CHAPTER VIII. COMPOSTING

A. Introduction

In economically developing countries, constraints related to economics, technology, and qualified personnel have narrowed the choice of acceptable solid waste management, treatment, and disposal options. Viable options include minimisation, recycling, composting, incineration, and sanitary landfilling. Composting is the option that, with few exceptions, best fits within the limited resources available in developing countries. A characteristic that renders composting especially suitable is its adaptability to a broad range of situations, due in part to the flexibility of its requirements. As a result, there is a composting system for nearly every situation; i.e., simple systems for early stages of industrial development to relatively complex, mechanised systems for advanced industrial development.

The compost option affords the many advantages of biological systems: lower equipment and operating costs; in harmony with the environment; and results in a useful product. On the other hand, composting is sometimes attributed with disadvantages often associated with biological systems -- namely, a slow reaction rate and some unpredictability. Regarding the attributed disadvantages, slow reaction rate may be justified, in that retention times are in terms of weeks and months. However, the attribution of unpredictability is not justified. If all conditions are known, applied, and maintained, the course of a given process will be predictable.

Among the major prerequisites for successful composting are a satisfactory understanding and application of the basic principles of the process. Without this understanding, inadequacies of design and operation are practically inevitable. An understanding of the biology rests upon a knowledge of the basic principles of the process. Such a knowledge enables a rational evaluation of individual compost technologies and utilisation of those technologies. An obvious benefit of the knowledge is the ability to select the system most suited to an intended undertaking. An accompanying benefit is the ability to critically evaluate claims made on behalf of candidate systems.

B. Definitions

Two definitions of composting are presented. The first is a definition in the strict sense of the term, which differentiates composting from all other forms of decomposition. The second one is an ecological definition.

B1. DEFINITION in the strict sense

A definition that distinguishes composting from other biological processes is:

“Composting is the biological decomposition of biodegradable solid waste under controlled predominantly aerobic conditions to a state that is sufficiently stable for nuisance-free storage and handling and is satisfactorily matured for safe use in agriculture”.

The terms and phrases that collectively differentiate composting from other decomposition processes are: “biological decomposition”, “biodegradable”, “under controlled predominantly aerobic conditions”, “sufficiently stable”, and “matured”. The phrase “biological decomposition” implies that the decomposition is accomplished by living organisms. “Biodegradable” refers to the substrate and it requires that the substance be susceptible to decomposition attack by certain living organisms, e.g., bacteria and fungi. Such substances are organic compounds formed either by living organisms or by way of chemical synthesis (e.g., halogenated hydrocarbons).
Decomposition of synthetic organics generally involves the activity of certain microorganisms under special conditions. The phrase “under controlled predominantly aerobic conditions” has a twofold significance: 1) it differentiates composting from the random biological decomposition that takes place in nature (e.g., open dump, forest, field, etc.); and 2) it distinguishes composting from anaerobic digestion (biogasification). The criterion for “stable” is safe and nuisance-free storage. The criterion for “sufficiently mature” is oriented to use in agriculture.

B2. ECOLOGICAL definition

An “ecological definition” is as follows:

“Composting is a decomposition process in which the substrate is progressively broken down by a succession of populations of living organisms. The breakdown products of one population serve as the substrate for the succeeding population. The succession is initiated by way of the breakdown of the complex molecules in the raw substrate to simpler forms by microbes indigenous to the substrate.”

C. Active organisms

Mesophilic and thermophilic bacteria and fungi are the predominant organisms during the initial and the active stages of the compost process. The bacteria can be morphologically grouped into the “bacteria proper” and “filamentous” bacteria. In reality, the filamentous bacteria simply are “branched” bacteria, and are members of the actinomycetes. Usually the actinomycetes do not appear in sizeable numbers until the close of the high-temperature active stage of the compost process. Coincidently with their appearance is a rapid disappearance of cellulose and lignin. Although some nitrogen-fixing bacteria may be present, conditions are not conducive to nitrogen fixation [23].

The onset of the stabilisation stage of the process is attended by the appearance of saprophytic macroflora. Sources of nutrients for the macroflora are inactive microflora and the decomposing wastes. The more minute forms (e.g., paramecium, amoeba, rotifers) are the first to appear. Eventually, larger forms such as snails and earthworms become numerous. Among the earthworms are Lumbricuse terestris, L. rubellus, and Eisenia foetida [24,25]. The compost mass is fairly advanced by the time the earthworms make their appearance. Of course, the earthworms can be deliberately introduced successfully at some prior time, perhaps even in the relatively early stages [25].

The claimed potential benefits from the utilisation of earthworms in composting have led to the promotion of vermiculture.

C1. VERMICULTURE

In the discussion of vermiculture, it is important to keep in mind that earthworms constitute the end product of vermiculture; and that worm castings are a residue. The castings make up the “compost product” to which the vermiculture proponents refer. Among the numerous benefits claimed for vermiculture are the following: 1) increased particle size reduction, 2) enrichment of the compost product by earthworm nitrogenous excretions, 3) increase in the carbon and nutrient exchange brought about by the enhanced interaction between microflora and macroflora, and 4) the superiority of earthworm castings to the conventional compost product.

Not all of the species of earthworms are suitable for vermiculture (the production of protein and castings). Among the species that can be used in captivity are those commonly known as the red Californian (Eisenia foetida). Initially, this type of earthworm was selected in order to increase
the quantity of substrate that would be ingested and thus increase the amount of castings that would be produced. Unfortunately, the results of these attempts were not very positive and efforts were diverted toward improving the fertility of the species as well as to try to increase its lifespan.

Each adult earthworm of the Californian species measures between 6 and 8 cm in length and about 3 to 4 mm in diameter. The average weight is about 1 g. This species can live up to 6 years.

The principal component of an earthworm is water; it constitutes between 70% and 95% of its weight. The remainder (between 5% and 30%) is primarily protein. The composition of an earthworm on a dry-weight basis is as follows: protein between 53% and 72%, grease between 1% and 17%, and minerals between 9% and 23%.

Vermiculture can be carried out on a small scale. The basic production module typically has about 60,000 earthworms, which can be placed in an area of about 2 m long by 1 m wide, known as a bed. The substrate is placed on the worms at a depth of 15 to 25 cm. Depending upon the climatic conditions, the bed can be protected by means of a simple roof. Similar to any biological process, earthworms will seek favourable conditions. Consequently, the beds must be carefully managed to provide the earthworms with optimum conditions, especially nutrients, humidity (70% to 80%), and temperature (20° to 25°C). In addition, there are certain regimes for feeding (adding the substrate to) the beds to achieve optimum growth and degradation of the organic matter.

Estimates indicate that a basic module of 60,000 earthworms can produce on the order of 800 kg of humus in three months.

Although the earthworms produced in the process constitute a low level source of proteins, they also contain a major fraction of the heavy metal contaminants in the substrate. The reason is the tendency of the worms to store the contaminants in their tissue.

Although vermiculture merits careful consideration, it does have serious limitations and demands careful control, particularly in large-scale systems (i.e., larger than 10 Mg/day). Furthermore, there are situations in which conditions required for their culture may not be achievable. The process has potential in small-scale systems for the treatment of relatively homogenous substrates.

C2. INOCULUMS

The utility of inoculums in compost practice is open to many questions that could well be considered objections. Obviously, the utility of an inoculum is proportional to the extent of the need to compensate for a lack of indigenous population of microorganisms and macroorganisms to decompose (compost) the substrate. Characteristically, most wastes encountered in compost practice have such an indigenous population, and inoculation would be unnecessary. On the other hand, inoculation would be useful with wastes that either lack an indigenous population or have one that is deficient. Examples of such wastes are pharmaceutical manufacturing wastes, wastes that have been sterilised or pasteurised, and wastes that are homogeneous in composition (sawdust or wood chips, rice hulls, petroleum wastes, etc.).

If the need for an inoculum is indicated, one must be developed unless a suitable inoculum is available. As is shown by the discussion that follows, inoculum development is a difficult undertaking that requires highly qualified microbiologists who are thoroughly knowledgeable regarding the compost process.
A serious difficulty is the fact that composting involves a dynamic succession of several groups of microbes sequentially interacting with the substrate. The identification of these microorganisms is the first step in the development, followed by delineation of the respective roles of the identified organisms. Accurate identification and appropriate assignment are particularly difficult when mixed cultures are concerned. To be effective, the organisms in the inoculum must be able to successfully compete with organisms indigenous to the waste. The competitive ability of introduced organisms is adversely affected by the repeated subculturing involved in culture maintenance.

In conclusion, little is gained from the abundant indigenous population of microorganisms characteristic of most inoculated wastes destined to be composted. Before being accepted, claims for an inoculum must be demonstrated to be valid by way of unbiased conducted tests or demonstrations. Moreover, it should be noted that, generally, inoculated microbes do not compete well under practical conditions [26,27].

If an inoculum or additional microorganisms are desired, decomposed horse manure, finished compost, or a rich and loamy soil can serve the purpose. All three materials contain an abundance of microflora. A form of inoculation often used in compost practice is the “mass inoculation”, accomplished by recirculating a fraction of the final product, i.e., adding it to the incoming waste. Other than possibly improving the texture of the incoming waste, the efficacy of such a mass inoculation is debatable.

D. Process factors

In addition to the presence of the needed organisms, major factors can be grouped into three main categories -- namely, nutritional, environmental, and operational. The relative importance of an individual factor is determined by its bearing on the proliferation and activity of the key organisms in the process. The key organisms determine the rate and extent of composting, because they have an enzymatic complex that permits them to attack, degrade, and utilise the organic matter in raw waste. The other organisms can only utilise decomposition products (intermediates). Hence, the composting of a waste is the result of the activities of the previously mentioned dynamic succession of different groups of microorganisms. In short, groups prepare the way for their successors.

D1. NUTRITIONAL factors

A given nutrient in a waste can be utilised only to the extent that it is available to active microbes. Availability takes two forms -- namely, chemical and physical. A nutrient is chemically available to a microbe or group of microbes if it is a part of a molecule that is vulnerable to attack by the microbe or microbes. Usually, the attack, i.e., breakdown, is accomplished enzymatically by microbes that either possess the necessary enzyme or can synthesize it. Physical availability is interpreted in terms of accessibility to microbes. Accessibility is a function of the ratio of mass or volume to surface area of a waste particle, which in turn is determined by particle size.

D1.1. Macronutrients and micronutrients

Nutrients can be grouped into the categories “macronutrients” and “micronutrients”. The macronutrients include carbon (C), nitrogen (N), phosphorus (P), calcium (Ca), and potassium (K). However, the required amounts of Ca and K are much less than those of C, N, and P. Because they are required only in trace amounts, they are frequently referred to as the “essential trace elements”. In fact, most become toxic in concentrations above trace. Among the essential trace elements are magnesium (Mg), manganese (Mn), cobalt (Co), iron (Fe), and sulphur (S). Most trace elements have a role in the cellular metabolism.
The substrate is the source of the essential macronutrients and micronutrients. Even though an element of uncertainty is introduced into an operation, economic reality dictates that a waste constitute most or all of the substrate in compost practice. Any uncertainty is due to variation in the availability of some nutrients to the microbes. Variation in availability, in turn, arises from differences in resistance of certain organic molecules to microbial attack. Variations in resistance lead to variations in rate at which the process advances. Examples of resistant materials are lignin (wood) and chitin (feathers, shellfish exoskeletons), and several forms of cellulose.

D1.2. Carbon-to-nitrogen ratio

The carbon-to-nitrogen ratio (C:N) is a major nutrient factor. Based on the relative demands for carbon and nitrogen in cellular processes, the theoretical ratio is 25:1. The ratio is weighted in favour of carbon, because uses for carbon outnumber those for nitrogen in microbial metabolism and the synthesis of cellular materials. Thus, not only is carbon utilised in cell wall or membrane formation, protoplasm, and storage products synthesis, an appreciable amount is oxidised to CO₂ in metabolic activities. On the other hand, nitrogen has only one major use as a nutrient -- namely, as an essential constituent of protoplasm. Consequently, much more carbon than nitrogen is required. The ratios encountered in waste management vary widely. Generally, the ratio is higher than 8 to 10 parts available carbon to 1 part available nitrogen (the emphasis on “available” should be noted). In compost practice, it is on the order of 20:1 to 25:1. The general experience is that the rate of decomposition declines when the C:N exceeds that range. On the other hand, nitrogen probably will be lost at ratios lower than 20:1. The loss could be due to the conversion of the surplus nitrogen into ammonia-N. The high temperatures and pH levels characteristic of composting during the active stage could induce the volatilisation of the ammonia.

In a developing country, an unfavourably high C:N can be lowered by adding a nitrogenous waste to the compost feedstock. If economics permit, it also can be lowered by adding a chemical nitrogen fertiliser, such as urea or ammonium sulphate. Conversely, a carbonaceous waste can be used to elevate a low C:N. The nitrogen contents and the carbon-to-nitrogen ratios of various wastes and residues are listed in Table VIII-1.

D1.3. Carbon and nitrogen analyses

Among the several useful analytical methods available for determining nitrogen content, the venerable standard Kjeldahl method continues to be both practical and useful.

Carbon determination is rendered difficult in a developing country by the need for expensive analytical equipment and an appreciable skill on the part of the analyst. Obtaining a representative sample within the very small size limits specified by current methods is an extremely difficult task, especially when dealing with a waste as heterogeneous as is solid waste. A “stop-gap” approach suitable for composting in solid waste management is an estimation based on a formula developed in the 1950s [1]. The formula is as follows:

\[
% \text{ carbon} = \frac{100 \times \% \text{ ash}}{1.8}
\]
Table VIII-1. Nitrogen content and C:N of various wastes and residues

<table>
<thead>
<tr>
<th>Waste</th>
<th>Nitrogen</th>
<th>C:N</th>
</tr>
</thead>
<tbody>
<tr>
<td>Activated sludge</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Blood</td>
<td>10 to 14</td>
<td>3.0</td>
</tr>
<tr>
<td>Cow manure</td>
<td>1.7</td>
<td>18</td>
</tr>
<tr>
<td>Digested sewage sludge</td>
<td>2 to 6</td>
<td>4 to 28</td>
</tr>
<tr>
<td>Fish scraps</td>
<td>6.5 to 10</td>
<td>5.1</td>
</tr>
<tr>
<td>Fruit wastes</td>
<td>1.5</td>
<td>34.8</td>
</tr>
<tr>
<td>Grass clippings</td>
<td>3 to 6</td>
<td>12 to 15</td>
</tr>
<tr>
<td>Horse manure</td>
<td>2.3</td>
<td>25</td>
</tr>
<tr>
<td>Mixed grasses</td>
<td>214</td>
<td>19</td>
</tr>
<tr>
<td>Nightsoil</td>
<td>5.5 to 6.5</td>
<td>6 to 10</td>
</tr>
<tr>
<td>Non-legume vegetable wastes</td>
<td>2.5 to 4</td>
<td>11 to 12</td>
</tr>
<tr>
<td>Pig manure</td>
<td>3.8</td>
<td>4 to 19</td>
</tr>
<tr>
<td>Potato tops</td>
<td>1.5</td>
<td>25</td>
</tr>
<tr>
<td>Poultry manure</td>
<td>6.3</td>
<td>15</td>
</tr>
<tr>
<td>Raw sewage sludge</td>
<td>4 to 7</td>
<td>11</td>
</tr>
<tr>
<td>Sawdust</td>
<td>0.1</td>
<td>200 to 500</td>
</tr>
<tr>
<td>Straw, oats</td>
<td>1.1</td>
<td>48</td>
</tr>
<tr>
<td>Straw, wheat</td>
<td>0.3 to 0.5</td>
<td>128 to 150</td>
</tr>
<tr>
<td>Urine</td>
<td>15 to 18</td>
<td>0.8</td>
</tr>
</tbody>
</table>

According to one report [28], values determined by way of the formula were within 2% to 10% of those obtained in the laboratory studies.

In situations in which carbon and nitrogen analyses are not feasible, a workable assumption can be made on the basis of the substrate composition. The assumption is that if the ratio of green (in colour) raw waste (or of food preparation wastes, or of fresh manure) to dry, non-green waste is volumetrically about 1 to 4, the C:N will be within a “permissible” range.

D1.4. Particle size

The size of particles in the waste is a nutrient-related factor, because the waste is the substrate in composting and the substrate is the source of nutrients. The relation to nutrition is the effect of size of the individual particles on the physical availability of nutrients, i.e., accessibility to the nutrients. As was stated earlier, particle size determines the ratio of mass-to-surface and, hence, amount of a particle’s mass that is exposed to microbial attack. Inasmuch as the ratio increases with decrease in size, the rate of decomposition (composting) theoretically should increase with decrease in particle size. However, the theoretical increase does not always materialise in practice. The failure may be due to one or more factors. For example, the physical nature of the substrate may impose constraints in terms of minimum permissible size. The permissible minimum size is the one at which any further reduction would adversely affect the compost process. Ultimately, the criterion for determination of minimum permissible size is the ability to establish a substrate porosity that is consistent with necessary aeration.

Porosity is largely a function of the structural strength of the particle material. Structurally strong, crush-resistant waste materials, such as wood, straw, and paper, remain porous at very small
particle sizes. An appropriate particle size range for such wastes is about 1.5 to 7 cm. A suitable particle size for individual wood chips is about 1 cm in thickness and 2 to 5 cm in width. Particle sizes suitable for fibrous materials and woody trimmings (yard debris) are from about 5 to 10 cm. If the individual branches and twigs are less than 1 cm in diameter, the particle sizes may be somewhat larger. The minimum permissible particle size of soft materials tends to be large, because excessively size-reduced soft materials tend to compact into an amorphous mass that has little or no porosity. Thus, the minimum permissible particle size for fresh plant debris, fresh vegetables, and kitchen wastes could be as much as 15 cm, and even larger with softer materials. Fresh green residues such as lettuce and ripe fruits (e.g., papaya and mangoes) require little or no size reduction.

Unless they are intermixed with an abundance of bedding material, animal manures do not require size reduction. Any size reduction needed would be determined by the characteristics of the bedding material.

In a developing country, there are economic and technological obstacles to the size reduction of wastes intended for composting. Size reduction is usually accomplished with a shredder or grinder, which is a large, expensive piece of equipment. A possible alternative might be to rely upon some form of tumbling to accomplish the relatively limited tearing, breaking, and maceration that would be required. The tumbling could be done by way of a rotating drum or cylinder.

D2. ENVIRONMENTAL factors

The principal environmental factors that affect the compost process are temperature, pH, moisture, and aeration. The significance of environmental factors with respect to the compost process is the fact that individually and collectively they determine the rate and extent of decomposition. Consequently, rate and extent of decomposition are proportional to the degree that each nutritional and environmental factor approaches optimum. A deficiency in any one factor would limit rate and extent of composting -- in other words, the deficient factor is a limiting factor. It is important to keep in mind that the ultimate limiting factor is the genetic makeup of the various microbial populations.

D2.1. Temperature

Although convincing arguments can be made with respect to the advantages of thermophilic vs. mesophilic composting, the question has become moot in compost practice. The reason is that in normal practice, composting begins at ambient temperature (mesophilic range) and progresses to and through a thermophilic phase, followed by a descent to the mesophilic level. The process will follow this course unless preventive measures are imposed.

The compost process is more or less seriously adversely affected at temperatures above 65°C. The reason is that microorganisms characterised by a spore-forming stage do so at temperature levels higher than 65°C. Unless they are thermophilic, other microorganisms either lapse into a resting stage or are killed. Consequently, the current practice is to resort to operational procedures designed to avoid temperatures higher than about 60°C.

D2.2. pH level

The pH level of the composting mass typically varies with the passage of time, as is indicated by the curve in Figure VIII-1. As the figure demonstrates, the level usually drops somewhat at the onset of the compost process. However, it soon begins to rise to levels as high as pH 9.0. The initial drop reflects the synthesis of organic acids. The acids serve as substrates for succeeding
microbial populations. The subsequent rise, in turn, reflects the utilisation of the acids by the microbes.

Because the pH level reached in the initial descent is not inhibitory to most microbes, buffering is unnecessary and could have adverse consequences. For example, the use of lime (Ca(OH)_2) could result in a loss in NH_3-N at the relatively elevated temperatures and pH levels that occur as composting progresses. Nevertheless, the addition of lime may be advantageous in some cases. The addition improves the physical condition of the composting mass, perhaps partly by serving as a moisture absorbent. Furthermore, some researchers report that the addition of lime could be of use in the composting of fruit wastes [2], because the initial drop in pH level often is sharper when fruit wastes are composted.

![Graph showing pH variation as a function of time in composting](image)

**Figure VIII-1. Variation of pH as a function of time in composting**

D2.3. Moisture content

An important characteristic of MSW composting is the close relationship between moisture content and aeration -- particularly in windrow composting. The basis of the relationship is the fact that the principal source of the oxygen required by the microbial populations is the air entrapped in the voids (interstices) between the substrate particles. Diffusion of ambient oxygen into the composting mass is relatively minor in terms of meeting the microbial oxygen demand. Inasmuch as the interstices also contain the free moisture in the mass, a balance must be struck between moisture content and available oxygen. For convenience, this balance may be represented by the term “permissible moisture content”. Thus, the maximum permissible moisture content would be that level above which insufficient oxygen would be available for meeting the oxygen demand, and a state of anaerobiosis would develop. Figure VIII-2 indicates the relation between moisture content and air (i.e., oxygen).

Among the physical characteristics of the substrate that affect permissible moisture content is the “structural strength” of the particles that make up the substrate. Structural strength determines particulate susceptibility to deformation and compaction.

Moisture content is somewhat less critical to aeration in the applications that involve the use of in-vessel compost systems, in which the waste is mechanically, and more or less continuously, agitated. Nevertheless, factors other than interstitial limitations may impose an upper permissible
moisture content in those systems. The limitation arises from a general tendency of material to mat, clump, or form balls. This tendency increases progressively to the point at which a slurry is formed. The range of the moisture levels at which these problems appear coincides with that of most upper permissible moisture content levels.

The importance of keeping the moisture content of the substrate above 40% to 45% is often overlooked in compost practice. It is important because moisture content is inhibitory at lower levels, and all microbial activity ceases at 12%.

Figure VIII-2. Enlarged illustration of the relationship between air, water, and interstices in composting

D3. AERATION

D3.1. Aerobic vs. anaerobic composting

Originally, anaerobic composting was considered to be a viable alternative to aerobic composting, and strong arguments were made in its favour. One such argument was the supposed minimisation of nitrogen loss; another was a better control of emissions. The reality is that these supposed advantages never seemed to materialise. Even had these advantages materialised, they would not be sufficient to compensate for the demonstrated disadvantages of the anaerobic mode. Doubts about the effectiveness of anaerobic composting began to escalate, and by the end of the 1960s, anaerobic composting generally was considered as an unacceptable alternative. Recently, the trend has been to regard composting as being an entirely aerobic process. However, it is now beginning to be recognised that a transient anaerobic phase is essential in the destruction of
halogenated hydrocarbons by way of composting. This need, combined with conservation of nitrogen, may be sufficient for a transient anaerobic phase to merit serious consideration.

As compared to anaerobic composting, aerobic composting has several potential advantages. Among them are the following: 1) decomposition proceeds more rapidly, 2) temperature levels that are lethal to pathogens are attained, and 3) the number and intensity of objectionable emissions are sharply reduced. The emission of some objectionable odours is an inevitable accompaniment of waste treatment and disposal. The extent and intensity of the odours can be significantly ameliorated in aerobic composting by fully satisfying the oxygen demand of the active microbial populations by the institution of an appropriate aeration program. Emissions can also be controlled by capturing the gases of decomposition from the composting mass and treating them in chemical and/or biological gas treatment systems, which reduces the intensity of the objectionable emissions.

D3.1.1. Aeration rates

The rate of aeration at which a composting mass remains aerobic (i.e., satisfies the microbial oxygen demand) is a function of the nature and structure of the components of the waste and of the aeration method. For example, the oxygen demand of a large and active population, composting a mass of easily decomposed material, obviously would surpass the demand of a sparser and less vigorous population acting upon a refractory material.

The accurate calculation of a specific proper aeration rate is a difficult undertaking. The difficulty arises from problems in the acquisition of realistic data with the use of available techniques and equipment. The diversity of data reported in the literature is exemplified by the results obtained in the following investigations.

One of the early investigations [3,4] involved forcing air at various rates into a rotating drum and measuring the oxygen content of the exiting air. Although the experimental conditions did not justify a determination of the total oxygen demand of the material, the experimental results did indicate the rate of O₂ uptake. The respiratory quotient was found to be 1, i.e., CO₂ produced ÷ O₂ consumed = 1.0.

In another phase of the same investigation, the investigator’s concern was about relation of O₂ uptake to principal environmental factors. One of the observations was the not surprising one that rate of uptake increased in proportion to proximity to the optimum level of a factor. For example, the O₂ uptake increased from 1 mg/g volatile matter at 30°C to 5 mg/g at 63°C [4]. On the other hand, O₂ uptake declined in proportion to extent of departure from optimum levels.

The variability is further illustrated by results obtained by other investigators in later years. The following are three examples of these investigations:

1. In one investigation, it was found that O₂ requirements ranged from 9 mm³/g/hr for ripe compost to 284 mm³/g/hr with fresh compost serving as the substrate [5].

2. In another investigation, it was found that oxygen demand ranged from 900 mg/g/hr on day-1 of composting to 325 mg/g/hr on day-24 [6].

3. Uptakes observed in this investigation [7] were 1.0 mg O₂/g volatile solids/hr at a temperature of 30°C and a moisture content of 45%; and 13.6 mg/g/hr at a temperature of 45°C and a moisture content of 56%.
Inasmuch as results obtained by these and other investigators characteristically demonstrated that O\textsubscript{2} uptake depends upon intensity of microbial activity, it should, therefore, decline with increase in stability of the composting mass, i.e., as the mass approaches maturity.

D3.1.2. Prediction of oxygen demand

The full potential oxygen demand cannot be predicted solely upon the basis of amount of carbon that is to be oxidised. The reason stems from the impossibility of arriving at a precise estimate of O\textsubscript{2} requirement on the basis of the carbon content of the waste, inasmuch as some carbon is converted into bacterial cellular matter and some is in a form sufficiently refractory to render its carbon inaccessible to the microbial attack. For purposes of preliminary design of an in-vessel system and a forced-air windrow system, an input air-flow rate of 530 to 620 m\textsuperscript{3}/Mg waste may be assumed [3]. Aeration rates used in the final design should be based on O\textsubscript{2} consumption, as determined by way of early experimentation in which the waste to be composted serves as substrate. With turned windrow systems, the findings would be in terms of frequency of turning. An indication of the O\textsubscript{2} concentrations as a function of depth in a turned windrow may be gained from Figure VIII-3.

In the experimentation and subsequent designing, it should be kept in mind that all malodours emitted from a composting mass are not necessarily a consequence of anaerobiosis. The fact is that some decomposition intermediates and the substrate itself may be malodorous. Moreover, even if complete elimination were possible, accomplishing it in a composting mass larger than about one cubic meter would be technologically and economically unfeasible.

![Figure VIII-3. Oxygen concentrations (%) within compost windrow](image)

D4. OPERATIONAL parameters

D4.1. Monitoring the process

The identification and evaluation of pertinent operational parameters and their bearing on the compost process are essential elements in the development of an effective monitoring program. The attainment of these elements and understanding of their underlying principles can be greatly facilitated by a thorough knowledge of the sequence of events that takes place during the compost process when all conditions are satisfactory. Certain features of the course of the compost process can fill this role and serve as parameters in the monitoring of system performance. Three
prominent features are: 1) temperature rise and fall, 2) changes in physical characteristics (odour, appearance, texture), and 3) destruction of volatile solids.

D4.1.1. Temperature rise and fall

A typical temperature change as a function of time is presented in Figure VIII-4. As is indicated by the curve in the figure, the temperature of the material to be composted begins to rise shortly after the establishment of composting conditions, i.e., after the material has been windrowed or has been placed in a reactor unit. The initial change in temperature parallels the incubation stage of the microbial populations. If conditions are appropriate, this stage is succeeded by a more or less exponential rise in temperature to 60° to 70°C. The exponential character of the temperature rise is a consequence of the breakdown of the easily decomposable components of the waste (e.g., sugars, starches, and simple proteins). It is during this period that the microbial populations increase exponentially in population size. The temperature remains at this level (plateaus) over a period of time that is determined by the system used and the nature of the waste. Thereafter, the temperature begins to drop gradually until it reaches the ambient level.

![Figure VIII-4. Typical temperature variations in a compost pile](image)

The duration of the high-temperature plateau may be prolonged if the substrate is largely refractory, or if conditions are less than satisfactory. It should be noted that the magnitude or intensity of the rise is much reduced if the wastes have a significant concentration of inert material. Such a condition would be indicated by a low volatile solids concentration (e.g., tertiary municipal sludge). In these cases, the temperature level probably would be lower, i.e., in the 50° to 60°C range. If any other condition is less than satisfactory, the results would also be a prolonging of the duration and a reduction of the level of the high-temperature plateau.

Bacterial activity becomes less intense and the resulting temperature drops after the readily decomposable components have been degraded, and only the more refractory components remain. Consequently, it may be assumed in routine compost practice that by the time the temperature has descended to ambient or a few degrees above, the more biologically unstable components have been stabilised and, therefore, the material is sufficiently composted for storage or for utilisation.
Although heat generated in the compost process is a result of microbial metabolism, the accumulation of the heat energy also depends upon the effectiveness of the insulation provided by the composting mass. In short, the characteristic rise in the temperature is a measure of the heat generated in microbial metabolism and retained within the composting mass. Thus, two factors are responsible for the temperature rise -- namely, heat generated by the microbial population and the effectiveness of the thermal insulation provided by the compost mass and by any cover or container enclosing the mass. Effectiveness of the insulation is partly a function of the size of the composting mass. In areas in which the ambient temperature is higher than about 8° to 10°C, the minimum volume for heat accumulation is about 1 m³.

The maturation stage or phase is indicated by the onset of a persistent decline in temperature and other indicators of microbial activity despite the absence of limiting factors, i.e., maintenance of optimum conditions. In short, it coincides with the approaching completion of the compost process and resulting increase in stability. Past experience indicates that the compost mass can be safely used or stored after the temperature has finally dropped to about 40°C.

D4.1.2. Changes in physical characteristics

D4.1.2.1. Appearance

Provided that the process is progressing satisfactorily, the composting mass gradually darkens and the finished product usually has a dark grey or brownish colour.

D4.1.2.2. Odour

An assortment of odours replaces the original odour of the substrate within a few days after the start of the process. If the substrate is MSW, the original odour is that of raw garbage. If the process is advancing satisfactorily, the succeeding odours probably could be collectively described as “faint cooking”. However, if conditions are unsatisfactory (e.g., anaerobiosis), the predominant odour would be that of putrefaction. If the C:N of the substrate is lower than about 20:1 and the pH is above 7.5, the odour of ammonia could become predominant. An earthy aroma is characteristic of the curing and maturing stages.

D4.1.2.3. Particle size

Because of abrasion by the other particles and of maceration, the particle size of the substrate material becomes smaller. Additionally, decomposition renders fibres brittle and causes amorphous material to become somewhat granular.

D4.1.3. Volatile solids destruction

Extent and rate of volatile solids destruction are major operational parameters. Changes in this category include destruction of volatile matter, altered molecular structure, and increased stability. One of the more important causes of these changes is the destruction of some substrate volatile solids (i.e., organic matter) accomplished by bio-oxidation to CO₂. Inasmuch as composting is a controlled biodegradation process in which complex substances are reduced to simpler forms, complex molecular structures are replaced by molecules of a simpler structure. Molecules that are partially or completely impervious (refractory) tend to remain unchanged. This combination of volatile solids destruction and conversion of complex molecular structure to simpler forms constitutes an increase in stability of the substrate organic matter.
D4.2. Parameter utilisation

The role of operational parameters in the diagnosis and remediation of process malfunctions complements their monitoring function. Illustrative examples of the dual role are given in the succeeding paragraphs.

The following example pertains to the temperature parameter: It may justifiably be assumed that some condition is less than satisfactory or even inhibitory if the temperature of the mass to be composted does not begin to rise or rises extremely slowly after the material is windrowed or placed in a reactor. In such a situation, it is highly probable that the underlying problem either is that the moisture content of the mass is excessively high or that it is excessively low. A proliferation of malodours would be symptomatic of excessive moisture. Conversely, the absence of all odours would be indicative of an excessively low moisture content. A possible cause not related to moisture could be an unfavourably high C:N. The difficulty with that diagnosis is the fact that some increase in temperature would be detectable even though the C:N were high. A pH level lower than approximately 5.5 or higher than about 8.5 could be a third possibility.

A high moisture content can be remedied by adding a bulking material. An alternative is to intensify aeration. Aeration not only supplies needed oxygen, it also evaporates moisture. Addition of water is the obvious remedy for a low moisture content. A high C:N can be lowered by enriching the substrate with a highly nitrogenous waste (sewage sludge; poultry, pig, or sheep manure). Lime may be used to raise a pH level. Doing so, however, leads to the difficulties cited in the discussion on pH.

An abrupt, sharp change in an operational parameter is symptomatic of an unfavourable development. Thus, an unplanned interruption of the exponential rise in temperature would indicate the development of an inhibitory situation such as excessive moisture in a windrow or an aeration malfunction in an in-vessel reactor. Either inadequate aeration or insufficient moisture could account for an unscheduled slowing of the exponential temperature rise or shortening of the duration of the high-temperature plateau.

Malodours are indicators of an O₂ deficiency, often brought about by an excess of moisture in the substrate. If excessive moisture is not the cause, the deficiency could be due to an inadequate aeration system or program. Inasmuch as malodours usually are associated with anaerobiosis, the olfactory sense can serve as a monitoring device, albeit somewhat crude. However, a more effective, and more costly, approach is to rely upon especially designed O₂ measuring instruments. With an in-vessel system, the O₂ of “input” air obviously should be greater than that of the discharge air stream.

D4.3. Measurement of stability

The search for an economical and technologically practical test for degree of stability began almost simultaneously with the recognition of composting as a waste treatment alternative. Consequently, many tests and techniques have been and continue to be proposed. The problem is that the tests have one or more deficiencies that diminish their utility. For example, tests that are based on superficial changes in physical characteristics involve a high degree of subjectivity and the unreliability often associated with subjectivity. This is illustrated by the confusion of the temporary stability imparted by a very low moisture content.

A far more frequently encountered deficiency is the lack of universality in terms of applicable values. Lack of universality is illustrated by a test that is based on the concentration of volatile solids. The fallacy arises from the assumption that all materials containing volatile solids degrade with equal rapidity or are equally biodegradable. This deficiency, lack of universality, and other
deficiencies are rapidly disappearing due to refinements in analytical procedures and advances in analytical technology. Unfortunately, these advances involve the services of highly qualified personnel and the use of very expensive equipment.

A list of tests that have been used to determine stability would include low C:N; final drop in temperature; self-heating capacity; redox potential [12]; oxygen uptake [13]; growth of the fungus *Chaetomium gracilis* [13]; the potassium permanganate test [21]; the starch test [14]; and the lipid test [23,29-31]. A sampling of these and other representative tests and their associated analytical procedures is made and discussed in the paragraphs that follow.

**D4.3.1. Low C:N**

Possession of a C:N lower than 20:1 is not necessarily indicative of stability; and, hence, is not suitable as a measure of stability or maturity. The C:N of fresh manures (without bedding) usually is lower than 20:1.

**D4.3.2. Drop in temperature**

In one of the earliest tests, the criterion for attainment of stability is the final and irrevocable drop in the temperature of the composting mass. The specification is based upon the fact that the drop is due to the depletion of readily decomposed (unstable) material. This parameter has the advantage of being universal in its application; the course of the temperature (i.e., shape of the temperature curve) rise and fall remains the same qualitatively, regardless of the nature of the material being composted. Although it is reliable, it is time-consuming, lacks universally applicable specifications, and depends upon degree of self-heating capacity [10]. Nevertheless, the test is fully satisfactory for application in developing countries and for small- and medium-scale operations in industrialised regions.

**D4.3.3. Self-heating capacity**

The test, self-heating capacity, is a variation of the final drop in temperature parameter [10]. The conduct of this test involves the insertion of samples in Dewar flasks. The flasks are swathed in several layers of cotton wadding or other insulating material. The swathed flasks are placed in an incubator. Degree of stability is indicated by the extent of subsequent rise in temperature. The method has the universality of the final drop in temperature parameter. Its disadvantage is the length of time involved, in that it may require several days to reach completion. Nevertheless, it is simple, relatively inexpensive, and satisfactory for use in a developing country.

**D4.3.4. Degree of oxidation**

The criterion of another measure of stability is the breadth of the difference between the percentage of decomposable material in the feedstock and that in the sample being tested. The measure of decomposability was the concentration of oxidizable matter. Accordingly, the method was designed to determine the amount of decomposable, i.e., oxidizable, material in a representative sample [11]. The rationale for the test is that the difference between the concentrations of decomposable material in the raw waste and that in the sample to be tested is indicative of the degree of stability of the latter. The basic procedure involved in the test is the determination of amount of oxidizing reagent used in the analysis. Because stability in composting is a matter of extent of oxidation, the amount of oxidizable material in a product is a measure of its degree of stability. In the conduct of the test, the sample is treated with potassium dichromate solution in the presence of sulphuric acid. The treatment brings about the consumption of a certain amount of the dichromate that had been added in excess to oxidize
organic matter. The oxidizing reagent remaining at the end of the reaction is back titrated with ferrous ammonium sulphate and the amount of dichromate used up is determined.

The amount of decomposable organic matter can be determined with the use of the following formula:

\[ DOM = (mL)(N)(1 - \frac{T}{S}) 1.34 \]

where:
- \( DOM \) = decomposable organic matter in terms of wt % of dry matter,
- \( mL \) = millilitres of dichromate solution,
- \( N \) = the normality of potassium dichromate,
- \( T \) = the quantity of ferrous ammonium sulphate solution for back-titration in millilitres, and
- \( S \) = the amount of ferrous ammonium sulphate for blank test in millilitres.

Quantitatively resistant organic matter is equal to the difference between the total weight lost in the combustion and that degraded in the oxidation reaction.

The basis for oxidation-reduction potential as a test for maturity [12] is the apparent rise in oxidation-reduction potential that accompanies increase in mineralization of the organic matter. The increase is brought about by microbial activity made possible by the presence of decomposable material. The presence of decomposable material results in an intensification of microbial activity and, hence, an accompanying increase in oxygen uptake; which, in turn, leads to a drop in the oxidation-reduction potential. One researcher [12] states that stability has been reached if the oxidation-reduction potential of the core zone of a windrow is <50 mV lower than that of its outer zone. Obviously, this standard is not applicable to in-vessel composting. An important shortcoming of the oxidation-reduction potential is the test’s lack of accuracy and its vulnerability to interfering factors.

D4.3.5. Fungus growth

The effect of maturity of the substrate upon the rate of growth and upon the development of fruiting bodies of the fungus *Chaetomium gracilis* is the basis of another measurement of maturity [13]. The test involves the culturing of the fungus upon a solid nutrient medium that contains pulverised compost. On the 12th day of incubation at 37°C, the fruiting bodies of the fungus are counted. Supposedly, the number of fruiting bodies diminishes with an increase in maturity. The utility of the test is gravely reduced by the lengthy test time, as well as the dependence upon analysts who are skilled and knowledgeable in mycological procedures.

D4.3.6. Starch test

Another potential test, known as the starch test, is based upon the assumption that the concentration of starch in the substrate declines with destruction of organic matter i.e., increase in stability [14]. The rationale is that inasmuch as starch is a readily decomposable, and hence, unstable ingredient of all wastes, its decomposition should increase the stability of a waste. Therefore, a fully matured compost should contain no starch. Consequently, starch concentration is an indication of stability.
The determination of starch concentration involves the formation of a starch-iodine complex in an acidic extract of the compost material. Difficulty in the avoidance of false results combines with the absence of universally applicable values to detract from the utility of the starch test.

D4.3.7. Oxygen consumption/carbon dioxide evolution

The level of O₂ consumed or of CO₂ evolved by microorganisms during decomposition of organic matter is a measure of stability of the material. High unit rates of utilisation of O₂ and, consequently, of production of CO₂ indicate substantial availability of decomposable matter in the substrate to microbial attack, i.e., the material is not biologically stable. Stability of the substrate is indicated when the unit rate of O₂ consumption or of CO₂ formation approaches a low value. There is no definitive endpoint of microbial metabolic activity because metabolic rate gradually decreases as the material is decomposed. Consequently, the results of analyses of reference materials, practical experience, or both are required to judge the degree of stability of the tested material.

Collectively, tests that measure consumption of O₂ or production of CO₂ fall under the general category of respirometry. Several organisations have promulgated respirometry tests, including the following:

- “Specific Oxygen Uptake Rate, Test Methods for the Examination of Composting and Compost (TMECC), 5.08-A”, US Composting Council; and
- “Carbon dioxide Evolution Rate (TMECC), 5.08-B”, US Composting Council.

Additionally, various researchers have reported developing and using methods of respirometry for measuring oxygen required for composting [37,38].

E. Technology

E1. PRINCIPLES

Compost technology has three important functions, the first of which is “pre-processing”. Pre-processing consists of the preparation or processing of a raw waste such that it constitutes a suitable substrate for the compost process. The waste of concern in this section of the book is the organic fraction of municipal solid waste. The second function is the conduct of the compost process. The third function is the preparation of the compost product for safe and nuisance-free storage and/or the upgrading of the product so as to enhance its utility and marketability.

E2. EQUIPMENT

The principal role of equipment is to provide an economically and technologically feasible set of optimum environmental conditions or factors for the microbes. Ranking high in the set of factors is the oxygen availability supplied by aeration of the composting mass. Recognition of this importance is reflected by the emphasis placed upon the development of effective aeration in the design of compost equipment, reactors, and procedures.

Air in the space between the particles of the composting material (interstitial air) is the source of oxygen for the active microbial populations. However, oxygen in ambient air that impinges upon the outer surface (surface air layer) may also constitute a significant source in some compost
systems. Thus, oxygen availability generally is largely a function of the porosity of the composting mass.

As decomposition progresses, interstitial oxygen and oxygen in the surface air layer are consumed in the respiration carried on by the active microbes and are replaced by the CO₂ generated in the respiration. Unless interstitial air and surface air now devoid of oxygen are replaced by fresh air with its oxygen content intact, anaerobic conditions soon prevail. Consequently, aeration equipment must be designed such that interstitial air and surface layer air are renewed at a rate such that O₂ is always available.

Renewal of the oxygen supply can be accomplished by physically rearranging the particles (agitation). Agitation establishes new interstices and surface air layers and an accompanying infusion of oxygen.

Agitation can be accomplished either by tumbling or by stirring, or by a combination of the two. Tumbling is done by way of lifting particles and then allowing them to fall or drop. In windrow composting, tumbling occurs in the “turning” of the composting material. Tumbling is accomplished in some in-vessel systems by way of dropping the composting mass from one floor to another or from one conveyor belt to a lower one. A slowly rotating drum or cylinder equipped with interior vanes is used for accomplishing tumbling in a group of in-vessel systems. In systems involving stirring, movement is primarily sideways (horizontal), and tumbling is practically non-existent.

In several compost systems, the particles remain stationary and only the interstitial air is exchanged more or less continuously. The exchange consists of removing interstitial air saturated with CO₂ and replacing it with fresh air. Surface air also is continuously exchanged. The exchange is accomplished by forcing fresh air into, and simultaneously exhausting spent air from, the composting mass. Appropriately, systems involving such an exchange are termed “forced-air systems”. The effectiveness of a forced-air system is determined by both the rate and the extent to which the forced air is uniformly distributed throughout the entire composting mass.

E3. BIOFILTERS

As mentioned previously in the chapter, the composting process generates odours as a byproduct of the process. The types and intensities of the odours are a strong function of the types of feedstocks, compost process design, and operating conditions that are employed at the facility. Since the odours generated can be bothersome or otherwise a nuisance to the public, the control of odours generated by sources within composting facilities is an important design consideration if the facility is to be located near human populations. Factors that determine the intensity of the odours at offsite locations include chemical composition and intensity of the odours generated at the facility, local meteorological conditions (e.g., atmospheric stability and wind velocity), and distance to the nearest sensitive human receptor. Sources of odour include but are not limited to the raw feedstocks, actively composting material, and unstabilized compost storage piles.

Biofiltration is an effective method of treating and lessening the intensity of the odours generated from the processing of organic materials [35]. Currently, most of the aerated-pile composting facilities in the United States are relying on the application of biofilters for odour control. In addition, the majority of these facilities utilise traditional, above-ground biofilter units. Recent trends in the industry indicate that other designs, such as the application of agitated beds, the use of roll-off containers, and the use of other types of enclosures, may be incorporated into the designs.
During the 1990s and continuing to this day, the proliferation of green waste composting facilities in the United States and organic composting facilities in Europe has contributed to close scrutiny of odour generation and control from composting facilities. Research and development has been concentrated on biofilter design and performance [35,36].

The most common biofilter medium consists of a mixture of compost and wood chips. In some cases, other materials such as peat, lime, bark mulch, or sand may be added. The type and characteristics of the filter medium have a direct impact on the effectiveness of the filter, as well as on its lifespan. Medium selection also depends upon the concentration of odorous compounds in the gaseous stream and on the porosity of the mixture that comprises the medium. Porosity, in turn, has a direct impact on the pressure drop and, thus, the power requirements for operating the system and its ability to support a microbial population.

A biofilter can be constructed as follows: the gases to be treated are conveyed to a network of perforated pipes. The pipes are placed at the bottom of the bed to serve as the air distribution system. A 45-cm layer of round, washed stones is placed over the perforated piping. In order to prevent clogging of the perforations and to allow the upward migration of the gases, a filter layer is placed on top of the stones. One alternative that is commonly used in composting facilities in the United States is the application of geotextiles. Proper functioning of geotextiles depends upon the size of openings in the fabric. After the geotextile (or any other type of filter) is in place, a 100- to 120-cm layer of filter medium is placed on top. The filter medium should be properly selected in order to perform according to specifications. In some cases, an additional 30-cm layer of a different filter medium is placed on top of the previous layer. The effectiveness and efficiency of the filter medium depend upon the following parameters: temperature, moisture content, C:N, nutrient content, and others.

The temperature of the material in the biofilter is affected by ambient conditions, as well as by the flow rate, humidity, and temperature of the gas being treated. Several designers are considering other approaches for lowering the inlet temperature of the gas from thermophilic to mesophilic levels. Some of these approaches include dilution with building air or outside air, or scrubbing with water. The levels of dilution must be properly calculated because the dilutions can lead to additional power requirements for the fans without achieving the necessary temperature decline.

In order to maintain a desired population of microorganisms in the biofilter, it is necessary to keep the moisture content in the range of 50% to 55%. Moisture content can be controlled by means of humidifiers in the piping or by the installation of spray nozzles over the beds. Moisture addition must be carefully designed in order to maintain the desired moisture levels and, at the same time, prevent the generation of free “leachate” and clogging of the open spaces in the bed and in the piping.

The C:N and nutrient content contribute to the maintenance of the microbial population responsible for treating the exhaust gases. These parameters are dealt with through proper media selection.

Other parameters that exert an impact on the performance of a biofilter include: porosity, field capacity, and particle size distribution. Porosity and moisture distribution can be corrected by periodically agitating the beds. The biofilter medium will eventually reach a point beyond which its efficiency for odour removal drops substantially and should be replaced. Although the actual replacement point of the medium will vary and will depend upon local conditions and type of materials used, operators should generally plan on replacing the material at two- to three-year intervals.
E4. SYSTEM selection decision factors

Application of appropriate decision factors is essential not only to the rational selection of system and equipment but also to the successful implementation of an entire compost enterprise. Practical experience has demonstrated the genuine utility of the general principles and decision factors discussed in this section.

A basic and exceedingly valuable principle is that complexity does not ensure success, particularly because complexity does not beget efficiency of process. Product quality is not necessarily improved by complexity. More importantly, the economics of composting allow very little margin for complexity. Thus, any reduction in the time requirement that might be gained from increased complexity would not be sufficient to warrant the additional expense involved. Conceivably, it would be possible to design a reactor such that a product could be produced within the detention times of one or two days. An example of such an approach would be to make an ultra-fine slurry of the waste and then subject the slurry to the activated sludge process conventionally used in wastewater treatment [22]. However, the capital and operating costs of such a setup would be economically prohibitive.

Among the other key decision factors is one directly related to economics. Simply stated, the selected system must be adaptable to the economic and work force conditions of the locale in which it is to be used. This factor would render thoroughly inadvisable the selection of even a moderately automated system by a non-industrialised country in which there would be an excess of labour and that almost certainly would lack the necessary economic and qualified personnel resources.

An important guiding decision factor is one that is related to the evaluation of prospective systems to operate an automated system. Such an evaluation should take into consideration the tendency of some vendors to make unrealistic claims of superior performance regarding acceleration of the process, magnification of efficiency, or production of a superior product. Claims regarding process time should account for all stages of the compost process -- namely, incubation, active (high temperature and curing), and maturing. Ideally, an evaluation would include firsthand observation of a candidate system while it is in operation. It is essential that the observation and evaluation be made by an individual or individuals who are thoroughly conversant with composting as well as with solid waste management. Moreover, the compost product should be sampled and inspected directly at the compost facility on the day it is produced.

Finally, being a biological process, composting is subject to the limitations characteristic of all biological systems. Thus, the rapidity at which a process progresses and the extent to which decomposition proceeds under optimum substrate, environmental, and operating conditions are ultimately functions of the genetic makeup of the active microbial populations. As a result, further sophistication of reactors and/or equipment could not bring about further advances in rapidity and extent of decomposition.

F. Types of compost systems

Compost systems currently in vogue can be classed into two broad categories -- namely, “windrow” and “in-vessel”.

F1. WINDROW systems

As one would suspect, the designation “windrow systems” reflects the distinguishing feature of such systems -- namely, the use of windrows. Windrow systems can be mechanised to a
considerable extent and may even be partially enclosed. Two versions of windrow systems are practiced at present -- namely, static (stationary) and turned. As was mentioned in the section, Aeration, the principal difference between the “static” version and the “turned” version is the fact that in the static version, aeration is accomplished without disturbing the windrow; whereas with the “turned” version, aeration involves tearing down and rebuilding the windrow.

A windrow composting process involves the following principal steps: 1) incorporation of a bulking agent into the waste if an agent is required (e.g., biosolids), 2) construction of the windrow and aeration arrangement, 3) the composting process, 4) screening of the composted mixture to remove reusable bulking agent and/or to meet specifications, 5) curing, and 6) storage.

F1.1. Static windrow

The two principal versions of the static pile are: “passive” and “forced-air”. Despite the distinction between the two designations, the terms static pile and forced aeration often are used interchangeably in current literature.

F1.1.1. Passive aeration

In keeping with the accepted meaning of the word “passive”, the windrow is allowed to remain undisturbed and aeration is a function of natural phenomena. The method or approach does not involve the intervention of mechanical equipment (e.g., fans or turning equipment). Consequently, it would seem to be a method of aeration well suited to a developing nation.

In passive aeration, convection is the principal moving force whereby external air enters the windrowed material and displaces CO₂, although some oxygen may enter the outer layer of a windrow by way of diffusion. Theoretically, the intervention of mechanical equipment for injecting air would not be required. Convection arises from the existence of an imbalance between the temperature of the interior of the windrowed composting mass and that of the ambient (external) air layer, differences in concentrations of oxygen, and from the flow of air over the windrows.

In some cases, units have been incorporated in the designs to promote convection and air movement. The designs usually take the form of chimneys and vents inserted into the composting mass. For instance, in the People’s Republic of China, a system of composting that relies on passive aeration has been used. In the system, organic matter to be treated (in the observed cases, it was organic matter from refuse and nightsoil) is mixed. The mixture is piled to a height of approximately 15 to 20 cm. Subsequently, four timbers having a diameter of about 6 to 8 cm are placed horizontally on top of the mixture in the shape of “#”. The timbers are placed about 1 m apart. At the points where the timbers cross, four vertical timbers (or bamboo poles) are erected. After this, waste is piled until the windrow reaches a height of approximately 1 m. The entire windrow is then covered with mud (see Figure VIII-5). Once the mud has dried, the timbers are removed. According to representatives of the municipality visited (Tianjin), it takes about 3 weeks during the summer and about 4 weeks during the winter for the compost process to be completed. The designers of the system claimed several advantages, including: 1) achievement of high temperatures in the composting mass, 2) achievement of a relatively even temperature distribution, and 3) minimum release of odours. Unfortunately, the effectiveness of such designs, and of convection in general with respect to the maintenance of aerobiosis throughout the composting mass, leaves much to be desired. The problem is the inadequate lateral movement of air.
The designation “forced-air aeration” reflects the fact that aeration involves either mechanically forcing air up (positive pressure) or mechanically pulling it down (negative pressure) through the undisturbed composting mass. The forced-air version was introduced and studied in the late 1950s [15]. However, appreciable attention was not accorded it until the 1970s. Despite a practical demonstration of its utility in the composting of dairy cattle manure [8], the primary reason for the renewal of interest was the ready adaptability of the method to the treatment of sewage sludge [16,32].

An attractive feature of the suction (negative pressure) mode of forced aeration is the ability to pass the exiting air through an emission treatment device. Such a device could be a biological filter consisting of a mass of stable organic matter. The application of a biofilter to control gaseous emissions from composting facilities is a very appropriate solution for developing countries. Alternative devices may incorporate modifications of technology conventionally used in treating combustion emissions.

In the absence of an excessively high moisture content, aerobic conditions can be maintained at a satisfactory level in a static windrow, despite periodic brief interruptions of aeration. (A safe
moisture content is one within a range of 40% to 55%. Because of its dependence upon several variable factors, the specific requisite rate of air input for a particular operation should be determined experimentally [19,20]. The following example provides a tentative indication of rates that could be encountered. The example assumes a 17-m windrow containing about 73 Mg of biosolids. For this setup, an adequate timing sequence would involve forcing air into the pile at 16 m³/hr for 5 to 10 minutes at 15-minute intervals. This particular rate was based upon an assumed need of about 4 L/sec/Mg of dry biosolids.

F1.1.3. Design and construction

The basic arrangement of a static windrow system is shown in Figure VIII-6. The construction of a static windrow conventionally proceeds as follows: A loop of perforated pipe, 10 to 15 cm in diameter, is installed on the compost pad. The loop is oriented longitudinally and is centred such that it will be under the highest part of the windrowed mass. Short-circuiting of air is avoided by adjusting the length of the pipes such that they end about 2 to 3 m short of the edges of the windrow. Non-perforated pipe is used for connecting the loop with a blower. The installed loop is covered with a layer of bulking material or finished compost. This “foundation” layer should cover the entire area to be occupied by the windrow. The foundation layer facilitates the movement and makes possible a uniform distribution of air during the course of the compost process. Due to its absorption potential, it can lessen seepage from the windrow by absorbing excess moisture. Construction of the windrow is then completed by stacking upon the foundation layer the material destined to be composted. The completed windrow should have the configuration shown in Figure VIII-6. Suggested dimensions of a constructed pile are: length, indeterminate; width (at the base), about 4.6 m; and height, about 2.3 m. Usually, the constructed windrow is covered with a 0.3 to 0.4 m layer of matured (finished) compost. The covering layer serves as insulation; it ensures the attainment of high-temperature levels that are lethal to pathogens throughout the composting mass and, thereby, accomplishes a more complete pathogen “kill”.

The “extended aerated pile” is a forced-air version of a “continuous culture”. It is an advantageous approach when large amounts of material are involved. An extended aerated pile is begun by constructing on day-1 a pile in the manner described in the preceding paragraphs. However, only one side and the two ends of the pile are blanketed with insulating cover material - leaving one side exposed. To minimise emission of malodours, the exposed side is lightly covered with a shallow layer of matured compost. On each succeeding day thereafter, an additional loop of piping and accompanying windrow and its appropriate covering are added.
Composting with Forced Aeration

Exhaust Fan
Perforated Pipe
Water Trap for Condensates
Filter Pile
Screened Compost
Woodchips and Sludge
Screened Compost

*a* Piping under pile is perforated for air distribution.

**Figure VIII-6. Schematic diagram of an aerated pile, showing location of aeration pipe**

Each day’s addition is installed immediately adjacent to the preceding day’s loop. Procedures closely akin to those followed in constructing the day-1 pile also are followed in constructing each day’s addition. This procedure is repeated over the succeeding days. After 21 days, the manifestation of this program is an elongated windrow. Continuity is achieved through the removal of day-1 (pile-1) material and replacing it with new (fresh) material. Such an exchange is made on each succeeding day. In short, finished product (compost) is removed twenty-one days after the construction of pile-1. (If the material is not sufficiently composted, the removal may be delayed to the extent deemed necessary.) If it is sufficiently matured, day-2 material is removed on the 22nd day and is replaced with fresh material. A similar exchange is made on the 23rd day. Daily exchanges are made until all piles are reconstituted. Thereafter, the external manifestation is an elongated pile from one end of which an increment of material is removed and is replaced by adding a comparable increment of fresh material to the opposite end of the pile. In effect, continuity is attained and maintained; and the residence time is 21 days.

An important advantage of the extended approach is a substantial reduction in spatial requirements. With respect to wastewater solids (biosolids), the land area needed for a single-pile compost system, together with area involved with runoff collection, storage, and administration, amounts to approximately 1 ha per 7 to 11 Mg (dry wt) of biosolids processed.

**F1.1.4. Evaluation of the static pile approach**

Because its capital cost is largely site-specific, it is difficult to arrive at a generally applicable capital cost for static pile composting. Modest equipment requirements and cost apparently render the static pile economically attractive. The problem is that the method is sufficiently satisfactory only with wastes that have a granular texture, that have relatively uniform particle size, and in which the size of the particles is less than 3 or 4 cm. Otherwise, there is a tendency of anaerobic pockets to develop in substrates that are characterised by a wide diversity of overly large particle sizes. This tendency is a consequence of the resulting uneven distribution and movement of air through the composting mass (channelling).
F1.2. Turned windrow

The current consensus is that the turned windrow approach antedates the forced-air (static) approach. As was stated earlier, a distinguishing characteristic of the turned windrow is the accomplishment of aeration by way of the periodic turning of the windrowed material, i.e., tearing down and reconstructing the windrow.

Although the ultimate reason for the turning process is the accomplishment of aeration, turning does simultaneously fulfill other beneficial functions. It periodically exposes all parts of the composting mass to the interior of the pile, i.e., to the zones of highly active microbial activity. It also may further the reduction of particle size. Turning accelerates loss of water from the composting mass. This is beneficial if the moisture content is unfavourably high; conversely, it is disadvantageous when the moisture level is unfavourably low.

F1.2.1. Windrow construction

Conventionally, windrows are roughly conical in cross section. However, certain conditions may dictate a variation from the conventional shape. If a variation is indicated, it should be one that best fits the situation. A loaf-shape, characterised by a flattened top, would be appropriate for dry, windy periods because the ratio of exposed surface area-to-volume would be less than it would be with other configurations. However, a flat top would be a drawback during rain or snow. If turning is done by machine, the configuration and dimensions of the windrow are functions of the design of the turning machine.

To avoid compaction, the height of the windrow should not exceed 2.3 m.

F1.2.2. Turning space requirement

The total space involved in the turning process can be significantly large. The area requirement is particularly large if turning is done manually. At the other extreme, the area requirement is minimal with certain types of mechanical turning.

According to the logistics of turning indicated by the diagram in Figure VIII-7, from 2 to 2.5 times the area occupied by the original pile is required for manually turning a single day’s input. The second day’s manual turning returns the pile to its original position. The double space requirement for each day’s increment continues until the material is sufficiently composted.

![Figure VIII-7. Process for turning windrows manually or with front-end loader](image)

The spatial requirement for mechanised turning is a function of the type of machine utilised for the operation. Thus, the turning space required by a certain type of machine can be quite small. Machines of this type usually are designed to straddle the windrow. As the machine advances, it tears down the straddled windrow and directly reforms the composting mass into a new windrow.
Consequently, the turning space involved is only slightly more than that occupied by the original windrow. The additional space is that which is needed for positioning the machine.

The turning space required with machines that do not straddle the windrow is comparable to that needed in manual turning. The reason is that the position of the reconstructed windrow is adjacent to that of the torn-down windrow.

F1.2.3. Windrow reconstruction

Obviously, windrow reconstruction in the turning process should be done such that pathogens that may be present in the composting mass are destroyed. Moreover, the reconstruction should promote uniform decomposition. Pathogen destruction and uniform decomposition can be accomplished by reconstructing the torn-down windrow such that material in the outer layer of the torn-down pile is in the interior of the reconstructed windrow. Certain circumstances, e.g., design of the turning machine, could make it unfeasible to reverse positions at every turning, which could be compensated for somewhat by an increase in frequency of turning. For example, the frequency could be adjusted to 2 or 3 turnings per day.

F1.2.4. Turning frequency

Ideally, the turning frequency should be such that: 1) sufficient O₂ always is available to meet oxygen demand, and 2) all pathogens are destroyed. Nevertheless, economic and technological realities may compel a compromise between the practical and the ideal.

With respect to meeting oxygen demand, turning frequency depends upon the available pore volume. Available pore volume is a function of the porosity of the pile and its moisture content. Pore volume, in turn, depends upon the structural strength of the windrowed particles and consequent ability to retain pore integrity. Therefore, the drier the material and the firmer the structure of the particles, the less frequent will be the indicated turning.

A variable factor regarding turning frequency is the rate of decomposition desired by the operator. The bearing of this factor on turning frequency is by way of the effect of aeration on rate of decomposition. Until another factor becomes limiting, rate of decomposition increases with intensification of aeration, and intensification increases with increase in turning frequency.

Practical experience [9,17,20] indicates that rate of composting can be accelerated through the establishment of two sets of conditions. The first set involves the use of a substrate in which: 1) sufficient microbial nutrients are readily available; 2) a bulking material, such as dry grass, dry leaves, wood chips, sawdust, or paper, is used; and 3) moisture content is on the order of 60%. The second set of conditions calls for a turning schedule according to which the first turning takes place on the third day following the institution of compost conditions and four subsequent turnings, i.e., one every other day. After the fourth turning, the frequency need be only once each four or five days. Both sets of conditions most likely would exclude MSW and biosolids composting.

Increasing the frequency of turning, e.g., one turn per day, often can lessen the emission of putrefactive odours, inasmuch as such odours are symptomatic of anaerobiosis. A once-per-day turning regimen also can promote the loss of excess moisture from a windrow.

F1.2.5. Manual turning

Manual turning is a very appropriate approach in small-scale operations in any location but particularly applicable in areas where there is a surplus of unskilled labourers. The most practical
tool for use in manual turning is the pitchfork (trinche). There are some key factors that should be kept in mind when piles are to be turned manually.

1. The height of the pile should not exceed that of the typical labourer.

2. Sufficient space must be incorporated in the design such that a new pile can be formed in the process of aeration.

3. During rebuilding of the pile, material from the outside layers of the original pile should be carefully placed in the interior of the newly formed pile. Since it is not always convenient to turn the pile in such manner, in practice, supervisors should aim at trying to place material from the exterior of the pile in the interior of the new piles as often as possible during the course of the composting process. If this ideal situation cannot be achieved, the deficiency can be compensated by increasing the frequency of turning (e.g., from two times per week to three times per week).

4. The new pile should be reconstructed such that the composting material is not compacted as to impede some air circulation.

Based on the authors’ experiences, a motivated labourer can turn approximately 8 to 10 Mg of organic matter per 8-hr day. In practice, manual turning has been employed in composting programs processing on the order of 20 to 30 Mg of organic matter per day. It is important to emphasise that if manual turning is to be employed, the workers must be carefully trained on the composting process and on safety procedures. In addition, the workers must be provided with safety equipment such as dust masks, boots, gloves, and uniforms. The composting facility should be equipped with a first-aid kit, as well as with bathrooms and showers.

F1.2.6. Turning equipment for windrows

When manual turning is not feasible, some form of mechanised turning must be used. Forms presently available can be conveniently classified into two broad categories: 1) machines specifically designed to turn windrowed compost material, and 2) machines designed to move earth. Machines in the first category are often termed “mechanised turners”.

F1.2.6.1. Mechanised turners

Currently, several types of mechanised turners are available. Serious obstacles to the acquisition of the machines are the relatively high capital and operating costs associated with the machines. The magnitude of these costs very frequently places the acquisition beyond the economic and technological resources of most developing nations and small operations in industrialised countries. In situations in which sufficient financial and technological resources are at hand, the scale of the operation must justify the expenditure.

Several types of mechanical turners are on the market. The machines differ among themselves in degree of effectiveness and durability. Capacities vary with the model of machine; with some models the capacity may be on the order of 1,000 Mg/hr, with other models it may be as much as 3,000 Mg/hr. Prices range from about US$20,000, to more than US$180,000, FOB.

F1.2.6.2. Conventional earth moving machines

Examples of conventional earth moving machines that are used for constructing and turning windrows include the bulldozer, front-end bucket loader, and backhoe ditch digger. The objection to the use of such equipment is the tendency to compact the composting material, to inadequately
agitate and aerate it, or both. This is especially true when a bulldozer is employed. Almost certainly, objectionable odours will be generated. Although the performance of these types of equipment as compost turners is far from satisfactory, it can be acceptable if the machines are used carefully by knowledgeable operators.

The conventional rototiller has been used with considerable success for turning relatively small amounts of compost material (i.e., less than a few Mg per day). The rototiller is a relatively small piece of equipment designed to till garden soil. Turning with the use of a rototiller is done in four steps:

1. tear down the pile or windrow;
2. spread the material to form a 30- to 60-cm layer;
3. rototill (“agitrate”) the compost mass, i.e., pass the machine back and forth through the layered mass; and
4. reform the pile or windrow.

F1.3. Site preparation

Site preparation involves a number of activities: A surface is provided that can satisfactorily accommodate all phases of the operation; and provision is made for the collection and treatment of leachate and for the diversion of runoff. In desert regions, a windbreak is erected to shield windrows from drying winds and, thereby, avoid excessive loss of moisture by way of evaporation. In situations characterised by moderate to heavy rainfall, roofing is provided to shelter the windrows, particularly during the active and early maturing stages.

With respect to surface, windrows should be kept on a paved surface throughout the time they must be worked, i.e., until the material is ready to be stored. A paved surface is necessary because it: 1) facilitates materials handling, 2) enables control of leachate and diversion of runoff, and 3) prevents migration of fly larvae to surrounding areas. The only paving materials suitable for operations that involve the use of a mechanical turner are asphalt and concrete. The weight of a mechanical turner makes it essential that the machine be operated on a surface that provides a firm footing. Only asphalt pavement and concrete pavement furnish such a surface. For operations that do not involve the use of a mechanical turner, the list of suitable paving (surfacing) materials expands to include not only concrete and asphalt, but also packed gravel, crushed stone, and thoroughly compacted soil. However, compacted soil is only marginally suitable because turning and ancillary traffic are seriously impeded when the soil becomes wet, such as during periods of rainfall.

F1.4. Windrow facility

An idealised version of a windrow compost installation is one that would be housed in a shelter. The shelter would be provided with the ventilation equipment needed to control and treat gaseous emissions. Windrows would be turned by means of an automatic turning machine. Maturation could take place either within the shelter or outside.

Plastic particles and similar contaminants in the compost product can be removed by way of screening. Inasmuch as the screen oversize consists mainly of plastics, it is removed immediately. The tendency of plastics to be concentrated in the oversize stream is due to the low density of plastics combined with their characteristically two-dimensional shape and, of course, their tendency to be oversize in terms of screen opening size.
Should the finished product contain glass particles, a second stage of size reduction can be included into the process. The degree of size reduction used in the process, particularly in developing countries, must be carefully evaluated since size reduction is an energy- and maintenance-intensive process.

F1.5. Economic considerations

The many variations between approaches to windrow composting render it difficult to formulate generalisations regarding the economics of the process. The only exception can be stated as follows: It can justifiably be expected that either turned or static windrow composting would be less costly than in-vessel composting. Current versions of windrow composting differ among themselves with respect to size, degree of mechanisation, and process. An example of the effect of the differences is the wide spread between the economics involved in a few-Mg per day operation and those of a several-hundred Mg per day facility.

The cost of the mechanical turner is a major item in the economics of medium- to large-scale operations. If a shelter is provided, it need not be elaborate; it should, nevertheless, include provisions for the control and treatment of problem emissions such as malodours and dust. Shelters would be particularly important if the facility is built relatively close to residential or commercial areas. Reported costs for composting MSW, manures, and biosolids range from US$30 to US$60 per Mg.

F1.6. Constraints

Aside from economics and political and sociological constraints, the principal constraints on windrow composting are either of public health or of environmental origin. The presence of human excrement or of the remains of diseased animals in the compost substrate generates a potentially serious public health constraint, depending upon the degree to which temperature levels that are lethal to pathogens are reached and maintained. The problem is that it frequently happens that lethal temperatures do not entirely pervade a windrow; this is especially true for the outermost layers. Another problem is the likely recontamination of already sterilised material by unsterile material during the turning operation. However, such recontamination can be compensated considerably by increasing the frequency of turning.

The almost inevitable emission of odours, despite the establishment of a preventive regimen, constitutes a serious environmental constraint. This constraint and proposed methods of alleviating it are discussed in another section. However, it should be emphasised that the inevitability of malodour emission is characteristic of most systems that involve the handling and processing of community wastes.

The relatively long process times and the attendant greater area requirements frequently are construed as constituting a constraint on windrow composting. This constraint is not necessarily a disadvantage in that, as was explained earlier, rapid composting is an advantage either when land area is a critical factor, or when in-vessel composting is involved. The rationale in the latter case is that cost savings through reduction of the monetary expenditure on land acquisition can be used to partially or entirely compensate the cost of the in-vessel reactor.

F2. IN-VESSEL reactors

Goals underlying the design of an in-vessel reactor are to: 1) accelerate the compost process through the maintenance of conditions that are optimum for the microbes active in composting, and 2) minimise or eliminate adverse impacts upon the ambient environment.
Excepting for minor variations, current reactors commonly have these characteristics: 1) the design of each reactor represents a relatively minor deviation from other reactors in a comparable category; and 2) various methods or combinations of them are used to aerate the composting mass, some more successfully than others. The aeration design usually calls for one or more of the following features: forced aeration, stirring, and tumbling. Forced aeration is employed to some extent in most in-vessel reactors. Stirring is accomplished by rotating ploughs or augers through the composting mass. Tumbling can be accomplished by dropping the composting material from one level to a lower level (from belt to belt, or floor to floor). Another mechanism for tumbling is a rotating horizontal drum equipped with internal, horizontally-oriented vanes.

F2.1. Examples of proprietary in-vessel reactors

There are many types of in-vessel systems that have been used over the years. A few of these systems are described in this section.

F2.1.1. Dano drum

Dano reactors have been on the market since the 1940s [33]. The Dano reactor typifies the horizontal drum category. As such, its distinguishing feature is a long, almost horizontal, drum that is three or more meters in diameter and is rotated at about 2 rpm. Severe economic constraints restrict residence time in the drum to the active stage of the process. Therefore, maturation takes place outside the drum and involves windrow composting. It is highly doubtful that a Dano facility would be within the economic and technological resources of most developing countries. Not only are Dano reactors expensive in terms of capital expenditures, they also involve high operational and maintenance costs.

F2.1.2. Other horizontal drum systems

The design of the Eweson system differs from that of the Dano system in that its drum is divided into compartments such that the residence time can be varied throughout the drum. The system used in the Ruthner System and the PLM-BIAS systems are two additional versions of the drum design [18]. Although some of these systems are no longer being marketed at the time of this writing, an example of an operating Eweson-type drum is shown in Figure VIII-8.
F2.1.3. Naturizer system

The original Naturizer system exemplifies the tumbling floor approach. The system involves the use of two vertical silos positioned side-by-side. Each silo has three floors. The distinctive feature of the silos is the use of floors that consist of V-shaped troughs placed side-by-side. Transfer of the compost mass from an upper floor to the one immediately below is accomplished by inverting the upper-floor troughs. A conveyor belt dumps processed wastes on the top floor of the first silo. The wastes are retained on this floor over a 24-hr period. At the end of the period, the composting mass is dropped to the middle floor on which it is held over a second 24-hr period, and then is dumped upon the bottom floor. After having been size reduced, the composting mass is then transferred to the top floor of the second silo, where the routine is repeated. Thus, the total retention time in the tandem silos is six days. Following discharge from the second silo, the material is windrowed and allowed to mature over a one- to two-month period.

F2.1.4. “Metro”- or channel-type

Metro- or channel-type in-vessel systems combine forced aeration with tumbling. The system involves the use of an elongated, horizontal open channel or reactor, equipped with a perforated bottom and a mobile agitator designed to tumble the contents of the channel (see Figure VIII-9). (Typically, the agitator is some version of the travelling endless belt or a rotating drum.) These types of systems are also sometimes called “aerated, agitated bed” systems. In addition to that brought about by tumbling the composting material, aeration includes the forcing of air into the
composting mass by way of the perforations in the floor of the trough. It is likely that through a suitable adjustment in the frequency of the passage of the agitator through the trough contents, it would be possible to eliminate the forced-air feature without adversely affecting system performance. An exception would be the use of forced air as a means of controlling temperature.

Figure VIII-9. Metro- or channel-type system, showing channels and agitator at left centre

The compost operation cycle begins with the discharge of size-reduced waste into the tank and subsequent passage of the travelling agitator through the wastes. Simultaneously, air is forced through the material. The agitator is passed through the mass on the order of once each day. The residence time recommended by the vendor is six days. Thereafter, the material is windrowed for one to two months. There are currently several systems on the market that utilise designs similar to those of the Metro system.

F2.1.5. Fairfield reactor

The Fairfield reactor is representative of in-vessel systems characterised by the use of stirring, combined with forced-air injection, to accomplish aeration. The reactor consists of an open cylindrical tank in which is installed a set of screws (“augers” or “drills”), which are hollow and are perforated at their edges. The set is supported by a bridge attached to a central pivoting structure. The reactor is shown in Figure VIII-10. The bridge with its collection of augers is slowly rotated. The augers are turned as the arm rotates. Air is discharged from the perforations and into the composting material as the screws are forced through the material. Residence time varies. If the time is less than two or three weeks, the material must be windrowed in order to attain stability.
F2.2. Economics

Intuitively, one would surmise that the economics of in-vessel systems in a developing country would be less favourable than those for windrow composting. In the early 1970s, capital costs for compost plants in the United States were on the order of US$15,000 to US$20,000/Mg of daily capacity; and operational costs were US$10 to US$15/Mg. In the late 1990s, capital costs were in the range of US$40,000 to US$100,000/Mg of daily capacity; and operational costs have varied between US$30 and US$60/Mg. A common failing in estimating and predicting capital, maintenance, and operational costs is the tendency to hold down apparent cost by basing the costs upon underdesigned equipment and underestimated labour requirements. Other factors to consider in making a comparative evaluation of in-vessel systems were discussed in the section, Technology.

G. Marketing and distribution of compost

G1. POTENTIAL markets

The benefits of using compost as a soil amendment are well documented. Compost increases the organic content of the soil and can improve its texture, its nutrient content, and its water retention and aeration capacities. Because of the utility of compost, it can be used in a variety of applications. Examples of such uses include [34]:

- Agriculture -- food and non-food crops, and sod farms
- Landscaping -- commercial properties and grounds maintenance
- Nurseries -- potted plants, bare root planting, and forest seedling crops
- Public agencies -- highway landscaping, recreational areas, other public property
- Residences -- home landscaping and gardening
- Other -- land reclamation and landfill cover

The quality of the compost dictates which types of uses are appropriate. For example, nurseries require a high-quality product; whereas, a lesser quality material would be suitable for land reclamation or landfill cover. Product quality is a function of a number of factors, including the types and characteristics of the feedstock material; the design and operation of the composting facility; and the post-processing, if any, that is employed to upgrade the product. Examples of post-processing activities include shredding, screening, nitrogen addition, and bagging.

The agriculture industry is the largest potential market for compost, especially in economically developing countries, although it can be difficult to penetrate. Factors that can militate against the use of compost in agriculture, as well as in other market segments, include: shortage of readily available, reasonably priced compost; unawareness of the general utility of the product; indifference; difficulty in applying the material; and cultural or other bias against the use of products generated from waste.

G2. SELLING PRICE

Not all of the considerations that normally should enter into the determination of a suitable selling price of a commodity are applicable to the compost product. One such exception is the fact that the selling price need not fully defray the monetary cost of producing the product, the reason being that composting is a service in that it is a viable option in the treatment and disposal of organic wastes. Because of its role as a service, composting need not generate a revenue. On the other hand, practicality dictates that the cost of utilising the service should be competitive with other options, e.g., landfill and incineration. Obviously, the competitiveness of the composting option would benefit from revenue derived from the sale of the product. As of the early 2000s, the prevailing selling price of biosolids and yard waste composts in the United States is on the order of US$7 to US$25/Mg. In developing countries, the price of compost is on the order of US$5/Mg.

Competitiveness is enhanced by the fact that composting is a resource recovery activity, characterised by a formidable array of environmental credits.

Despite the many benefits inherent in the compost option, the establishment of the selling price of the compost product is subject to certain important constraints. One such constraint is the sharp limitation exerted by the economics of the farming industry upon chemical fertilisers and inorganic additives. This, in turn, exerts a dampening effect on the establishment of the selling price of compost.

In the establishment of policies regarding the value of organic amendments, local, regional, and national governing bodies in developing nations should be aware that continued soil fertility depends upon maintenance of the soil’s organic content. Inasmuch as this maintenance is best done through the use of the compost product, lowering of the product’s selling price through subsidisation might be justifiable. However, this justification is not valid if the product is destined solely for landscaping and cultivation of ornamentals, unless such use is the maintenance and care of public grounds and recreational areas.
G3. MARKET development

As is true with other products, development of a market for compost involves instilling in potential users an awareness of the utility of the product. Additionally, it often is necessary to overcome existing inertia and bias.

In this section, the discussion of market development consists of a description and explanation of a plan conceived in, and formulated for, an agriculturally-oriented community situated in an elevated (about 2,600 m), semi-arid rural region. Corn (*Zea maiz*) is the principal agricultural crop. The soil is in dire need of organic matter. The proposed plan has the attractive feature of offering a program that adapts education to the promotion of the compost product.

The project plan calls for a cooperative undertaking in which a city and a farmers’ cooperative are the active parties. An important component of the planned undertaking is a recycling/composting endeavour. According to the plan, the city would embark upon a resource recovery program in which it would process its wastes (MSW) such that reusable materials would be separated and removed, leaving a compostable residue. This residue would be delivered to the participating farmers’ cooperative. The cooperative would then compost the material on sites controlled by the group. The compost product would be distributed among its members for use on their individual farms. Figure VIII-11 depicts a similar type of demonstration performed jointly by the authors and a rural farm cooperative in an Eastern European country.

![Image](image_url)

Courtesy: CalRecovery, Inc.

**Figure VIII-11. Compost Demonstration and market development project performed at a rural farm cooperative**

A key feature of the plan is the combined education/promotion program, designed to convince the farmers regarding the utility of the compost product in crop production. Consequently, the program would be in the form of a demonstration of the beneficial effect of compost on crop production.
According to local, experienced government agriculturalists, the first step in such a demonstration
should be to encourage leading members of the farmers’ cooperative to test the product on their
farms. The leaders’ participation would be valuable, if not essential, because they have earned the
respect of their fellow farmers by virtue of demonstrated superiority in farming and in the
conduct of farm affairs. In the first year of the demonstration, the leaders would be supplied with
compost at no cost. To the extent permitted by circumstances, the leaders would use the compost
in the conduct of scientific tests under the guidance of agricultural agents. The rationale of
relying upon leaders to conduct the tests is obvious -- if the leaders are convinced as to the utility
of the product, it should require no great effort to convince the other farmers.

The objectives of the tests were to be threefold:

1. to arrive at a determination of the extent to which chemical fertiliser requirements (NPK)
could be met by the compost;

2. to demonstrate an increase in crop yield solely attributable to the addition of compost; and

3. to demonstrate an increase in water-holding capacity of the soil and the resulting
enhancement of efficiency of irrigation water utilisation. (This benefit is a strong
motivational factor, because of an unavoidable dependence in the region upon irrigation
water. Hence, required expenditure for water is a significant element in a farmer’s budget.)

It should be noted that the experimental plan did not include provisions for “control plots”, i.e.,
plots in which compost serves as the only source of NPK. The omission was deliberate for a very
practical reason -- extreme scarcity of land available to individual farms in the project region
precluded farmers in that region from exposing themselves to any risk that could result in a
diminution of a normal crop yield. Not surprisingly, no participant would be willing to include a
control plot.

G4. PRODUCT distribution and transport

Having developed the market demand essential to the viability of a compost enterprise, logically,
the next step is to devise and establish an effective and efficient distribution system. To be both
effective and efficient, the distribution system must be such that the greatest number of
consumers has ready access to the product at the lowest cost. Among the key considerations in
devising an ideal, or at least, satisfactory system is the minimisation of haul distance between the
point of production and the consumer. This factor derives its importance from the fact that
transport cost is a decisive element in the magnitude of the eventual monetary burden to be borne
by the consumer. Ultimately, transport cost is largely a function of distance.

A variety of strategies have been developed whereby required haul distance can be manipulated.
One of the strategies calls for the production facility to be located centrally. The advisability of
this strategy is a function of the relative advantages of centralised production facilities versus
scattered production facilities. Greater economies of scale can be achieved with centralised
production. However, transportation costs also would usually be expected to increase. The
reduction of potential economies of scale characteristic of widely scattered facilities is
compensated by a reduction in haul costs. Finally, in a developing country, economy of scale
does not have the high degree of significance that it does in an industrialised country.

If the compost facilities are scattered, distribution would best be accomplished by having the
individual consumer take delivery at the facility, inasmuch as no great distances would be
involved. On the other hand, if a sizeable central facility is involved, the indicated course would
be to establish a system of outlets at which prospective consumers could take delivery.
The mechanics of distribution are as diverse as the variety of possible situations.

**H. References**


