taken from the reservoir and then circulated through the digester heating coil.

Perhaps the largest share of the heat energy expended in heating a large-scale digester is in the elevation of the temperature of incoming feed to the level required to maintain the culture at the desired degree of activity. Heat dissipated in warming the feed is proportional to the mass flow rate and the difference between the temperature of the feed stream and that of the digester contents. This relation may be expressed as:

\[ Q = Sc (T_1 - T_0) \]

where:
- \( S \) = the feedstream (kg/hr);
- \( c \) = the specific heat of the fluid (Cal/kg-°C);
- \( T_1 \) = the temperature of the culture (°C);
• \( T_0 \) = the feedstream temperature (°C); and

• \( Q \) = the heat required (Cal/hr).

Other heat losses are through convection and radiation, and through evaporation of water vapour from the gas stream. The energy lost in a large-scale operation by way of convection and radiation is usually minor compared to that required to heat the feed stream. Any such loss can be compensated by insulating the digester. Insulation can be used to lessen convective and evaporative heat losses in smaller operations. Some insulation can be acquired by surrounding a digester unit with soil, i.e., “sinking” it. However, such protection is only at the level of the soil temperature.

G5. SMALL-SCALE digester design and construction

The information in this section pertains to small-scale applications (less than 1 m\(^3\), to several m\(^3\)). It cannot be applied to large-scale systems because safety demands that large-scale units be constructed according to carefully developed engineering design, and made of durable materials. Moreover, abundant information on large-scale digesters is available in the sanitary engineering literature.

This presentation is prefaced with the reminder that regardless of the size, design, materials, and type of structure, methane generation is a hazard associated with anaerobic digestion. Methane and air become an explosive mixture at concentrations of methane as low as 5%. Consequently, no open flame should be permitted in the vicinity of a digester or gas storage unit. In addition, the over-simplification of designs and the lack of adequate skills of builders have led to several failures.

G5.1. Gobar (India) research station application

The design of the Gobar, India digester is diagrammatically shown in Figure XI-4. The greater part of the digester is below ground level. Heating of the digester contents is accomplished through the use of a submerged hot-water coil, and mixing apparently is accomplished by recirculating the digester culture. Potential daily gas production is reported as being 9.5 m\(^3\).

A list of materials used in constructing the digester is given in Table XI-5. The list is given because it is fairly typical of digestion systems of this nature. With the use of the list, it is possible to arrive at some concept as to types and quantities of materials required for digesters of designs proposed for other applications. Digester design, construction, and application particulars are described in detail in References 11, 12, and 13.
Table XI-5. Materials required for a small-scale digester (gas production 2.8 m$^3$/day)

<table>
<thead>
<tr>
<th>Material</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement</td>
<td>40 bags</td>
</tr>
<tr>
<td>Sand</td>
<td>8.5 m$^3$</td>
</tr>
<tr>
<td>Brick ballast</td>
<td>2.84 m$^3$</td>
</tr>
<tr>
<td>Bricks</td>
<td>7,500</td>
</tr>
<tr>
<td>12 or 14 gauge M.S. sheet drum (1.5 m in diameter and 1.2 m in height), open at bottom</td>
<td></td>
</tr>
<tr>
<td>M.S. angle iron for structure and gas holder guide</td>
<td>30 m</td>
</tr>
<tr>
<td>Alkaline pipe (0.125 cm in diameter)</td>
<td>15 m</td>
</tr>
<tr>
<td>Alkaline pipe fittings B end, elbow and sockets of 2.5 cm, and 1.25 cm fittings</td>
<td>3 each</td>
</tr>
<tr>
<td>Wire gauge - 80 mesh</td>
<td>0.93 m$^2$</td>
</tr>
<tr>
<td>Miscellaneous fittings</td>
<td></td>
</tr>
<tr>
<td>Paint (enamel)</td>
<td>3.8 L</td>
</tr>
</tbody>
</table>

Sources: References 11, 12.

G5.2. Manure-latrine application

The designs of two digesters that had been constructed on farms in France and Germany and were in operation in the late 1950s are diagrammatically sketched in Figures XI-5 and XI-6. Figure XI-5 shows the connection between the digesters and the latrine. A detail of the digesters is shown in Figure XI-6. The direct connection between the latrine and the digester is a feature of the design. The digester designs are described in Reference 5.

G5.3. Chinese version

A version of digester design in The People's Republic of China in the 1970s is diagrammed in Figure XI-7. The gas is stored in the plenum above the culture. Inasmuch as the digester cover is fixed, the gas is under increasing pressure because of the continuing gas production. In practice,
the actual pressure is a function of the rate of gas usage and gas production. A description of the digester is provided in Reference 8.

![Diagram of manure digester connected to latrines](image1)

**Figure XI-5. Diagram of manure digester connected to latrines**

![Detail of manure/nightsoil digester](image2)

**Figure XI-6. Detail of manure/nightsoil digester**
The steel tank digester is an example of design variation to accommodate the demands of certain situations. Steel tanks adapted for use as digesters usually are replicates of steel tanks fabricated for the containment of a liquid (e.g., water). An essential feature of adaptation is the coating of the tank's interior with a material that is resistant to corrosion by substances formed in the digestion process.

Various non-proprietary adaptations were tried during a short-lived flurry of farm-scale undertakings in the 1980s in the United States. The objective was the combining of energy production with treatment of animal wastes [2]. Digester volumes usually were less than 5 m$^3$. The flurry dwindled rapidly when state subsidies were discontinued. Foremost among the reasons advanced regarding the farmers' loss of interest were the increased burden involved in operating and maintaining a digester, and the illusory abundance of fossil fuel on the market.

Currently, a proprietary version of a steel digester is on the market in Europe. It is purported to be particularly effective for digesting liquid wastes.

G5.5. Lined excavated pit

As its name indicates, a lined pit digester is constructed by lining an excavated pit with a wall of native material found at the site of the proposed operation. The interior of the walled pit is then lined with an impervious material such as plastic film. The lined pit is suitably capped and an arrangement is made for gas collection. It is claimed that the lined excavated pit has features that enhance its potential utility in developing regions.
The plug-flow digester diagrammed in Figure XI-8 is an example of a lined-pit adaptation. According to the reference, results obtained in an investigation involving the use of the reactor in a 65-cow operation indicate that the net energy production from a 100-cow unit could be on the order of \(600 \times 10^3\) kcal/day. A pilot-scale plug-flow bioreactor is modelled in Reference 6.

The lined-pit approach is not without serious problems. Ranking high among the problems is the difficulty encountered in finding a sufficiently durable membrane that will remain genuinely impermeable throughout the life of the operation. It often happens that an initially impermeable membrane gradually becomes increasingly permeable with the passage of time because certain of the organic acids slowly affect the mechanical properties of plastics.

H. End products of the biogasification process

H1. PROPERTIES of the biogas

The composition and quality of raw (untreated) biogas directly after its emission from a digester or a landfill vary widely from day to day. The result is a wide range of values for each component. As stated in the section on parameters, the two principal components of biogas are methane (\(\text{CH}_4\)) and carbon dioxide (\(\text{CO}_2\)). From 55% to 65% of the biogas is methane; and 34% to 44% is carbon dioxide. Lesser gases include \(\text{H}_2\text{S}\), \(\text{N}_2\), and \(\text{H}_2\text{O}\). The heating value of raw biogas ranges from 18,630 to 26,080 kJ/m\(^3\). The raw gas can be burned and the resulting heat can be used in any one of several uses. Although the raw gas can be used as a fuel in internal combustion engines, its hydrogen sulphide content would cause considerable corrosion in the engine.

Table XI-6 lists estimates of biogas production required for satisfying the energy needs of certain applications.

H2. BIOGAS purification

Most of the potential uses of biogas demand that the quality of the gas be uniformly high and the composition vary minimally. Unfortunately, the moisture content of raw biogas may range from as low as 5% to saturation. Variations in moisture and hydrogen sulphide content can be as much as 50% from day to day and season to season. An intrusion of atmospheric oxygen in the gas could have serious repercussions in terms of explosion potential.
Table XI-6. Biogas consumption in assorted applications

<table>
<thead>
<tr>
<th>Use</th>
<th>Specification</th>
<th>Quantity of Gas Required (m³/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooking</td>
<td>5 cm burner</td>
<td>0.33</td>
</tr>
<tr>
<td></td>
<td>10 cm burner</td>
<td>0.47</td>
</tr>
<tr>
<td></td>
<td>15 cm burner</td>
<td>0.64</td>
</tr>
<tr>
<td></td>
<td>5 to 10 cm burner</td>
<td>0.33 to 0.47</td>
</tr>
<tr>
<td></td>
<td>per person/day</td>
<td>0.34 to 0.42</td>
</tr>
<tr>
<td>Gas lighting</td>
<td>per mantle</td>
<td>0.07 to 0.08</td>
</tr>
<tr>
<td>Gasoline or diesel engine</td>
<td>converted to biogas, per hp</td>
<td>0.45 to 0.51</td>
</tr>
<tr>
<td>Refrigerator</td>
<td>per m³ capacity</td>
<td>1.20</td>
</tr>
<tr>
<td>Gasoline</td>
<td>1 L</td>
<td>0.33 to 1.87b</td>
</tr>
<tr>
<td>Diesel fuel</td>
<td>1 L</td>
<td>1.50 to 2.07b</td>
</tr>
<tr>
<td>Boiling water</td>
<td>1 L</td>
<td>0.11c</td>
</tr>
</tbody>
</table>

Sources: References 11, 12.

a Using 25% efficiency.
b Volume of biogas required to provide energy equivalent to 1 L of fuel.
c Volume of biogas needed to boil off 1 L of water.

Currently available purification technology probably is so expensive as to place purification beyond the economic resources of most developing countries. Nevertheless, the technology is described and discussed in this book, because circumstances peculiar to some developing countries or regions may be such as to render purification feasible. Purification procedures may range in extent from simple dehydration to complete H₂0, CO₂, and N₂ removal. Dehydration can increase the heating value by about 10% of the original value. Combining dehydration with CO₂ and H₂S removal can bring the heating value up to 22,360 to 26,000 kJ/m³.

Among the dehydration procedures are the use of in-line gravity outflow, filtering, triethylene glycol system (TEG), molecular sieves, heating, air cooling, and refrigerant cooling.

H2.1. Molecular sieve

The molecular sieve technology is both relatively inexpensive and quite efficient. Its absorptive capacity is much greater than that of other absorbents. Molecular sieves are crystalline and aluminosilicates, honeycombed with cavities interconnected by pores, which range from about 3 to 100 angstroms in diameter. Because of the highly localised polar charges characteristic of molecular sieves, polar or polarizable compounds are strongly adsorbed on the molecular sieves.

H2.2. TEG system

The use of triethylene glycol (TEG) for gas dehydration is common. Among the reasons for the widespread usage include the following five: 1) its unusual hygroscopicity, 2) its excellent thermal and chemical stability, 3) low vapour pressures, 4) ready availability, and 5) moderate cost.

The first step in the passage of biogas through a TEG system is compression. Thereafter, bulk contaminants are removed in a “knockout drum”, and the gas is cooled. The treatment thus far has removed the greater part of its water content. The cooled gas is passed through a TEG absorber/sePARATOR tower. Action in the tower is as follows: free liquids are removed in the lower
part of the tower (separator section), and the gas stream then ascends to the upper part of the
tower (absorber section). In this section of the tower, the gas comes in contact with lean triethylene glycol on bubble-cap trays.

H2.3. Potassium carbonate system

Coupling the TEG dehydration system with a hot potassium carbonate scrubbing system makes it possible to remove water, CO₂, and H₂S simultaneously.

H2.4. Iron sponge

Some uses of biogas require the removal of hydrogen sulphide only. For those uses, hydrogen sulphide can be removed by passing the gas through a dry gas scrubber, i.e., an “iron sponge” consisting of ferric oxide mixed with wood shavings. Experience indicates that the removal capacity is on the order of 3.7 kg of sulphur/bushel (0.0352 m³ of iron sponge). A sponge can be regenerated by exposing the sponge to air. Exposure results in the conversion of the ferric sulphide formed in the scrubbing operation into ferric oxide and elemental sulphur.

H3. USE of purified gas

Purified biogas can be used onsite or offsite. Offsite use could involve injection of the upgraded biogas into a public utility transmission line. Onsite use generally involves use of the gas as a fuel in the generation of electricity. With respect to generation, the gas is used to fuel the internal combustion engine that drives the turbine. For such use, the gas should be compressed to about 5 psig. If a gas turbine is used, the pressure must be increased to 150 psig.

Due to the high costs involved and complexity of required equipment, any undertaking that includes the upgrading of biogas to pipeline quality would, with rare exception, be imprudent in a developing country. The practical procedure in almost all cases would be to burn the gas directly at the site of generation and to put the heat to some immediate use.

I. Residues

Combustible biogas constitutes the product, because its formation is the objective of anaerobic digestion (i.e., biogasification). Hence, all discharged non-gaseous components (i.e., solid and liquid materials) make up the residues. Accordingly, prior to further processing, digested sludge constitutes the collective residue. As was indicated earlier in this chapter, unprocessed digested sludge consists of a liquid phase (the supernatant) and a settled solids phase (cf. Fig. XI-2). In an anaerobic digestion operation, supernatant and settled solids (sludge) are the two principal residues that require management and treatment.

II. SUPERNATANT

The supernatant is an aqueous suspension in which the suspending medium contains an assortment of dissolved solids and a variety of suspended colloidal solids and bacterial cells. Because its dissolved and colloidal solids contents are highly biodegradable and therefore unstable, the supernatant must be properly treated before being discharged into the environment. In practice, a sizeable portion of the supernatant is returned to the digester; i.e., it is recirculated. In a two-stage operation, the supernatant is returned to the first digester. Recirculation promotes the build-up of the microbial population and more complete utilisation of nutrients. Application on land is a beneficial means of disposing of supernatant that is not recirculated.
I2. SLUDGE (biosolids)

The settled sludge layer, i.e., the bottom layer in Figure XI-2, constitutes the sludge residue. In “everyday” practice, the term “sludge” often has a much broader connotation, in that occasionally it is applied indiscriminately to the solids in the sludge layer and to the combined solids and supernatant. Another classification that may be encountered in practice and in the literature is based on the division of the solids layer into two layers -- namely, the digesting sludge and the inactive sludge layers. In this chapter, sludge (“biosolids”) refers solely to the layer of settled solids.

As stated previously, the term “sludge” is often applied both to the effluent at the point of discharge from the digester and to the solids mass formed by dewatering the effluent (dewatered sludge). In the absence of dewatering, the solids content of the effluent generally is 1.5% to approximately 4% or 5%. Undewatered effluent frequently is directly spread upon or incorporated into the soil. The extent to which the effluent may be dewatered depends upon the intended disposition of the dewatered sludge.

The technology of dewatering is broad, ranging from simply spreading upon a sand bed to processing through complex equipment. With the sand bed method, dewatering is by way of drainage and evaporation. Mechanical removal of water is by way of vacuum filtration or centrifugation. Because of its simplicity and low cost, the sand bed method is usually the appropriate approach in a developing nation. During sunny, dry weather, a solids content of 15% to 20% can be attained within a week with the use of a properly designed and operated sand bed. Sand beds should be sheltered from rain and snow.

The physical and chemical characteristics of a dewatered sludge generally are comparable to those of its composted counterpart, excepting that its nitrogen content is greater. Despite the many similarities between non-composted and composted sludges, public health considerations dictate that digested sewage sludge containing human excrement be composted prior to utilisation in agriculture.

The term “excrement” includes collected human faeces and urine, nightsoil, septic tank cleanings, raw sewage sludge, and any other material that may contain human body waste. As is stated in an earlier chapter, the hazard posed to public health by excrement is the likely presence of enteric pathogens. Table XI-7 presents a list of such organisms. Unfortunately, despite the substantial destruction of pathogens that occurs during conventional (mesophilic) digestion, the number of surviving pathogens is great enough to constitute a health hazard (see Table XI-8). However, extent of destruction probably would be sufficient if digestion took place at thermophilic temperature levels.

In summary, conventionally digested sludge generally can be used interchangeably with composted sludge in agriculture, unless the sludge feedstock contains human excrement. A constraint on the use of either digested sludge or composted sludge, independently of excrement, would be the presence of toxic metals and toxic synthetic organic chemical compounds (e.g., halogenated hydrocarbons) found in many sludges of industrial origin. However, industrial sludges are not likely to be encountered in a developing country because they involve industrially generated wastes. Problems resulting from the presence of heavy metals and toxic chemicals, as well as methods of alleviating them, are discussed in Chapter VII, Use of Waste-Derived Organic Matter as a Soil Amendment. Additional information can be found in Reference 7.
J. Feasibility considerations

Among the factors that determine the practical and economic feasibility of biogas production in a developing country, either as a waste management option or as an energy resource, or both, two are particularly important: 1) availability of the required technology, and 2) the extent of the country's economic resources. However, superseding the two factors is magnitude of the proposed undertaking. The decisive influence of magnitude arises from the fact that technological and economic requirements escalate almost logarithmically with increase in magnitude, and soon exceed available technological and financial resources of all but the more highly industrialised countries.

Table XI-7. Enteric pathogens

<table>
<thead>
<tr>
<th>Category</th>
<th>Disease</th>
<th>Organisms (where identified)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Viral</td>
<td>Infectious hepatitis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Gastroenteritis</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Respiratory illness</td>
<td>adenovirus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>reovirus</td>
</tr>
<tr>
<td></td>
<td>Poliomyelitis</td>
<td>enterovirus (poliovirus)</td>
</tr>
<tr>
<td>Bacterial</td>
<td>Typhoid fever</td>
<td>Salmonella typhosa</td>
</tr>
<tr>
<td></td>
<td>Salmonellosis</td>
<td>Salmonella spp. (Exp. S. paratyphi, S. schottmueleri)</td>
</tr>
<tr>
<td></td>
<td>Bacillary dysentery</td>
<td>Shigella spp. (Shigeillosis)</td>
</tr>
<tr>
<td></td>
<td>Cholera</td>
<td>Vibrio cholera</td>
</tr>
<tr>
<td></td>
<td>Tuberculosis</td>
<td>Mycobacterium tuberculosis</td>
</tr>
<tr>
<td>Protozoan</td>
<td>Amebiasis</td>
<td>Entamoeba histolytica</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(Amebic dysentery)</td>
</tr>
<tr>
<td>Helminthic</td>
<td>(Roundworm)</td>
<td>Ascaris lumbricoides</td>
</tr>
<tr>
<td></td>
<td>(Pinworm)</td>
<td>Oxyaris vermicularis</td>
</tr>
<tr>
<td></td>
<td>(Whipworm)</td>
<td>Trichurus trichiura</td>
</tr>
<tr>
<td></td>
<td>(Tapeworm)</td>
<td>Taenia saginate</td>
</tr>
<tr>
<td></td>
<td>(Hookworm)</td>
<td>Ancylostoma duodenale</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Necator americanus</td>
</tr>
</tbody>
</table>

Table XI-8. Survival of pathogens in the anaerobic digestion process

<table>
<thead>
<tr>
<th>Organisms</th>
<th>Temperature (°C)</th>
<th>Residence Time (days)(^a)</th>
<th>Die-Off (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poliovirus</td>
<td>35</td>
<td>2</td>
<td>98.5</td>
</tr>
<tr>
<td>Salmonella ssp.</td>
<td>22 to 37</td>
<td>6 to 20</td>
<td>82 to 96</td>
</tr>
<tr>
<td>Salmonella typhosa</td>
<td>22 to 37</td>
<td>6</td>
<td>99</td>
</tr>
<tr>
<td>Mycobacterium tuberculosis</td>
<td>30</td>
<td></td>
<td>100</td>
</tr>
<tr>
<td>Ascaris</td>
<td>29</td>
<td>15</td>
<td>90</td>
</tr>
<tr>
<td>Parasite cysts</td>
<td>30</td>
<td>10</td>
<td>100(^b)</td>
</tr>
</tbody>
</table>

Sources: References 28-30.
\(^a\) Time in digester.
\(^b\) Does not include Ascaris.

An arbitrary but logical and convenient classification of “magnitude” is into “large-scale” and “small-scale”. Accordingly, a large-scale operation is one that involves 100 Mg or more per day,
and serves a metropolitan area. The primary function of a large-scale plant is the treatment of wastewater solids (sewage sludge), and biogas production is secondary and coincidental. Small-scale operations are suited to villages and individual farms, or to groups of farms. In operations on that scale, biogas production ranks with waste treatment in terms of priority.

J1. LARGE-SCALE undertakings

As of this writing, the record of large-scale biogas installations, other than conventional wastewater solids treatment, is singularly scarce and unimpressive in developing countries. Available technology for non-sewage sludge, large-scale operations based on low-solids digestion has not been successful, largely because of operational problems and deficiencies in digester design and construction. Currently, the trend is toward high-solids digestion. However, the largest high-solids digester presently in operation is modest in size. It is only relatively recently that some European designs have been applied to the anaerobic digestion of primarily manures and the highly putrescible fraction of domestic waste. A photograph of a new high-solids anaerobic digester is shown in Figure XI-9. The facility is in Salzburg, Austria and processes on the order of 18,000 Mg/yr. The digested residue is dewatered and composted in tunnel reactors. A portion of the gas produced by the digester is used to generate electricity for use by the facility. The remainder of the gas is burned in a flare. Digesters of this type operate under the following conditions: digester loading, 10 to 30 kg of COD/m$^3$ of digester volume-day; temperature, 50° to 58°C; and a detention time of 15 to 30 days. Based on these conditions, one could expect a production of about 4 to 8 Nm$^3$ of biogas/m$^3$ of digester volume per day, with a concentration of methane of about 60% (by volume) [24]. Several of these and similar units have been installed in primarily Western European countries.
Technical problems encountered in small-scale operations generally are related to maintenance and functioning of the digester [10]. Examples are corrosion of gas holders, “wear and tear” of components such as the guide pipe of the gas holder and of hoses, and the development of cracks in the digester walls. Financial constraints arise mainly from the relatively high costs of construction materials, scarcity of land on which to locate the plant, and diversion of labour to unrelated activities. In some countries, sociological and cultural problems may be manifested by a prejudice against connecting latrines to a gas plant, or in a reluctance of farmers to use a latrine [10]. The problems are aggravated by the low levels of gas production that occur during cold weather.

Problems that beset small-scale farm operations can be alleviated through integration into a community installation. The integration would be accompanied by the establishment of an organisational program designed to: 1) provide follow-up service; 2) ensure frequent contacts with relevant agencies for technical advice; and 3) establish a mechanism for access to reliable and regular supply of raw materials and plant components, and provide for personal contacts by biogas technicians.
K. References


