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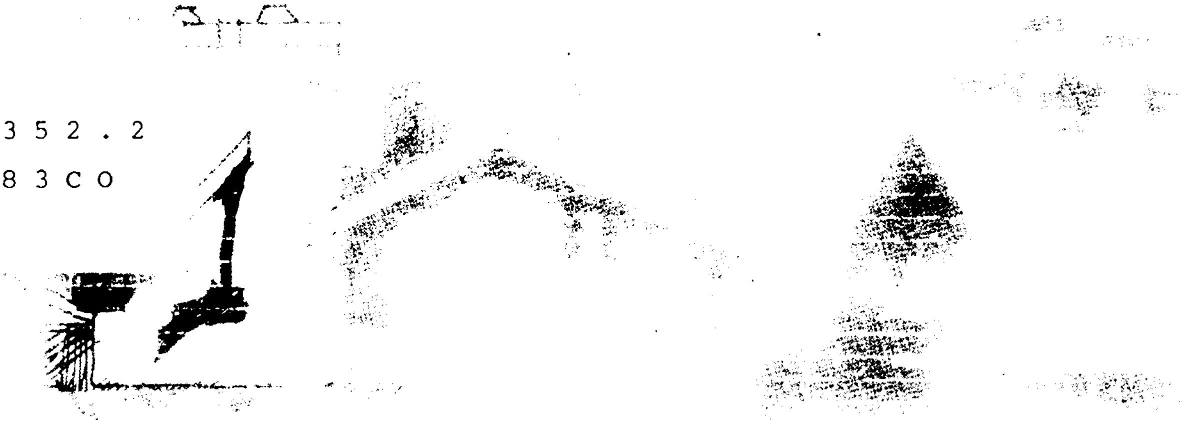

Composting of Domestic Refuse

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COMPOSTING OF DOMESTIC REFUSE

by

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Preface

This review deals mainly with the composting of domestic refuse, that is to say all solid wastes generated from the house.

The issue is important for a number of reasons.

First of all proper disposal of domestic refuse is vital for eliminating considerable risks to health and to the environment, particularly with regard to the rapidly increasing urbanization taking place in developing countries.

In addition, the conversion of domestic refuse through composting provides a most valuable source of soil conditioners and fertilizers, which are in great demand for Third World agriculture. These fertilizers have the advantage of avoiding the adverse effects of chemical fertilizers and of decreasing the dependency of developing countries on foreign currency consuming imports, at a time when stepping up food production is becoming a most urgent need.

The present state-of-the-art reviews will hopefully guide interested parties in developing countries in efficient disposal and reuse of domestic refuse.

The Editors

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Composting of Domestic Refuse

by

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H. Kubota

I. INTRODUCTION

I.1 The Scope of the Review

This review is mainly about composting of domestic refuse and not other waste materials. For nightsoil (human excreta) composting, the reader may refer to the recent publication brought out by the World Bank (Shuval et al., 1981). Animal wastes and human excreta will be mentioned when they have some relevance to the discussion, but will not be the main theme for this review.

I.2 What Is Domestic Refuse ?

Domestic refuse is understood in this review as a combination of all solid wastes generated from the house, such as organic food wastes, paper and paper products, wood, plastics, leather & rubber materials, rags and textile products, glass, metallics, inert stones, clay, earthen products and yard, and other bulky wastes. These are more or less similar throughout the world, but the proportions vary widely from country to country and even within a city, because the variations are closely related to income levels, living patterns, etc. As personal income rises, paper increases, kitchen wastes decline, metals and glass increase, total weight generated rises, and the density of the wastes declines.

The characteristics of domestic refuse from various cities in developing countries have been studied well. Tables 1 and 2 present some data compiled by Pickford (1977) and Lohani & Thanh (1979), respectively. Generally, the refuse generated in developing countries is characterized by :

- 20% to 75% vegetable-putrescible matter,
- 5% to 40% inert matter,
- 2% to 60% paper,
- 0 to 10% glass,
- 0 to 15% metals.
- the generation rate is usually between 300 and 500 g per person per day,
- the density is from 100 to 400 kg/m^3,
- thus the volume may range between 0.8-1.5 liters/person-day.

Table 1: Composition of Town Refuse*

Place		World range	Bangkok, Thailand		Calcutta, India		Deshapara India	Delhi, India	Dubai	Enugu, Nigeria	Ibadan, Nigeria		Madras, India	Nagpur, India		Poona, India	UK	USA
Date		1971	1957	1970	1970	1964	1970	1974	1973	1973	1972	1972	1970?			1970?	1968	1972
Fruit and vegetable	% by weight (generally wet weight)	5-90	47.5	2.6-5.1	16.0	14	20	20.3	40				57	3.8	4-6	68	1706	
Leaves, grass, straw wood, coconut shells				6-75	18.0		21			83	80.7	9.6		12.9	4-6			9
Food wastes			0.7							9.1	9.1	70.3						14
Paper and cardboard		0.25-55	4	7-13	3.2			5.9	25.5		3.4	10.0	4.8	2.0	3-6	8.7	36.9	55
Rags			5.4	0.3-0.6	3.6	2	1	3.6	8.0	4.1	4.1	1.6	3.8	0.6	3-7	1.6	2.4	3
Glass, crockery, bones			1.9	1.6-6.9	7.4	4	1	0.6	5.0		0.5	2.5	0.5	0.2	0.3-0.8	0.6	9.1	9
Metal, tins			2.3	0.8-1.3	0.7	4		0.6	12.5	2.3	2.3	5.9					8.9	9
Plastics		0.1-7		2-7	0.6			0.5	4.5				0.6	0.3	0-2	0.7	1.1	1
Dust, ash, cinder			24.1		41.6	69	57	6.0									21.9	
Miscellaneous			14.1			7			4.5	1.0							2.1	
Moisture content					41			14.7			43-65			42	10-32			
Weight per person kg/d		0.2-3			0.51	0.39	0.32	0.31			0.4-0.6		0.56			0.3	0.80	2.6
Density kg/l		0.1-0.5		0.163 0.335	0.52 0.57	0.46	0.38	0.47			0.28		0.435			0.298	0.157	
Volume per person l/d					1.08	0.8	0.85	0.66			1.4		1.29			1.0	5.1	
Calorific value kJ/kg					6300		1400	6600					6700	5300	4600	7100	8000-10 500	

**Data compiled from various sources. For details, see Pickford (1977).*

Table 2. Comparative Refuse Analysis

	Britain*	Bangkok*	Bangalore*	Bangalore*	Hong Kong[1]	Jakarta[1]	Seoul[1]	Taiwan[1]	Singapore[2]
	Typical	Analysis by Municipality	Analysis by Flintoff Burner	Analysis by NEERI Sumner					
Vegetable/putrescible	28	44.0	75.2	65.1	9.42	60	–	24.6	4.6%
Paper	37	24.6	1.5	2.7	32.46	2	4	7.5	43.1%
Metals	9	1.0	0.1	0.4	2.17	2	0.4	1.1	3.0%
Glass	9	1.0	0.2	0.2	9.72	2	0.15	2.8	1.3%
Textiles	3	3.0	3.1	0.9	9.58	–	–	3.7	9.3%
Plastics and Rubber	3	7.0	0.9	0.3 (exe. rubber)	6.24	2	1.8	2.3	6.1%
Misc. Combustable	1	–	0.2	0.2	4.94	7 (egg Shells)	0.6 (Wood)	–	3.9%
Misc. Incombustable	1	3.5	6.9	1.2	–	–	78.0 (ashes)	56.0 (ashes)	–
Inert below 10 mm	9	4.8	12.0	–	14.09	–	–	–	6.4%
Fine Earth	–	–	–	29.0	–	–	–	–	–
Other Materials	–	–	–	–	10.47	25	13.7	0.8	22.3%
Density kg/m^3	150	250	570	405	–	–	–	–	175

Note: * *Solid Wastes Management Practises in Southeast Asia, Report by Frank Flintoff, WHO Consultant.*

[1] *Country Reports on Solid Waste Management Seminar, Bangkok Thailand 25 Sept. – 30 Sept. 1978.*

[2] *Personnel Communication.*

Just as domestic refuse comprises a vast number of materials, they arise from a multitude of separate sources : a city of a million inhabitants may have a quarter of a million separate sources, as well as many kilometers of streets upon which solid wastes accumulate.

1.3 Disposal of Domestic Refuse - A Problem

There are potential risks to health and the environment from improper handling of solid wastes. Apart from odor and aesthetical ugliness, risks to public health arise from the breeding of disease vectors, primarily flies and rodents. With an increasing population worldwide, very high population densities in urban areas and rising standards of living, the volumes of domestic solid wastes have increased greatly.

In developed countries, where the domestic wastes are estimated to be increasing at a rate of up to 1 tonne/family-year (Flintoff, 1976), the services for the regular removal of these domestic wastes along with trade wastes have been in operation for a hundred years or more. By contrast, many developing countries are suffering all the problems of urbanization, often with population densities much higher than those in any Western city, but usually without the resources (budget, personnel, infrastructures, etc.) needed to provide solutions of the kind used in Western countries. Still worse, not all developing countries are aware of the importance of abating the environmental pollution which once heavily shadowed the urbanization and industrialization in Europe and North America. The quality of the urban environment is a matter of growing concern to them and the importance of efficient solid waste management is increasingly recognized. The West has often been able to provide developing countries with technical guidance in environmental matters, but solid wastes may prove to be an exception, since there are too many climatic, economic and social differences for systems to be successfully transplanted.

1.4 Composting as One of the Answers

A major constituent of domestic refuse is organic matter, mainly in the form of vegetable matter. Urban areas generate domestic wastes on a large scale, between 300 and 800 g/person-day. At the mean of this range, a city with a population of one million would generate over 500 tonnes a day. At least 25%, and up to 75%, of this weight comprises vegetable and putrescible matter.

Over the past 50 years, the disposal of such urban wastes has become an increasingly difficult problem. Sanitary landfilling has always been the most common disposal method in developed countries and is likely to remain so due to its low cost and simple operation. But as proper landfill sites become scarcer and scarcer, additional expenditures necessary to transport the wastes to distant sites have made it increasingly important to adopt treatment methods which reduce the volume of wastes to be accommodated on scarce landfill sites. Incineration is an effective solution for developed countries, but is not always feasible for developing countries, since (i) it is expensive for any kind of waste, and particularly expensive for wastes having a high proportion of vegetable and putrescible matter, which implies a high moisture content and a low calorific value, and (ii) it requires sophisticated equipment which developing countries may not be able to afford or to operate and maintain properly.

It is natural, therefore, to explore the possibility of converting domestic refuse - or a substantial proportion of it - into a state in which it can be handled, stored and/or reused without adversely affecting the environment. One such process is composting. The process itself is not new and in fact has been in practice for thousands of years. Nevertheless the technology developed has yet to reach the mass diffusion level - the level at which composting could be used by the common mass of people in a simple and safe way.

1.5 Other Benefits from Composting

Apart from the need for controlled and hygienic disposal of vast quantities of organic refuse, a gradual decline in soil fertility has also generated a renewed interest in composting.

In nature, dead vegetables and animal remains, where they happen to fall, are decomposed by soil organisms. The products of such decomposition add to the fertility of the soil by improving its physical properties for the support of plants and by providing plant nutrients. A similar process takes place with human and animal excrement. Throughout history, until the invention of chemical fertilizers, farmers were solely dependent upon organic manures, derived from animal excrement and decayed vegetation, for the maintenance of soil fertility. The compost product, a humus-like substance, can serve as a good soil conditioner and fertilizer to maintain intensively cultivated soils in a state of adequate fertility. As the farmer depends more and more on chemical fertilizers, seldom does he realize that these fertilizers, although convenient to use, may impart adverse effects to his soil if used improperly. This ecological blacklash has been observed in various Asian countries, whose agriculture is the blackbone of the economy. Then again, the increasing price and the unavailability of adequate foreign currency to import inorganic fertilizers - at a time when the more populated regions of the world are in an urgent need to boost food production - have led many people to reconsider the old idea of composting.

1.6 From Different Viewpoints to Different Goals

The attention focussed on composting in the recent past in industrialized countries arose from the energy crisis, the need for non-water carriage sewage treatment, and the prohibitive cost of incineration plants or lack of availability of space for land filling, coupled with the problem of polluting the environment. The technology developed in industrialized countries is often far from effective in developing countries because of the sharp contrast in the conditions existing between them. The temperate climate in most developed countries requires attention on BOD reduction of wastewater treatment, whereas the hot, humid tropical climate prevailing in most areas of Third World countries requires emphasis on pathogen reduction rather than BOD reduction. For example, the mechanized composting plants, and particularly the composting toilet developed in Sweden, are hardly within the means of the common mass of people in developing countries. The concern for composting is also different: there is an increasing interest in the West on composting of dewatered sludge cake from sewage treatment plants, whereas in developing countries, where sewers serve only 6.5% of the people (Rybczinski & Bhatt, 1979), the major interest for composting is in human and animal excreta and other domestic wastes.

II. HISTORICAL REVIEW

The history of composting, shows a general trend from anaerobic to aerobic composting. The reasons for this trend could be :

a) The anaerobic process is slow, and hence takes much time and space. These two disadvantages were not significant in former times, but have now become more and more unacceptable.

b) As the mechanisms of the process are known better and the concern over pathogens is growing, the aerobic process is preferred because it provides better pathogen inactivation.

c) As the level of technology is updated, equipment has been designed to effectively put into practice the aerobic process.

The process akin to composting was being practiced long before it was formally introduced in the scientific literature. People in the past used to recycle the organic waste materials through composting in different parts of the world. One noteworthy example has been that of the Chinese in the river deltas. By returning to the soil their crop residues and human wastes, the Chinese could maintain a relatively high agricultural productivity to support very high population densities. By the practice of excellent horticulture requiring enormous inputs of human energy, their land has supported population densities of perhaps 12 people per hectare and has continued to do so for some 4,000 years without the soil fertility and structure giving way under such pressure.

Other noted exponents of composting are the people of Hunza in the Himalayas who have practiced their agriculture in terraced fields on the mountain sides - a method which has already been extensively studied.

II.1 Pre-1940 Period

Composting, as practised by the Chinese, had probably changed very little over the centuries, being essentially a small-scale batch operation. With the adoption of the process by the Western world in this century, some progress has been made in understanding the fundamental reaction and its application to large-scale waste treatment.

The arousal of interest in composting in the West probably stemmed from an extended visit to China, Japan and Korea in 1909 by Professor F.H. King, of the U.S. Department of Agriculture, and his observations were carefully recorded (King, 1927). His text was read by Sir Albert Howard, a British economic botanist employed by the Indian Government, who was able to put King's observations on composting in China to the test in an Indian context (Gray et al., 1973). It was in the early 1930's when Sir Albert Howard and his collaborators, F.K. Jackson & Y.D. Wad, began to systematize the traditional compost procedures. After several years of experimentation, Howard established that the composting method developed by him - known as the Indore System - gave optimum results in terms of the vegetable and animal wastes, the supply of labor and the climatic conditions available to him.

Immediately preceding Sir Albert's work, and for a time thereafter, the major non-agricultural interest in composting outside of the U.S.A. was the use of the method as a means of treating nightsoil in those regions lacking sewer facilities. As such, the concern was more in using composting as a hygienic measure than as a conservation measure, although conservation was offered as an added incentive.

The development of a truly systematic approach to composting began with Albert Howard's work in Indore, India, in the early 1930's.

As originally developed at Indore (Howard, 1953), Howard's process was normally constructed in pits 9x4x0.6 m deep to conserve heat and moisture. In the monsoon period, an above-ground heap was built. Preparation of the compost consisted of building up a layer of vegetable materials 51 mm thick, a thin layer of animal manure and dustings of earth and wood ashes; the mass was then watered. This layering was repeated until a height of 0.6 m was reached. The materials were carefully prepared and measured into the heap. The vegetable wastes had been put into the bullock shed for several days, where they were well crushed and homogenized. The heap was turned after 16, 30 and 60 days, with intermittent watering; it was removed to the fields after 90 days. Based on a manure supply from 40 head of cattle, the output from Howard's site was approximately 764 m^3 of compost in 1930-31. He required no extra labor other than the 5 people usually employed in the cattle shed.

A large number of analyses were carried out at Indore, e.g. fractionation of the vegetable wastes, nitrogen balance, moisture content of the heaps, temperature surveys and composition of the final products. The nitrogen analyses indicated that, in a well-constructed compost heap, there was normally a net gain in nitrogen. Trials were made with different single vegetable materials, with mixtures and with various sources of nitrogen - dung, urine, earth, etc. The results showed the advantage of using mixed feed material.

At about the same time (during the first World War), Hutchinson & Richards (as cited by Grey et al., 1973), working on the production of "artificial farmyard manure" by the composting of straw, brought out the activator Adco as a chemical source of the nitrogen needed in this reaction. In the following years much work was done to evaluate other chemical activators. Howard considered that an organic source of nitrogen gave a somewhat better product than did a chemical activator.

In the years immediately following 1931, the Indore method was taken up by many people in several parts of the world. As a result, a number of minor changes in working were incorporated which increased the output per mass employed from the processes. The pit was now dug 0.9 m deep; vegetable wastes were applied in 152 mm layers followed by manure in 51 mm layers, a thin sprinkling of earth and wood ashes, and then watering. The layering was continued until a height of 1.46 m was reached. Vertical aeration vents, about 102 mm diameter, were made with a crowbar every 0.9-1.2 m across and down the pile of wastes. The heap was then turned twice, after two to three weeks, and after again about five weeks; the material was ready in three months.

According to Grey et al. (1973) as a result of the work of Howard et al. in their large-scale field investigations, a fair appreciation of the effect on composting of the major physical and chemical parameters was reached. Howard's work was complemented by the laboratory-scale studies of Walksman and his team during the same time period on humus and the interplay of the microorganisms involved in its production from organic wastes.

Another early worker who applied composting to the treatment of night-soil was van Vuren (1949). Both Howard and van Vuren relied on the reduction of fly breeding as an indicator of hygienic quality.

While Sir Albert was refining practices that had been in use in India and China, others, especially in Europe, were directing considerable effort towards mechanizing the composting process. The modern approach to composting has arisen in response to a need for controlled and hygienic disposal processes to deal with the vast quantities of solid organic waste resulting from an exploding human population and rising standards of living.

A variety of mechanical devices were designed and patented during the 1920's to the 1930's. Some of the devices were intended to improve the aesthetics of the process by enclosing it, while others were developed in the hope of speeding up the process.

II.2 1940 - Early 1960 Period

The 1940's and the early 1950's marked the beginning of a surge of interest in the use of composting as a means of reclaiming plant nutrients in municipal refuse, and thereby as a solid waste "disposal" process. The term "disposal" is used in the popular sense, namely processing the wastes after they have been collected and concentrated at a designated site.

It was at this time that there was felt to be a need for undertaking studies to develop the scientific principles of composting. The Inter-Departmental Committee for the Disposal of Organic Wastes (1951) of the New Zealand Government conducted some research and published two reports exploring the scientific aspects of the mechanics of soil improvement accomplished by incorporating compost in the soil. Consequently the University of California began its research on composting (McGauhey & Golueke, 1953). The U.S. Public Health Service of the Department of Health, Education, and Welfare also conducted research and pilot-scale studies in the late 1950's (Maier et al., 1958; Wiley, 1957).

During this period, the European researchers were largely concerned about the hygienic aspects of composting. They made actual observations on the survival of selected pathogens under a variety of conditions in composting (Knoll, 1959; Parakova, 1962).

The new concept of using composting as a means of treating municipal wastes induced activities directed towards the development of a complicated mechanization of the composting process. This zeal to develop mechanical devices finally reached a level at which over-mechanization became as much a threat to the cause of composting as any other factor. In spite of this fact, this period marked the development of reliable equipment and mechanized processes, e.g. the University of California windrow process, the Dano process, and the Naturizer System. Another process, the V.A.M. process which had been practiced in Holland since 1932, also has some interesting aspects.

II.3 Mid-1960 Period

Considerable research on composting was carried out in the U.S.A. in the mid-1960's due to the beginning of public concern for the environment and the passage of the 1965 Solid Wastes Act (Golueke, 1972). This research was in fact the rediscovery of the findings of the earlier researchers. Unfortunately, many of the new "discoverers" were unaware of the findings of their predecessors.

Regrettably, the mid-1960 period was marked by a succession of financial failures of composting plants. In fact, the economic picture became so bleak for composting as a waste treatment process that only the far-sightedness and dedication of a few kept the interest in composting from waning entirely.

II.4 Late 1960's to the Present

The late 1960's brought a deepening public concern with preserving the quality of the environment, and also a willingness to do something about it. Now the idea that composting must be a paying propostion in a purely monetary sense has gradually faded. Instead, the process is being evaluated in terms of its complete social benefits. At one time the worth of the compost was judged primarily by the monetary value of its nitrogen, phosphorus and potassium (NPK) content. Now the emphasis has been tilted towards environment protection and improvement of soil quality. Nevertheless, although the other benefits are becoming more appreciated, some people still expect to make money out of composting.

III. PRINCIPLES AND FUNDAMENTALS

III.1 Classification

Composting processes may be classified according to various viewpoints, such as oxygen usage, temperature, and the technological approach.

If oxygen usage is the basis, there are two divisions to consider:

- aerobic composting
- anaerobic composting

It should be noted that, in contrast with wastewater treatment for example, the terms "aerobic" and "anaerobic" have relative meanings. They simply indicate what conditions are predominant in the process. In a compost heap, there always exist anaerobic pockets, which are few in "aerobic" composting and abundant in "anaerobic" composting. Still, some processes - such as the traditional ones practiced by the Chinese and the Vietnamese - are aerobic at first and become anaerobic during the later stages.

When temperature is the basis, the divisions to consider are:

- mesophilic composting
- thermophilic composting

Finally, using technology as the key, the classification is:

- open or windrow composting
- mechanical or "enclosed" composting

Haug (1980) pointed out that the term "mechanical" is a misnomer, as all modern compost systems are mechanical to some extent. Also, the terms "enclosed" and "open" are poorly defined. Composting material might be housed under a roofed structure but not enclosed in a reactor, and in either case it might be termed mechanical.

III.2 Aerobic Composting

Aerobic composting is characterized by a rapid decomposition rate and release of a great deal of energy in the form of heat from the oxidation of organic carbon to carbon dioxide. It generally creates no odor problems and the resulting high temperature should be quite effective in reducing the pathogenic potential of the waste material.

The overall process flowsheet for the basic composting process is given in Fig. 1 (Gray et al., 1971a).

The general consensus in developed countries is that the aerobic composting system is much more popular than the anaerobic process, particularly for the four important reasons described below.

a) Aerobic processes are not characterized by objectionable odors. Since the social benefits of composting are becoming more important in the West, anaerobic composting, which detracts from these benefits, is generally not encouraged. Anaerobic composting is malodorous and poses a hazard to health, and very often the malodor is the key factor to lack of consumer demand.

b) The benefits pertaining to public health and crop production. The high temperature generally obtained in an aerobic pile reaches levels above the thermal death point of most plant and animal pathogen and parasites (Golueke, 1977), and also helps kill weed seeds.

c) Aerobic composting is a relatively rapid process, taking approximately 21 days (for the static pile forced-aeration method) as compared with several months in the anaerobic process.

d) As the composting process is more and more applied to large-scale operations, the availability of space has become a constraint. The anaerobic process, therefore, is losing ground to the aerobic one.

In aerobic composting, there might be some loss of nitrogen due to the high temperature and eventual alkaline conditions. Aerobic composting also needs more handling and equipment than anaerobic composting.

III.3 Anaerobic Composting

In anaerobic composting, the anaerobic organisms accomplish the decomposition, and free oxygen (air) is excluded from the composting mass. An idealized illustration of the process is shown in Fig. 2 (Sanderson & Martin, 1974).

Aerobic composting may be distinguished from anaerobic digestion in that, the wastes are usually maintained in a solid state in the former process, while in the latter wastes are in slurry form. Anaerobic decomposition is characterized by low temperatures (unless heat is applied from an external source), the production of

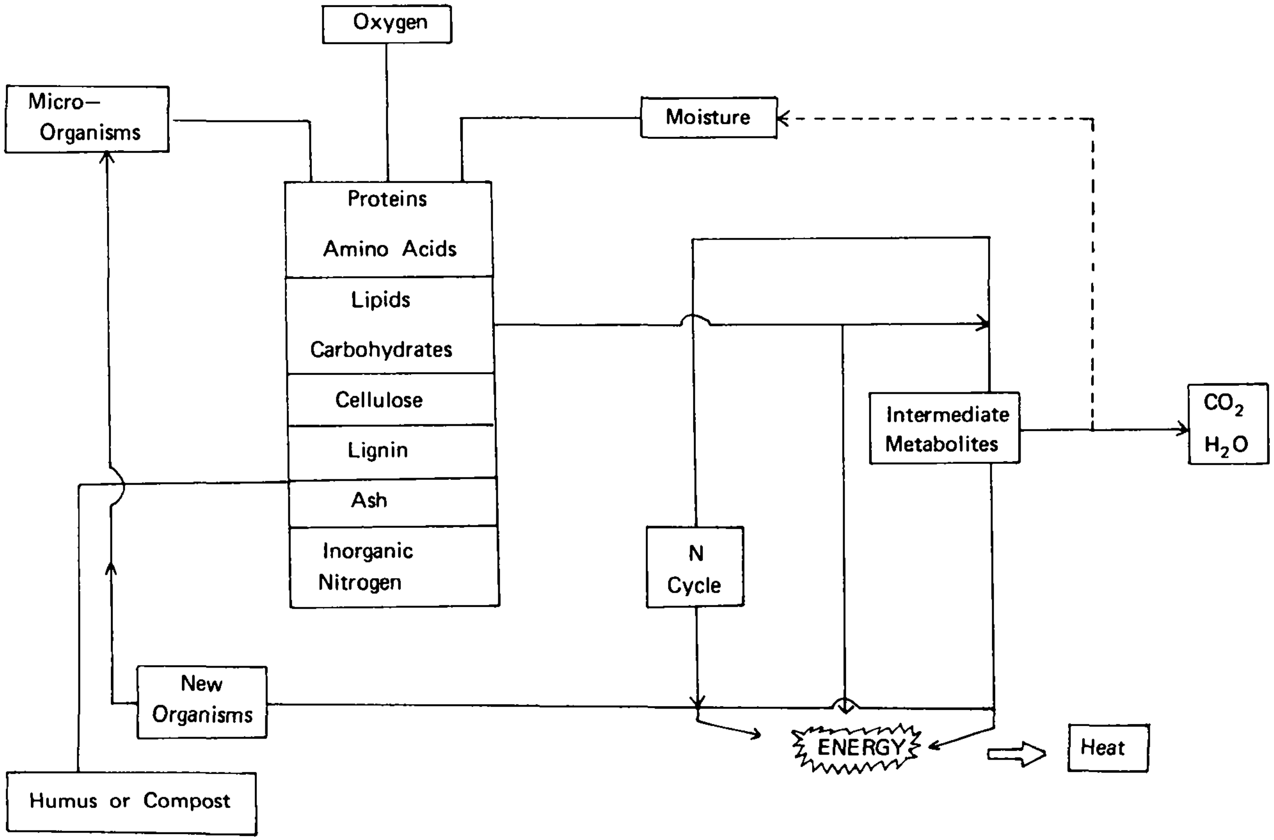


Fig. 1 Process Flowsheet for Basic Composting

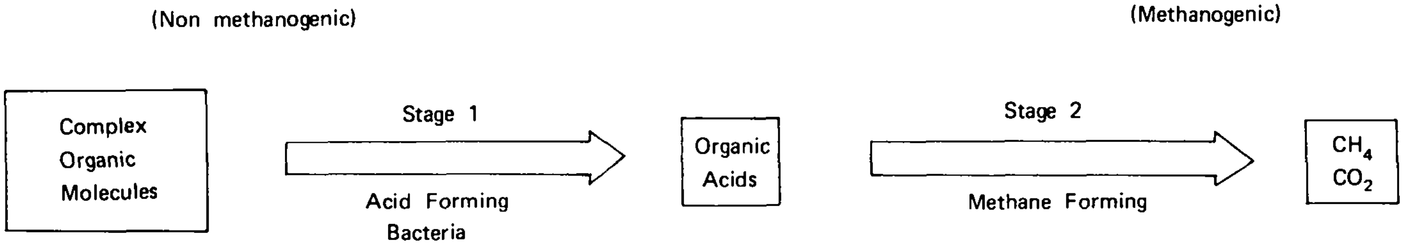


Fig. 2 Two Stages in Anaerobic Composting

odorous intermediate (reduced) products, and generally proceeds at a slower rate than does aerobic composting.

The advantages of aerobic composting over anaerobic composting are that it is a more rapid process with high temperatures and without odors.

The main advantages in anaerobic composting is that the process can be carried out with a minimum of attention, and as such it can be sealed from the environment.

III.4 Mesophilic and Thermophilic Composting

As the term implies, in mesophilic composting the temperatures are in the intermediate range (15°C to 40°C), which in most cases is the ambient temperature. Thermophilic composting is conducted at temperatures from 45°C to 65°C. In practice, most processes include both of the ranges.

III.5 Windrow and Mechanical Composting

Compost systems falling under the category of "open" or "windrow" are those in which the entire process is carried out in the open. The manner of arranging the material for handling or processing usually is without using a digester, but stacking the material in elongated windrows. The open pile or windrow placed directly on the ground or on a paved area, or the pile placed in a shallow pit, are being widely used for the aerobic decomposition and maturing of organic refuse. The exact use and arrangement of windrows, piles, and shallow pits depend on the local requirements relating to materials - handling equipment, labor costs, and climatic conditions such as temperature, rainfall and wind.

A manual process may be problematic in process control, such as C:N ration control. Experience in Nigeria (Peel, 1976) indicates that it is extremely difficult for manual operation to estimate the proportions of the various ingredients or to limit the particle size of municipal refuse, and thus the C:N ratio of the mixture cannot be standardized.

In mechanical systems, the greater part of the initial composting activity takes place in an enclosed unit, a digester.

An important point to be mentioned here is that most mechanical processes involve windrowing towards the end of the process to allow the composting material to "mature".

III.6 General Constraints Due to Biological Factors

As composting is a biological process, it is subject to well-defined biological limitations (Golueke, 1972) which are:

a) A suitable number of microorganisms must be present;

b) The rate and efficiency of the process are functions of the rate and efficiency of microorganisms' activity;

c) The capacity of a given operation is limited by the size and nature of the organisms;

d) The substrate subject to composting generally must be organic;

e) Environmental factors are of key importance.

The origin of the first constraint is quite obvious. Since the process is a biological one, living organisms are the agents for accomplishing it. The limitation to microorganisms is directly implied by the term "decomposition", Since in nature decomposition, in the commonly accepted sense of the term, is done by microscopic organisms. Not only must a microbial population be present, but it must also be the one that suits the task (Golueke, 1972).

The limitation on rate is of practical importance, because it means that no matter how well a piece of compost equipment is designed mechanically, composting with it will proceed at a pace commensurate with that of the bacterial activity permitted by the particular set of conditions provided by the machine. The limits of microorganisms on capacity also has practical ramifications. It means that once the maximum-sized microorganisms has been reached under the conditions provided by a given piece of compost equipment, the loading cannot be increased without giving rise to nuisances. Loading in excess of the maximum permissible microorganisms will inhibit the process either partly or entirely, and to say the least will result in only partial treatment of the waste material.

The constraint arising from the influence of environmental factors usually manifests itself through the mechanism of the limiting factor. If any factor is present in less than optimum concentration or level, the functioning of the entire process is inhibited in proportion to the extent of the deficiency of the factor. For example, for a given digester in which the temperature is optimum, aeration is complete, and a suitable microorganism population is present, but nitrogen is deficient, the only way to increase the efficiency of such a digester would be to add nitrogen in an amount sufficient to make up for the nitrogen deficiency. Adding more bacteria or other organisms will only aggravate the problem, since the nitrogen is not sufficient even for the existing population. Building a more elaborate digester would not suffice, since the effective component of the process, namely the bacteria, do not have the nitrogen to meet their metabolic requirements.

III.7 Microbiological Aspects

As early as the late 1930's and during the 1940's, it has been shown that a variety of microorganisms have a variety of specific functions, and that no single organism, no matter how active it is, can compare with a mixed population in producing rapid and satisfactory decomposition (Carlyle & Norman, 1941; Forsyth & Webly, 1948; Waksman & Cordon, 1939; Waksman, Cordon & Hulpoi, 1939; Waksman, Umbreit & Cordon, 1939). It appears that more species of bacteria are involved in the aerobic process than in the anaerobic one. There is little information on the bacterial species active in anaerobic composting, although several investigations concerning the bacteria involved in anaerobic digestion of sewage sludge have been made. Many of the same organisms are, no doubt, as active in anaerobic composting as in sludge digestion. However, since the environment of anaerobic compost stacks differ greatly from that of sludge digestion tanks, especially in terms of moisture and nutritional materials, the biological population would also be expected to differ (Gotaas, 1956).

Although many types of organisms are required for decomposition of the different materials, the necessary variety is usually present and the organisms thrive when environmental conditions are satisfactory.

The Food Web - Dindal (1978b) illustrates the food web pattern associated with a typical composite pile as shown in Fig. 3. The figure shows that this generalized food web applies to all types of organic deposits.

Microorganisms such as bacteria, actinomycetes and fungi are of major importance in the food web as the initial decomposers. Also, many other organisms like protozoa and roundworms feed directly on them. Some idea of the types and numbers of organisms involved in composting was cited by Gray, et al. (1971a) as shown in Table 3.

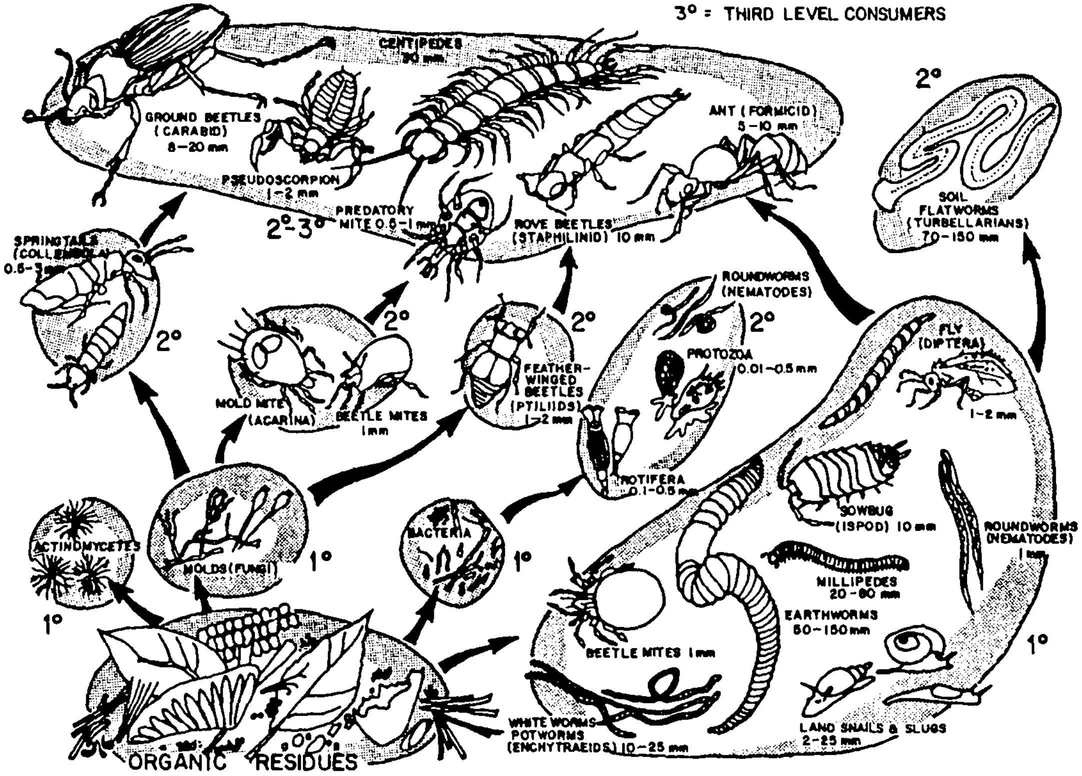
Table 3. Organisms Involved in Composting

		Numbers per gramme of compost
Microflora	Bacteria	$10^8 - 10^9$
	Actinomycetes	$10^5 - 10^8$
	Fungi	$10^4 - 10^6$
	Algae	$< 10^4$
	Viruses	?
Microfauna	Protozoa	$10^4 - 10^5$
Macroflora	Fungi, e.g. Coprinus spp.	
Macrofauna	Nematodes (eelworms)	
	Ants	
	Springtails	
	Millipedes	
	Worms	

A typical succession of micro-organisms appear to be as described by Golueke (1972), Gotaas (1956) and also Gray et al. (1971a). Acid-producing mesophilic bacteria are the first to appear. Thereafter, as the temperature rises, thermophilic bacteria appear, which inhabit all parts of the stack where the temperature is satisfactory; this is, eventually, most of the stack. Thermophilic fungi usually appear after 5-10 days, and actinomycetes become conspicuous in the final stages, when short duration, rapid composting is practiced. If the temperature becomes too high, i.e. greater than 65-70°C, the fungi, actinomycetes and most bacteria are inactive, and only spore-forming bacteria can develop. In the final stages, as the

ENERGY FLOWS IN THE DIRECTION OF THE ARROW

1° = FIRST LEVEL CONSUMERS
2° = SECOND LEVEL CONSUMERS
3° = THIRD LEVEL CONSUMERS



LENGTHS OF ORGANISMS GIVEN IN MILLIMETERS (25 mm = 1 in)

Fig. 3 Food Web of the Compost Pile

temperature declines, members of the Actinomycetaceae become the dominant group, sometimes to the extent that the surface of the composting mass takes on the white or grey color typically of this group.

The successive changes of the different groups of microorganisms during the various stages of the process have been studied by Ahrens et al. (1965) and by Albonetti & Massari (1979). The latter reported that a number of fungal species disappeared in the thermophilic phase, whereas they were always present in other tests which differed only in the frequency of turning. This disappearance was probably due to the daily pile turnings and did not influence the regular development of the process.

Various investigations have shown that many different types of thermophilic bacteria apparently play a major role in decomposting protein and other readily broken down organic matter. They appear to be solely responsible for the intense activity characteristic of the first few days, when the temperature has reached 60-70°C and major changes in the nature of the compost stack are taking place, i.e. when the stack is drastically shrinking and the appearance of the material is undergoing rapid change. They continue to predominate through the process in the interior of the piles, where temperatures are inhibitory to actinomycetes and fungi. Carlyle & Norman (1941) noted that bacteria constituted the active flora in all their mixed flora experiments on thermogenesis in plant decomposition.

The thermophylic fungi from composting vegetable matter are a relatively well defined group. In spite of being confined primarily to the outer layers and becoming active only during the latter part of the composting period, fungi and actinomycetes play an important role in the decomposition of cellulose, lignins and more resistant materials, which are attacked after the more readily decomposed materials have been utilized.

Gray et al. (1971a), when compiling the findings from other investigators, listed at least eight species of thermophilic fungi indigenous to the compost of hay, grass, garden wastes and stable manure which are capable of growth in the range of 40-60°C. Above this temperature range, they die out and disappear completely, reappearing, presumably by re-invasion, as the temperature falls below 60°C again. However, they prefer temperatures between 45 - 50°C. Also according to Gray et al (1971a), in one experiment no thermophilic fungi could be found in the composts of refuse and sewage sludge after three days at 64°C, but as the temperature dropped below 60°C a re-invasion of fungi took place. The only contradictory report to this view was given by Spohn (1970) that even at a temperature of up to 90°C there was evidence of extensive fungal growth.

Yung & Hudson and Yung (cited by Grey et al., 1971a) were able to divide the fungi that occurred in composting into three characteristic groups. In a research project carried out in Britain at the University of Cambridge (Gray, 1970), seventeen types of fungi from compost were isolated. In a more recent study of the stabilizing phase of the municipal solid waste of Rome by Albonetti & Massari (1979), the fungi isolated from the different composting stages were reported as shown in Table 4. According to Albonetti & Massari, a new field of investigation has been opened to explore the role of these fungi and the value of their absence during the thermophilic stage of solid waste composting. Gotaas (1956) urged that for the benefits of the activities of fungi, turning should not be more frequent than is necessary.

Table 4. Fungal Taxonomy

Mesophilic stage (until 40° C)

Aspergillus candidus link
Aspergillus versicolor (Vuill.) Tiraboschi
Cephalosporium sp.
Cladosporium cladosporioides (Fres.) De Vries
Fusarium sp.
Gliomastix sp.
Graphium state of Petriella sp.
Monascus ruber Van Tieghem
Oidiodendron sp.
Penicillium cyclopium Westling
Penicillium expansum Link
Penicillium thomii Maire
Scopulariopsis brevicaulis (Sacc.) Bainier
Tritirachium sp.

Thermophilic stage (to 40 until 60° C)

Humicola lanuginosa (Griffon and Maublanc) Bunce
Mucor miehei Cooney and Emerson

Cooling down stage (to 40° C until ambient air temperature)

Aspergillus sydowi (Bain, and Sart.) Thom and Church
Aspergillus versicolor (Vuill.) Tiraboschi
Aspergillus versicolor group
Penicillium cylopium Westling
Scopulariopsis brevicaulis (Sacc.) Bainier
Scopulariopsis sp.

The thermophilic actinomycetes in composts have been studied much less than the fungi, and their behavior is much less predictable. However, it is known that they are capable of growth at a higher temperature than thermophilic fungi and can become abundant or even dominant at the higher temperatures reached in composting. Detailed studies of either the ecology or the degradation ability of the thermophilic actinomycetes are even less frequent. Waksman & Cordon (1939) concluded from the studies of the decomposition of various constituents of straw that the actinomycetes utilized cellulose only to a very limited extent. However, they attacked hemicellulose readily and, to some extent, the lignin. Fergus also found that the actinomycetes are much less capable of degrading cellulose than are the fungi. Golueke (cited by Grey et al., 1971a) found that in the final stages of composting mixed refuse, vegetable trimmings and refuse, when the temperature began to decline, actinomycetes became the dominant group. He observed two groups namely "Streptomyces" and "Micromonospora".

Alexander (1961) postulated that the actinomycetes develop far more leisurely than most bacteria and fungi, and are rather ineffective competitors when nutrient levels are high; they are, therefore, more prominent in the later stages of composting.

Yung & Hudson found that the actinomycetes lagged slightly behind the thermophilic bacteria in straw composts, but otherwise their behavior was similar, their numbers reaching a maximum at temperatures over 70°C and remaining high for several days. Some idea of the changes in numbers of the thermophilic actinomycetes and fungi during the composting of wheat straw is given in Fig. 4 (as cited by Grey et al., 1971a).

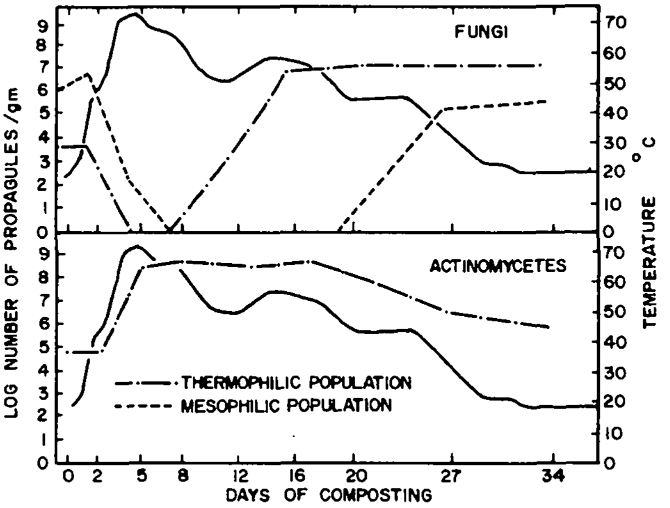


Fig. 4 Population changes in wheat straw composting

Spohn reported the presence of a number of species of actinomycetes in composts of municipal refuse at temperatures between 80°C - 90°C.

III.8 Biochemical Aspects

The overall process flowsheet for the basic composting process is as illustrated in Fig. 1 (Gray et al., 1971a). The heterogeneous organic material will normally have an indigenous mixed population of microorganisms derived from the atmosphere, water or soil. Once the moisture content of the material is brought to a suitable level (50-60%) and the mass aerated, microbial metabolism speeds up. For their growth and reproduction the microorganisms require, in addition to oxygen and moisture, a source of carbon (the organic waste), macro nutrients such as nitrogen, phosphorus and potassium, and certain trace elements. Energy is obtained by biological oxidation of part of the carbon from the waste. Some of this energy is used in metabolism, the remainder is given off as heat.

As implied by the definition of composting, the waste, with rare exceptions, must be organic. The term "organic" in the chemical sense covers a multitude of materials. In terms of composting, it refers mostly to paper, wood, manures, food preparation wastes, crop wastes, etc. In terms of microbial nutrition all of these forms are highly complex substances, and thus are not available to a large number of groups of microbes. It is only as the materials are decomposed to simpler and yet more simple forms, that the spectrum of potential microbial users broadens. The course of breakdown for the protein content is :

Protein --> peptides --> amino acids --> ammonium compounds --> bacterial protoplasm and atmospheric nitrogen or ammonia.

This outline of breakdown is highly abbreviated, since it does not take into account many possible intermediates and side reactions. For instance, each step actually is accompanied by the synthesis of bacterial protoplasm, insofar as when an organism decomposes a substrate, some of the nitrogen is transformed into protoplasm. The following scheme for the complex carbonaceous part of the substrate can also be over-simplified as:

Carbohydrate --> simple sugars --> organic acids --> CO_2 and bacterial protoplasm.

Organic wastes suitable for composting vary from the highly heterogeneous material present in municipal refuse/sewage sludge to virtually homogeneous wastes from food processing plants. However all these wastes are mixtures of sugars, proteins, fats, hemicellulose, cellulose and lignin in a wide range of concentrations as shown in Table 5 (Alexander, 1961).

Table 5. Composition of Organic Matters

Fraction	Percent, in dry weight	
	Plants	Manures
Hot/cold water solubles – sugar, starches, amino-acids, aliphatic acids, urea and ammonium salts	5–30	2–20
Ether/alcohol solubles – fats, oils, waxes and resins	5–15	1–3
Protein	5–40	5–30
Hemicelluloses	10–30	15–25
Cellulose	15–60	15–30
Lignin	5–30	10–25
Minerals (ash)	1–13	5–20

Manure composition depends on the type of animal, its feed and to a smaller extent, its age. In plants, the concentrations depend on the type of plant, its environment, and very much on its age. Fresh green material, such as young grass, contains a lot of water-soluble matter, minerals and proteins which hold most of the nitrogen and sulphur of the plant. As the plant ages, minerals tend to return to the soil and low molecular weight compounds are converted to the polymers-hemicelluloses, cellulose and lignin.

There is a singular lack of information in the literature on the precise details of the biochemical changes taking place during the complex processes of composting. Some indication of the extent of the biochemical changes taking place in a heap is given in Fig. 5 plotted by Gray et al. (1971a) from the results of Yung Chang on composting wheat straw amended with ammonium nitrate. The straw had lost over half of its dry weight after 60 days of composting; this took place mainly in the first 34 days. The greatest rate of loss occurred over the first five days, averaging 2.66% per day, as compared with an average of about 1.30% per day over the following 30 days. Decomposition after 34 days was very slow; a further loss of only 3.96% was recorded after 165 days. The loss of total dry weight could be accounted for almost completely by the loss in hemicellulose and cellulose. Cellulose degradation slowed down during the middle of the cycle, presumably because the fungi were killed by the high temperatures. Hemicellulose was broken down fairly evenly, however, since hemicellulolytic actinomycetes are more tolerant of high temperatures. The ethanol soluble fraction, which contains among other things, sugars and glucosides, is probably continually replaced by the breakdown of polymers.

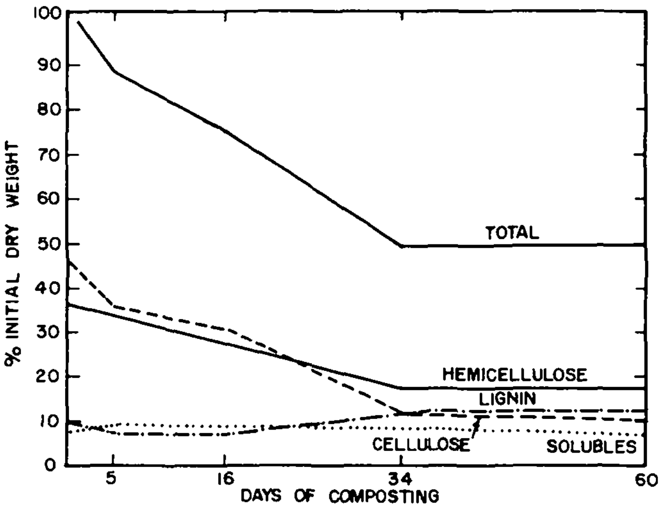


Fig. 5 The breakdown of wheat straw

The work of Yung Chang & Hudson was carried out in compost boxes (Grey et al., 1971a). In large-scale installations for treating municipal wastes, the natural process is frequently accelerated by the use of forced aeration and mechanical agitation. In one plant recently a high degree of maturity was claimed in a period of only 7 days. With such accelerated processes the microbial population and the type of biochemical change may well differ from those in a slowly-degrading compost heap.

III.9 Fermentation Phases

Several phases can be distinguished in the composting process, as shown in Fig. 6 (AGHTM, 1975). Briefly, the phases consist of:

- Latent phase : which corresponds to the time necessary for the microorganisms to colonize in the new medium created for them.
- Growth phase : which is characterized by a temperature raise.
- Thermophilic phase : the phase at which the temperature rises to the highest level. This is the phase where any intervention is most effective, for example, to prolong or to stop the phase.
- Maturation phase : which corresponds to a secondary fermentation, which is slow and favors humification, that is, the transformation of some complex organics to humic colloids closely associated with minerals (iron, calcium, nitrogen, etc.) and finally to humus. The compost can be used right at the end of the thermophilic phase, and the humification process will occur in the soil. In contrast, this maturation takes place during storage. In order to avoid exessive mineralization, the storage time should not be prolonged unnecessarily.

IV. ENVIRONMENTAL FACTORS, KINETICS AND PRACTICAL PROCESS

According to Finstein et al. (1980), the stability of the composting process is independent of any highly specialized group of organisms. Any process failure may be due to excessively high temperatures and some gross chemical or physical operational inadequacies.

IV.1 Nutrient Balance

One of the important ratios with respect to composting is the carbon:nitrogen (C:N) ratio, which is also termed the carbon-nitrogen balance. Phosphorus is next in importance, and sulphur, calcium and trace quantities of several other elements, all play a part in cell metabolism.

Alexander (1961) postulated that between 20-40% of the carbon substrate in the feed (composting waste) is eventually assimilated into new microbial cells in composting, the remainder being oxidized to carbon dioxide in the energy-producing processes. However, these cells contain approximately 50% carbon and 5% nitrogen on a dry weight basis. Accordingly, the requirement of nitrogen in the feed is 2-4% of initial carbon, i.e., a C:N ratio of about 25. If the initial C:N ratio is greater than this, the microorganisms must go through many life cycles, oxidizing off the

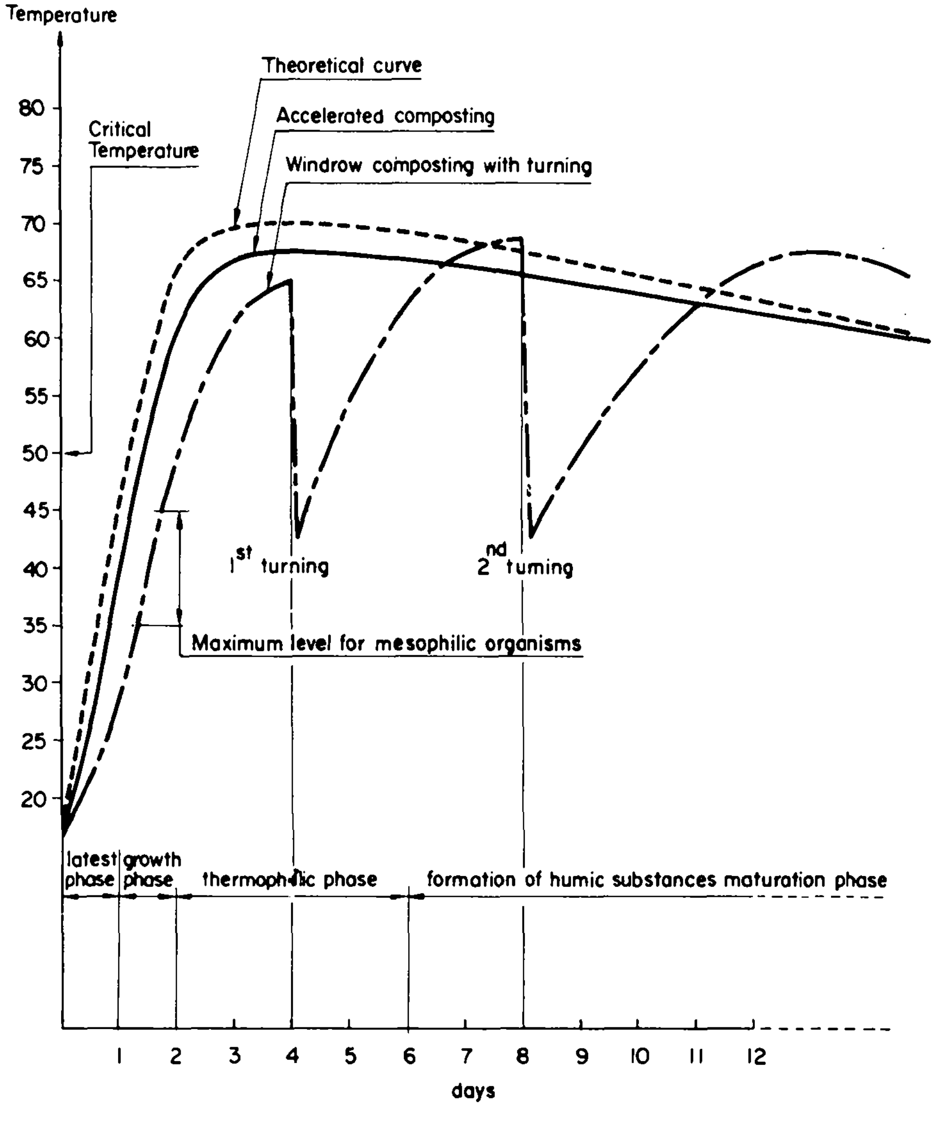


Fig. 6 – Thermogenesis of Solid Wastes

excessive carbon until a C:N ratio of 10 is reached; the result is that much extra time is needed and a smaller quantity of final humus is obtained. With lower than optimum initial C:N ratios, nitrogen will probably be lost as ammonia, especially at high temperatures, and in forced aeration condition.

Accurate calculation of optimum nitrogen requirements in a practical process is made difficult by three factors (Gray et al., 1971a):

a) some of the carbon substrate is in the form of resistant cellulose and highly resistant lignin which take little part in the composting process, and are only decomposed over a long period of time when the compost is added to the soil;

b) some of the nitrogen is in an accessibly difficult form, e.g. as keratin-type proteins, and is not available during much of the composting process; and

c) some nitrogen fixation takes place through the bacteria Azotobacter spp., especially in the presence of adequate phosphatic material.

It is indeed difficult to arrive at a generalized value of optimum C:N ratio for every kind of material. The C:N ratio is to some extent a function of the nature of the material of the wastes, especially of the carbonaceous component. An easily biodegradable organic compound will render its carbon available to the microbes in a better way than that of a lesser bio-degradable compound. However, a general optimum C:N ratio for most types of organic wastes have been reported by many researchers as being about 25-35 (Haug, 1980; Sanderson & Martin, 1974). Polprasert et al. (1980) reported an optimum C:N ratio of 30 in composting a mixture of nightsoil and water hyacinth following a continuous aerobic process. Other researchers reported still wider ranges for the C:N ratio, which is presented in Table 6.

Such a wide diversity in the range of the C:N ratio reported in the literature, as is apparent from Table 6, obviously raises the question of re-examining the validity of this parameter. Some variations might be justified due to the heterogeneity of the materials being used. As can be seen from Table 7 (Gotaas, 1956), even for the same kind of feed, divergent optimum C:N ratios have been reported. The waste organic materials amenable to composting have a wide range of nitrogen contents and C:N ratio, as shown in Table 7 (Gotaas, 1956).

Jeris & Regan (1973) reported results of experiments to define the critical concentrations of nutrients (N and P) necessary for composting mixed refuse and to ensure maximum biological activity. Although they could not define the minimum nitrogen requirement for optimum microbial activity, the concentration used in the experiment was thought to be in the optimum range. It was also found that excessive quantities of nutrients were partially lost before biological utilization, indicating an upper limit for economical use.

Table 6. Recommended C/N Ratio for Composting

Feed Material	C/N Ratio	References
1. Human Excreta, grass/leaves, food scrap	15: 1	156
2. a) Dairy manure, rice hulls	29: 1	52
b) Dairy manure, rice hulls, corn starch	48: 1	
c) Dairy manure, rice hulls, raw cabbage	19: 1	
3. Human excreta, garbage, sawdust/Peatmoss	21: 1	173
4. Human excreta, kitchen waste, rice chaff	28: 1	172
5. Human excreta, water hyacinth	30: 1	140
6. Human excreta, grass/vegetable cuttings, straw/ sawdust	15–30: 1	145
7. Human excreta, organic wastes	30–40: 1	170
8. Human excreta	30: 1	15
9. General	15: 1 (best) ranging upward to 30: 1	22, 171
10. General	30–35: 1	15
11. General	25–30	16

Table 7. Approximate Nitrogen Content and C/N Ratios for Some Compostable Materials (Dry Weight Basis)

Material	N (%)	C/N Ratio
Urine	15–18	0.8
Blood	10–14	3
Mixed slaughter-house waste	7–10	2
Nightsoil	5.5–6.5	6–10
Activated sludge	5–6	6
Grass clippings (young)	4.0	12
Garbage	3.6	12
Grass clippings (mixed)	2.4	19
Farmyard manure	2.15	14
Seaweed	1.9	19
Potato hauls	1.5	25
Combined refuse	1.05	34
Oat straw	1.05	48
Wheat straw	0.3	128
Fresh sawdust	0.11	511
Newspaper	nil	

IV.2 Loss of Nitrogen and Other Nutrients

Of the major nutrients - nitrogen, phosphorus, and potash - nitrogen conservation is the most important. Nitrogen may be lost by leaching, but the major loss comes from the escape of ammonia or other volatile nitrogenous gases from the compost material into the atmosphere. Nitrogen loss as ammonia in composting is affected by the C:N ratio, the pH, the moisture content, aeration, temperature, the form of nitrogen compounds at the start of composting, and the adsorptive or nitrogen-holding capacity of the composting material (Gotaas, 1956).

Vogtman & Besson (1978) stated that all methods of composting to prepare farmyard manure lead to losses in nitrogen. Bayens found higher concentrations of ammonia in anaerobically as compared to aerobically treated manure (Table 8), as cited by Vogtman & Besson (1978). The loss of nitrogen varied considerably depending on the kind of treatment, as shown in Table 9 (Kershaw, 1968).

Table 8. Ammonia–N in Manure Piles

Temperature	Ammonia–N in % of total–N	
	Aerobic	Anaerobic
15° C	4.5	75
35° C	1.8	18

Table 9. Nitrogen Loss during Farm Yard Manure Treatment

Material	Nitrogen Loss %	Authors
Anaerobic composting	10 – 15	Riibensahm and Rouhe
Partialy aerobic	21.8	Roemer et al.
Aerobic composting	22.8	Becker and Dillingen
Stock piled and packed	25	
Stock piled not packed	50	
Stock piled not packed	30.3	Roemer et al.
Manure piled on top of a layer of fermented manure	16.9	
Stock piled packed and slurry added	16	Diehl
Stock piled not packed	35	

Vogtmann and Besson made a comparison between not turning and turning the material four times during a four months period. The average nitrogen loss is shown in Table 10. The average total nitrogen loss in composting with forced aeration was found to be similar to that found in the windrow experiments (Table 11).

Table 10. Average Nitrogen Loss of Not Turned and Turned Compost Piles of Farm Yard Manure (FYM)

Material	Average Nitrogen Content % of Dry Matter[1]		Average Nitrogen Loss %	
	Total – N	NH_3–N	Total – N	NH_3–N
Not Turned				
FYM, fresh	2.09	2000	28	95
FYM, compost	1.51	100		
Turned				
FYM, fresh	2.10	2024	31	94
FYM, compost	1.45	120		

[1] *Recalculated for total amount of dry matter and nitrogen in the fresh material at the beginning.*

Table 11. Average Nitrogen Loss During Composting of Farm Yard Manure with Forced Aeration

Rate of Aeration	Nitrogen Loss in Percent of Total – N at the Beginning
10 1 air/min.	25
30 1 air/min.	28
50 1 air/min.	30

Different investigations (Gotaas, 1956) showed that there is very little loss of nitrogen during storage of composts, the except when the compost contains large amounts of ammonia.

Gotaas (1956) described various suggested methods, and tried out measures to conserve the nitrogen during composting. Conservation of phosphorus and potash in composting is not difficult, since about the only loss occurs through leaching during rainy weather.

IV.3 Moisture Content

The Moisture content becomes a limiting factor when it drops below 45 or 50%. Both Snell (1957) and Spohn (cited by Gray et al., 1971a) showed that the rate of composting fresh materials at moisture contents of 20-25% was less than 15% of the rate at optimum moisture levels, although Spohn could still detect slight activity at 5% moisture. Working with materials that had been through most of the composting cycle and had reached the maturing stage, Schulze (cited by Gray et al., 1971a) found no activity at 11.2% moisture content.

The upper level of moisture, conducive to good composting, depends greatly on the structural wet strength of the organic feed. Weak materials, e.g. paper, collapse readily on composting. Thus in the presence of excessive moisture, the pores fill with water and oxygen diffusion is restricted and anaerobic conditions set in. Rigid materials, e.g. straw, retain their wet strength for a long time, until most of the wall fibers have been degraded, and consequently they can be composted with initial moisture contents of as much as 85%.

In practice, the optimum range of this parameter is 50-70%, the lower figure applying to composting in static heaps or windrows, and the upper figure being permissible in mechanically-agitated systems with forced air injection.

Golueke (1972) suggested the maximum permissible moisture contents for various wastes, as listed in Table 12.

Table 12. Maximum Permissible Moisture Contents

Type of Waste[a]	Moisture Content
Theoretical	100
Straw	75–85
Wood (sawdust, small chips)	75–90
Paper	55–65
"Wet" Wastes (vegetable trimmings, lawn clippings, garbage etc.)	50–55
Municipal Refuse	55–65
Manures (without bedding)	55–65

[a] *The major component of the waste.*

As the table indicates, the maximum permissible moisture content for composting wastes that are largely "fibrous" (straw, hay, dry leaves, etc.) or woody (sawdust, small wood chips, bark, etc.) is within the range of 75 to 85% (Regan & Jeris, 1970). On the other hand, wastes consisting mostly of paper or of green vegetation (lawn clippings, vegetable trimmings, wet garbage, etc.) have a maximum permissible moisture content within the range of 50% to 60%.

Experimental work to evaluate this optimum range, when composting ground refuse, has been reported by Wiley & Pearce (1955), Snell (1957) and Spohn (as cited by Grey et al., 1971a). Wiley & Pearce concluded that optimum values lie in the range 55-69%. Snell, with slightly more detailed work, narrowed the range to 52-58%. Spohn reported an optimum value of about 50%.

In a subsequent paper, Wiley (1957) noted that lipids - fats, oils and waxes - which are present in significant amounts in most organic wastes, are liquids at optimum composting temperatures. Accordingly, he postulated that they should be considered together with the water content in assessing optimum wetness for decomposition. He proposed the term "percent liquid" as having better applicability than moisture content, where:

$$\%\ \text{liquid} = \frac{100 \times (\%\ \text{moisture} + \%\ \text{lipids})}{(100 - \%\ \text{ash})}$$

If the maximum permissible moisture content for a given waste is excessively low, the problem can be lessened by adding an absorbent waste to the material. Thus, if straw is added to vegetable trimmings, the maximum permissible moisture rises in proportion to the amount of straw added. The addition of an absorbent is also required if the moisture content of the waste in its "raw" state is excessively high, as for example in the case of cannery wastes.

During the composting process, moisture is released as one of the end products of microbial metabolism. If aeration is poor in a compost heap, then this increased moisture can accumulate and lead to the onset of anaerobic conditions.

Where there is reasonable aeration by diffusion and the climate is temperate, little extra moisture is necessary on occasional turning of the heap. In hot climates, however, rewetting is certainly required.

In plants with forced aeration, desiccation will normally occur. Using an air flow of 6.6 m^3/d-kg of volatile solids, approximately the minimum rate consistent with good aerobic conditions, then about 16% of the initial moisture content will be lost over five days if the exit gas is at 50°C. With air flows five times the minimum rate, which is quite a reasonable practice, then considerable desiccation will occur and frequent moisture addition will be needed.

IV.4 Temperature

The optimum temperature or temperature regime for composting has been the subject of many researchers (Atchley & Clark, 1979; Clark et al., 1978; Jeris & Regan, 1973; Mote & Griffis, 1979; Stead, 1978).

Golueke divided the total range of temperatures, at which life is possible, into three "sub-ranges" into which can be grouped those organisms whose optimum temperature falls within one of the sub-ranges. The three sub-ranges are cryophilic, mesophilic, and thermophilic. The boundary temperatures of each of the ranges have been somewhat arbitrarily assigned as being from about 5°C to about 10°C for the cryophilic range; from 10°C (or as high as 15°C) to 40°C or 45°C for the mesophilic range; and from 40°C or 45°C to 70°C for the thermophilic range (certain blue-green algae and bacteria can survive and even grow at temperatures as high as 80°C to 90°C).

Based on the temperature range within which the process takes place, composting involves two major states of reaction: mesophilic followed by thermpohilic. During the mesophilic temperature range, it is the mesophilic organisms which are more active, while the thermophilic organisms take over during the thermophilic range. Temperatures reached may vary over wide ranges, and the so-called optimum temperatures to the mesophilic and thermophilic organisms are shown in Table 13. An important reason for the normal occurence of a succession of mesophilic followed by thermophilic conditions is that the temperature in an aerobic mass of material inevitably rises to thermophilic level unless positive measures are taken to prevent it from doing so.

Table 13. Temperature Range for Various Organisms

References	Optimum Temperature Range °C	
	Mesophilic	Thermophilic
15	25–40	55–65
16	8/10–45/50	45/50–55/60
50	< 42	55
14	< 40	< 60
51	40	59

The typical shape of temperature/time and temperature/pH curves for the center of a compost heap as given by Gray et al. (1971a) is shown in Fig. 7. Gray et al. divided the process into four stages, namely mesophilic, thermophilic, cooling down and maturing.

There exists for each microorganism a temperature at which its metabolism rate is maximal. Since the composting process represents the integrated activity of a number of different microbes, the chances of the temperature being optimum at any single instant for every individual group of the microorganisms present would be nil. However, at peak activity of the pile as a whole, the chances of the temperature being within the vicinity of the optimum would be good. It follows, therefore, that there is an optimal temperature or temperature regime to maximize the degradation of the waste material.

The point as to whether maximum decomposition takes place in the mesophilic or thermophilic range is open to question. The earlier works on the relation of temperature with microbial activity as evidenced by oxygen consumption, carbon dioxide production, or chemical and physical changes have been reported by Clark et al. (1978), Jeris & Regan (1973), and Suler & Finstein (1977).

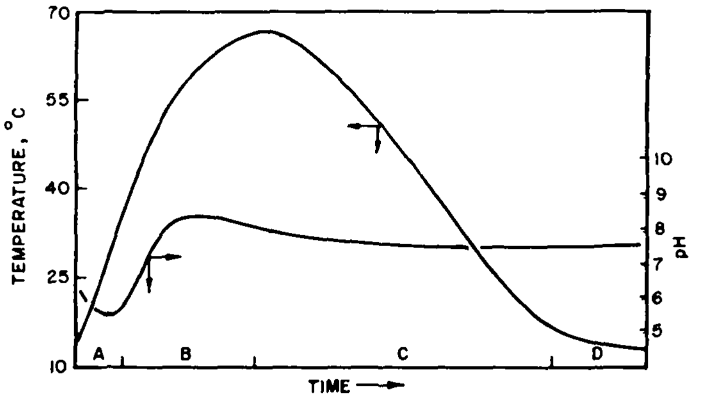


Fig. 7 Temperature and pH variation with time indicating the phases of microbial activity
A - mesophilic, B - thermophilic, C - cooling, D - maturing

The previous studies indicated maximum stabilization of refuse under thermophilic conditions, leading to a re-examination of the optimum temperature range required for maximum stabilization efficiency of municipal refuse having a typically high cellulose concentration (Jeris & Regan, 1973). The summarized results of their experiment is presented in Table 14.

Table 14. Optimum Temperature for Composting Solid Wastes with High Paper Content

Material	Composting Rate (m–mol CO_2/day–gVM)	Optimum Temperature (°C)
Newsprint	0.35	48
Stabilized Municipal Refuse	0.28	40
Mixed Refuse	3.7–4.5	59

Clark et al. (1978), when investigating the effect of temperature on composting garbage (mixed refuse) within a temperature range of 42-57°C in 3°C increments, providing six different temperature levels, reported a bi-model carbon dioxide production profile at all temperatures as shown in Fig. 8.

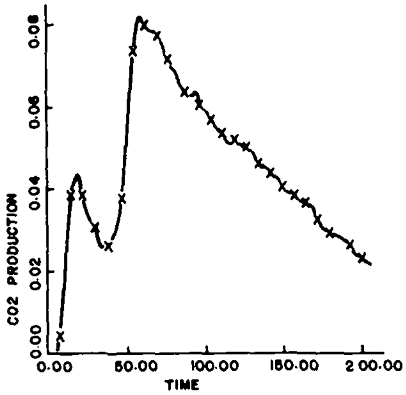


Fig. 8 Typical Co$_2$ production profile using standard synthetic food and garden soil inoculum

The instantaneous carbon dioxide production rate at each of the peaks of activity and the total carbon dioxide production per gram of initial dry weight of feed are shown in Table 15.

Table 15. Effect of Composting Treatment on Respiratory Activity

Temperature (1)	Total CO_2 evolved in 120 hr, in millimoles of CO_2 per gram dry weight (2)	Instantaneous CO_2 evolution rates, in millimoles of O_2 per hour-gram dry weight	
		First peak (3)	Second peak (4)
42	0.24	0.075	0.072
45	0.23	0.10	0.064
48	0.23	0.07	0.062
51	0.21	0.096	0.051
54	0.19	0.13	0.046
57	0.086	0.11	0.018

The first peak, steep and of short duration, increased in height with increasing temperature. It is possible that this peak is caused by thermophilic bacteria, whose optimal growth temperature is approximately 55°C. This peak contributed only 16-17% of the total carbon dioxide in the runs showing high total carbon dioxide production. The second peak, less steep and of longer duration, decreased in height with increased temperature. It appears that this peak is due to a mesophilic microorganism (or microorganisms) whose optimal growth temperature is at or below 42°C. As this second peak accounts for the major portion of carbon dioxide produced, its inhibition at higher temperatures resulted in reduced total carbon dioxide production.

The concept that there are two distinct phases in composting, mesophilic and thermophilic, does not totally apply in refuse-sludge composting. The mesophilic stage is thought to be promoted by an abundance of available nutrients and ambient temperatures. The mesophilic organisms are highly active and cause an increase in the temperature of the composting mass. This rise in temperature causes cessation of the mesophilic stage and the onset of the thermophilic stage. It is the abundance of the thermophilic sites that produces a high average temperature for the mass. However, the entire mass does not undergo a shift from one temperature range to another, but only shows a trend in those directions (Atchley & Clark, 1979).

Suler & Finstein (1977) reported maximum carbon dioxide evolution at 56-60°C and sub-maximal at 64°C and higher. The effect of temperature and aeration on the cumulative amount of carbon dioxide formed at a moisture content of 60% is summarized in Fig. 9. The optimum temperature at lower than 60°C contradict the widely held impression that in composting hotter is necessarily better.

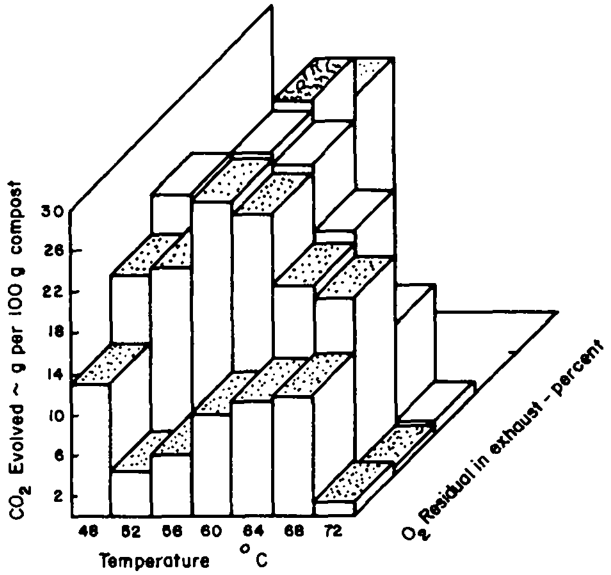


Fig. 9 Effect of temperature and aeration on CO_2 evolution per 100 g. of compost (dry weight) during 96-h trial periods. The moisture content was 60% (wet weight). The top of the 52°C, 18% O_2 column is almost hidden.

Forsyth & Webley (1948) showed that the cellulose and lignin fraction are scarcely attacked at temperatures over 60°C, but waxes, proteins and hemicelluloses were readily degraded. As the rapidly degradable material becomes used up, the reaction rate slackens, until eventually the rate of heat generation becomes less than the rate of heat loss from the surface of the heap, and the mass starts to cool down.

Once the temperature falls below 60°C, the thermophilic fungi from the cooler outsides of the mass can re-invade the heap center and commence their major attack on the cellulose. Yung Chang & Hudson reported that at this point during the degradation of wheat straw, another (though smaller) temperature peak occurred. A similar effect was also noted by Rao & Block when composting corncob and hay mixtures. However, in similar experiments with composts of grass clippings, Yung Chang & Hudson found no such secondary peak. In this case the temperature curve resembled that shown in Fig. 6. The temperature curves for both grass and straw composts given by Webley (cited by Grey et al., 1971b) are similar, showing no second peaks. Yung Chang & Hudson noted that the differences between these curves are obviously a function of the type of material - and other factors, such as the age of the material. That the latter point may be true is suggested by Festenstein et al. (cited by Grey et al., 1971b), who investigated the self-heating of hay in Dewar flasks. Old stored hay had a multipeaked heating pattern, while a similar good-quality, air-dried hay harvested a year later showed a single temperature maximum.

Whatever the optimum temperature for waste decomposition in composting is, and this may vary somewhat with different wastes and process conditions, it is certainly lower than the maximum that can be attained. Although peak temperatures in the vicinity of 70°C are more common, large composting masses sometimes reach 80°C. The management of a composting process which aims at exceeding 60°C presumably favors extreme thermophiles. The presence of such organisms in compost is yet to be demonstrated. Whether thermophiles are present or not, any benefit derived from them may be more than offset by a loss of population diversity (Suler & Finstein, 1977).

IV.5 pH (Hydrogen Ion) Level

Generally, fungi tolerate a wider range of pH than do bacteria. The optimum pH range for most bacteria is between 6 and 7.5, whereas for fungi it can be between 5.5 and 8.0.

Typical pH changes in a composting mass were shown in Fig. 6. The diagram illustrated that the initially slightly acid material normally falls in pH to a range of 5.0-5.5 during the mesophilic stage of composting. However, during the thermophilic stage, it rapidly becomes alkaline, reaching a pH of 8.0-9.0, and ammonia is frequently liberated at the peak temperature. The pH then falls slightly during the cooling-down stage, and reaches a value in the range the 7.0-8.0 in the mature compost. The effect of pH control has been investigated by a few workers.

In the University of California project (McGauhey & Golueke, 1953), studies were made on the effect of adding 0, 2, 6, and 8% industrial calcium carbonate to refuse composting in a 5-gal (19-liter) jars and 55-gal (208-liter) drums. The presence of alkali had aided the evolution of ammonia during the temperature peak, Faced with lower availability of nitrogen, the microorganisms had oxidized off greater amounts of carbon in order to reduce the C:N ratio towards 10.

Wiley examined the effect of both alkali and acid additions to refuse in his laboratory composters (cited by Golueke, 1972). Addition of 16-27% of calcium dihydroxide resulted in a sharper increase in temperature and faster decomposition. The addition of acetic acid showed retarded thermophilic action, as long as the pH was suppressed below 6.0. Stabilization of the refuse was incomplete under these acid conditions.

Snell postulated that the composting process is much less sensitive to volatile acids than is anaerobic digestion, though the composting may be incomplete while the volatile acid level is greater than 0.5%.

The object of most composting operations is to maximize both the quantity of humus product produced and its nitrogen concentration. These aims far outweigh any consideration of the marginally faster rate of reaction obtained by the use of excessive and uneconomic additions of alkali. Also, nitrogen conservation becomes a constraint while taking steps to raise the pH level of the compost mass, as the addition of lime usually is accompanied by an increase in ammonia formation and a consequent loss of nitrogen (Anon., 1964; McGauhey & Golueke, 1953). Accordingly, it would appear that, for most composting feedstocks containing a reasonable variety of constituents, control of the pH is neither necessary nor desirable.

IV.6 Availability of Oxygen (Aeration)

The matter of aeration is not only important for the reaction, but also indirectly to the public health and aesthetics of a compost mass. Aerobic conditions are essential to the development of thermophilic conditions.

When composting materials are in heaps, windrows or bins using natural aeration, the diffusion of the free oxygen and carbon dioxide results from the difference in partial pressure of each component in the atmosphere and at the site being degraded. This gas movement is opposed by the pressure drop caused by the narrow tortuous passages through the heap. It has been shown (McCauley & Shell, 1956; Shell & Boyd, 1969; Snell, 1957) that this diffusion is quite inadequate to maintain good aerobic conditions during the period of peak oxygen demand, even allowing for the natural "chimney" effect with the gases being warmed in the heap, ascending and creating a draught.

Frequent turning of the composting heaps is a way to promote the natural aeration of the composting mass (Gotaas, 1956; Kochtitkky et al., 1969; Wiley et al., 1961). Spohn suggested the building up of windrows in several stages and the use of a side-arm turning machine. Maier et al. (1958) proposed the mounting of heaps on perforated grids to improve the natural aeration.

To find a simple, cheap and yet effective way of a providing aerobic environment, forced aeration has received considerable attention as a substitute for turning, particularly for bin and windrow composting. Golueke (1981) pointed out that the success of forced aeration depends upon the presence of a granular (or its equivalent) material of a consistency that does not lead to compaction into amorphous masses, and upon a moisture content that is not in excess of a level appropriate to that material. As cited by Gray et al. in their review of composting, Kershaw

(1968) and Livshuts mentioned the use of perforated pipes laid under windrows, while Kailbuchi (1961) and Snell (1957) described forced aeration in bins and mechanical digesters. Spohn described the problems arising from forced aeration of unagitated boxes, the maldistribution of air, moisture and temperature. McGarry & Stainforth (1978) reported two Chinese methods of composting (excreta, animal manure, plant wastes and soil) in which the aerobic environment is provided in a simple way. In the ground-surface continuous aerobic composting method, the materials to be composted are piled up to a height of 15 cm and placed on 8 cm diameter timbers horizontally on top to form a shape with a distance of 1 meter between the timbers, as shown in Fig. 10.

Where the timbers cross, four vertical timbers are erected and waste is piled up to a height of 1 m and then covered with earth, and the timbers are withdrawn when the earth cover has dried slightly. The other method - large pot aerobic composting is carried out in a trapezoid rectangular pit, as shown in Figure 11.

A cross-linked ventilating channel is excavated along the middle of the pit floor. Then a layer of millet stalks is placed on top of the ventilating channels and timbers erected, as shown in Fig. 10. The pit is then filled with composting materials and covered with earth.

Gray et al. felt maintain that there is now sufficient experimentally determined data in the literature on the microbiological, chemical and physical parameters of composting for reasonably accurate process design of composting plants. Optimum values of the important parameters are summarized in Table 16 (Suler & Finstein, 1977).

Table 16. Optimum Values of Major Composting Parameters

Parameter	Value
C/N ratio of feed	30–35: 1
C/P ratio of feed	75–150: 1
Particle size	0.5–1.5 in for agitated plants and forced aeration 1.5–3 in for windrows, unagitated plants and natural aeration
Moisture content	50–60%
Air flow	10–30 ft^3 air/day/lb volatile solids during thermophilic stage, being progressively decreased during cooling down and maturing
Maximum temperature	55 °C
Agitation	Short periods of vigorous agitation, alternating with periods of no agitation which vary in length from minutes in the thermophilic stage to hours during m maturing
pH control	Normally none desirable

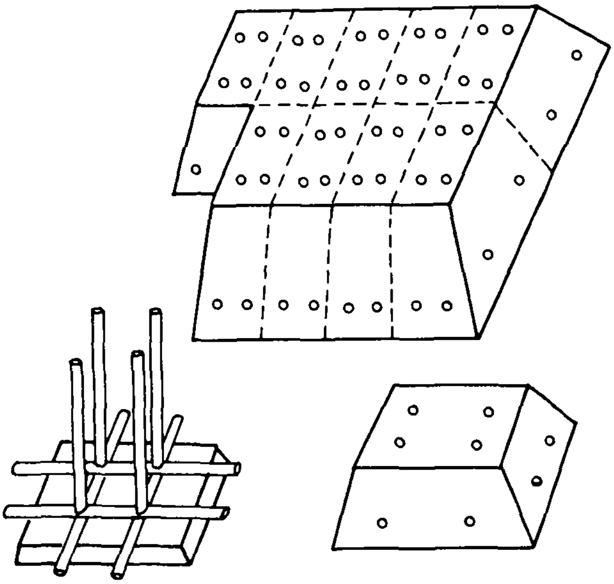


Fig. 10 Ground-surface continuous aerobic composting pile.

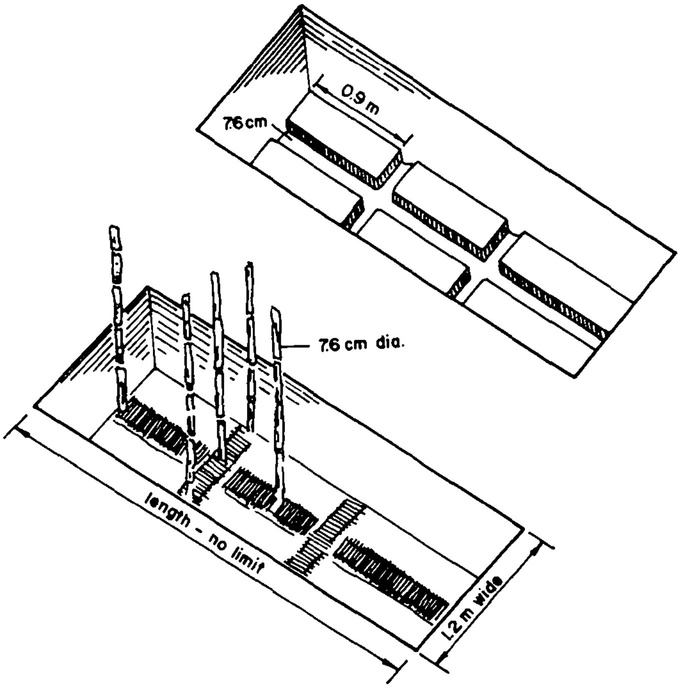


Fig. 11 Fully aerobic composting pit.

IV.7 Genetic Traits

Though not an environmental factor, genetic traits constitute the ultimate rate limiting factor, as mentioned by Golueke (1972). The significance of this statement is that, regardless of how closely we can achieve all optimum environmental conditions, the rate of decomposition ultimately depends upon the capability of micro-organisms to break down the material. The capability of micro-organisms depends upon their genetic make-up; and the environment permits the expression of the genetic make-up.

A practical aspect of genetic limitations is that no amount of sophistication in the equipment will hasten the decomposition of resistant materials beyond the limit permitted by the genetics of the organisms involved. It is this limitation that should prompt one to be skeptical of claims for one- to three-day compost schemes, or of inoculations that will greatly accelerate decomposition beyond that normally encountered. Another practical aspect is that maintaining environmental conditions beyond the optimum level is a waste of effort, insofar as the potential, as determined by the genetics of the organisms, cannot be surpassed. On the other hand, there is no doubt that the process could be considerably accelerated over present-day rates by making a more effective provision for optimum conditions. However, the amount of gain would not necessarily warrant the extent of the required expenditures.

V. KINETICS

V.1 Kinetics of Composting Reaction

Kinetics deals with the rates or velocities of reactions. As Hang (1980) warned, kinetics must be distinguished clearly from the related subject of thermodynamics. Thermodynamics is concerned with energy changes accompanying chemical reactions, but does not reveal how fast these reactions will occur. The same energy is released whether the paper is burned or biologically oxidized to carbon dioxide and water. However, the kinetics of the two cases are remarkably different.

The kinetics of composting systems is a subject of vital interest to the design engineer, who must determine the type of reactor and detention times required to achieve a certain degree of organic stabilization.

V.2 Thermodynamics

A brief overview of the thermodynamics of composting will be beneficial in understanding the composting process. As thermodynamics is the study of energy and its transformations, it places distinct limits on the energy tranformations within systems, as small as a single microbe or as large as the universe. According to Haug (1980), no single science will so unify the diverse aspects of composting as will thermodynamics.

The first law of thermodynamics states that energy can be neither created nor destroyed. The concepts of heat, work, internal energy and enthalpy are related by the first law, also referred to as the law of conservation of energy. The second law explains the direction in which spontaneous changes in an isolated system occur with an increase in entropy or randomness.

Free energy gives the useful work which can be derived from a chemical reaction occurring under constant pressure and temperature conditions, e.g. most microbial processes. Therefore, a measure exists of the useful energy available from the feed substrate being used by a biological population.

All chemical reactions have a standard free energy change, measured with all reactants and products at unit activity (approximately a 1 M concentration). Spontaneous chemical reactions proceed in the direction of decreasing free energy. If the free energy change is zero the reaction is at equilibrium. The standard free energy change can be related to the equilibrium constant for the reaction, and can be adjusted for the effect of the product and for reactant concentrations which differ from the standard concentration.

The effect of temperature on the rate constant for chemical reactions can be estimated from the Arrhenius equation:

$$\frac{d(\ln k)}{dT} = \frac{Ea}{RT^2} \qquad (1)$$

where K : reaction rate constant

Ea : activation energy for the reaction, cal/mol

T : absolute temperature, ° K

Simplifying for a temperature change of T_1 to T_2 the above equation finally comes in the form:

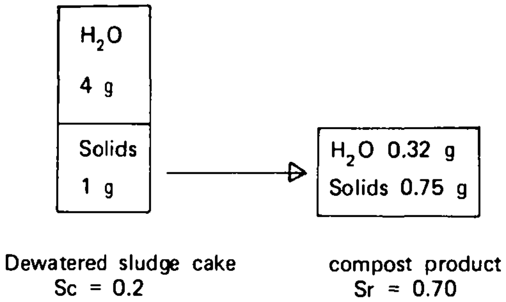
$$K_2 = K_1 e^{0(T_2 - T_1)} \qquad (2)$$

where 0 = Ea/RT_2T_1 is considered as a constant.

Heats of combustion vary from - 2,100 to - 9,300 cal/g for the three major foodstuffs, namely protein, carbohydrates and lipids (fats). Lipids generally contain twice as much energy per gram as protein or carbohydrates. Expressed on a COD basis, however, most organics have a heat of combustion of about 3.4 ± 0.2 Kcal/g COD of the organics. It is often difficult to estimate the heat of reaction for organic wastes from standard thermodynamic tables because the wastes are likely to be composed of a mixture of compounds of unknown composition. Open and bomb calorimetric techniques can be used to determine experimentally the heat of combustion for such unknown materials. A number of empirical equations are also available which yield reasonably consistent results and which require only routine laboratory analysis (Haug, 1980).

Haug & Haug (1978) estimated composting energy demands for a composting stack of 20% solids, and these are tabulated in Table 17. Heat liberated from the decomposition of organics will be used to increase the temperature of solids and liquid in the composting mixture. Furthermore, as drying occurs, heat must be supplied to evaporate the water - otherwise compost temperatures will fall. Since the compost is at a higher temperature than the surroundings, energy losses will occur from the exposed surfaces of the compost. These losses will be mitigated to some extent by the insulating effect of the compost, which limits the conduction of heat from the pile or windrow interior. Losses will also occur as windrows are turned for aeration. In the aerated pile system, energy will be continually expended to heat air mechanically drawn into the pile. Under equilibrium conditions, the compost temperature will rise to a point where energy inputs are balanced by outputs. However, the maximum obtainable temperatures are limited to about 65-70°C, since rates of biological activity, and hence heat evolution, decrease above about 55°C.

Table 17. Energy Requirements during Composting



Heat to raise solids to 60° C, qs		
$Gs = mc_p (\Delta T)$		
$= (1g)\ 0.25\ cal/g - {}^\circ C\ (60 - 20){}^\circ C$	10	calories
Heat to raise water to 60° C, q_w		
$q_w = 4(1.0)\ (60 - 20)$	160	-
Heat to evaporate water, q_w		
$q_v = 540\ cal/g\ (4 - 0.32\ g)$	1987	-
Heat to evaporate produced water, q_v		
$q_v = 540\ cal/g\ (0.08\ g)$	43	-
Heat to air, q_a		
$q_a = 154$	154	-
Total required energy	2354	calories

V.3 Rates of Oxygen Consumption

Among the earlier reports on oxygen uptake are those by Chrometzka (1968), Popel (1961) and Schulze (1960, 1961). Chrometzka identified oxygen requirements ranging from 9 mm^3/g-h for ripe compost to 284 mm^3/g-h for "fresh" compost (4 weeks old); 7 days old "fresh" refuse required 176 mm^3/g-h. Schulze estimated that an air supply equivalent to 480-585 m^3 per tonne of volatile matter per day was necessary in his studies to maintain aerobic conditions, during peak oxygen demands. Lossin (1971) reports average chemical oxygen demands ranging from almost 900 mg/g at one day to about 325 mg/g at 24 days. In a review by Regan & Jeris (1970), the lowest oxygen uptake of 1.0 mg per g of volatile solids per hour took place when the temperature of the mass was 30°C and the moisture content was 45%. The highest uptake, 13.6 mg/g VS-h, occurred when the temperature was 45°C and the moisture content was 56±2 %.

Experimental data on aeration rates and oxygen consumption have been reported by Wiley (1955); Schulze (1960); Snell (1957); Arditti; Sharma; and Gray & Sherman (as cited by Grey <u>et al.</u>, 1971b). Some of these data are shown in Fig. 12.

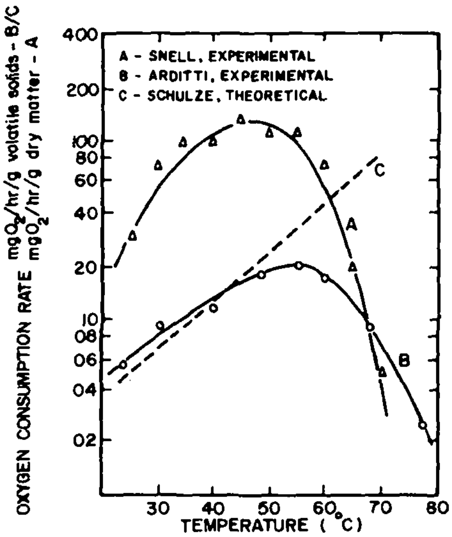


Fig. 12 The effect of temperature on oxygen consumption rate

From all his results, Schulze postulated that the oxygen consumption (expressed in mg/h-g of VS), Y, is related to the temperature, T°C by an equation of the form:

$$Y = a.10^{KT} \tag{3}$$

He calculated the constants as $a = 0.1$ and $K = 0.028$ over the experimental temperature range of 20-70°C.

Numerous other rate studies have been conducted using batch and continuous composters on a variety of feed materials. A summary of some of the available data is presented in Fig. 13.

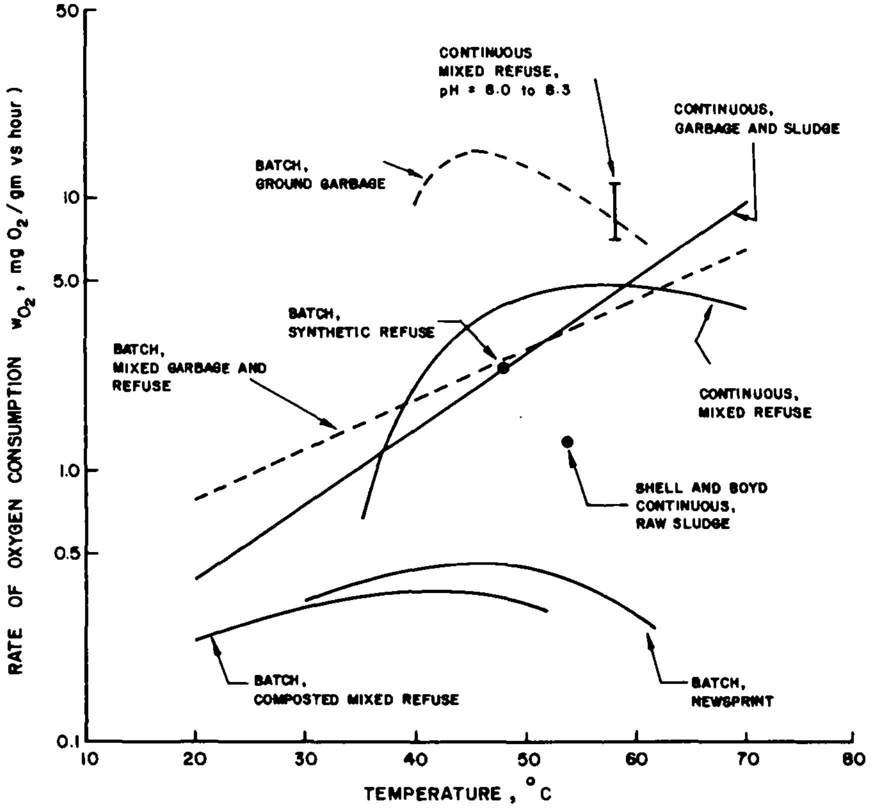


Fig. 13 Observed oxygen consumption rates for various composting mixtures and reactor types as a function of temperature. Each curve represents the best fit of observed data.

Despite the variety of procedures and feed materials, the data are remarkably consistent. All studies show an increase in the rate of oxygen uptake with increasing temperature.

It may be inferred here that there are three basic aeration requirements, namely:

1) The total quantity required to satisfy the stoichiometric demand;

2) The air quantity required to remove moisture and thus dry the remaining solids; and

3) The rate of air supply required to satisfy peak oxygen consumption rates. An additional air supply is also required to remove heat from the system and prevent excessively high temperatures.

In a classification of microbe-substrate systems by Haug, composting of organic residues and decomposition of organic solids in soils are categorized as "heterogeneous system-solid substrate", and they are shown in Fig. 14.

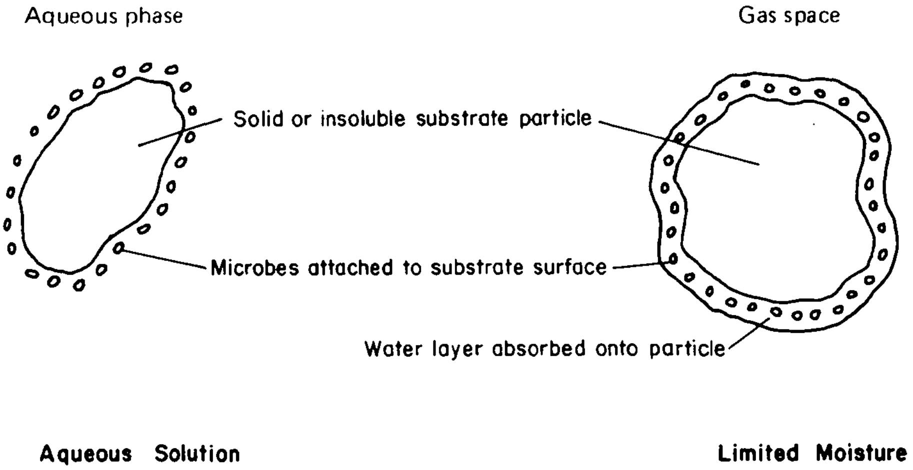


Fig. 14 Types of biological systems normally encountered in biochemical and sanitary engineering practices.

Haug summarized the sequence of events involved in metabolism of the substrate as follows:

1) Release of extracellular hydrolytic enzymes by the cell and transport of the enzymes to the surface of the substrate;

2) Hydrolysis of substrate molecules into lower molecular weight, soluble fractions;

3) Diffusion transport of solubilized substrate molecules to the cell;

4) Diffusion transport of substrate into the microbial cell, flocs or mycelia;

5) Bulk transport of oxygen (usually in air) through the voids between particles;

6) Transport of oxygen across the gas-liquid interface and the unmixed regions which lie on either side of such an interface;

7) Diffusion transport of oxygen through the liquid region;

8) Diffusion transport of oxygen into the microbial cell, flocs or mycelia; and

9) Aerobic oxidation of the substrate by biochemical reaction within the organism.

Any one of the events described above could limit the overall process kinetics.

Some researchers conducted an investigation to study the kinetic behavior of the composting process. They concluded that the reaction mechanism for the composting process may be considered as forming an intermediate organism substrate complex under a quasi-equilibrium state, with the reaction rate being, expressed by the equation:

$$R = \frac{K_2(c)}{K_1 + C} \qquad (4)$$

The kinetic constant K_1 is a characteristic constant of a given biological system, while K_2 is a kinetic variable of the system.

Haug derived the kinetic equation as follows:

The rate of product formation V is given by

$$V = \frac{-ds}{dt} = K_3(ea) = \frac{K_3(a_o)e}{K_a + e} = \frac{K_3 a_o e_o}{K_a + e_o} \qquad (5)$$

where,

e : number of free enzymes per unit volume of the reaction mixture.

a : number of free sites (for adsorbing free enzymes) on the substrate surface per unit volume

(ea) : number of sites with an adsorbed enzyme

K_3 : rate constant

a_o : total number of adsorption sites per unit volume $[e_o = a+(ea)]$

e_o : total concentration of enzyme at the start of the experiment $[e_o = e+(ea);\ e_o - e]$

Ka : $\frac{K_2 + K_3}{K_1}$ (K_1 & K_2 are reaction rate constants)

The concentration of extracellular enzymes e_o is probably a function of the mass concentration of microbes X in the reaction mixture. Also a_o is probably related to the available surface area per unit volume Av.

Thus equation (5) can be rewritten as:

$$V = \frac{-ds}{dt} = \frac{KA_vX}{K_x + X} \qquad (6)$$

where,

$\frac{ds}{dt}$: rate of hydrolysis of solid substrate

K : maximum rate of solid substrate hydrolysis which occurs at high microbial concentration

K_x : half velocity coefficient equal to the microbial concentration, where ds/dt = K/2

V.4 Practical Process

Actual composting practices certain fundamental steps which are essential in planning a composting project or in analysing composting operations. These steps are interdependent and in their order of sequence are as follows:

a) Sorting and salvation

b) Grinding or shredding the material (particle size effect)

c) Blending or proportioning of wastes (amendments & bulking agents)

d) Use of inocula

e) Placement of materials for composting

f) Aeration, mixing/turning patterns

g) Evaluation of the completion of composting (maturity)

h) Testing the quality of compost product

i) Storage and final usage of compost product

V.4.1 Sorting

On the basis of practical evidence, it appears that grinding of the raw material is one of the essential steps in aerobic composting. Hence, some degree of segregation, i.e. sorting out of non-combustibles and combustibles at the sources, and removal of salvable and non-compostable material is desirable.

In cities using separate containers, the responsibility for segregating refuse might be imposed upon the individual householder by requiring that only specific organic material such as garbage, paper, natural rubber, leather, and rags be placed in the container intended for compostable material. However, it is difficult to believe that such an ordinance could be strictly enforced. There might be severe damage or at least wear-and-tear to most of the several types of grinding mechanisms which would be used.

Materials which would normally require removal before grinding include tin cans, miscellaneous metals, and glass and ceramic ware. Excess paper might be removed for salvage, or in some cases to decrease the C:N ratio. Rags of natural fiber might be removed for salvage; whereas those of synthetic fiber should be removed because of their adverse effect on the appearance of the compost product.

Tin cans and other ferrous metal objects are commonly removed by a magnetic separator as the refuse moves along a conveyor belt. Rags and non-ferrous objects are presently removed by hand. As time progresses and the necessary technology is developed, hand sorting will be replaced by mechanized sorting. Excess paper is removed by a blower with its suction intake.

Segregation is not a difficult problem and need not deter composting. It is unlikely that segregation and grinding at the composting site will be important in villages and agricultural areas, since segregation of metals and other materials will be done at the source and normally only small amounts of non-compostable wastes will be present.

V.4.2 Grinding or Shredding

Grinding or shredding of refuse produces a number of beneficial results which hasten decomposition. The material is rendered more susceptible to bacteria invasion through exposing a greater surface area to attack and destroying the natural resistance of vegetation to microbial invasion. Large pieces of the waste material cannot be decomposed in a relatively short time in a compost pile. Also, sufficient free oxygen is not available in the center of such objects to permit aerobic decomposition. Through grinding, the refuse acquires a structure which facilitates handling and increases its response to moisture control and aeration. If the waste then contains a substantial amount of glass after grinding, the ground glass does not adversely affect any of the above advantages of grinding, but does increase the already phenomenal abrasiveness of refuse. The abrasiveness is capable of destroying the cutting edges of a hammer mill and similar blades in a single day's operation. Furthermore, unless the glass is pulverized, shards left in the material detract from the quality of the compost product.

The aim of grinding is to chop refuse into small pieces. A fairly small initial particle size reduces the depth of oxygen diffusion and microbial advance with the particle, aids the homogenizing of an initially heterogeneous material and improves insulation. On the other hand, too fine a particle size will involve very small interparticle voids. These will impede the diffusion of O_2 to, and carbon dioxide from, the sites being attacked, especially during the thermophilic stage of composting, when oxygen consumption is highest. This consideration is particularly important in heaps and windrows relying on natural aeration, rather than on a forced air supply.

Additionally, it is important that when used on the land, particularly for opening up heavy clay soils, the product compost should not be of a dust-like consistency, but should contain a significant proportion of lignin/cellulose residues of about 6 mm screen size.

The size of raw material particles is important, since it has been proved (Lobe & Novak, 1964) that materials which are too fine are subject to considerable loss of heat, whereas composts which are too coarse do not allow the oxygen-carbon dioxide exchange between the atmosphere and the air in the compost heap, and consequently will not warm up effectively by biological processes.

Gray et al. (1971b) suggested that the size range to which feed material should be comminuted is approximately 1.3-5.0 cm, the lower end being appropriate to forced aeration and adequately-agitated systems, the upper end to heaps and windrows. After composting and reasonable maturing, most of the organic material should breakdown to particles below 2.5 mm screen size.

Very few experimental results have been published on the effect of particle size on rates of composting. Fig. 15 plots the data of Arditi (cited by Gray et al., 1971b) who composted grass/straw mixtures. Over the temperature range 45-60°C, a significant increase in reaction rate was obtained by size reduction, the rate at the optimum temperature of 55°C being approximately double.

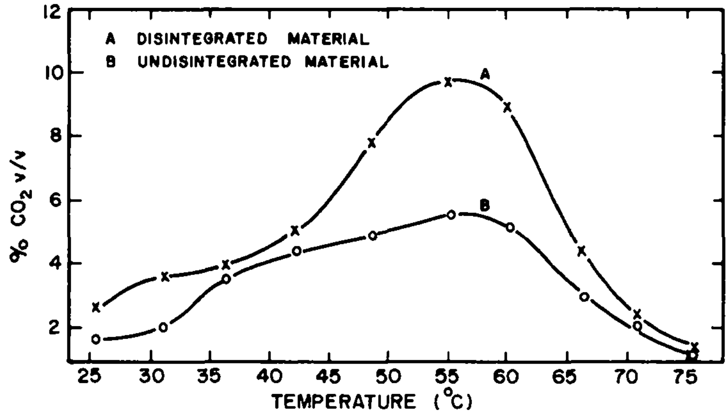


Fig. 15 The effect of particle size on decomposition rate

It should be emphasized that whether grinding or shredding is practised or not depends upon the nature of the raw material, the desired features of the final product, such as the appearance, size and quality, and the economic requirements of the operation.

V.4.3 Blending of the Materials

The composition and proportion of the materials in the compost pile, which will provide a good compost, is a very important step to be judged carefully by the compost operators. Various materials may be used as additives to optimize the proportioning in the composting waste. There have been several criteria, opinions and practices regarding the preparation of feed material for composting.

The C:N ratio and the moisture content are the two factors to be considered in blending. There is no need for blending when the C:N ratio is between 25 and 50, although 30 to 40 is a better range. If materials containing much paper, straw, sawdust or other substances rich in carbon and other materials such as slaughter waste, fish scrap, blood or night soil are delivered to the plant in separate loads, the high and low C:N ratio materials should be proportioned to provide a near optimum C:N ratio.

Similarly, materials too dry for good composting and materials too wet to compost without nuisance should be blended in proper proportions. Where initial shredding is practised, proportioning can usually be done at the shredder; otherwise, the materials are mixed and placed in stacks or pits together.

Addition of organic amendments is an approach to control composting mixture volatility. An amendment refers to inorganic material added to the feed substrate - primarily to reduce bulk weight and increase air voids, allowing for proper aeration. Amendments can also be used to increase the quantity of degradable organics in the mixture. Amendments that have been used by many researchers include sawdust, straw, peat, rice husks, manure, tree and lawn trimmings, and a variety of other waste organics. The ideal amendment would be dry, have a low bulk weight and be readily degradable. Compost recycling can be used to accomplish the reduction in bulk weight and in this sense should be considered as an amendment. It has been distinguished from other amendments because it allows the feed substrate to be composted without any external organic additives. Compost recycling along with amendment addition has been used in some cases.

V.4.4 Bulking Agents

A bulking agent is a material, organic or inorganic, of sufficient size to provide structural support and maintain air space when added to wet waste. Bulking material forms a three-dimensional matrix of solid particles capable of self-support by particle-to-particle contacts. This perhaps explains Haug's preference for the term "bulking particle" instead of "bulking agent". The waste or refuse material can be viewed as occupying part of the void volume in the interstices between particles. Thus the function of a bulking agent is to provide structural support to the compost waste pile, but if the bulking agent is organic, an increase in the quantity of degradable organics may be a secondary benefit.

Wood chips are most commonly used as bulking agents although the use of pelleted refuse, shredded tires, peanut shells, tree trimmings, rocks and other materials are also reported as having been used (Haug & Hang, 1978).

V.4.5 Use of Inocula

Composting developments have been accompanied by considerable discussion of the importance of special inocula, supposedly containing several pure strains of laboratory cultured organisms, or other biological factors essential in the decomposition of organic matter and nitrogen fixation, e.g. "enzymes", "hormones", "preserved living organisms", "activated factors", "biocatalysts", etc. In fact, several commercial composting processes are built around the use of some special inoculum, often known only to its discoverer and proponent, who claims it to be fundamental to the successful operation of the process. The need and value of such inocula have always been debatable (Acharya, 1950), and most composting studies have strongly indicated that they are unnecessary.

Farkasdi (1963) and Obrist (1965) report experiments on a variety of inocula or starters. Golueke (as cited by Grey et al., 1971a) investigated the use of horse manure, composted material, normal soil and special commercially prepared bacterial cultures in the composting of mixed garbage, vegetable trimmings and refuse, both on a laboratory scale and in large heaps. They found that these inocula failed, in terms of temperature pattern and chemical analyses, to benefit the composting process, and the reaction proceeded at equal rates in inoculated and uninoculated materials.

Many similar studies have indicated that inocula in composting or digesting organic wastes containing garbage, refuse, manure, night-soil, vegetable wastes, etc. are not necessary or advantageous. This seems logical, since bacteria are always present in very large numbers in such material and can be eliminated only by drastic sterilization methods. In any case, the number of bacteria is rarely a limiting factor in composting because, provided that the environmental factors are appropriate, the indigenous bacteria, which are much better adapted than forms attenuated under laboratory conditions, multiply rapidly, and the rate of composting is governed simply by the environmental conditions.

If a waste material should be sterile, which is most unsual in normal composting, microbial additions would be necessary. The success of compost operations without the use of special inocula in the Netherlands, New Zealand, South Africa, India, China, the U.S.A., and a great many other places, is convincing evidence that inocula and other additives are not essential in the composting of waste materials.

The steps to be taken, namely placement of the material for composting; aeration, the mixing/turning pattern; the evaluation of the completion of composting, testing the quality of the compost product and finally the storage and use of the compost product, will be covered separately in further sections of this review report.

At this point it will be appropriate to represent a generalized schematic diagram for composting, as shown in Fig. 16.

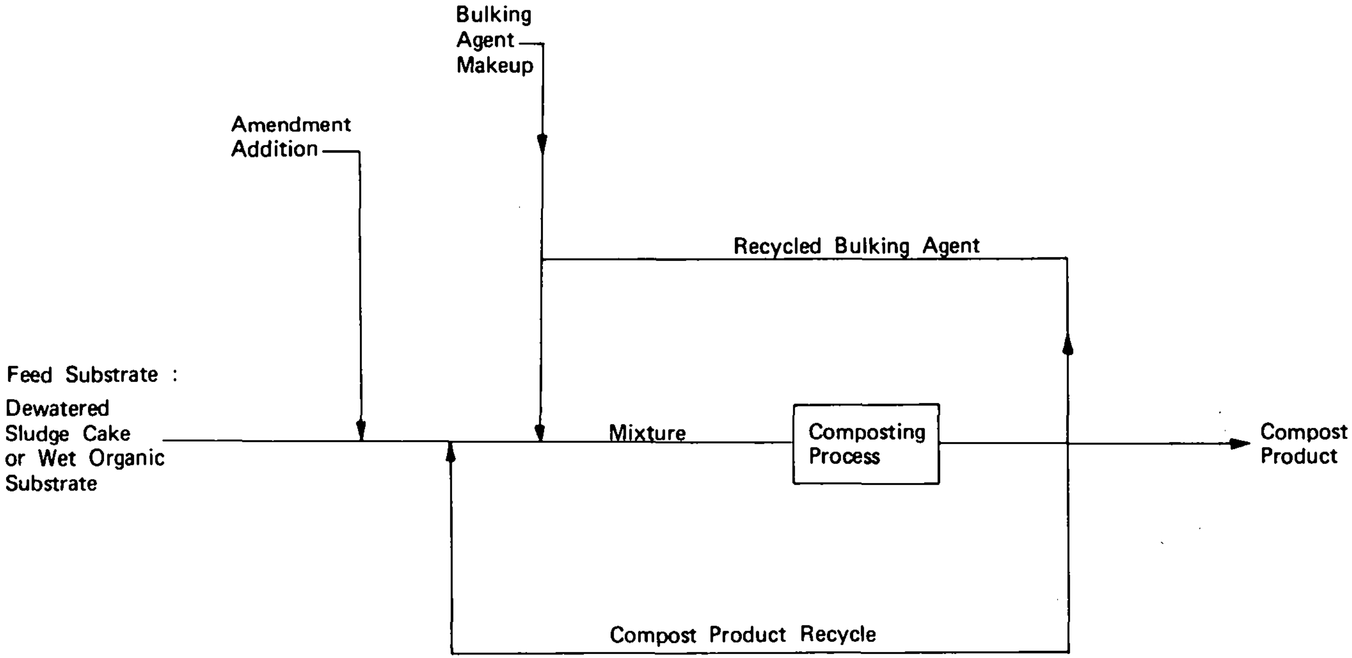


Fig. 16 **Generalized Diagram for Composting Showing Inputs of Feed Substrate, Compost Product Recycle, Amendment and Bulking Agent**

A process flow diagram of a complex plant for composting municipal wastes, as given by Gray et al. (1971b) is shown in Fig. 17.

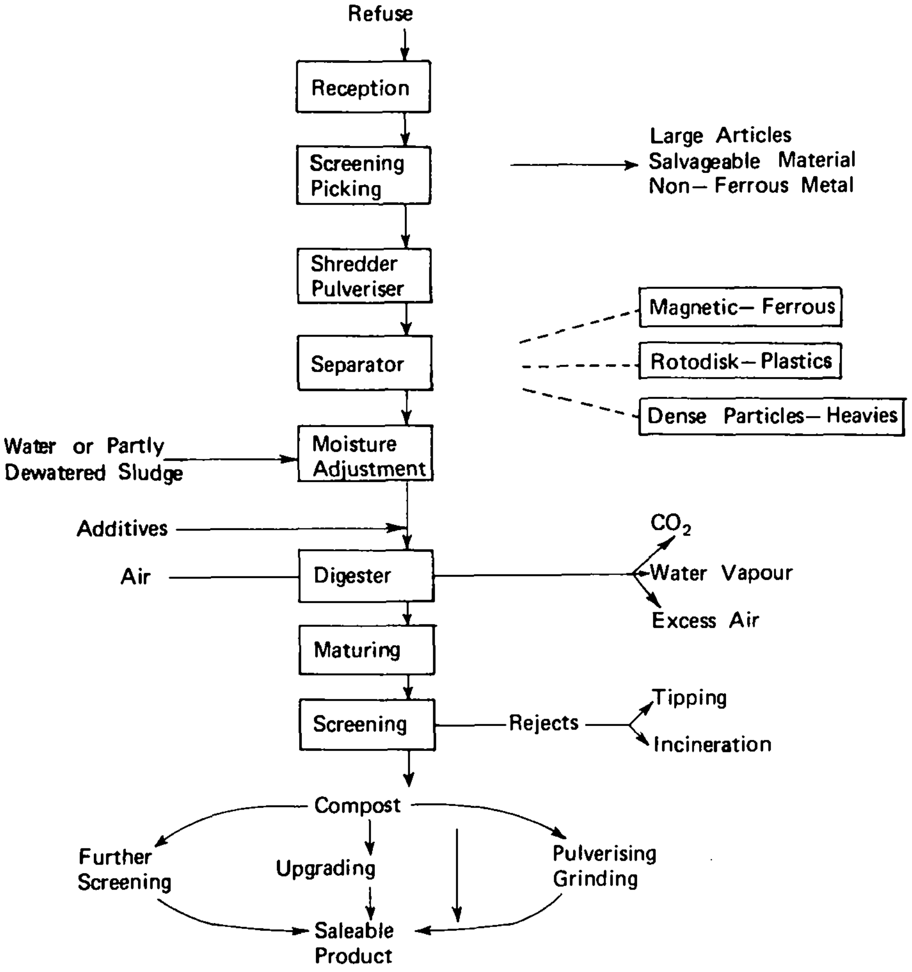


Fig. 17 Typical Process Flow Diagram – Composting Plant

VI. TECHNOLOGICAL ASPECTS

Over the past four decades, at least 30 different processing schemes for composting municipal wastes have been tried out, with varying degrees of success. All the processes comprise some of the stages given in the typical process flow diagram shown in Figure 16. Equipment for feed preparation and product finishing is very similar in most of these processes. The major differences arise in the fermentation stage, which has been attempted in all manner of pits, heaps, cells, bins, digesters, solos and drums. This variety reflects the lack of research into the subject, or incomprehension of the research results, and the difficulties in following the course of the reaction by meaningful chemical or physical parameters, and in evaluating the quality of the product.

Good descriptions of plants in use in the 1950's are given by Gotaas (1956) and Wiley (1960), while Tincolini et al. (1970) discuss systems employed in France and Italy during this period.

Among the early mechanical processes was the one developed by G. Giovanni Beccari of Italy. The Beccari process combines an initial anaerobic fermentation stage and a final aerobic stage. The anaerobic fermentation takes place in an enclosed cell designed to prevent the escape of foul odors usually associated with the initial breakdown of putrescible material under anaerobic conditions. As time goes by, vents are opened to admit air, and thereby to permit further decomposition under partially aerobic conditions. The process was later modified to provide for recirculation of gases or of drainage liquors. The modified process became known as the "Verdier process".

According to Golueke (1972), in 1931 Jean Bordas further modified the Beccari process and attempted to eliminate the anaerobic stage by introducing forced air into a fermentation silo.

The concept of aeration was carried a step further by the development of a multiple grate digester to produce compost by a continuous aerobic process. The process was patented in 1939 by Earp-Thomas. In the Earp-Thomas silo, aeration is accomplished by a combination of rotating plows and forced air. Earp-Thomas also insisted on the use of special cultures of bacteria furnished by himself.

A later variation of the digester type of enclosed cell was designed by Ralph W. Riker Company of Lansing, Michigan. It consisted of a double-walled silo with multiple floors. The inner silo was aerated both internally and externally, and the decomposing mass was sprayed continuously with drainage liquor pumped from a collecting sump positioned in the base of the silo.

Also, according to Golueke (1972), a different approach to digester design was represented by Frazer in 1949. The Frazer process is a fully mechanized and continuous one in which composts are supposedly produced rapidly and under aerobic conditions. Organic matter is shredded and introduced into a machine where it is kept continuously agitated as it moves from one level to another and is brought into contact with the gases of decomposition. The finished product passes through and out of the bottom through a screen. Tailings from the screen are recycled.

The Dano process marked a step in the direction of a more sound approach to the design of equipment for composting. As originally designed, the Dano process was essentially a separating and grinding process. Later developments involved the use of a slowly rotating horizontal drum suitably equipped for injecting air, applying moisture, and controlling temperature.

VI.1 Various Composting Systems

A variety of techniques can be used to classify composting systems. Haug (1980) used a chemical engineering approach to classification which emphasizes that the basic distinction between the systems is between reactor type and the non-reactor type. The reactor-type refers to those systems in which the composting material is contained in a reactor and the non-reactor type refers to those in which the composting is not done in digesters. Systems with reactors are popularly termed "mechanical", "enclosed", or "within-vessel" compost systems, whereas those which do not use such systems are often termed "open" systems.

According to Haug, the term "mechanical" is not appropriate and is misleading, since all modern compost systems are mechanical to some extent. One system might be considered more mechanical than another but the basic distinction is illusive. The terms "enclosed" and "open" are also poorly defined. For example, composting material might be housed under a roofed structure and thereby be enclosed but not contained in a reactor. That is why, classifying the two basic types as reactor and non-reactor systems is a better way to avoid such confusion. Simplified sketches of the basic reactor and non-reactor systems, as given by Haug (1980), are shown in Figs. 18 through 21.

VI.2 Non-Reactor Systems

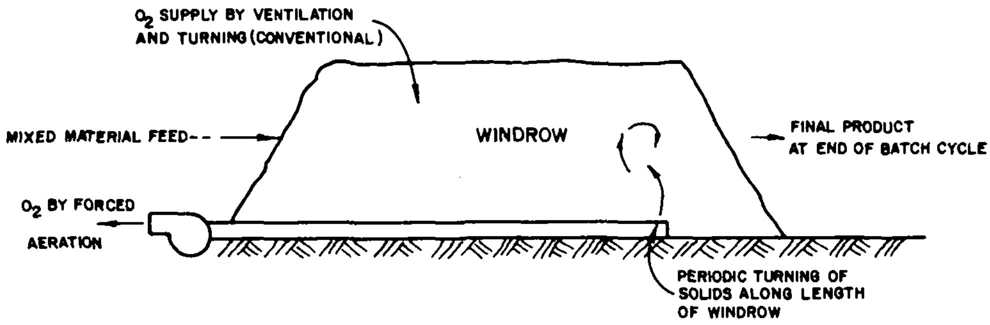
The non-reactor system can further be divided into two kinds:

1) Agitated solids bed type - These systems maintain an agitated solids bed, i.e. the composting mixture is disturbed or broken up in some manner during the compost cycle. This may be by periodic turning, tumbling or other methods of agitation. Agitation is not synonymous with mixing. For a system to be well mixed it must be agitated in some manner. However, an agitated system may be either well mixed or not. A typical example of a non-reactor agitated solids bed system is the windrow composting system, which is derived from the Bangalore or Indore system.

2) Static solids bed type - These systems employ a static bed. In general there are two kinds of static solids bed systems defined by the method of aeration. The first uses forced aeration and is named as "aerated static pile process". The second relies on natural ventilation and diffusion of oxygen, e.g., the "Brikollor process". In either case, no agitation or turning of the static bed occurs during the compost pile.

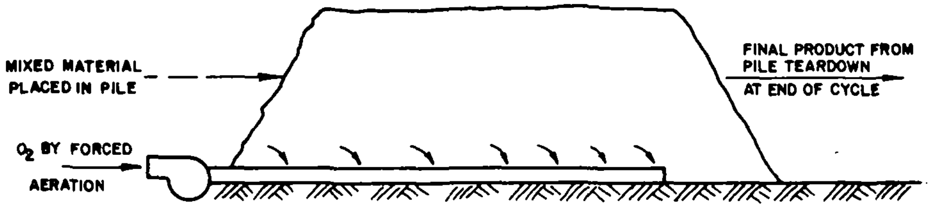
VI.3 Reactor Systems

Many simple, and also some relatively complicated composting methods, using reactors to contain composting material and provided with various mechanical devices have been practised. Reactor systems may be divided into vertical flow (Fig. 19), horizontal flow (Fig. 20) and inclined flow reactors (Fig. 21).



B. Static Solids Bed – No agitation or turning of static bed. Batch feed of solids. No dispersion or mixing of solids in bed.

1. Forced Aeration: Example - aerated static pile process.



2. Natural Ventilation and Diffusion of O_2: Example - Brikollari Process.

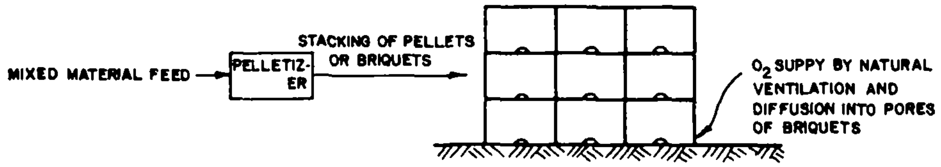
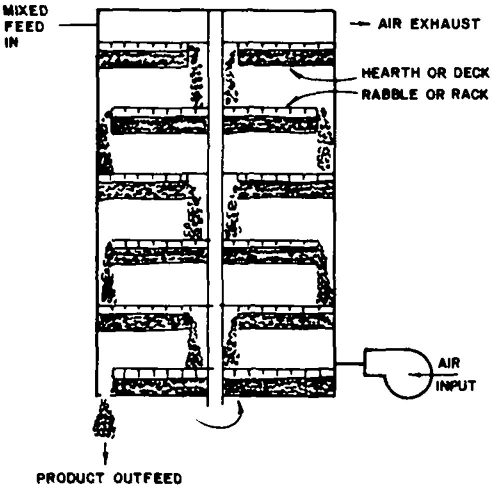
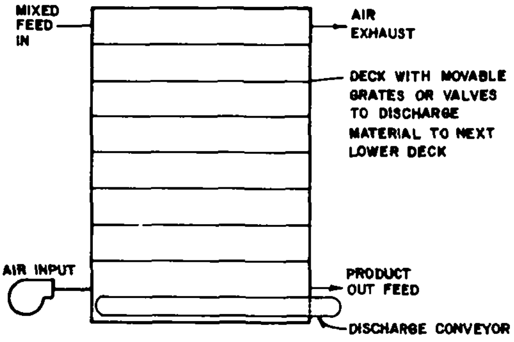


Fig. 18 Nonreactor composting system.

A. Moving Agitated Bed Reactor - Solids are agitated during movement down the reactor. Forced aeration. Continuous or intermittent feeding. Some mixing in reactor.



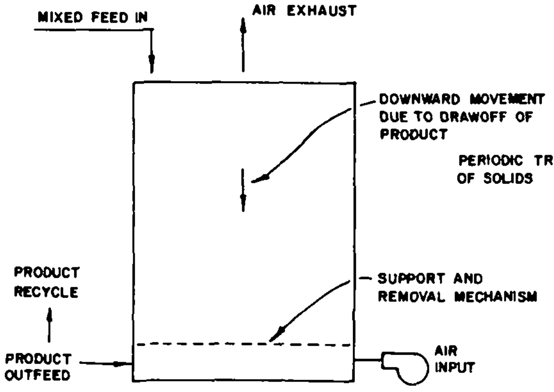
Example - Earp Thomas Reactor



Example - Schnorr Reactor

B. Moving Packed Bed Reactor - Solids are not agitated during movement down the reactor. Forced aeration. Plug flow of solids in reactor.

1. Continuous or Intermittent Feed
Examples - BAV, Kneer, ABV, Trigo system.



2. Batch Feed : Example - Euramco Process.

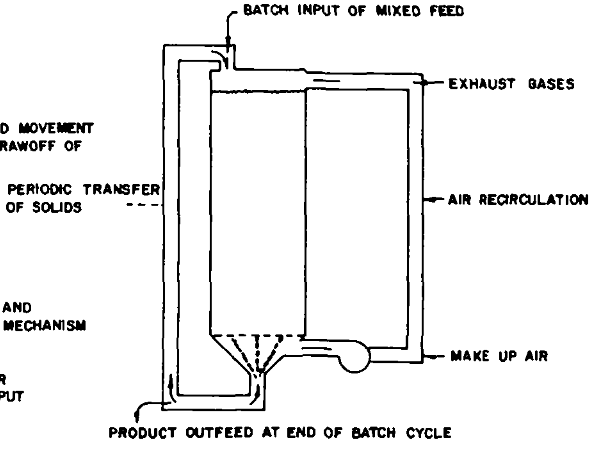
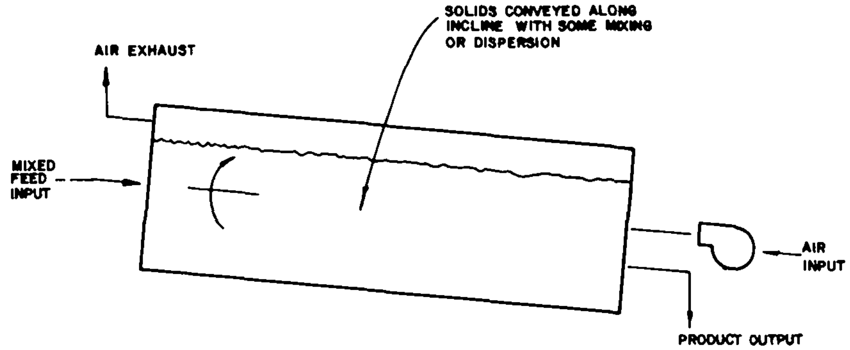


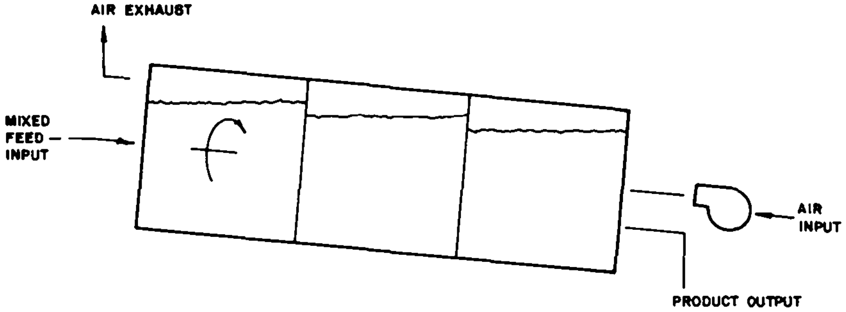
Fig. 19 Vertical flow reactor system (tower or silo reactors).

A. Tumbling Solids Bed Reactor (Rotating Drum) - Solids are agitated by nearly constant rotation of a drum and are fed on a continuous or intermittent basis. Forced aeration is usually provided.

1. Dispersed Flow: Dispersion is provided by constant tumbling action. Example - Dano process.



2. Cells in Series: Solids flow is by periodic emptying and transfer of material from one cell to another. Each cell is well mixed. Example - Geochemical- Eweson.



3. Complete Mix: Uniform feed and discharge are maintained along with a high level of mixing. Example - HKS process.

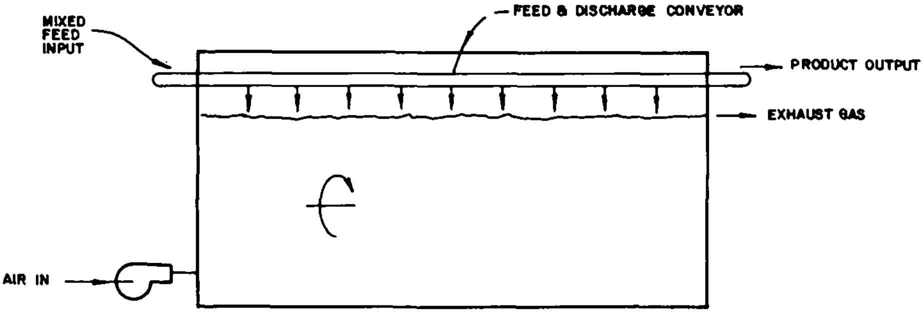
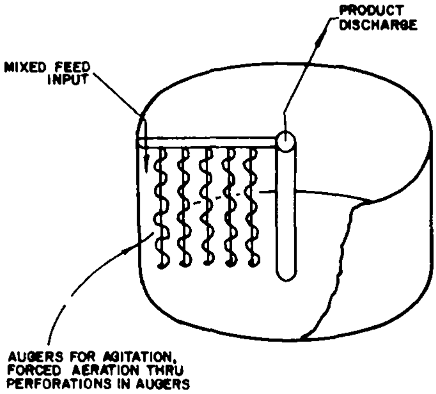
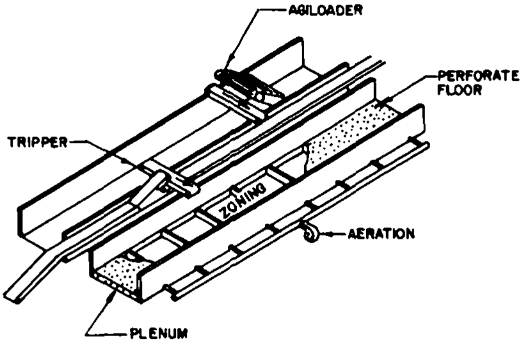


Fig. 20 Horizontal flow reactors

B. Agitated Solids Bed Reactors (Bin Reactors) - Solids are agitated by mechanical turning devices and are fed on a continuous, intermittent or batch basis. Forced aeration is provided.



Examples : Fairfield - Hardy, Aerotherm, Snell (rectangular tankage)



Example : Metro - Waste System.

Fig. 21 Inclined flow reactors

VI.4 Windrow Composting Systems

Types of windrow systems range from the rather primitive one, which was designed by Sir Albert Howard, to the relatively advanced one, which was developed at the University of California in the 1950's. As is obvious from the classification, "windrow" or "open" composting systems are characterized by having the composting take place in the open by placing the ground refuse in elongated piles, i.e. "windrows". The piles can also be placed in a shallow pit instead of on the ground surface. Aeration is accomplished by periodically turning the piles in a manner such that all the particles are exposed to comparable conditions at some time during the course of the active period of the composting process.

If the composting process is to be maintained on an aerobic basis by relatively frequent turning for aeration, windrows or stacks on the surface of the ground appear to be more efficient than pits (Gotaas, 1956). On the other hand, if the decomposition is to be entirely anaerobic, or aerobic only during a short initial period, pits of about 1 m deep and varying in length and breadth in accordance with the daily quantity of raw material should be used.

A typical process flow diagram for a windrow composting system is represented in Fig. 22 (Haug, 1980).

The windrow method appears to be practical for plant-scale use and should adequately decompose refuse or refuse-sludge mixtures in a total time of about 5 weeks with vigorous turnings during the first 3 weeks (Wiley & Spillane, 1961).

VI.4.1 The Pile

For a pile on the ground, a maximum of 2 m height was recommended by Golueke (1972). As the material loses volume during decomposition, any desired height of pile can be maintained by reducing or expanding the width of the windrow at the time it is turned. It has been recommended that the initial width of a windrow should not exceed 3 m at the base for convenience in turning. In dry weather, the cross section is usually made trapezoidal, with the top width governed by the width of the base and the angle repose of the material, which is something like 30 degrees from the vertical. In rainy climates or in wet weather, the cross section of the windrow should be approximately semi-circular like a haycock in order to shed water. In that case, the maximum permissible height of pile will govern its maximum width. Fig. 23 gives the dimensions of a typical windrow.

Other than maximum and minimum heights of pile, there is nothing critical about the stacking of ground refuse for composting; hence in each individual case, experience with the materials handling equipment employed will establish the best practice to be followed.

In accordance with suggestions by Gotaas (1956), Fig. 24 shows a compost stack and pile, Fig. 25A shows windrows with different types of aeration indicated, and Fig. 25B a compost pit.

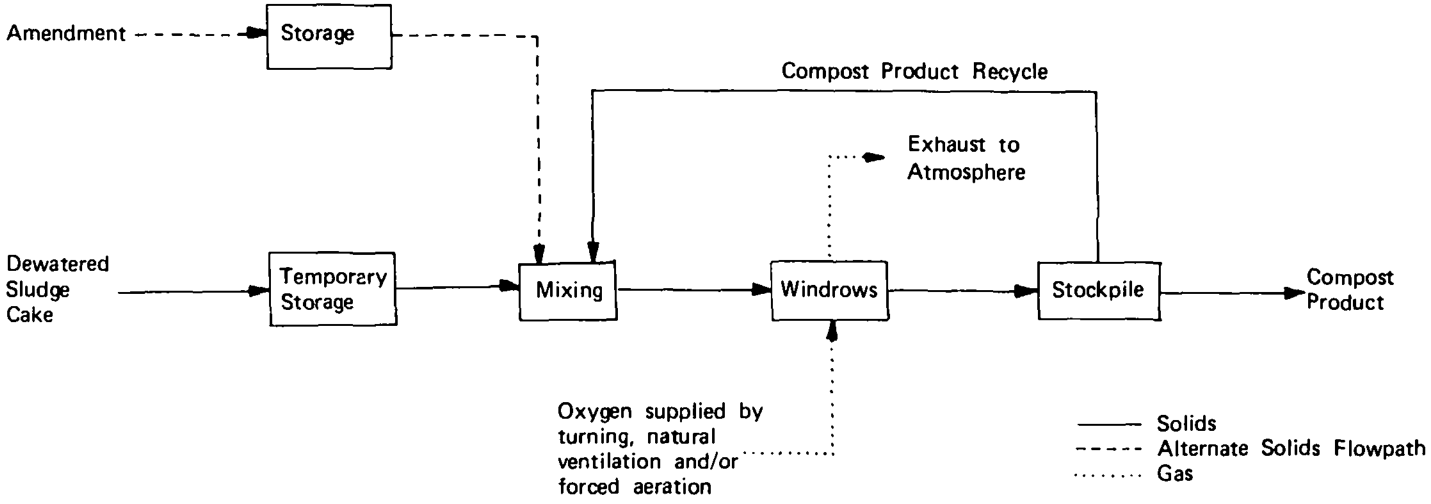


Fig. 22 Process Flow Diagram of a Windrow Sludge Composting Operation

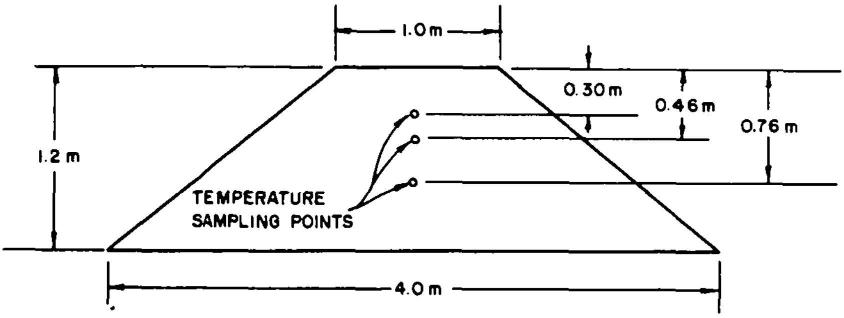
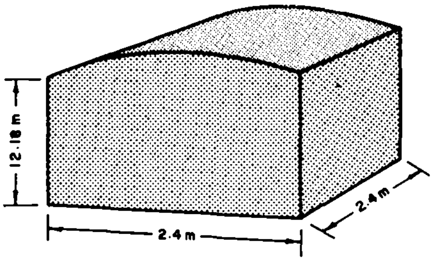
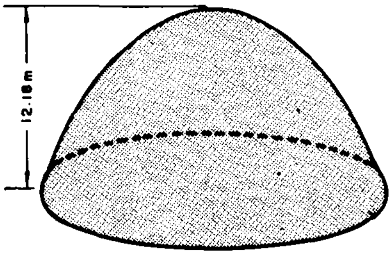


Fig. 23 Typical windrow formed from a mixture of sludge and recycled compost Actual dimensions are largely a function of the feedstock and turning machine

COMPOST STACK AND PILE



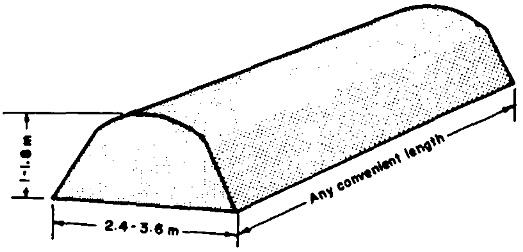
A. Stack with flat or rounded top according to the climatic conditions



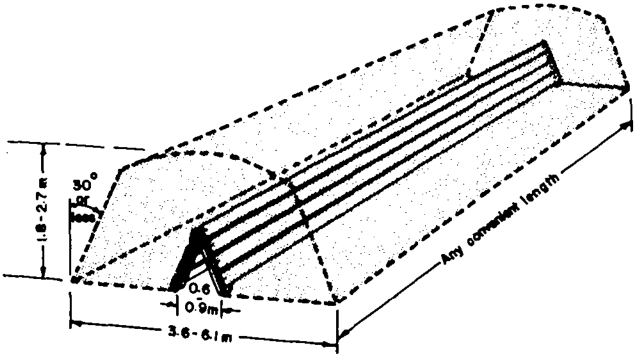
B. Pile with diameter of 2.4 - 3.6 m

Fig.24 (A) & (B)

COMPOST WINDROWS

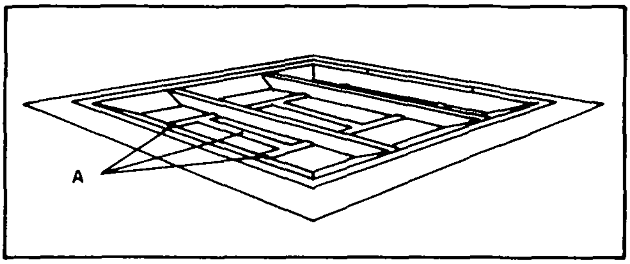


A. Windrow turned for aeration



B. Windrow with frame channel (wood, bamboo, rotan, etc.) for aeration from interior

COMPOST PIT



A = drainage and aeration channels

Fig. 25 (A) & (B)

VI.4.2 The Pit

The methods for stacking compost and adding night soil and other supplementing material are the same for windrows or piles on the ground surface or in shallow pits. For the case of pits, either the walls and bottom of the pit are lined with brick or masonry or the natural earth is tamped and packed.

When the ground water table is high, pits cannot be used satisfactorily. If they are used, drainage from the bottom of the pit is desirable and provision should be made to prevent surface run-off into the pit.

The advantages of pits over surface stacks and turning for aeration can be questioned. Savings in labor may be at the expense of more flies and odors, and less certain destruction of pathogens. According to Gotaas (1956), experience in India shows evidence that greater conservation of nutrients is achieved in pit composting. But at the same time, it has not been entirely proved that much more nitrogen can be conserved by anaerobic composting than aerobic composting when other nitrogen conservation practices are used.

VI.5 Mechanized Composting

The design of most mechanical composters is based on providing aeration by some type of tumbling or stirring action. Thus, some digesters are equipped with moving plows to stir the material. A horizontal digester has valves to carry the composting material to a point at which it drops or tumbles to the bottom of the cylinder and again is carried up. Other types provide the tumbling by having the material drop from one floor to the next in a multi-storied digester. A successful system (e.g., the Metrowaste process) combines bottom aeration and aeration by tumbling accomplished by passing a mobile endless belt from one end of the compost chamber (bin) to the other. As the belt moves, it picks up compost at its front, lifts it to a height of about 3 feet and allows the material to drop behind it. Another method (e.g., the Fair Field-Hardy process) combines stirring with forced aeration by having large hollow augurs rotating through the composting mass. The augurs have nozzles out of which air is forced into the material as the augurs are rotated.

In addition to providing aeration, mechanical digesters are equipped to ensure adequate temperature and moisture control. Mechanization in composting has provided many alternatives in terms of separation, shredding, agitation and mixing, addition of supplement materials, control of various environmental factors through aeration, and control of temperature and moisture content.

Methods currently in use for removing salvageable materials from domestic or even municipal wastes include hand-picking of clean paper, rags, non-ferrous metal and glass, screening of dust and large objects, rotor disc separation of sheet plastic, magnetic separation of ferrous metal, and ballistic separation of glass and crockery fragments. Processing schemes are described by Brunt (1961), Gotaas (1956) and Thorstensen (1967). More recent methods attempt to make use of the significant density difference between organic materials and minerals, both in air classification and in water. There have been some experiments at the University of Birmingham on a water elutriator column for the separation of pulverized wastes. Similarly, in another process named as the "Hydrososal process", the refuse is treated in a device in which the friable, grindable and pulpable components are turned into a water slurry and are separated from heavy metal objects. The slurry is then passed through a cyclone separator to remove glass, sand and small metal particles. It is subsequently processed to obtain long fibers, intermediate-sized fibers and a compostable residue.

Over the next few years there will doubtless be a transfer of ideas on separation methods and machinery from the mineral dressing and other process to cheaply effect this necessary upgrading of organic wastes prior to composting.

VI.5.1 Grinding Methods

The major methods of size reduction for refuse are (i) hammer milling, (ii) rasping, and (iii) self-abrasion/attrition in rotating drums.

Hammer mills consist of rapidly-rotating horizontal or vertical shafts attached to which are a series of fixed or pivoted hammers. Pulverization results from impact and attrition between the refuse, the hammers and the machine housing. Examples of such devices in use in the UK are the British Jeffrey-Diamond, Buhler, Gannow, Lightnin, Gondard & Tollemache machines. In the two latter mills some separation of hard materials is achieved by ballistic action. To reduce refuse to a particle size range appropriate for rapid composting, two stages of hammer-milling are often employed.

In raspers, the refuse is shredded and abrased by slowly rotating elements. The Dorr-Oliver machine, for example, consists of a vertical rotating shaft attached to which are several radial arms. These sweep the refuse over a perforated floor, from which a number of steel pins project. A depth of about 2 ft (0.6 m) of refuse is maintained and the rasped material falls through the perforations which are approximately 1" in diameter. Although raspers achieve good size reduction and feed homogenization with little mechanical wear, they require frequent shutdowns for the removal of rags and strings which tend to build up around the rotating shaft.

Rotating-drum pulverizers of a circular or multi-sided cross-section are employed in a number of installations in the U.K. The machines contain no internal tearing mechanism and rely on abrasion and attrition for size reduction. The refuse is usually moistened with the intention of reducing the physical strength of materials such as paper. Both batch-and-continuously operated machines are available, typical examples being the John Thompson Ferma screen, the Vickers Seerdrum, the Dano Biostabiliser and the Head Wrightson drum. This type of pulverizer appears to work satisfactorily, although in some early models a high degree of internal wear was experienced from the abrasive refuse. This has now been overcome by appropriate engineering.

Initial shredding or grinding of all the material is not necessary in the composting operation. At Wijster, in the Netherlands, the refuse is composted without previous shredding (Gotaas, 1956) and then is pulverized by a hammer-mill. Tin cans and thin metal objects become so corroded in aerobic composting that they can be readily broken. Some other composting plants use shredding before composting. A special grinder developed by a company named VAM of the Netherlands resembles a rimless wheel with U-section spokes pin-hinged at the hub, and rotating above a horizontal base with a diameter of about 4.5 m or more with alternate rough rasp plates and sieve plates. The shredding is accomplished by the revolving hinged spokes rasping over the roughened plates. The refuse, after shredding, as it falls through the sieve plates, is picked up on a moving belt and conveyed to a place where it can be readily sprinkled to control the moisture, and turned from time to time to provide aeration during the composting period.

Dano Corporation of Denmark also developed a refuse separating and grinding device in which the garbage and refuse are fed into a slowly rotating cylinder, with the axis sloping slightly downwards from the horizontal, where the material is aerated to remove odors, and partly broken up into smaller particles. After the magnetic separation of ferrous metals the material passes to a grinding and homogenizing machine, known as the Egsetor. Grinding to a desired size of particle is accomplished by friction between the particles of refuse and between the refuse and the roughened walls of the rotating Egsetor. It takes 4 to 6 hours for the material to go through the grinding machine. The Dano grinder overcomes some of the abrasion problems of hammer-mill grinders.

The compost corporation of America developed a refuse grinder which is reported to be very efficient and economical. This grinder is an adaptation of the swinging-hammer type of shredder to effect high capacity operation and low power consumption. The Lightening Pulverizer, a hammer-mill type of device: is used for compost in England. The Gruendler Crusher and Pulverizer Company, St. Louis, Ma, U.S.A. also developed a grinding device, the mature compost is passed through a shredder or through a vibrating screen.

Regrinding near the end of the period of active stabilization serves as the last turn for aeration, and the remaining stabilization takes place in large stock piles. Some grinders are provided with a means for adjusting the grinder and screen to produce smaller particles, and can therefore be used for both the initial and the final grinding.

VI.5.2 Agitation

It is reasonable to assume that a composting process can be speeded up by the use of agitation. Movement of the material aids aeration, especially in heaps and windrows, introducing a fresh supply of air into the middle of large masses where diffusion alone may be insufficient to maintain high free oxygen and low carbon dioxide levels. Agitation assists homogeneity of the composting mass, aiding an even spread of organic materials and nutrients. It will cause particles to rub together, leading to abrasion, size reduction and exposure of unattacked material. It assists the uniformity of temperature, preventing overheating in the center of large masses, and cooling at exposed surfaces. Some degree of agitation is consequently vital when handling materials bearing pathogens, in order to expose the latter to thermal destruction.

On the other hand, too much agitation is to be avoided as it can lead to excessive loss of heat and moisture at the surfaces. Additionally it can cause shearing of both fungal and actinomycete mycelium, thereby reducing the rate of metabolism and the degradative ability of these organisms. However, little research has been reported on the effect of agitation on the rate of composting. Wiley & Pearce employed two horizontal stirring arms in 15-gallon (57-liter) vertical fermenters to evaluate the effect of three ranges of stirring, 0.035-0.12, 0.19-0.35 and 0.52-0.61 rpm on composting refuse. The compost temperature pattern was recorded over eight-day cycles. The results indicated very little difference within these speed ranges and the experimenters admitted that this type of stirring sometimes cut paths through the compost, rather than properly mixing the contents of the fermenters.

In their work on windrows, Kochtizky et al. (1969) compared the effect of turning windrows eight times in five weeks with that obtained by turning then in the first 17 days with no agitation after that. Better results were found with the former treatment. Other results on the turning of windrows are reported by Spohn (as cited by Golueke, 1956) and from the extensive project at the University of California.

Kailbuchi (1961) gives data on a small-scale mechanized pilot plant with horizontal ploughs revolving at 0.0833 rpm. On a small rotary-drum composter Stoller et al. (as cited by Grey et al., 1971b) employed 0.125 rpm. Shulze's small drum made two revolutions (Schulze, 1961), while his continuous, batch-fed machine of 55-gallon (208-liter) capacity was turned at 1 rpm for 5 minutes before and after each daily feeding (Wiley, 1955). Jeris & Regan rotated their small drum at 0.8 rpm for 4 minutes every 6 hours. They believed that intermittent rotation was more advantageous than continuous movement.

In trials on a rotary drum Ferma screen without forced aeration, Sharma tried several agitation techniques (cited by Grey et al., 1971b), and deduced that the best techque was periodic agitation for 5 minutes, either whenever the free oxygen level at the center of the mass fell below 10%, or when the center temperature rose over 60°C.

In full-size practice, Dano Biostabiliser drums are turned at 1 rpm during daytime, when they are being fed, and at 0.25 rpm during the night.

Gray et al. (1971b) suggested that for rapid degradation, the concept of periodic agitation is the best approach. At the start of composting, immediately following pulverization, there is no need to agitate while temperatures and oxygen consumption rates are low. During the thermophilic stage, and the start of the cooling-down one, sufficient agitation should be provided to maintain high oxygen levels close to the surfaces being degraded, and to keep the mass temperature below 60°C. During the remainder of the cooling-down stage, and in the maturing one, the need for agitation is to reduce particle size and expose fresh surface. Periodic disturbance of particles at intervals of several hours enables the actinomycetes and fungi to extend their network of mycelium for a reasonable time before disruption. Such agitation is thus a compromise between the biological and the physical needs of the process.

VI.5.3 Aeration : Turning/Mixing Pattern

As previously indicated, aeration is necessary for thermophilic aerobic composting in order to obtain rapid nuisance-free decomposition. Aeration is also useful in reducing a high initial moisture content in composting materials. Several different aeration techniques have been utilized with varying degrees of success. Turning the material is the most common method of aeration when composting is done in stacks.

Hand turning of the compost in piles or pits is most commonly used for small village or farm operations. Mechanical turning is most economical in large-scale operations.

The most important consideration in turning compost, apart from aeration, is to ensure that the material - on the outside of the pile is turned into the center, where it will be subjected to high temperatures. In hand turning with forks, this can be readily accomplished, e.g., piles or windrows on top of the ground are simply reconstructed with the material from the outer layers placed on the inside of the new pile. In the case of composting in pits or trenches, the material can be moved from one pit to another for aeration or, if a little space is left at the end of the pit at the initial filling, the material can be turned within the pit. The loss of volume of the material during the stabilization period will facilitate turning within the pit. If desired, piles or windrows can be combined when they are being turned, particularly if long composting periods are used.

The frequency of aeration or turning and the amount of aeration or the total number of turns are governed primarily by the moisture content and the type of material, the moisture content being the most important criterion. A high moisture content reduces the pore space available for air as well as reducing the structural strength of the material, and hence permits greater compaction and less interstitial or void space for air in the pile. Materials with a high C:N ratio or containing large amounts of ash and other inert material may not have to be aerated as often as material which decomposes more actively and rapidly.

The Bangalore system, developed in India, uses little aeration, in general relying on the air present in the material when first placed in the pits as being sufficient for high temperatures to be maintained for several days. The material apparently later undergoes anaerobic digestion for some months until it is relatively well decomposed. While this procedure is economical from the standpoint of turning costs, it does introduce the problems of controlling odors, assuring destruction of pathogenic organisms, and preventing fly-breeding. Howard using the Indore process, Scharff (1940), and Stovroff (1954), turn the material in pits or piles from 1 to 4 or 5 times over a period of 1-6 months. The temperature rises immediately after each turn until the material is stabilized. If a long interval between turns or aeration is permitted, active decomposition of the material is retarded by a change to anaerobic conditions, and a much longer time is required for stabilization.

The University of California studies indicated that turning at fairly frequent intervals during the first 10-15 days of composting achieved approximately the same degree of stabilization as making the same number of turns over a long period. Greater aeration during the initial stages of decomposition intensifies the activity of the microorganisms, shortens the period of active decomposition, and, consequently, reduces the time and land area needed for composting. Naturally, if it is intended to maintain at least partially aerobic conditions and high temperatures, it would appear that turning at intervals necessary to maintain more or less continuous aerobic decomposition requires little more effort than turning at long intervals over a greater period of time.

The availability of air is a function not only of the turning frequency but also of the moisture content and structure of the material. Also, the air requirement for the biological activity depends to some extent on the availability of nutrients in the waste. Therefore, it is impossible to specify a minimum frequency of turning or number of turns for a variety of different conditions. Studies on the composting of mixed refuse (garbage, lawn and tree trimmings, and considerable quantities of paper and combustible rubbish) at the University of California indicated that the following schedule of turning is adequate to permit rapid decomposition.

If the initial moisture content is below 70%, the first turn should be made on about the 3rd day. Thereafter the material should be turned approximately as follows until the 10th or 12th day:

Moisture 60% - 70% : turn at 2-day intervals
approximate number of turns, 4 to 5

Moisture 40% - 60% : turn at 3-day intervals
approximate number of turns, 3 to 4

Moisture below 40% : add water

If the material initially contains much more than 70% moisture, it should be turned every day until the moisture content is reduced to less than 70%, the above schedule should then be followed.

This turning schedule will permit rapid decomposition at thermophilic temperatures. Fewer turns would not produce such rapid composting, but might be sufficient to prevent serious anaerobic conditions and odors. Experience soon enables the operator to estimate the need for adding water and the need for turning. A good rule of thumb is to turn the pile daily if foul odors of anaerobic and putrefactive conditions are evident when the pile is disturbed, either by turning or by digging into it for inspection purposes. The pile should be turned daily until septic odors disappear. Daily turning is also sometimes necessary for controlling fly-breeding.

VI.5.4 Bottom Aeration

Various substitutes have been proposed for turning as an aeration method. Among these are placing the ground refuse in wire containers (Maier et al., 1958; Wiley, 1957), stacking the material on slotted or perforated floors, and forcing air into the pile by way of bottom aeration.

While the concept of forced aeration may be sound in many applications, many difficulties combine to diminish its utility in the windrow composting of municipal refuse. Even were forced aeration successful in its purpose, the piles would have to be turned occasionally so as to bring about the necessary exposure of all particles to the high interior temperature and to insure uniform decomposition.

The amount of aeration with respect to temperature and moisture can be accurately controlled in mechanically aerated digesters. Since the mechanically aerated digester is enclosed, there is practically no fly control problem during composting.

VI.5.5 Process Control : Analytical Methods

Although the vast majority of composting processes are run with very little analytical control compared with most chemical processes (Grey et al., 1973), it is probable that in the future tighter control will be needed to optimize production, obtain a product close to specification and reduce loss of ammonia to the atmosphere or nutrients to the ground.

On simple composting systems, changes are made on a time basis or by visual tests, e.g. turning the Indore heaps after two to three weeks and five weeks

(Howard, 1945), adding water when a handful of compost does not give up moisture on squeezing like a sponge, judging maturity by the crumbliness of the product, the lack of smell and the departure of earthworms.

Temperature is a good guide and, in an agitated composter with adequate moisture and air, it gives a fair approximation as to when the maturing stage has been reached. Temperature variation with time indicating the phases of microbial activity is represented in Fig. 7, as given by Gray et al. (1971a). An important point to keep in mind is that the temperature pattern is not such a good guide when composting large particulate material in unagitated windrows or bins; such material will frequently warm up again on turning, regrinding and remoistening.

For more accurate control of the process, samples of material must be taken. This immediately raises the problem of inhomogeneity, both on the macro- and the micro-scale. Because of the wide variety of organic wastes processed, especially in municipal operations, a compost heap is extremely heterogeneous at the start of degradation. Then, in an unagitated system, there are wide differences in temperature, aeration and moisture between the center and the outside of the mass; these lead to very different rates of reaction. Thus, to obtain for analysis a compost sample which is really representative of the whole heap is virtually impossible. The problem is greatly reduced but not entirely eliminated in well-agitated systems.

Obtaining a suitable sample for analysis from a fairly homogeneous mass was well described by the Fertilizer & Feeding Stuffs Regulations, 1968 (Gray et al., 1973). These cover most organic manures, though none are as heterogeneous as composts, which are not covered. The regulations lay down sampling and analysis criteria for final products prior to sale. For process plant control analyses, a less stringent sampling of compost is satisfactory.

Moisture determinations are necessary in many composting operations, to keep the moisture content in the range of 50-70%. Such determinations need not be very precise, and are made by drying at 105°C for 2-3 hours. A far quicker method is the use of the speedy moisture kit, based on the generation of acetylene from calcium carbide; the resulting pressure increase gives a direct reading in percentage moisture. Gray et al. (1973) found this method satisfactory.

The progress of a composting reaction can be followed by the temperature pattern, by the rate of carbon dioxide evolution (as shown in Fig. 26) or oxygen consumption, by the build up of humic acids, or by the decrease in cellulose or the hemicelluloses. For plant control purposes, only the temperature profile is really suitable: the other methods are too time-consuming or expensive in equipment or chemicals. Gray et al. (1973) found the best guide to the reaction progress to be the changes in the ash content, obtained by combustion of the dried material at 500°C for several hours in a muffle furnace. The aeration rate for composting is then based on the percentage volatile, which is 100% - % ash.

The pH of compost is often measured, although the result is rarely used as an operating parameter. The compost sample is diluted with distilled water, then stirred, and the pH is measured with a glass electrode pH meter.

The C:N ratio is an important parameter for blending components of the compost feed and assessing the maturity of the product. When analysing for these and other chemical constituents, the air-dried compost needs to be ground in a laboratory mill or by pestle and mortar, and to be passed through a sieve with a mesh size of less than 1 mm; this is to improve homogeneity. Municipal composts are very difficult to homogenize and the sample should be visually inspected for obvious heterogeneities such as lumps of metal; these should be removed.

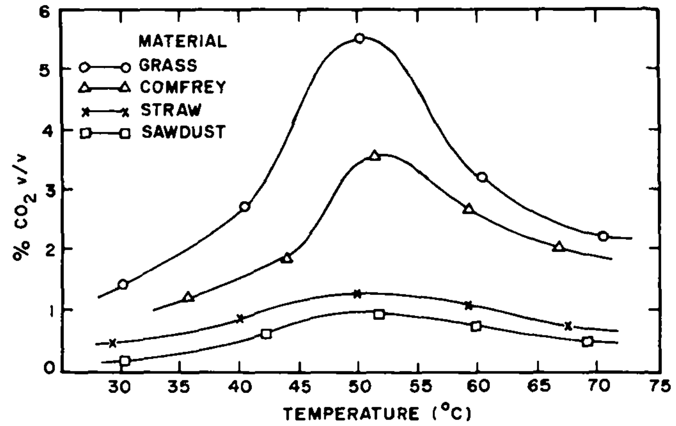


Fig. 26 Variation of decomposition rate with temperature for materials of various C:N ratios

The simplest assessment of carbon is the formula:

$$\% \text{ C} = \frac{(100\% - \text{ash})}{1.8}$$

This equation has been tested on municipal composts by the University of California team (McGauhey & Golueke, 1953), and was found to give satisfactory results.

Analytical test procedures for carbon, macro and micro nutrients, and heavy metals, in agricultural materials such as compost, are given by the American Society of Agronomy (Black, 1965), and in the U.K. in the Fertilizer and Feeding Stuffs Regulations 1968 (Anon, 1968), and by the Ministry of Agriculture (ADAS) through their Conference of Analysts and Analysts Technical Committee.

For carbon, the dry combustion method to carbon dioxide is extremely accurate, but is slow, expensive, needs skilled supervision and since only small samples can be used, it requires highly homogeneous material. Its only real application in composting is as a standard for checking more suitable methods. The wet combustion methods of Van Slyke and Folch, and Allison also require much care in operation. For compost analyses the wet oxidation methods of Tinsley or Walkley Black (Golueke, 1972) are far more appropriate, being simple, quick and reasonably accurate. They employ the oxidation of the organic matter by potassium dichromate;

the results can be affected by the presence of daily-oxidizable substances other than carbon, and they need to be standardized against the highly accurate combustion methods.

Nitrogen in compost masses can be present as ammonium, nitrate, nitrite and organic forms. Nitrite nitrogen is normally negligible while at compost maturity ammonium nitrogen and nitrate nitrogen have been almost entirely converted to organic nitrogen, mainly in the form of protein and to a lesser extent, amino sugars. In the calculation of the C:N ratio, the total nitrogen content is needed. This is best determined by the Kjeldahl method, preferably on a macro rather than a micro scale, because of sample inhomogeneities. Catalysts - copper, mercury or selenium - are used, while the salicylic acid modification of the method allows satisfactory recovery of any nitrate or nitrite present. Analytical procedures are available for measuring phophorus, potash, and other macro and micro nutrients and trace elements.

When following the course of a composting cycle in a research investigation, it is often desirable to chart the breakdown of the various constituents of the feed materials, e.g. sugar, lipids, proteins, hemicelluloses, cellulose and lignin. In order to do this, the compost samples are fractionated into products. Unfortunately, such fractionation does not result in clean cut separation into definite chemical entities and it can be lengthy and expensive. Many procedures are based on the orginal "proximate analysis" technique of Waksman and Stevens. Passer et al. (Golueke, 1972) modified this method in order to cope with large-scale analysis of peat samples.

Three methods for large-scale compost testing have been published by Lossin from work for the US Public Health Service - Tennessee Valley Authority Composting Scheme (Golueke, 1972). One method is for qualitative determination of the degree of degradation by analysis of starch, using the starch-iodine complex. The second technique is for the estimation of cellulose by an anthrone colorimetric method and by a gravimetric method, which unfortunately needs large quantities of solvents. The third method (Kailbuchi, 1961) is for the determination of chemical oxygen demand (COD) - a parameter used frequently in sewage treatment.

VI.6 Comparative Review of Various Composting Systems

Over the past four decades, more than 30 different processing schemes for composting wastes have been tried out, with varying degrees of success. In Table 18, 37 composting processes are listed, grouped according to their major method of operation. Many of these schemes involve the addition of sewage sludge to refuse, fermentation of the mixture in a digester for several days, followed by maturing in windrows. Table 19 represents brief descriptions of nearly all of the representative compost systems as given by Haug (1980).

Golueke (1978) describes the principles for evaluating and selecting composting systems - from reliability and economics, energy and labor, to the state-of-the-art in closed and windrow systems. Three important criteria are suggested to evaluate a given system, namely (i) it must do a satisfactory job of composting ; (ii) it must be reliable ; and (iii) it must be economically feasible in its operation. Golueke (1978) also gives details on technical evaluation regarding varous operations of the process. Various types of equipment used for pre-processing raw materials are described by Shelton (1972).

Table 18. Municipal Composting Systems

No.	Type and System	Form	Aeration	Agitation	Some Locations
1	*In heaps*				
1.1	Artsiely	Annular F–S	–	–	–
1.2	Biosimplex	F–S	F	U	Bacares; Kuwait
1.3	Biotank	Annular W	F	U	Annecy; Calais; Valencia
1.4	Buhler	F–S	N	I	Chesterfield; Wetherby
1.5	Dorr–Oliver	F–S	N	U or I	Delft; Arnhem; Tel Aviv
1.6	Indore/Bangalore	F–S	N	I	Many in India
1.7	Metro–Waste	W	N + F	I	Gainesville; Houston
1.8	Sceba–Edifesa	W	N	I	Madrid; Pamplona
1.9	Tollemache	W	N + F	I	Salisbury (Rhodesia)
1.10	van Maanen	F–S	N	I	Mierloo; Wijster
1.11	Vitahum	F–S	N	I	Brno; Madrice
2	*In batches*				
2.1	Stacks				
2.1.1	Caspari–Brikollare	Briquettes	N	U	Schweinfurt
2.2	Special chambers				
2.2.1	Aquamatic	S	N	U	Nogent–le–Rotrou
2.2.2	Beccari	S	F	U	Avignon
2.2.3	Boggiano–Pico	S	F	U	Montevideo
2.2.4	Dunfix	R	F	C	–
2.2.5	Fermascreen/ Thompson	R	N	I	Hong Kong; Worcester (SA)
2.2.6	Mitchell Eng	S	N	I	Kirkconnel
2.2.7	Omnium	S	N	I	–
2.2.8	Prat	S	Usually N	U	Narbonne; Toulouse
2.2.9	Renova	S	F	U	Blauberen
3	*Continuous flow*				
3.1	Carel Fouche	P. 5 floors	N + F	I	Dunkerque; Orleans
3.2	Crane	P. 3 floors	F	C	Kobe
3.3	Dano	R	Usually F	C	Leatherhead; Leicester
3.4	Earp–Thomas/ Fertilia/ Multibacto	C. 8 floors	F	C	Athens; Palermo; Verona
3.5	Ebara–Infilco	R	F	C	Amagasaki
3.6	Eweson	R	F	C	Oslo
3.7	Fairfield–Hardy	C	F	C	Altoona; San Juan (Puerto Rico)
3.8	Head Wrightson	R	F	C	Worthing
3.9	Jersey/Thompson	P. 5 or 6 floors	N	I	Jersey; Bangkok
3.10	Krige	R	F	C	Pretoria
3.11	Naturizer/ Westinghouse	P. 6 floors	F	C	St Petersburg, Florida; San Fernando, California
3.12	Nusoil	C. Several flrs	F	C	Teheran
3.13	Riker	P. 4 floors	F	–	Williamston, Michigan
3.14	Snell	P	F	C	Houston
3.15	Triga	C	F	C	Moscow; Versailles
3.16	Varro	P. 6 floors	F Q	C	New York

Key Form:

Free-standing	*F–S*	*Cylindrical*	*C*	*Agitation – Undisturbed*	*U*
Between walls	*W*	*Parallelepiped*	*P*	*Intermittent*	*I*
Stationary	*S*	*Aeration – Natural*	*N*	*Continuous*	*C*
Rotary	*R*	*Forced*	*F*		

Table 19. Composting Processes Developed Primarily for Mixed Solid Wastes as Main Feed Component

Classification	Process Name	General Description
Nonreactor		
Agitated Solids Bed	Bangalore (Indore)	Developed by Sir Albert Howard (1925) in India. Trench in ground, 2-3 ft deep. Material placed in alternate layers of refuse, night soil, earth, straw, etc. No grinding. Turned by hand as often as possible. Detention time of 120-180 days. Used extensively in India.
	Conventional and Forced Aeration Windrow	Open windrows with a haystack cross section. Refuse ground. Aeration by turning windrows. Detention time depends upon number of turnings and other factors. Once used in Mobile, AL (270 ton/day); Boulder, CO (90 ton/day); and Johnson City, TN (47 ton/day); currently used in Israel and Mexico City.
	Van Maanen	Raw refuse without any pretreatment except moisture adjustment placed in open windrows for 120-180 days. Turnel once by grab crane. Must be conducted in remote areas because of odors, fly and rodent problems. First used in Netherlands in 1931.
	Others	Numerous process names have been applied to the windrow system, often taking the name of the front-end equipment manufacturer.
Static Solids Bed	Brikollari (Caspari) (Briquetting)	Ground material is compressed into blocks and stacked for 30-40 days. Aeration by natural diffision and airflow through stacks. Curing follows initial composting. Blocks are later ground. Sludge can be added to mixture up to moisture content of about 53%. Plants in Schweinfurt, Germany and Biel, Switzerland. No present U.S. installations.
Vertical Flow Reactor		
Moving Agitated Bed	Earp-Thomas	Possibly the oldest reactor system. Silo type with decks stacked vertically. Center shaft drives a plow which agitates the compost and moves it downward from deck to deck. Air passes upward through the silo. Digestion of 2-3 days followed by windrowing. Installations reported in Seoul, Korea; Verona, Italy; and Basel, Switzerland. No present U.S. installations.

Contd. Table 19.

Classification	Process Name	General Description
Vertical Flow Reactor Moving	Frazer–Eweson	Ground refuse placed in vertical bin with 4 or 5 perforated decks and special arms to force composting material through perforations. Air is forced through bin. Detention time of 4-5 days. Problems with bridging of solids across perforated deck. An 18-ton/day facility operated on garbage in Springfield, MA from 1954 to 1962. No known facilities presently in operation.
	Jersey (John Thompson)	Structure with 6 floors, each equipped to dump ground refuse onto the next lower floor. Aeration effected by dropping from floor to floor. Detention time of 6 days; 6-8 weeks of additional curing in unturned piles. A 300-ton/day plant constructed in Bangkok, Thailand.
	Naturizer (International)	Five 9-ft wide steel conveyor belts arranged to pass material from belt to belt. Each belt is an insulated cell. Air passes upward through digester. Detention time of 6-8 days. Plants once located in Norman, OK (1959-64), San Fernando, CA (1963-64), St. Petersburg, FL (1966-?). The last was a 90-ton/day facility, but was closed because of uncontrolled odor.
	Riker	Four-story bins with clam-shell floors. Compost is dropped from floor to floor to provide agitation. Forced aeration. Total detention time of 20-28 days. Treated mixture of ground garbage, corn cobs and sludge. Problems reported in maintaining aerobic mixture. A 4-ton/day facility operated in Williamston, MI, from 1955 to 1962. No known facilities presently in operation.
	T.A. Crane	Two cells consisting of three horizontal decks. Horizontal ribbon screws extending the length of each deck recirculate ground refuse from deck to deck. Air introduced in bottom of cells. Three days composting followed by curing for 7 days in a bin. 18-ton/day pilot refuse and sludge system was installed in Kobe, Japan.
	Varro	Ground refuse placed in 8-deck digester and moved downward from deck to deck by plows. Each deck pair had own recirculating air supply to control CO_2 level. Output dried, reground and used as base material for fertilizer, soil conditioner, wallboard, etc. Digestion time 40 hr. ~ 55-ton/day system constructed in Brooklyn, NY in 1971.

Contd. Table 19.

Classification	Process Name	General Description
Vertical Flow Reactor		
Moving Packed Bed	Triga	See Table 2-2 for description. As of 1978, two plants were in operation in France using mainly municipal solid waste (MSW) with some sludge.
Horizontal and Inclined Flow Reactor		
Tumbling Solids Bed	Dano	Dispersed flow rotating drum, slightly inclined from the horizontal, 9-12 ft in diameter, up to 150 ft long. Drum kept about half full of refuse. Drum rotation of 0.1-1.0 rpm. One to five days digestion followed by windrowing. No grinding. Forced aeration into drum. Probably the most popular reactor process for MSW with 160 plants worldwide as of 1972. Plant in Rome, Italy handles over 450 ton/day. Plant in Leicester, England composts refuse and sludge. U.S. installations once located in Sacramento, CA (1956-1963) and Phoenix, AZ (1963-1965).
	Fermascreen	Hexagonal drum, three sides of which are screens. Refuse is ground and batch-loaded. Screen are sealed for initial composting. Aeration occurs when drum is rotated with screens open. Detention time about 4 days.
	Geochemical—Eweson	Cells-in-series type. Unground refuse placed in rotating drum, 11 ft diam, 110 ft long, slightly inclined from horizontal. Three compartments in drum. Refuse transferred to next compartment every 1-2 days for total digestion time of 3-6 days. Screened output cured in piles. 35-ton/day facility constructed in Des Moines, IA and Big Sandy, TX in 1972. Latter composted a mixture of 27 ton/day refuse and 9 wet ton/day sludge.
Agitated Solids Bed	Fairfield—Hardy	Circular tank. Vertical screws, mounted on two rotating radial arms, keep ground material agitated. Forced aeration through tank bottom and holes in screws. Continuous flow type. Detention time about 5 days. Original plant constructed at Altoona, PA in 1951 with capacity of 25 ton/day is still in operation. 135-ton/day facility constructed in San Juan, PR in 1969. In 1978 a 45-ton/day facility for composting garbage and sludge was constructed in Toronto, Ontario and is currently operating.

Contd. Table 19.

Classification	Process Name	Ground Description
Horizontal and Inclined Flow Reactor		
Agitated Solids Bed	Snell	Rectangular tank about 8 ft deep with porous floor equipped with air ducts for forced aeration. Tank inclined on a 6° slope. Traveling bridge with vertical paddles provides agitation and movement of material along incline of tank. Detention time 5-8 days. 275-ton/day facility constructed in Houston, TX in 1967. Reported to operate successfully but local problems forced closure.
	Metro–Waste	Rectangular tanks about 20 ft wide, 10 ft deep, 200-400 ft long. Refuse is ground. Residence time of about 7 days. "Agiloader" moves on rails mounted on bin walls and provides periodic agitation by turning. One of the more successful reactor types. 275-ton/day MSW facility operated in Houston, TX from 1966-1970. Other refuse installations once operated in Largo (45 ton/day) and Gainesville (135 ton/day), FL. A similar facility in Ohio (1972-present) composts 360 ton/day of cattle manure.
	Tollemache	Similar in design to Metro-Waste system. Installations reported in Spain and Rhodesia in 1971.

According to Gray et al., the heap or windrowing operation is undoubtedly the most inefficient process. Little control is possible over temperature distribution, aeration and moisture content, and the space requirement is large as adequate gaps must be allowed between windrows for turning operations. Moreover, in very hot climates, as in most tropical countries, the surface of the windrows often becomes baked to a very hard, virtually impermeable crust. This is not due to the process per se, but mainly due to mismanagement. The turning process should be frequent enough to prevent caking of the surface. For this reason, although in most circumstances in developing countries where land and labor costs are low, windrowing is the cheapest method, it is not always the most desirable.

According to Haug (1980), many systems which appear simple on a small scale become remarkably complex when expanded to large scale facilities. Many of the earlier methods of composting appear to have been designed solely on a materials handling basis. They have made little real attempt to provide for the needs of the biological population in terms of adequate and readily available nutrients, well homogenized feed, and evenly distributed air, moisture and temperature patterns. During the 1950's, however, new designs were brought out which tried to take note of at least some of the major parameters. These plants mainly attempted to improve aeration, either by intermittent agitation or by forced air supply, and used rotating drums, vertical digesters or multideck houses. Some new designs were started to show a keener appreciation of composting. Two such methods were Spohn's Renova method employing pulsed aeration (Spohn, 1970; Spohn, 1978) and the Nusoil digester which was started in Teheran. Both of these processes claimed to reach full compost maturity without the necessity of windrowing. Table 20 shows a comparison of these systems with Dano Biostabilizer as based on Gray et al. (1973).

Table 20. Comparison between Three Composting Systems

System	Dano (24, 100, 101, 122, 123)	Nusoil (121)	Renova (31, 120)
Type	Horizontal drum	Vertical silo. multi-deck	Cell
Operation	Continuous	Continuous batches	Batch
Feed preparation (grinding)	No pregrinding	Single-stage pregrinding (hammer milling)	Rasping to 38 mm (1·5 in) then kneading
Degree of agitation in digester	Continuous	Intermittent, as required	None
Aeration	Forced	Forced; varied throughout process	Forced; pulsed
Air flow, times recommended minimum requirement	6	3–5	1–2
Degree of filling of space in digester	Below 0·5	0·66	1·0
Temperature attained (C)	50–55	60, controlled maximum	Cyclic variation up to 90 C
Time in digester (days)	2–5	7	42
Need for windrowing	Yes	No	No
Total time to maturity (days)	84–112	7	42

If reactor systems are to be considered, which systems offer the most promise? First, a composting system should provide the operator with the maximum degree of freedom possible in operating the plant. In other words, the more variables the operator can control, the more tools he has to produce acceptable compost. Systems which provide both agitation and forced aeration during the compost cycle meet this criterion. Aeration rates can be controlled by the operator in response to feed characteristics, weather conditions, desired temperature elevations and other factors. Rates of agitation can be controlled to average out errors in the initial mixing of feed components, assure that all materials come into contact with oxygen, break up clumps or balls of material which may form, and reduce the chances of air channeling during forced aeration. Such systems are favored because of their increased operating flexibility.

Another factor that should be considered is the cost per unit volume of the reactor. Obviously, this should be as low as possible to minimize capital expenses. Simple designs using common building materials are probably more cost-effective on a per-volume basis than complex systems requiring extensive fabrication.

VII. COMPOST MATURITY

Ultimate stabilization of organic matter does not occur in conventional composting, nor is it to be desired either in terms of utility of the compost product or of practicality of attainment. The impracticality arises from the excessive time factor involved. The utility of the compost depends upon its further breakdown in the soil. The desired degree of stability is one at which the material will not give rise to nuisances when stored - even if it should be wettened. The problem in a compost operation is one of determining when this point is reached.

The answer to the question of whether the compost has reached a sufficiently advanced stage of maturity is a very important one to be adjudged by any operator for several reasons, such as (Niese, 1963):

1) It determines when the material is ready for use in crop production. Insufficiently composted material can be detrimental to crop production because of damage wrought on the plants root systems.

2) It determines when the material is free from health and environmental hazards and other nuisances, e.g., odors.

3) It permits the most efficient use of land and equipment. Since processing requires access to land area, prolonged treatment beyond the point where wastes have attained compost maturity results in an excessive land requirement.

4) It becomes possible to objectively evaluate the claims of promoters of specific compost systems.

Two important points to be considered are the time required for composting and monitoring the conditions of the compost.

VII.1 Time Required for Composting

As far as the C:N ratio and the humus characteristics are concerned, the compost is satisfactory for application to the soil as soon as the period of active stabilization is over and high temperature can no longer be maintained in the material although it is still aerobic. Some further stabilization, particularly cellulose and lignin breakdown, takes place slowly. But the actual decline in the C:N ratio is during the "ripening" period.

The time required for satisfactory stabilization depends primarily upon (i) the initial C:N ratio; (ii) the particle size; (iii) the maintenance of aerobic decomposition; and (iv) the moisture content.

Assuming that the moisture content is in the optimum range, that the compost is kept aerobic, and that the particles of material are of such size as to be readily attacked by the organisms present - all of which factors can be controlled in the composting operation - the C:N ratio determines the time required for stabilization. Low C:N ratio materials are decomposed in the shortest time, because the amount of carbon to be oxidized to reach a stabilized condition is small. Also, in low C:N ratio composts, a larger part of the carbon is usually in a more readily available form, while with a higher C:N ratio more of the carbon is usually in the form of cellulose and lignin, which are rather resistant to attack. The cellulose and lignin are attacked last by the changing biological population in the changing environment. When the available C:N ratio is above 30, additional time is required for the recycling of the nitrogen present.

The results of studies at the University of California (McGauhey & Golueke, 1953) on the composting of shredded mixed municipal refuse in aerobic piles, with a moisture content below 70%, indicated the times required for active stabilization for different C:N ratios, and are presented in Table 21 (Knoll, 1959):

Table 21 : Time Required for Active Stabilization for Different C:N Ratio

Initial C:N ratio	Approximate composting time required (days)
20	9 - 12
30 - 50	10 - 16
78	21

If the material is not kept aerobic so that high temperatures can be maintained during the active-decomposition period, or if the particle size is so large that the bacteria cannot readily attack the material, or that the interior of the particles becomes anaerobic, longer composting periods are required.

Under aerobic conditions at high temperatures and when the initial C:N ratio is in the optimum range or below, the material takes on the appearance and odor of humus after 2-5 days of active decomposition. However, active decomposition is not complete at this stage, and the C:N ratio may not have been lowered to the level desired for fertilizer.

Earp Thomas, the Dano Corporation, Snell, and others have suggested composting periods of 2 or 3 days in the mechanically aerated silo-type digesters. Acharya (1950), Scharff (1940),van Vuren, (1949) and many other workers use longer composting periods, which usually include "ripening". The longer periods of active stabilization are often due to less aeration and turning. Table 22 shows the composting periods used under different conditions in different parts of the world.

The actual composting time is not particularly important, provided it is sufficient for pathogens and parasites to be destroyed and for nitrogen to be conserved.

VII.2 Monitoring the Degree of Stabilization

The stability of compost cannot be judged merely by its appearance, fragrance or age. Seemingly good-looking and well-aged composts sometimes turn out to be anaerobic and noxious, or may still be at the stage of being mineralized (Spohn, 1972).

There are many tests and checks by which the various stages of the composting process and the degree of stabilization can be judged. From the viewpoints of the overall operation and the final product, there are three groups of tests as suggested by Gotaas:

a) Tests of the sanitary quality of the operation and of the finished product, i.e., pathogen and parasite destruction and the absence of flies and odors;

b) Tests of the fertilizing or agricultural value, i.e., the amount of nitrogen, phosphorus, potash, and other nutrient conservation, the C:N ratio and the compost value as indicated by crop returns; and

c) Economic tests, i.e., whether the total cost of producing the compost is less than its value as fertilizer plus the cost of disposal by other means, such as incineration or landfill.

With the older, traditional systems of composting, the process was allowed to proceed in such a leisurely fashion that the particle size of the components declined to a granular size simply through natural microbial decomposition. By the time that stage was reached, the attainment of maturity not only was assured, but indeed often was past. This being the case, particle size could be used as a criterion for maturity, and thus, passing a screen opening of a given size was an acceptable test. But with mechanical grinding, the screen test no longer is valid.

For quite a long time it was believed that the appearance of a brownish or black color along with an earthy odor were indicators of compost maturity. Later it was established that the change in appearance is not a criterion. The University of California studies showed that the dark color typical of composted material may be attained long before the necessary degree of stability is reached. The same can be said about the development of the earthy odor. The earthy odor is characteristic of actinomycetes. Thus their presence is an indication of the existence of "unstable" organic matter.

Table 22. Composting Periods Reported from Different Operations

System	Materials	Reported by	Time	Conditions
Aerated digester	Selected garbage plus sewage sludge	Frazer, N.Y.	7 days	Field production
Aerated digester	Garbage	Michigan State College	3–5 days	Pilot plant
Aerated digester	Mixed refuse	Dano Corporation	3–5 days	Pilot plant
Pile turned	Garbage and straw	University of California	5–9 days	Experimental
Piles turned	Mixed municipal refuse containing garbage	University of California	10–21 days	Field production
Piles turned	Mixed municipal refuse containing garbage plus sewage sludge	University of California	10–16 days	Field production
Piles turned	Cow and pig manure and straw	University of California	10–16 days	Field production
Pits turned	Air-dried refuse and nightsoil	Ficksburg, South Africa	30 days in pit; 4–6 weeks " ripening"	Field production
Pits turned	Air-dried refuse and nightsoil	Calcutta, India	20 days	Field production
Piles turned infrequently	Mixed municipal refuse	Dannevirke, New Zealand	20–30 weeks	Field production
Pits aerated	Selected refuse and sewage sludge	Dumfriesshire, Scotland	6 weeks' composting; 6 weeks' maturation	Field production
Piles turned	Mixed municipal refuse	Compost Corporation of America	20–30 days	Field production
Piles turned	Municipal refuse containing no garbage	VAM at Schiedam, Netherlands	3–6 weeks	Field production
Piles not turned	Municipal refuse containing no garbage	VAM at Wijster, Netherlands	4–6 months	Field production
Pits not turned	Refuse containing no garbage, nightsoil, ash, etc.	India	4–6 months	Field production
Piles	Refuse, vegetation, and nightsoil	Malaya Kenya	2 months 2 months	Field production
Pits turned	Refuse containing no garbage, nightsoil, manures, straw, and soil	North China	2–6 months	Pilot plant and field production

As the particle size (screen test), color and odor were considered unreliable indicators, other parameters of waste stabilization were suggested by many researchers, such as: the final drop in temperature (McGauhey & Golueke, 1953), the degree of self-heating capacity (Niese, 1963), the amount of decomposable and resistant organic matter in the material (Rolle & Orsanic, 1964), the rise in redox potential (Moller, 1968), the oxygen uptake (Chrometzka, 1968), the growth of Chaetomium gracile (Obrist, 1965), and the starch test.

Chemical tests for nitrogen in its different forms, phosphorus, potash, and the organic character of the material (e.g. cellulose, lignin breakdown) can be made by standard techniques and are useful in analysing the finished product and in determining the effect of different composting procedures.

The University of California Studies observed that the attainment of a satisfactory degree of stabilization was always accompanied by a final and inevitable decline in temperature. The finality of the decline was confirmed when the temperature failed to rise despite the imposition of favorable environmental conditions. It was also observed that once the temperature had receded to about 45°C to 50°C, the material had become sufficiently stabilized to permit indefinite storage. Therefore, as far as windrow composting is concerned, the final drop in temperature is an excellent measure of stability.

Niese's self-heating capacity analysis is a variation of the "final-drop in temperature" parameter. With Niese's method, the results obtained indicated a temperature above 70°C for raw refuse, 40° to 60°C for "medium" decomposition, and under 30°C for "complete" stabilization.

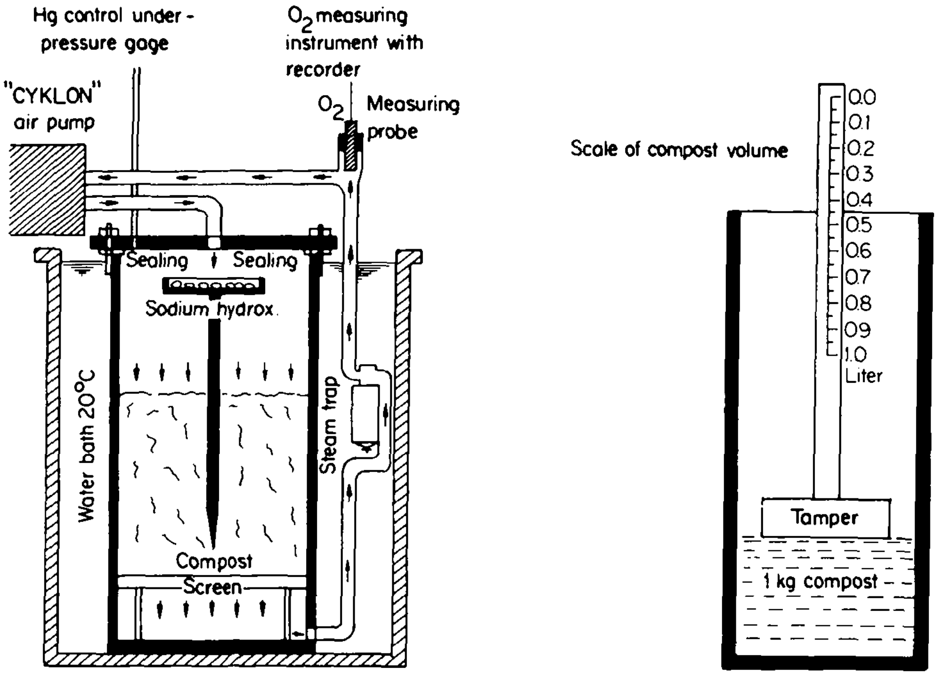
The principle underlying Rolle & Orsanic's method of determining, decomposable and resistant organic matter is ascertaining the amount of oxidizing reagent used in the test.

As the presence of decomposable organic substances leads to an intensification of microbial conversion, which in turn brings about an increase in oxygen uptake and an accompanying drop in oxidation-reduction potential. According to Moller (1968), the material in a pile of compost may be regarded as sufficiently stabilized when the redox potential of the core of the pile is less than 50 mV below that of the outer layer.

The degree of compost maturation can also be monitored by biochemical tests such as the determination of phosphatase and cellulase, as suggested by Obrist (1965). These enzyme analyses furnish a certain evaluation of the microbial activity, provided they are carried out regularly throughout the process. Due to this requirement, the tests are not practical for routine work.

The "Chaetomium method" (Obrist, 1965) is based on the measurement of growth and the formation of fruiting bodies of the fungus chaetomium gracilis cultured on a solid nutrient medium containing pulverized refuse or compost. After an incubation period of 12 days, the fruiting bodies are counted. Growth and the number of fruiting bodies are functions of the amount of decomposable material present in the tested material.

A "Compost Measuring Instrument Horgen" for measurement of oxygen intake is described by Allenspach (1969). It is based on the following principles : a weighed quantity of loosely packed compost is introduced into a hermetically closing measuring cylinder of a known air volume (Fig. 27). By taking into consideration the pore volume of the compost, the total quantity of air in the device can be calculated. This air volume contains a known percentage of oxygen. By correlating this quantity to the prevailing temperature and air pressure, the weight of the initial amount of oxygen can be established. The total amount of air is now circulated in the measuring cylinder, so that the compost confined therein is constantly aerated. Changes in the oxygen content of the air within the measuring cylinder can be registered by a variety of instruments. Oxygen uptake is also a parameter which can be used to monitor the stabilization of compost, and it can be measured directly by a Warburg apparatus (Chrometzka, 1968).



Compost Measuring Instrument Horgen

Volumetric Determination of the Compost Pores.

Fig. 27 Equipment for Compost Monitoring

The starch determination method, as developed by Lossin, depends on the assumption that the more advanced the degree of decomposition, the less the amount of decomposable organic matter. He states that three types of carbohydrates are found in composting material, namely, sugars, starch, and cellulose. In windrow composting, sugars disappear within a week after the start of the process. Starch passes through its maximum degradation in the fourth to fifth week of composting.

Spohn (1978) proposed a do-it-yourself method to detect qualitatively nitrate and sulfide in the compost, considering them as indicators of well-matured compost. This test for ripeness is based on the premise that no sulfide should be present in mature compost, and nitrogen should be as nitrate and not as ammonia.

As the composting proceeds by the action of microorganisms through their metabolism occurring via the liquid phase, the water extract from the solid phase will change characteristically with the progress of the composting reaction. With this idea, a gel chromatogram of a water extract from solid samples was proposed as an ideal measure of composting degradation (Zucconi et al., 1980; Kubota & Chanyasak, 1980).

A characteristic of all the preceding tests, excepting perhaps the two depending upon temperature level or drop, is that they are relative, in that the determination rests on a change in values, rather than on a standard, consistent number. Hence, they cannot be used as standards for wide-scale applications. Also, some of them are tedious and time-consuming and dependent to a large extent on the skill of the tester.

VIII. FINAL PROCESSING AND HANDLING

VIII.1 Final Processing

After the material is adjudged sufficiently stable to store, it is ready for "rough" applications, i.e., in large-scale agriculture, land reclamation, etc.

In practice, the usual procedure is to sort the compost into fractions on the basis of quality. This is usually done by screening the material. The coarsest material is reserved for the home gardeners for "luxury" crops. Often the material remaining after the separation of the coarser fraction is ground and screened. Grinding compost is somewhat easier than grinding raw refuse due to the fact that the material has been rendered more amenable to grinding because of having been composted. Of course, the major benefit of the second grinding is the increase in "eye" appeal which results.

Properly composted material can be stored without danger of subsequent generation of nuisances. Although decomposition will occur during storage, unless the moisture content is too low for bacterial activity, the rate of decomposition will be very slow, and no odorous intermediates are formed.

VIII.2 Utilization of the Finished Product

VIII.2.1 Chemical Composition of Compost

While qualitatively the chemical composition may be fairly similar from one compost to another, insofar organic matter is the substrate, quantitatively variation in the nutrient value will be great due to the differences in type or combinations of types of material being composted. In one instance the material may have a high nitrogen (low C:N) content; while in another, nitrogen may be on verge of being limiting. The trace elements also vary. Mixed municipal refuse may have a wider range of trace metals than would a particular crop or manure. Unfortunately, the broad array of metals in the municipal refuse may include a metal or toxic substance of public health significance. Some idea of the chemical analyses of typical composts may be gained from the information in Table 23.

Table 23. Chemical Characteristics of Compost

Substance	Percentage by Weight
Organic matter	25–50
Carbon	8–50
Nitrogen (as N)	0.4–3.5
Phosphorus (as P_2O_5)	0.3–3.5
Potassium (as K_2O)	0.5–1.8
Ash	20–65
Calcium (as Cao)	1.5–7

In general, compost has an NPK content which is not high enough to permit it to be designated a fertilizer in the legal sense. Therefore, unless fortified with one or all of the three elements, it cannot be legally sold as a fertilizer. The usual designation is "soil conditioner".

VIII.2.2 Value as a Soil Conditioner

Finished compost may be designated by the general term "humus". When used in the soil, humus has many characteristics beneficial both to the soil itself and to growing vegetation. In conjunction with commercial fertilizers, humus exhibits certain additional and very desirable characteristics. Organic acids resulting from the metabolic breakdown of organic material form a complex with the inorganic phosphate. In this form, phosphorus is more readily available to higher plants. Both phosphorus and nitrogen are involved in a storing effect peculiar to humus. The precipitation of phosphorus by calcium is inhibited; and nitrogen, by being converted into bacterial protoplasm, is rendered insoluble. Thereafter, the nitrogen becomes available as the bacteria die and decompose. The effect is to prevent leaching of soluble inorganic nitrogen and to make its rate of availability more nearly equal to that at which plants can utilize it. The gradual decomposition of insoluble organic matter by microorganisms results in a continual liberation of nitrogen as ammonia, which is then oxidized to nitrites.

The physical effects of humus on the soil are perhaps more important than the nutrient effects. Soil structure may be as important to fertility as is its complement of nutrients. Soil aggregation or crumb tendency as promoted by humus improves the air-water relationship of soil, thus increasing the water retention capacity, and encouraging more extensive development of the root systems of plants. Aggregation of soil particles is brought about by cellulose esters resulting from bacterial metabolism (Quastel, 1952). Other beneficial effects of bacterial metabolism associated with humus include an increased ability of the soil to absorb rapid changes in acidity.

VIII.2.3 Application of Compost on Crops

The effect of compost, especially composted municipal refuse, on plant growth has been the subject of extensive study both in the U.S.A. and in Europe. Among the reports are those by Hasler & Zuber (1966); Hortenstine (1970); Sanderson (1970); Sanderson & Martin (1966-67); and Shinn (1970).

Based on these studies it might be stated in general that regardless of the species of plant concerned, growth is always enhanced by the addition of compost to a greater degree than by mineral fertilizers alone - provided of course, that a proper C:N ratio is maintained in the soil receiving compost. The C:N ratio of the compost is in fact an important determinant of its immediate utility in crop production. If the C:N ratio is too high, i.e. above 20:1, the danger of nitrogen "robbing" becomes imminent. Nitrogen robbing is manifested by stunted growth and a chlorotic condition of the higher plants making up the crop being cultivated. It arises from the competition for nitrogen between the bacteria decomposing the compost and the roots of the crop plants. Bacteria which are more efficient in assimilating the nitrogen obtain the major portion of the available nitrogen, and thus in effect "rob" the higher plants. The nitrogen robbing effect can be avoided by applying sufficient nitrogen to the soil to compensate for any deficiency. This nitrogen "deficiency" explains why crop production may actually drop when compost is first applied. However, even if no nitrogen is added, the problem will disappear within a year.

Hortenstine's finding added a new dimension to the usefulness of compost, as it pointed out that nitrification in the soil is reduced almost to zero. This characteristic is of value in preventing the nitrate contamination of ground waters. He also noted that compost brought about a reduction of nematodes in the soil.

The use of compost can supply boron to the treated crops, and this is a beneficial factor since boron is usually inadequate in the soil. Results of vegetation culture tests show the boron utilization of refuse compost to be good (Hasler & Zuber, 1966). Boron-sensitive crops, such as bush beans, should receive moderate amounts of refuse compost. Other plants, such as spinach and celery, tolerate without damage large amounts of compost. Spinach is particularly tolerant of high boron concentrations.

The use of compost in place of chemical fertilizers can help minimize man's total daily intake of fluorine, a carcinogen present in phosphatic fertolizers (Schatz & Schatz 1972). The argument is that fluorine in phosphatic fertilizers must be given the most serious consideration because fluorine is a carcinogen and a health hazard in many other ways.

In Europe, composting usage ranges from about 1 percent of municipal waste in West Germany to 17 percent in the Netherlands (General Electric Company, 1975). However, the high percentage in the Netherlands is based on 1968 data and may be revised downward as the Hague plant switches over to incineration of its refuse. In general, the compsot products in Europe are used for the luxury agriculture market

(General Electric Company, 1975; Teensma, 1965). Several composting plants are being kept open to continue serving this market, but new municipal refuse processing plants use other, lower-cost disposal techniques.

Specifically, the main areas of compost utilizaiton in Europe are (Goosmann, 1979):

- landscaping, e.g. park and sports grounds development and maintenance, highway construction, etc.;
- special cultures, e.g. vineyards, mushroom growing, etc.;
- horiticulture, agriculture, especially on intensively used land;
- forestry, tree nurseries;
- waste land reclamation; e.g. landfills, erosion control, etc.;
- other uses, e.g. as a filter material in biological filters for odor control.

VIII.2.4 Land Reclamation

The application of compost is the obvious solution to land reclamation in areas where the top soil has been lost due to strip mining. The problem in such areas is to stop erosion and to supply a substrate on which a plant cover can take hold. Compost would supply both needs very readily. A kindred type of reclamation is the protection of hillsides denuded of vegetation by fire. An unreported study conducted in the Los Angeles area involved the spraying of a very thick slurry of composted municipal refuse, to which suitable grass seeds had been added, on burned hills. When placed on the hillsides, the slurry dewatered to a state much like a paper machine. When the rains came, the seeds sprouted, and together with the compost effectively prevented mudslides or erosion from taking place. Compost is also useful for retaining soil on highway cuts and other excavations.

A potential use for compost is the reclamation of lands covered with mining tailings, fly-ash deposits, and various chemical sludges to support a good growth of vegetation through the addition of compost.

IX. PUBLIC HEALTH ASPECTS

IX.1 Pathogen Destruction

Several extensive experiments on pathogen destruction have shown that aerobic composting at high temperatures is effective in destroying pathogenic organisms. The apparent absence of health hazards has been demonstrated as a characteristic of well-managed composting operations in many parts of the world (Blair, 1952; van Vuren, 1949). This gives significant evidence of the effectiveness of thermophilic composting.

The major factors in the destruction of pathogenic organisms in the compost process are high temperature, interspecific competition, antibiosis, and time.

Of the four, high temperature is the most effective in pathogen-kill in composting - with time, antibiosis, and competition, following. Thermal death points of some common pathogenic microorganisms, parasites and parasite ova, as shown in Table 24, give support to the belief that pathogenic organisms would not survive in a well-managed compost operation.

Table 24. Temperature and Time of Exposure Required for Destruction of Some Common Pathogens and Parasites

Organism	Observations
Salmonella typhosa	No growth beyond 46 °C; death within 30 minutes at 55°–60° C and within 20 minutes at 60° C; destroyed in a short time in compost environment
Salmonella sp.	Death within 1 hour at 55° C and within 15–20 minutes at 60° C
Shigella sp.	Death within 1 hour at 55° C
Escherichia coli	Most die within 1 hour at 55° C and within 15–20 minutes at 60° C
Entamoeba histolytics cysts	Death within a few minutes at 45° C and within a few seconds at 55° C
Taenia saginata	Death within a few minutes at 55° C
Trichinella spiralis larvae	Quickly killed at 55° C; instantly killed at 60° C
Brucella abortus or Br. suis	Death within 3 minutes at 62°–63° C and within 1 hour at 55° C
Micrococcus pyogenes var. aureus	Death within 10 minutes at 50° C
Streptococcus pyogenes	Death within 10 minutes at 54° C
Mycobacterium tuberculosis var. hominis	Death within 15–20 minutes at 66° C or after momentary heating at 67° C
Corynebacterium diphtheriae	Death within 45 minutes at 55° C
Necator americanus	Death within 50 minutes at 45° C
Ascaris lumbricoides eggs	Death in less than 1 hour at temperatures over 50° C

It has been observed and stated that the highest thermal death points are appreciably lower than the maximum temperatures found inside the composting pile. Not only are high temperatures reached, but they persist for a matter of days, i.e., in excess of the time required to kill the organisms.

Studies of a more scientific or definitive nature were made in 1959 and in the 1960's in Europe by Banse et al. (1968), Knoll (1959) and Strauch (1965).

Knoll (1959) demonstrated that the extermination of pathogens is not solely a thermal reaction. Antibiosis plays an important part. Also, competition for nutrients must also have a part in the destruction. However, the effects of competition for nutrients would probably be more inhibitory than lethal. The lethal effect of temperature is magnified by the dampness of the composting material.

Studies on virus activity were nonexistent until a few years ago, and even now leave a high degree of uncertainty. Cooper & Golueke, 1981; Lund, 1978; and Kawata et al. 1977, in their studies of samples during composting digested sludge, found enteric viruses the windrow phase. But following stock-piling they were no longer detected. Lund (1978) also reviewed the factors influencing the persistence of viruses in the environment, with particular attention to tropical situations.

Neil & Siechers (1978) and Peel (1976) reported very high temperatures (70-80°C) in composting nightsoil and refuse, resulting in the destruction of pathogens, but the rate of composting at such high temperatures declines.

Cooper & Golueke (1981) raised doubts regarding the role of temperature as the primary factor in the destruction of pathogens, at least in windrow composting, because at no one time was every particle in the pile exposed to a lethal temperature.

Golueke (1972) emphasized that the beneficial effects of composting can be realized only by careful control of all phases of the process. Care must be taken that all particles are exposed to high temperatures and that all particles receive full exposure to the process. In view of the well-nigh impossibility of maintaining perfect control at all times, the composting of nightsoil or of raw sewage sludge with refuse should be undertaken with great reluctance. The resulting compost product should be subjected to heat sterilization. If it is not sterilized, its use should be restricted to applications that involve no human contact, directly or indirectly.

IX.2 Fly Control

The higher temperatures are considerably in excess of the thermal death point of the fly in all of its stages of development. Chemical and physical changes in the nature of the materials being composted soon render them unfit as a nutrient source for flies. Consequently, while adult flies may alight on a pile, they rarely remain long enough to deposit eggs.

Some of the procedures - particularly grinding, turning, and systematic cleanliness - which are useful in providing compost of good quality and in destroying parasites and pathogens, are also most effective for controlling flies. Initial shredding or grinding produce a material which can be more readily attacked by bacteria, and also destroys a large number of the larvae and pupae in the raw material.

The Compost Corporation of America, when composting materials which were attractive to flies and which contained larvae and pupae, found that insulating the piles with stabilized compost, produced high temperatures sufficiently near the surface for fly-breeding to be controlled.

Acharya (1950) developed different techniques for controlling flies in compost operations in pits without turning. He reported successful control in compost mixtures of municipal refuse and nightsoil by putting a 9" (23 cm) layer of refuse over the top of the pit stack and a 2" (5 cm) layer of dirt on the refuse. The refuse and dirt layers serve to insulate the compost and retain the heat to kill the larvae.

University of California researchers (McGauhey & Golueke, 1953) observed that while the refuse coming into the process had a heavy concentration of fly larvae, by the time the material had been passed through the grinder, all larvae were destroyed. No fly development was found either in composting manures or garden wastes (Golueke & Gotaas, 1954).

Golueke (1954) proposed daily turning of the compost pile in order to control fly-breeding, as many larvae and pupae would migrate to the cooler outer surfaces and so were not exposed to the heat of active composting. Acharya (1950), and van Vuren (1949) also proposed the same control measure.

Another method for dealing with the fly problem is to provide gutters filled with water all around the edge of the pits. The fly larvae which attempt to leave the hot compost are drowned in the gutters. The gutters must be cleaned daily. A fly-trap constructed by van Vuren (1949) provided good fly-control, but the time required for composting was increased.

The above methods of sealing off the compost pit or stack are satisfactory means of controlling flies in aerobic (open) composting. Enclosed bins, such as used in the Beccari process, will prevent the development and escape of flies when decomposition takes place anaerobically.

Composting at high temperatures in the mechanical silo-type digesters presents no fly-control problem if the material is stabilized to a point where it is no longer attractive to flies when it is removed.

To conclude, turning is the most effective method for fly control and, when properly done, produces highly satisfactory results.

If mixed garbage and refuse or animal manures are being composted, particularly on a large scale, the use of stacks or windrows placed on concrete slabs or hard ground and turned by hand or by machinery, which is usually cheaper, will be the most economical. When feces or nightsoil are being composted, pits and bins have the advantage of confining the infected material and not spreading it over a considerable ground area when turning, as is the case in using windrows. Mechanical turning of the material in pits can be utilized when economical.

IX.3 Occupational Health Hazards for Workers in Compost Operations

- Exposure to pathogens, e.g., enteric bacteria & viruses, especially when excreta are being composted.

- When turning by hands is involved, the danger of getting hurt by pieces of glass and metal, etc.
- During grinding, agitating and turning, dust emission hazards, can cause bronchoidal troubles as a resulting in hailing the dust particles.
- There is a potential risk of exposure to some of the hazardous wastes, e.g., heavy metals, etc.

X. ECONOMICAL ASPECTS

The economics of refuse composting have been discussed in generally terms by McFarland (1972).

X.1 Alternative Disposal Methods

Composting, which combines the recycling of raw materials with the production of organic manure, has a strong ecological appeal. But it is a municipal service, paid for from taxes, and a city will naturally seek to employ the disposal method which offers the lowest cost. Therefore, the common attitude is that every composting proposal must be able to stand comparison on financial grounds with alternative methods of obtaining equivalent hygienic standards.

From this point of view, it can be seen that hardly any situation can be favorable for refuse composting. However, one of the most ardent prononents of refuse composting can be found in Schatz & Schatz (1972), who state that the objection that it will cost too much to produce and use compost in place of chemical fertilizers is not true from an overall point-of-view. The reason is that the hidden costs incurred by environmental impacts (entrophication, methhemoglobiremia, cancer, etc.) as a result of the use of chemical fertilizers are usually disregarded in comparing the economics of compost vs chemical fertilizers. But when these hidden costs are taken into account, compost is far less expensive than chemical fertilizers.

The important aim in producing and marketing compost is to keep the operation efficient enough to allow the compost to be sold at prices that the farmer can pay. This is being done in the Netherlands and India, and in many other countries (Gotaas, 1956).

Some large-scale plants can sell their compost products, and this results in substantial reduction of costs (for example, see Spohn, 1972; Franz, 1972).

Among the principal economic factors involved in the designing of a composting operation are:

** facilities for receiving, segregating, salvaging, and possibly shredding the materials;

** equipment and installations;

** land areas, labor, power, and other operational and maintenance costs;

- ** capital costs and depreciation; and
- ** the market value of the final product.

When the compost produced by a large city cannot be entirely consumed by farms in the immediate area, transportation costs may be a major factor in its economical disposal.

The costs of composting operations vary widely according to the conditions of composting and the factors mentioned above. Experiences in India have provided much information on labor and other costs of operation in agricultural villages.

Flintoff (1976) presented a convenient way of setting out a summary of the cost of composting in an Indian city, and this is shown in Table 25.

Table 25. Summary of the Cost of Composting in an Indian City

Expenditure	Rs./tonne of Wastes Received
Compost plant operating costs (including amortisation)	50
Disposal of contraries (20 % of input x Rs. 10/tonne)	2
Transport of compost (50% of input x 20 Kms x Rs. 0.7/tonne Km)	7
Total cost of operation	59
Income	
Sale of salvage (2% of input x average value of Rs. 250/tonne)	5
Sale of compost (50% of input x Rs. 50/tonne)	25
Total income	30
Net disposal cost of wastes	29

Note: 1 US$ ≃ 9 Indian Rs.

In this hypothetical situation, if the only alternative to composting was incineration at a net cost of Rs. 150/tonne (US$14/tonne), then composting would be the obvious choice, given adequate assurances on marketing. If, however, sites were available at which sanitary landfill to high standards could be operated at Rs. 10/tonne (US$1/tonne), composting would impose an unnecessary financial burden upon the city, however great its attractions may be from the agricultural stand point.

Information is available, provided with the cost data of composting, gained through several studies in many parts of the world, but any such data may not be directly applicable as a generalized guideline. Each operation requires an analysis of the specific problems of compost production costs and of the market potential for the products.

The Natural Resources Committee of Great Britain (Agricultural Research Council, 1948), stated that in its opinion composting of municipal wastes appeared to be generally uneconomic in England. But the report did not show cost analyses for composting in England as compared with other methods of disposal of organic wastes. At the same time Gothard & Brunt (1954) contradicted the findings of the committee.

The cost analysis for a proposed compost plant at Oakland, California to be operated by Compost Corporation America indicated that if the mixed refuse were received at a nominal charge for disposal, a very good profit could be made through the compost product for use as a fertilizer use, and at a much low cost than the cost of incineration of the material.

Seabrook (1954) estimated that Washington city could show a profit from composting the refuse and sludge without including the present cost of disposal by sanitary landfill.

The Dano Corporation (Gotaas, 1956) estimated that for a plant receiving 50 tons of raw refuse per day in Los Angeles, California, the cost of composting the refuse in a biostabilizer-type plant, including depreciation, would be about the same as the cost of incineration. Thus if the compost has a market value, the net cost will be lower than that of incineration.

The latest cost data available to the authors can be found from Martin (1982). The net system cost of a mechanical digester aerobic composting plant with ferous recovery is about US$28 per ton. The annual capital and operating costs per tone are US$18 and US$10, respectively. Adding the revenues from compost sales and substracting by the landfill cost of the residues, the total net cost is US$26.05 per ton per annum. The economics of aerobic composting, at a capacity of 100 tonnes per day, are detailed in Table 26.

X.2 Mechanical vs Manual Methods

On the question of mechanical vs. manual methods of operation, the choice is limited to certain specific work areas. Some processes are practicable only by mechanical means, such as pulverization and ballistic separation. On the other hand, there are certain processes for which manual methods may be superior or even essential, as for example the sorting of non-ferrous metals. Also, there are some work areas in which the amount of mechanization has to be decided in the light of current forecast labor costs, plant and energy costs, and comparative performances. It might appear that the windrow method is much more economical than the small mechanically aerated digesters. At the same time, small digesters may compete economically by being located at a number of points in a city, and thereby reducing the costs of handling the raw refuse. Small, enclosed, mechanically aerated digester plants will not involve as great a nuisance hazard, and may be established in areas where it would be unwise to set up a large windrow-type plant.

Table 26. Cost Analysis for a Representative Aerobic Compost Plant with Ferrous Recovery[1] (100 TPD)

		Initial Costs	Life (Years)	Amortization Factor (8%)	Annual Costs
CAPITAL COSTS ($1,000)					
Shredder, including dust control		$ 350	5	0.250	$ 88
Air Classifier and Bag House		250	5	0.250	63
Magnetic Separator		30	5	0.250	8
Baler		30	5	0.250	8
Compost Equipment		980	5	0.250	245
Auxiliary Equipment		50	5	0.250	13
Small Front-End Loader	40				
Office Furniture, Refuse Bins	10				
Construction & land		474	20	0.101	47
Building: 11,750 ft^2 $30/$ft^2$	353				
Site Development: 20% of bldg	71				
Land: 5 acres @ $10,000/acre	50				
TOTAL		$2164			$472
OPERATING COSTS ($1,000)					
Labour:[2] 4 operators @ $48 1 supervisor @ $16					64
Supplies: 3% of labor & maint.					
Energy:[3] Stationary equipment		96.7			
Mobile equipment		3.2			
Light		1.0			
Building heat		1.7			103
Maint.: 3% of total capital cost					65
Misc.: (taxes, licenses, insurance, administrative and management costs) 1% of total initial capital costs					22
TOTAL					$258
TOTAL ANNUAL SYSTEM COSTS ($1,000)					$730
COSTS/REVENUES PER TON ($/ton)					
Systems Cost					$ 28.08
System Revenue[4]					4.19
Net System					23.89
Landfill[5]					2.16
Total Net					$ 26.05

Footnotes:

1 Data calculated by SCS Engineers from literature and vendor sources.

2 Operator wage rate is $5.80 per hour which includes fringe benefits of 15 percent. Supervisor wage rate is $7.80 per hour, including fringe benefits.

3 Energy:

Stationary equipment – operation conditions are:

o Electric Power Consumption	50 kWh/ton
– Cost	$2,640/month
o Natural Gas Consumption	9 therms/ton
– Cost	$0.2776/therm

Mobile Equipment – operation conditions are:

o Gasoline Consumption	2.5 gallons/hour
– Cost	$0.60/gallon

4 Revenue Factors:

o Compost ($3.11/input ton)	
– Percent compostables in wastertream	69%
– Recovery rate	90%
– Market value	$5.00/ton FOB the recovery site
o Ferrous ($1.08/input ton)	
– Percent ferrous in wastestream	8%
– Recovery rate	90%
– Market value	$15.00/ton FOB the recovery site

5 Cost Factors:

o Compost: Weight reduction	62%
o Ferrous: Weight reduction	72%
o Cost to haul to landfill and disposal	$7/ton

Windrows can be turned manually or by front-end loaders. If it is known that one man can turn 5 tonnes/day and a front-end loader of a certain size, 120 tonnes/day. The comparative costs of 24 men against 1 loader provide the information on which decision can be made. In making such comparisons allowance is necessary for the cost of standby equipment required during plant maintenance as well as for labor on costs arising from welfare facilities and fringe benefits.

X.3 Indigenous Equipment

Mechanized refuse disposal methods were first developed in industrialized countries, and these countries are still the main suppliers of equipment, particularly items of patented design. Composting plants erected in developing or partly industrialized countries are usually of foreign manufacture and this can involve risks to long-term reliable operation through dependence upon imported spare parts, and may add to the maintenance cost if heavy items have to be transported over great distances. It is recommended, therefore, that a plant should be designed in the country in which it is to be erected and that the design should be based as far as possible on indigenous equipment. Where patents are involved, the possibility should be explored for local manufacture under licence. This applies with special force to items which are rapidly consumered, such as hammers for hammer mills, or are subject to sudden damage and require immediate replacement, such as conveyors or belts.

X.4 Energy Aspects

It is important to recognize that there may be constraints on energy consumption of two kinds, namely rising energy costs and uncertainty of continuous supply.

In a high energy cost area it may be possible to modify plant design to minimize energy consumption. Hammer mills of 10 tonnes/hour capacity require at least 150 Hp, and up to 350 Hp for 20 tonnes/hour capacity, when used for the treatment of raw wastes. However, if hammer mills or rasps are used exclusively as a final treatment after decomposition, the power requirement is greatly reduced as a result of the structural changes which occur in the wastes during decomposition. If the decomposed wastes are first screened and only the oversize material passed through a hammer mill, the energy requirement may be reduced to 20% or less of the energy required for fresh unscreened wastes.

When a large capital investment is made in a composting plant, it is vital to ensure that the public power supply is 99% reliable. Cases have been known where seasonal power cuts occur for long periods, as for example in many places in India. This will be intolerable if the compost plant provides the only means of refuse disposal for a city. In some circumstances diesel engines may offer a more reliable energy source.

X.5 Economics of Salvage Extraction

The viability of salvage extraction at any given time is a function of wage rates and salvage values at a given locality. These may change significantly over the life of a plant, which is normally about 20 years.

The history of the industrialized countries as well as trends in developing countries show that wage rates steadily increase, mainly because of rising productivity and partly as a result of inflation. The market values of salvaged materials, however, rise at a much slower rate, and sometimes do not rise at all. For example, in Britain, wage levels have risen much faster than salvage values: 1976 wages were probably at 15 times pre-war levels, but the selling price of paper increased only 5 times, and the price of glass was unchanged. For most British cities, salvage is no longer profitable (Flintoff, 1976).

X.6 Transportation Cost: Size of a City

Transportation between the compost plant and the farm is an important cost element; in most situations this cost limits the marketing range to about 25 km. If the potential marketing area for compost is a circle of 25 km in diameter and if the plant is in a very large city, much of that circle will be occupied by urban areas. Therefore, the larger the city the smaller the potential market for compost. However, the larger the city, the greater the quantity of wastes. Thus composting as a policy suffers from the paradox that the potential market is in inverse ratio to potential wastes production.

The consequence is that no major city has ever been able to base its waste disposal policy entirely on composting. The most successful composting plants have been those which serve small towns in agricultural areas, and the widest application of composting in the past has been in the form of simple manual methods in villages.

XI. CASE STUDIES IN DEVELOPING COUNTRIES

Traditional composting as one of the oldest practices in agriculture used in India and China has been successfully adopted by many developing countries. A summary of composting practices in some countries is presented in Table 27.

India

In a recent survey (Singh, 1982) on some existing mechanical composting plants in India, it has been shown that most of these plants perform unsatisfactorily, and the main reason is frequent mechanical troubles. Marketing of the compost product is also difficult.

Nigeria

Outside India and China, it was in Africa where some early composting practices were started long ago. In Kano, Northern Nigeria, composting was initiated to deal with domestic refuse, street sweepings, and animal and human excreta (Gilles, 1946).

Based upon the Indore process, the Kano method of composting consisted in thorough and complete mixing of nightsoil with domestic wastes, loading the mixture into chambers, and turning the mixed mass on three successive occasions. The chambers were emptied on the 30th day and the resulting product was a dark blackish brown material resembling soil, which was quite inoffensive and did not attract flies.

Table 27. Practice of Sanitation in Developing Countries

Country	Method of Composting	Feed Materials	Basis	Construction Cost
China (Peoples Republic)	Aerobic/Anaerobic	Nightsoil (feces) Garbage/Refuse Animal manure Plant wastes Soil	Off–site (community basis)	Operation cost is offset by price of nightsoil
India	Gopuri (Double vault) – Anaerobic	Nightsoil (feces) Leaves/Wood ashes	On–site (Individual/community)	
	Bangalore Method – Anaerobic	Nightsoil City refuse	Off–site	
Vietnam	Double Vault – Anaerobic	Nightsoil (feces) Ash	On–site (Individual/community)	
Philipines	Aerobic (Minimus)	Excreta	On–site	Pesso 385 (1976)
Tanzania	Anaerobic (Discontinuous, alternating) Aerobic (Continuous)	Excreta Grass/Weeds Kitchen refuse Husk	On–site	
Nigeria	Aerobic (Indore)	Excreta City garbage/Litter Slaughter waste	Off–site	
Botswana	Anaerobic (Double vault)	Excreta	On–site	
Algeria	Anaerobic (Single vault)	Excreta Palm leaves	On–site	

In his review paper for the Health Department of Nigeria, Gilles (1946) concluded that prior to composting, trenching or dumping of nightsoil into Otway pits, and incinerating or dumping into depressions and covering with earth the vegetable and other refuse yielded no returns, while composting not only yielded to the producer some small financial return, but benefited the agricultural community incalculably. Marked results were observed in enrichment of the soil of a heavily farmed area that needed fertilizer badly. There was no difficulty in persuading farmers to use the compost made from human excreta. Practical demonstrations overcame all prejudices. In 1946, an average of 1,080 cubic yards of humus was being produced monthly in six sets of composting chambers. In 5 years compost productions in Kano totalled 43,800 tons - a wealth of black gold in the opinion of Gilles (1946).

Sri Lanka

At Kurungula, Sri Lanka, aerobic windrow composting is practised, turning at monthly intervals for several months, nightsoil being incorporated. The process suffers anaerobic lapses, perhaps because of excessive nightsoil, or because the windrows are too small to retain the heat (Polprasert & Muttamara, 1979).

Thailand

A compost plant with a capacity of 150 tonnes (450 m^3/day) of refuse per day was constructed in 1961 at Din-Daeng, Bangkok in Thailand. The plant is a "Jersey" system (John Thompson System) type and includes a receiving ramp for 4 trucks at a time, 2 shredders, magnetic scrap separators, centrifugal separators and belt conveyor lines, and the fermentation house. The fermentation house has 6 floors each 300 m^2 in area. The contents of each floor are dropped to the next lower floor daily to effect 6 days detention time and a daily output of 210 m^3 (70 tonnes) of compost (Polprasert & Muttamara, 1979). The compost is saleable and makes about 0.8 million baht (US$40,000) worth of compost annually. However, the uncomposted portion of the refuse is still very large and the open dumps are posing a great public health hazard.

Two more plants have also been built at a capital cost of about US$4 million for 300 tonnes/day capacity at 1968 prices.

A study for a master plan for Bangkok Metropolitan (JICA, 1982) reveals the following problems associated with the existing mechanical composting plants :

- The presence of a considerable amount of unsuitable materials for compost, such as plastics, glass, etc., and a small but not regligible amount of heavy metals. This is due to the deterorated performance of the mechanical classifier.
- Consequently, most of the compost produced cannot be marketed, but is simply disposed of in landfills.
- Nuisances and environmental pollution, such as malodors, water pollution caused by leachate, and air pollution caused by exhaust gas from the attached incinerator.

XII. CONCLUDING REMARKS

XII.1 Potential of Composting in Waste Management: Present Status

Golueke (1972) expressed his opinion that the present status of composting in solid waste management in the US is far from promising, and the situation in Europe is not much better. According to him, in the U.S.A. when composting was at its peak, only a tiny fraction (less than 1%) of the total wastes generated in the U.S.A. was processed by composting. In Europe, where composting has always received favorable attention, the fraction of refuse being composted is only 1 or 2% (Hart, 1967).

The reasons for the unsuccessful status of composting in terms of the extent of its practice are not the lack of utility of the product nor of technology, but the unfavorable economics when judged by today's short horizon pragmatic standards. The unfavorable economics stem from the inherent high cost of the process and from the absence of a demand for the product. In strictly monetary terms, less is accomplished by composting than by incineration with respect to volume reduction of the wastes. Moreover, an incinerator can be built on a more compact scale, and land requirements are less because little or no storage is required in an incineration operation.

Another difficulty in marketing is its seasonality. The product can only be applied to cropland at the end of, or prior to, the growing season - not during the season. Consequently, provision must be made for storing the daily production of a plant for long periods of time. Also, in most cases, the transportation costs exceed the monetary value of the product.

As a result of these handicaps, practically every compost enterprise undertaken in the U.S.A. has failed (Golueke, 1972). At one time, no other factor, including economics, was as responsible for the failure as untolerable odors (Haug, 1980).

XII.2 Future Prospectives & Research Needs

The unfavorable status of composting will be changed as people become sufficiently environmentally conscious to demand that waste management should include social and environmental benefits when evaluating the applicability of a given waste technology. In all of the potential applications, no monetary return is involved. In fact, not only would there be no cash return, but there would be actual expenditures because of transportation and application costs. However, the long-term benefits more than make up for the costs involved.

In fact, to judge the success of a compost operation in terms of its money-making record is a misconception that has always harmed the prospectives of composting, and is one that must be corrected. This is so because if the product cannot be sold with definite results in terms of operational and capital costs, the enterprise is regarded as a failure - regardless of how well the plant may have operated. Yet, no one expects an incineration operation to earn money. Since composting also is a method for treating wastes, its success should be judged on the basis of performance and not on the amount of profit (Golueke, 1972).

Millions of dollars have been spent and much research conducted in designing and constructing the sludge dewatering facility in developed countries like the

U.S.A. Unfortunately, similar attention was not given to the composting process (Haug, 1980). Reuse or disposal of the final product also depends on the success of the composting process. Therefore, it is important to understand the underlying principles of composting and to know what can and cannot be achieved, so that composting can be coordinated within the treatment strategy.

Golueke (1972) is quite hopeful about the future of composting. In his view, as the available land area for wastes burial is rapidly diminishing, and as air quality standards become stricter to a point at which air pollution control becomes so expensive as to rule out incineration, the only technology available for solid wastes processing will be composting.

XII.3 Applicability in Developing Countries

In the recent past, the use of organic fertilizers has considerably decreased due to the ease and availability of inorganic fertilizers. But this trend could not last long as the energy crisis deepened, leading to a corresponding price increase of inorganic fertilizers at a time when the developing countries are in urgent need of stepping up food production. Motivated researchers in both developed and developing countries were inclined towards the reexamination of the prospects of nutrients recycling through composting.

The Expert Consultation Group on Organic Materials as Fertilizers organized by FAO and SIDA in 1974 recommended (FAO, 1975), among other things:

> "It is now of the utmost importance and urgency to increase utilization of agricultural and municipal wastes as sources of plant nutrients. It is imperative that developing countries should immediately organize and adapt adequate and safe methods for the collection, processing and utilization of their organic waste materials. It is particularly important that the governments of developing countries should promote the utilization of organic materials in combination with inorganic fertilizers to the best advantage."

In the tropical regions of most of the developing countries, the heat and humidity tend to create ideal conditions for pathogen survival. This is further aggravated by the fact that wastewater, being at a high temperature, tends to turn anaerobic almost immediately. Composting would be a worthwhile solution of such problems in developing countries.

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