THE BIOCHEMISTRY AND METHODOLOGY OF COMPOSTING

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The CONNECTICUT Agricultural Experiment Station
NEW HAVEN

Foreword

Connecticut citizens, urban and suburban, are increasingly concerned with the disposal of organic waste.

An Agricultural Experiment Station, certainly this, the first in America, has a body of experiments and knowledge accumulated over many decades that can be marshaled when society encounters new biological problems or new needs. Because of the growing need and interest in disposing and recycling organic waste by composting, this bulletin marshals the Station's knowledge of composting and of decomposition of organic matter, and also reports new experiments.

A large part of these organic wastes are the garbage, leaves, and sewage sludge that are commonly disposed of by burying or burning, which make valuable plant nutrients unavailable.

Observant gardeners learned long ago that most of these materials can be biologically recycled by composting with soil. At this Station, we have always had scientists concerned with the role of organic materials in maintaining and improving soil fertility. So it is natural that a Station scientist, in this case, a biochemist, should combine old knowledge and new on the biochemistry and methodology of composting.

We anticipate that this work by the Agricultural Experiment Station will be useful to all who enjoy gardening, to those who are faced with decisions on organic waste recycling in their town or city, and to scientists interested in experimenting with the composting process.

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Biochemistry and Methodology of Composting

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I. Historical Development

Composting is a very old practice whose actual origin is lost in antiquity. Some of the earliest references to compost are to be found in the Bible. Accounts of composting in this country date back to the 18th century. One of the earliest American reports is contained in George Washington's diary: an entry on April 14, 1760 mentions a compost of stable manure and soil (1).

By the 19th century composting was known to most farmers and agricultural writers. One of these was Samuel W. Johnson, the second director (1877-1900) of the Connecticut Agricultural Experiment Station. Earlier, Johnson had written a book "Essays on Peat, Muck, and Commercial Manures," published in 1859 (2), which contained a very informative chapter on composting practices in Connecticut. Most compost was prepared by rotting 1 part stable manure with 2 or 3 parts of soil. One interesting compost prepared by a farmer of New Canaan, consisted of 12 parts of soil to 1 part fish and utilized as many as 220,000 whitefish per season. Various other compost materials, such as wastes from slaughter houses, sawdust, corn stalks, and leaves are also mentioned. Some compost was commercially available from the Liebig Manufacturing Company of East Hartford, according to Johnson.

The first important advances in the practice of composting were made about 40 years ago by Sir Albert Howard, a British agronomist stationed in India (3, 4, 5, 6). His improved and systematized process was named the Indore method after the state in central India where it was first formulated. The Indore process involves creating a layered pile about 5 feet high of garbage, night soil, animal manure, sewage sludge, straw and leaves. This pile is turned over twice and composting is completed in 3 months. Later, Howard demonstrated the usefulness of composting as a replacement for burning and dumping of sewage sludge and refuse (7, 8, 9). One visible outgrowth of Howard's efforts was the initiation of the organic gardening movement in 1942 by J. I. Rodale.

At the same time various methods were described and patented in Europe for mechanized composting of large quantities of refuse. One of the earliest was the Itano process of 1928 (10). Another was that developed by Dr. G. Beccari (11-16), while an improvement of the Beccari method was described by J. Bordas in 1931 (17). Other methods followed: the Frazer process, the Dano procedure, and the V. A. M. process (Vuil-Afvoer-Maatschappij) (18, 19, 20). The latter method is still in use in the Netherlands. The reader will find a brief description of these processes in Section VB. In 1953 an extensive investigation of composting procedures at the University of California at Berkeley resulted in a straightforward method for aerobic composting of municipal refuse (21).

Today there is renewed interest in composting as a means of solid waste disposal. One such project is the Johnson City, Tennessee plant operated jointly by the U. S. Public Health Service and the Tennessee Valley Authority (22, 23). This plant was designed to study the technology, economics, and market development of compost. Other plants recently in operation include those in Houston, Texas and Gainesville, Florida (24, 25).

The current interest in composting at this Station arose from two things. First, Connecticut was faced with the problem of disposing of increased amounts of waste on less and less land. Second, a group of scientists who work on agricultural problems recognized that the decomposition of organic matter or waste was a familiar problem to them. They knew about the rapid decomposition of organic matter in the soil from their years of experiments with increasing the concentration of this important organic component in the soil. Also, they were familiar with the biology, biochemistry, and methodology of the compost piles that farmers had been building for centuries.

Investigations of the possibilities of accelerating the composting process require an understanding of past compost research. This led to the review presented here, which covers published research to September, 1971. No attempt has been made to include composting in the soil (green manuring).

II. Biochemical and Microbiological Aspects of Composting

A. Biochemistry

1. Introduction

Before discussing the biochemical, and in the next section the microbiological aspects of composting, I will first describe the overall changes that occur. A heterogeneous collection of organic matter with its indigenous population of bacteria and fungi will start to decompose aerobically when moisture and oxygen concentrations are favorable. Microbial growth accelerates, utilizing some of the carbon, nitrogen, and other nutrient elements. As these life processes proceed, the temperature begins to rise above the initial stage (mesophilic) as heat is generated during the biological oxidation. Since organic matter acts as an insulator, much of this heat is conserved in the compost pile, and the resulting higher temperature leads to the thermophilic stage. As decomposition continues, the temperature begins to drop and finally returns to ambient, that of the surrounding atmosphere.

During these temperature changes several events occur within the pile of organic matter. The volume decreases considerably. The pH initially becomes acidic, then alkaline, and finally near neutral.

The chemical constituents are modified to various degrees, in the end resulting in a complex of organic material commonly known as humus. A short review on the characteristics of the composting process has appeared recently (26).

2. Temperature and Moisture

Initially, the composting mass is at ambient temperature, but a rapid rise occurs as the microorganisms multiply. When the temperature moves past 40° C (104° F), the mesophilic stage is replaced by the thermophilic stage. The time required to reach the thermophilic stage varies, but it frequently is achieved in 2 or 3 days (21, 27). The temperature stabilizes around 70° C (158° F) followed by a gradual cooling to ambient temperature. This temperature pattern has been observed by many investigators for typical garden compost as well as for municipal compost (28-32).

These temperatures are observed in the middle of the pile, and are characteristic of the large and small piles. However, there is considerable spacial temperature variation between the center and surface of large and small piles. In studies at Berkeley with municipal compost (21) in windrows approximately 7 feet wide and long, and 5 feet high, these characteristic temperatures were observed on all four sides midway between the top and bottom at a depth of 1 foot from the outside surface. In the same study, with smaller piles in bins 40 by 40 inches by 5 feet high, the temperature of the middle compared with that 2 inches below the surface varied no more than 10° C. Similar results were noted by Wiley (33). However, with still smaller piles of wheat straw compost in bins 40 by 40 by 40 inches, the difference in temperature between the middle and that 4 inches below the surface was 20° to 30° C, according to Chang and Hudson (31). The temperature gradient from the center outward lessens as the pile size increases. Since heat loss is proportional to surface area and heat generation is proportional to volume, the larger pile, having a smaller surface area to volume ratio loses relatively less heat.

In large compost piles, the temperature increases steadily with time to 70° C (158° F). In smaller piles there is usually a pause or leveling at 40° C while the transition from mesophilic to thermophilic microorganisms occurs (21). The Berkley studies (21) showed no effect on this temperature progression by changes in ambient temperature. In colder areas, winter temperatures may cause a slowing or even cessation of decomposition.

Decomposition of organic matter is fastest in the thermophilic stage (34). The optimal temperature, based on oxidation of organic matter into CO_2 and H_2O, has been found by Wiley (35) and Schulze (36) to be 60° C (140° F). Although studies by the U.S. Public Health Service showed a maximal temperature of 71° C (160° F) was optimal (37), more often it is found that temperature should not greatly exceed 70° C for any length of time, because a "thermal kill" of microorganisms will occur, resulting in a slowdown of decomposition (21, 38).

During turning and aeration (see Section IIA, 4), the interior temperature may drop 5° to 10° Centigrade. However, studies with municipal compost indicate that the pile returns to initial temperature within a few hours (21, 32, 33).

The moisture content of the pile is important in composting. At moisture contents below 40 percent (wet weight), organic matter will not decompose rapidly (21, 39). If the moisture content exceeds 60 percent, the process tends to become anaerobic (21). Since anaerobic compost decomposes more slowly and has a putrid odor, it is necessary to turn the pile or supply oxygen in order to restore aerobic decay (21). The optimal moisture content (wet weight) for composting is often observed to be 50 to 60 percent (21, 32, 36, 37, 40, 41, 42). When the compost is finished, however, the moisture content may be greatly reduced for easier handling (21).

3. Grinding

Grinding the materials to be composted speeds their decomposition by increasing their surface area and hence their susceptibility to microbial invasion (21, 40). Better initial aeration is also achieved due to increased availability of oxygen at particle surfaces. In addition, the material is more easily handled and moistened. Gray and Sherman (43) observed that grinding might double the amount of evolved CO_2 as compared to unground material. The greater part of the difference due to grinding was observed in the thermophilic temperature range (40° C to 60° C), while little difference was seen in the mesophilic stage.

4. Aeration and Gaseous Products

Oxygen is required by aerobic microorganisms during the decomposition process. For a mixed garbage-sewage sludge compost, Schulze (44) found that 5.0 to 9.0 cubic feet of air per pound of volatile matter per day was required. Kaibuchi found a requirement of 7.3 cubic feet of air per day per pound of volatile matter for municipal compost (41). Wiley and Pearce reported that 9 to 23 cubic feet of air was consumed per day per pound of volatile matter (37).

Windrows may be aerated by turning (outer edges mixed in with center of pile) or by thoroughly mixing by mechanical means. Ideally, the schedule of turning should be based on the oxygen concentration in the pile, although it is frequently based on temperature and moisture (21, 32). The oxygen concentration varies with depth according to Wiley and Spillane (33), who found that the percentage by volume of oxygen decreased from the surface to the interior of the pile. Immediately after grinding and turning the windrows, the oxygen concentration was as high as 18.6 percent at a 15 inch depth. Oxygen was usually as low as 1.0 to 2.0 percent at a 24 inch depth. For municipal compost in windrows, an oxygen content as low as 0.5 percent was observed in the interior of the pile without anaerobic symptoms (32). For rotating drum composters, operating at the thermophilic stage, Schulze suggested that a minimum of 5.0 percent oxygen be present in the effluent gases in order to insure aerobic conditions (44).

Inadequate aeration results in anaerobiosis which gives rise to very foul odors and a pale green color in the interior. If a pile does become anaerobic, it may be restored to its aerobic state by daily turning (21). Studies at the University of California indicated 5 turns in 2 weeks were sufficient for normal aerobic decomposition of municipal compost (21). Another study with municipal compost at Johnson City, Tennessee suggested that 8 to 14 turns in 5 weeks were enough (32).

During the biological oxidation processes, much of the organic matter is converted to carbon dioxide and water (45). At this time the odor of ammonia may be detected. This occurs when the carbon is unavailable which may happen, for example, when large amounts of newspaper are present, or when the C/N ratio is too low (section IIA, 5). If these conditions exist, some nitrogen is discharged to the air as ammonia instead of being utilized by the microorganisms for the synthesis of protein (21). Ammonia evolution may occur during the thermophilic stage, because the pH is slightly alkaline and the temperature favors volatilization.

5. Carbon:Nitrogen Ratio (C/N)

Probably the most important aspect of successful composting is the relationship between the C/N ratio (carbon dry wt./nitrogen dry wt.) and the rate of organic matter decomposition. Microorganisms require a carbon source for growth as well as a source of nitrogen for protein synthesis. Since microorganisms usually utilize 30 parts by weight of carbon for each part of nitrogen, a C/N ratio of 30 would seem most desirable for efficient composting (21, 46). The optimal value, as reported by many investigators, is in fact between 26 and 35 (21, 47, 48-52), providing for rapid and efficient composting. Ratios (C/N) below 26 result in the increasing loss of nitrogen as ammonia, and ratios above 35 lead to progressively longer times for composting.

Since the C/N ratio is so important, the nitrogen content and C/N ratios for materials which might commonly be composted are presented in Table I. The data were compiled from published analyses of many investigators (21, 32, 33, 53, 54-62).

Table I shows that the C/N ratio of municipal refuse varies greatly. The high C/N ratios are generally caused by the presence of paper: a change in the paper content from 16 to 21 percent can alter the C/N ratio from 40 to 55 (21), and higher paper contents may easily produce ratios of 80 (21). While composting can occur at these high ratios, the efficiency of the process is greatly diminished. The C/N ratio and hence the time required for composting can be lowered by adding a nitrogen source such as activated sewage sludge (Table I), as has been successfully demonstrated (21, 32, 33, 54). On smaller scale composting, as in a home garden, paper can be avoided and nitrogen content can be raised by a variety of materials (see Section VA, 4; Table VII).

TABLE I. NITROGEN CONTENT AND C /N RATIO OF VARIOUS MATERIALS USED IN MUNICIPAL COMPOST

Material	Nitrogen Percentage (Dry Weight)	C /N Ratio (Weight /Weight)
Garbage		
Washington, D. C.	2.70	--
Yonkers, N. Y.	2.50	--
Chicago, Ill.	1.24	--
Canton, Ohio	2.08	--
Raleigh, N. C.	1.92	15.4
Louisville, Kentucky	2.90	14.9
Total Raw Refuse (Residential - - includes garbage)		
Berkeley, Calif.	1.07	33.8
Savannah, Georgia	1.30	38.5
Johnson City, Tenn.	0.6	80
Raleigh, N. C.	--	51.5
Chandler, Ariz.	0.57	65.8
Garbage /Paper (fresh wt. ratio)		
5 /1	1.13	40.2
9 /1	1.25	34.6
Sewage Sludge (moisture free)		
Activated	5.60	6.3
Digested	1.88	15.7
Refuse /Sludge (fresh wt /sludge solids)		
Refuse	0.77	51.0
Sludge added (96 /4)	1.38	31.0
Fruit Wastes	1.52	34.8
Ground Bone (raw)	2.5-4.5	--
Wood (pine)	0.07	723
Meat Scraps	5.08	--
Fish Scraps	6.50	--
Paper	0.25	173
Grass Clippings	2.15	20.1
Grass Clippings /Garden Weeds	2.03	19.3
Leaves (freshly fallen)	0.5-1.0	40-80

6. Changes in Composition and pH During Composting

Various compostable materials typically have the composition shown in Table II, as compiled from many investigations (21, 26, 33, 53, 55, 57, 58, 62-66). During the process of decomposition, these substances are alttered to varying degrees. Degradative changes described by several researchers are summarized in Table III (32, 33, 65, 67-71). During the decomposition processes, microorganisms rapidly utilize the available sugar and starch. The large losses observed in water soluble materials result from the changes in the sugars and starches present in such extracts Lipids also undergo major decomposition, cellulose and hemicelluloses show intermediate decomposition, and lignin is perhaps the most resistant toward degradation. Decreases in total dry weight range from 26 to 60 percent (Table III), while the volume may decrease by as much as two-thirds. At first glance (Table III) the loss of total nitrogen and the gain in protein appear contradictory. However, the increase in the protein fraction coincides with a decrease of the soluble nitrogen fraction (Section IIA, 7). These patterns are generally observed for both municipal and small scale composting.

TABLE II. COMPOSITION OF VARIOUS MATERIALS USABLE FOR COMPOSTING

Component	Total Municipal Refuse[1]	Garbage[2]	Plant Material	Sewage Sludge (activated)
	Percent (Dry Weight)			
Moisture[3]	21-50	60-70	--	4.2[7]
Volatile Matter[4]	70-90	85-90	--	--
Protein	2-8	12-18	5-40	37.0
Lipids	5-10	9-15	5-15	4.7
Total Sugar	5	--	--	--
Total Carbohydrate	--	32	--	--
Cellulose[5]	35-55	10	15-60	2.6
Starch	2-8	--	--	--
Lignin	3-5	--	5-30	6.9
Water Soluble[6]	--	--	5-30	1.8-2.8
Phosphorus	0.4-0.7	0.5-0.6	0.05-1.5	2.5
Potassium	0.7-1.7	0.7-1.8	0.3-6.0	0.4
Crude Fiber	35-40	4-18	--	--

[1] Includes garbage, paper, household and yard trash.
[2] Food Wastes.
[3] Percent of total wet weight.
[4] Ash-free basis.
[5] Includes hemicellulose.
[6] Includes sugar, starch, amino acids, aliphatic acids, and some salts.
[7] Dewatered activated sludge.

During the decomposition process, changes in pH also occur. In compost windrows, the initial pH is usually slightly acid (pH 6) as is the cell sap of most plant material. During the early stages of decomposition, the production of organic acids causes a further acidification (pH 4.5-5.0). As the temperature rises, the pH also increases, and levels off at a slightly alkaline (pH 7.5-8.5) value (21, 26, 32).

TABLE III. COMPOSITIONAL CHANGES AFTER AEROBIC COMPOSTING

Type of Compost	Age of Compost	Total Weight	Crude Fiber	Volatile Solids	Carbon	Nitrogen	Lipids	Total Sugar	Starch	Protein	Cellulose and Hemicellulose	Lignin	Furfural	H_2O[5] Soluble	Ethanol[6] Soluble
		Percent (dry wt.) Loss (-) or Gain (+) From Original Values													
Municipal Refuse 1,2 (Outdoors)	7 weeks	–	–	–15	–15	+23	–	–	–100	–	–60	–	–	–	–
Municipal Refuse 1,3 (Outdoors)	34 days	–26	–37	–39	–37	–16	–76	–	–	–16	–	–	–	–	–
Municipal Refuse 1,4 (Laboratory Conditions)	8.8 days	–28	–7.1	–32	–31	– 2	–77	–100	– 89	– 2	–	–	–	–	–
Wheat Straw	60 days	–51	–	–	–	–21	–	–	–	–	–63	+5	–	–	–39
Oat Straw	110 days	–56	–	–	–	–24	–86	–	–	+197	–80	–14	–	–74	–
Rye Straw	290 days	–52	–	–	–	–	–88	–	–	+372	–78	–6	–	–27	–
Green Plants (Sorghum)	210 days	–51	–63	–	–	–16	–76	–	–	–	–	–24	–	–81	–
Corn Stalks	70 days	–51	–	–	–	–15	–91	–	–	+147	–84	+7	–	–83	–
Leaves-Hay	250 days	–62	–	–	–	–38	–73	–	–	– 32	–82	–55	–	–81	–
City Wastes (India)	240 days	–31	–	–	–	–	–73	–	–	– 39	–49	–30	–56	–	–

[1] Includes garbage, household and yard trash.
[2] Johnson City, Tennessee.
[3] Chandler, Arizona.
[4] Savannah, Georgia.
[5] Contains sugar, starch, amino and aliphatic acids, some salts.
[6] Contains some sugar, glucosides, and oil.

B. Microbiology

1. Introduction

During aerobic composting there is a continual change in the microfloral population. A typical pattern, as described by Chang and Hudson (31) and Golueke (92), follows. Initially fungi and acid producing bacteria appear during the mesophilic stage (Section IIA, 2). As the temperature increases above 40° C, these are replaced by thermophilic bacteria, actinomycetes, and thermophilic fungi. At temperatures above 70° C these are followed by spore-forming bacteria. Finally, as the temperature falls, the mesophilic bacteria and fungi appear again. Some examples of mesophilic and thermophilic bacteria, fungi, and actinomycetes isolated from compost are listed in Table IV (30, 31, 38, 40, 63, 92-100). The population densities of these microorganisms as a function of temperature are summarized in Table V (28, 31).

TABLE IV. BACTERIA, ACTINOMYCETES, AND FUNGI ISOLATED FROM COMPOST

Bacteria

Mesophilic

Cellumonas folia
Chondrococcus exiguus
Myxococcus virescens
M. fulvus
Thiobacillus thiooxidans
T. denitrificans

Thermophilic

Bacillus stearothermophilis

Actinomycetes[1]

Thermotolerant and Thermophilic

Micromonospora vulgaris
Nocardia brasiliensis
Pseudonocardia thermophila
Streptomyces rectus
S. thermofuscus
S. thermophilus
S. thermoviolaceus
S. thermovulgaris
S. violaceoruber
Thermoactinomyces vulgaris
Thermomonospora curvata
T. fusca
T. glaucus
Thermopolyspora polyspora

Fungi

Mesophilic

Fusarium culmorum
Stysanus stemonitis
Coprinus cinereus
C. megacephalus
C. lagopus
Clitopilus pinsitus
Aspergillus niger
A. terreus
Geotrichum candidum
Rhizopus nigricans
Trichoderma viride
T. (lignorum) harzianum[2]
Oospora variabilis
Mucor spinescens[3]
M. abundans[3]
M. variens[3]
Cephalosporium acremonium[3]
Chaetomium globosum[3]

Thermotolerant and Thermophilic

Aspergillus fumigatus
Humicola insolens
H. griseus var. *thermoideus*
H. lanuginosa
(Thermomyces lanuginosus)
Mucor pusillus
Chaetomium thermophile
Absidia ramosa
Talaromyces (Penicillium) duponti
Sporotrichum thermophile
S. chlorinum
C. t. 6 (Mycelia sterilia)
Stilbella thermophila
Malbranchea pulchella var. *sulfurea*
(Thermoidium sulfureum)
Thermoascus aurantiacus
Byssochlamys sp.
Torula thermophila

[1] Treated separately because of their common occurence in compost.
[2] Rafaai aggregate (ref. 100).
[3] Probably mesophilic, but not definite with available data.

2. Bacteria and Actinomycetes

Bacteria and actinomycetes play an important role in composting; however, much remains to be learned about them. For example, no detailed studies on the successional changes in bacteriological populations during composting appear to have been carried out.

Initially, large numbers of aerobic mesophilic bacteria are present (Table V). These multiply at first, but the increased biological activity causes an elevation in temperature, thereby decreasing the number of mesophilic bacteria. A minimal value is reached, according to Webley (28) and Chang and Hudson (31), during the 55°-65°C (131-149°F) range with compost of grass clippings or straw. These authors found an increase in mesophilic bacterial numbers, as the temperature drops below 40-50° C (104-122° F). The population of the thermophilic bacteria follows an inverse pattern, increasing to a maximum during the thermophilic stage (40°-70° C), then gradually decreasing as the temperature drops (31).

The role of mesophilic bacteria in composting is not clearly defined. The mesophilic stage is short; the primary role of mesophilic bacteria may be to raise the environmental temperature for the thermophilic microorganisms that follow. During the limited time that they flourish, they utilize the most readily accessible carbohydrates and decomposable proteins (26). Their activity produces heat, and since the compost pile has insulating qualities, the temperature rises and thermophiles begin to predominate.

TABLE V. MICROFLORAL POPULATION DURING AEROBIC COMPOSTING[1]

Numbers per gram wet compost at each temperature phase

Ambient ⟶ 40° C ⟶ 70° C ⟶ Ambient

	Mesophilic (M)	Thermophilic (T)	Cooling
Bacteria			
(M)	10^8	10^6	10^{11}
(T)	10^4	10^9	10^7
Actinomycetes			
(T)	10^4	10^8	10^5
Fungi			
(M)	10^6	0	10^5
(T)	10^3	10^7	10^6

[1] Data from Webley (28), Chang and Hudson (31), using compost prepared from grass clippings and also straw.

Thermophilic bacteria, as determined by Forsyth and Webley (101), initially decompose the protein and non-cellulose carbohydrate components in compost. These bacteria will also attack the lipid and hemicellulose fractions, but cellulose and lignin appear to resist their activity.

Investigations of thermophilic actinomycetes likewise have been very limited. Waksman and Cordon (102) concluded that actinomycetes attack hemicellulose but not cellulose. However, Stutzenberger (103) has recently isolated a celluolytic thermophilic actinomycete (*Thermomonospora* *curvata*) which he suggests may be important in cellulose decomposition. *T. curvata* was claimed to be the most frequently isolated actinomycete in municipal or mushroom compost (97, 103).

Thermophilic actinomycetes can grow at higher temperatures than thermophilic fungi, hence the actinomycetes become abundant or dominant at the highest temperature phase of composting (31, 92, 93, 97). Chang and Hudson (31) showed that over the range 42°-72° C (107°-162°F) the initial actinomycete population multiplied 500-fold compared to a 5-fold increase for thermophilic bacteria in wheat straw compost.

3. Fungi

Mesophilic fungi compete only for a short time as the compost heats up. According to Chang and Hudson (31) they are usually saprophytic sugar fungi. These organisms exhaust the simple carbon substrates and are quickly replaced by thermophilic fungi. However, as the pile cools again below 40°C (104°F), they reappear in large numbers (Table V). Evidently, they persist in the outer layers of the pile during the thermophilic stage and reinvade when the temperature drops sufficiently. These later mesophiles, according to Chang (67) can utilize cellulose and hemicellulose, but not as well as the thermophilic fungi.

Thermophilic fungi occur in the 40° to 60°C range, but die when the temperature reaches 60°C. However, like the mesophilic fungi they survive in the peripheral area of the pile and reinvade when the temperature declines. They decompose hemicellulose and cellulose and in pure cultures can affect up to 50 percent of the cellulose. They are therefore important in the decomposition of compost (30, 67, 102, 104). The most frequently encountered thermophilic fungi in wheat straw compost and in horse manure-straw compost were *Humicola griseus* var. *thermoideus, H. insolens, H. lanuginosa,* and *Chaetomium thermophile* (31, 97). They grow well in these composts because of their ability to utilize complex carbon sources (cellulose) and to thrive at high temperatures (31). *H. lanuginosa* is a special case, because it does not utilize cellulose, but nevertheless thrives. This is attributed by Chang (67) to the fact that it is a secondary sugar fungus, i. e., it uses sugars produced by the cellulases of other fungi.

The only detailed work to date on the successional changes in microfloral populations during composting is that by Chang and Hudson (31). They were concerned only with the fungal populations in wheat straw compost prepared in bins. They divided the fungi into three groups. Group one contained the mesophilic forms present on initial compost material such as *Cladosporium herbarum, Alternaria tenuis, Aureobasidium pullulans, Aspergillus repens, A. amstelodami, A. versicolor, A. candidus, A. nidulans, Penicillium* sp., and also the thermophilic *Mucor pusillus,* as well as the thermotolerant *Absidia ramosa* and *Aspergillus flavus.* Group two, isolated after 2 days, contained only thermophilic fungi such as *Humicola insolens, H. lanuginosa, Chaetomium thermophile, Malbranchea pulchella* var. *sulfurea,* and *Talaromyces duponti.* The final group in the sequence consisted of the thermophiles *Sporotrichum thermophile,* and a *Mycelia sterilia* which they designated C. t. 6 and the following mesophiles: *Fusarium culmorum, Stysanus stemonitis, Coprinus cinereus, C. megacephalus,* and *Clitopilus pinsitus.*

Waksman *et al.* (105) and later Chang (67) showed that the majority of the compost decomposition took place in the thermophilic phase. Whether thermophilic bacteria, actinomycetes, or fungi cause most of the decomposition remains to be answered. In Chang's pure culture studies *Chaetomium thermophile* caused a 40 percent breakdown of the total weight of wheat straw in 3 weeks at 45°C (67). Most of the material broken down was hemicellulose or cellulose. Waksman *et al.* (105) reached similar conclusions earlier. He indicated a mixed population of microflora was best, but thermophilic fungi were most active in decomposing stable manure compost. However, Stutzenberger (103) indicated that a thermophilic actinomycete, *Thermomonospora curvata,* was a major cellulose decomposer of municipal compost. One must view these pure culture studies with reservations since it is difficult to determine the contribution of individual species of fungi or bacteria in natural mixed populations because of competition and antagonism.

4. Inocula and Other Additions to Compost

The question of whether additives are necessary for the most efficient production of compost has long been a controversial one. These additions usually consist of chemicals, bacteria, and fungi, either alone or in various combinations. Success with additives has been claimed by some investigators (106-110), while negative results were obtained by another large group of workers (21, 55, 92, 111-114).

From the negative evidence gathered by most researchers, additives do not appear justified at present, except in a few special instances. If the C/N ratio is too high, adding a nitrogen source can speed up the composting process by lowering the C/N ratio (Section IIA, 5). This could account for the apparent success of some additives. Additives may also be beneficial in a compost pile low in indigenous organisms. Although this seldom occurs, it has been observed in composting sawdust. Here, inoculation with spores of the fungus *Coprinus ephemerus* (a cellulose decomposer) and addition of ammonia (NH_3), phosphate (H_3PO_4), and potassium sulphate (K_2SO_4) decreased the composting time from 1 or 2 years to 3 months, and produced a compost that does not rob nitrogen from soil as does fresh sawdust. (106, 107).

5. Pathogens and Parasites

Animal and human pathogens may be present initially in compost, especially when sewage sludge is added. For a listing of these various pathogens in compost and sewage sludge, the reader is referred to a recent survey by Krige (115).

The Connecticut State Department of Health has the following guidelines for the use of sewage sludge: Raw or activated sewage sludge should not be used for garden composting because pathogens or parasites may be present. Activated sewage sludge may be used in municipal composting, but only under carefully controlled test procedures. Dried digested sewage sludge may be used in garden composting. This compost may be utilized in the garden for above ground crops or for root crops cooked prior to eating. If root crops are to be eaten raw, the sludge-compost should be applied to the soil in the fall and dug in immediately, or the following spring before the crop is planted. No additional applications of sludge-compost should be made during the growing season of the root crop.

Various studies on the survival of pathogens and parasites during composting have been conducted. Gotaas (40) recommended a temperature of 60°C (140°F) for "thermal kill" of the common pathogenic microorganisms. Knoll (116, 117, 118) found that a temperature of 65° C (149°F) for one day ensured destruction of Salmonella species. Strauch (119) found destruction of *S. enteriditis, Erysipelothrix rhusiopathiae,* and the psittacosis virus under similar conditions. However, he found *Bacillus anthracis* destroyed under more rigorous conditions, i. e., temperature over 55° C for 3 weeks or longer and 40 percent or higher moisture.

Elevated temperatures may not be the only means whereby pathogens are destroyed in composting. Knoll (117, 118) concluded that some are killed by the antagonistic effects of other microorganisms found in compost. He compared cultures of *S. paratyphi B and S. cairo* incubated at 50° C and 50 percent moisture with duplicates added to compost under the same conditions. Those in the compost died in 7 days, those in the incubator in 17 days. An aqueous extract of compost, added to a medium containing these microorganisms killed them in 10 days, whereas those in the control medium survived beyond 4 weeks; this suggested an antagonistic effect from compost microorganisms.

Other studies on the destruction of parasites and pathogens during composting are as follows. Scott (120) and Scharff (121) found that resistant forms of parasites, such as *Ascaris eggs,* cysts of *Endamoeba histolytica.* and hookworm eggs were destroyed in compost windrows after 3 weeks. Fly larvae were also destroyed during the windrow composting process (21, 33). Composting (49° C or higher) appeared to destroy the agents (*Th. basicola, Rhizoctonia* sp., and Tobacco mosaic virus) causing the main tobacco seedling diseases (122). For a thorough review on pathogen survival during composting of municipal wastes, the reader may consult a review by Wiley (123).

Because of the nature of some wastes used for composting, the above pathogens and parasites could be present. The health hazard posed by these organisms is normally reduced by composting, if the minimal time-temperature conditions prevail. This requirement for windrow composting is apparently 18 to 21 days at temperatures above 55°C. Some pathogenic fungi may survive these conditions, but this point remains to be clarified (61).

C. Present Compost Research at the Station

1. Cellulose Degradation

Cellulose in the form of paper and paper products constitutes about 50 percent of typical East Coast municipal refuse (124). This large amount of paper produces an unfavorably high C/N ratio (Section II A, 5), which must be lowered for more efficient composting. Even under ideal conditions, 40 percent of the cellulose in municipal compost is extremely resistant to microbial attack even after 8 weeks (63). A recent review of cellulose decomposition in refuse by Regan and Jeris (104) concludes that it is probably the most serious rate-limiting step in the path of successful composting.

Many of the thermophilic microorganisms figure prominently in the degradation of cellulose (Section IIB, 2, 3). The more active of these cellulolytic fungi include *Trichoderma* sp. (especially *T. viride*), *Humicola* sp. (particularly *H. grisea and H. insolens*), *Chaetomium thermophile, Aspergillus fumigatus,* and *Thermomonospora curvata* (67, 103, 104, 125).

One factor that may limit cellulolytic action with these fungi is catabolite repression, i. e., the end product of cellulose degradation (glucose) caused by microbial enzyme (cellulase) inhibits the production of that enzyme by the microorganism. Indeed a recent report by Hulme and Stranks (126) suggests that fungal cellulases are subject to catabolite repression by glucose. Another limiting factor may be the association of cellulose with a protective substance such as lignin (63). The lignin content in paper may be as high as 12 percent (127) and lignin is very resistant to attack by microorganisms (Section IIA, 6).

Research on means to accelerate the decomposition of cellulose by bacterial, fungal, or enzymatic attack is presently being conducted by Dr. P. R. Day, Dr. L. Hankin, Dr. D. Sands, and myself at this Station. We (128) have developed an assay for screening large numbers of fungi for cellulolytic activity. Fungi are grown in a liquid culture containing a paper substrate as the sole carbon source. The paper has a blue dye covalently attached through the hydroxyl groups on the cellulose. The hydrolytic action of the fungal cellulase releases this dye which is then determined spectrophotometrically. This assay was used to determine the differences in cellulolytic activity among several strains of *Trichoderma viride*. The results were similar to those obtained by the laborious reducing-sugar assay, which depends upon the determination of glucose released by cellulase from a cellulose substrate. This dye release assay is an important tool in our search for microorganisms possessing high cellulolytic activity.

Another approach is to isolate induced mutants of cellulolytic fungi that would be more potent producers of cellulase because they are not catabolite repressed. A mutant *Trichoderma viride* QM 9123, obtained by

Mandels *et al.* (129) produces twice as much cellulase as its parent. *T. viride* QM 6a. However, the presence of glucose still causes repression. Our screening assay will be helpful in our search for useful cellulolytic mutants. A third approach is the investigation of fungi producing both ligninase and cellulase (white rotter and black rotter of wood) which could be useful in breaking down the cellulose protectively encapsulated with lignin.

2. Garbage Degradation

Typical municipal refuse contains 12 percent garbage (62, 124). Success in the acceleration of garbage decomposition has been achieved at this Station by Hankin and Zucker (130). Using pectate lyase, an enzyme which breaks down the pectin "glues" of plant tissues, they reported 72 percent liquifaction of common household garbage in 24 hours. The liquified garbage is easily handled and several uses for it are suggested or are being tried by the authors.

Field tests conducted by Stephens, Hankin, and Zucker (131) showed that 1 inch of liquid garbage (made from common household vegetable wastes) applied to an acre (146,000 pounds of garbage) supplied on the average 300 pounds of nitrogen (50 pounds of which were available immediately as nitrates and some ammonia), 3 pounds of phosphorus, 19 pounds of potassium, and 8 pounds of calcium.

When applied as a mulch, it was found to give improved yields in field trials with corn and beans over those of the control plots. The controls had an amount of nitrogen fertilizer equivalent to that initially available from the liquid garbage. This increased yield was attributed to the usual effects of a mulch, weed control and water conservation, and the additional nitrogen released over the growing season. It proved to be an effective mulch, as weeds were reduced in weight by 90 percent or more at an application of 2 inches per acre. Preliminary tests on forests showed no visible harmful effects with even 3 inches per acre. Some leaf greening was observed later in the season. Other future tests include the possibility of using pectate lyase to accelerate the decomposition of garbage in compost piles.

III. Chemical Analysis of Raw and Finished Compost

A. Chemical Analyses of Compost

Some very detailed analyses of municipal compost have been conducted in Europe, and particularly in the Netherlands (29, 91, 132, 133, 134). These studies include discussions and methods for sampling and analyzing for humus, coal, nitrogen, potassium, phosphorus, organic matter moisture, calcium, magnesium, copper, manganese, cobalt, boron, molybdenum, zinc, and chromium. These studies were carried out to evaluate the use of municipal compost in agriculture. Conclusions concerning the nutrient content (Table VI) and the value of compost as a fertilizer or soil conditioner will be discussed in Section IV.

TABLE VI. NUTRIENT CONTENT OF COMPOST

Type of Compost	Percent (Dry Weight) of Finished Compost		
	Nitrogen (N)	Phosphorus (P)	Potassium (K)
Municipal[1]	0.4–1.6	0.1–0.4	0.2–0.6
Garbage[2]	0.4–4.0	0.2–1.3	0.2–2.1
Garden	1.4–3.5	0.3–1.0	0.4–2.0

[1] Includes garbage, paper, household and yard trash.

[2] Food wastes.

For other analyses of compost, the reader is referred to a recent publication on analysis of refuse and compost (135). This contains the following: Initial sampling techniques, tests for moisture (oven drying, infrared, and toluene distillation methods), volatile solids and ash, lipids, crude fiber, sugars, starch (anthrone-sulfuric acid and direct acid hydrolysis methods), carbon, nitrogen (organic, ammonical, and Kjeldahl-Wilfarth-Gunning methods), protein, carbon-nitrogen ratio, phosphorus, potassium, pH, gross and net caloric value, sulfur, and hydrogen. Many of these testing procedures were developed or adapted for use by the Technical Development Laboratory Communicable Disease Center of the United States Public Health Service in Savannah, Georgia.

Carnes and Lossin (136) recently presented an excellent survey on the problems of determining the pH of compost as well as a procedure for measuring pH which compensates for these difficulties. According to them, the presence of complex buffer systems in compost can cause the pH to vary by as much as one unit when different amounts of water are used. They concluded that reproducible measurements are obtained at high dilutions (10 grams per 500 ml water). This difficulty in measuring compost pH is similar to that encountered in measuring the pH of soil suspensions. There the problem has been attributed to the junction effect at the calomel electrode.

B. Evaluation of Finished Compost

Many discussions are found in the literature (21, 65, 91, 137-140) on methods of determining when compost is finished (Compost is normally ready for agricultural purposes at a C/N ratio of 10 to 12, Section IIA, 8). From these studies it appears that no one method is adequate to determine when composting is finished. A discussion of the merits and shortcomings of the various procedures follows.

Physical factors have been used to determine when compost is finished. These include earthy odor, dark color, fluffy structure, low specific gravity, and a drop in temperature. Conclusions based solely on these factors can be erroneous. For example, a drop in temperature could also indicate the development of environmental conditions unfavorable to aerobic microbes such as excess heat, insufficient oxygen, or insufficient moisture. A drop in temperature, therefore, is a reliable indicator only if the compost does not heat up after being turned and moistened.

Chemical tests such as determination of the C/N ratio give a more obvious indication of when compost is finished. If a C/N ratio of 10 to 12 is found, the compost is finished. However, a higher ratio does not necessarily mean it is not, for the carbon could simply be unavailable cellulose from paper. Analyses of cellulose would be useful because unavailable carbon would be indicated if the cellulose content remains unchanged over a period of time. Two analytical procedures for determination of cellulose in compost have been presented recently by Lossin (141); one, an anthrone colorimetric method and the other, a gravimetric procedure. The latter is recommended by Lossin as easier and more rapid.

One shortcoming with the C/N ratio is that the carbon analysis involves the determination of carbon dioxide in a carbon combustion apparatus. One simple analysis (51) tested at Berkeley (21) involves only an ash determination, and the percentage of carbon is estimated by the equation, $\frac{100 - \% \text{ ash}}{1.8}$. This equation is based on the assumption that the dry weight percentage of organic carbon averages 56 percent ($\frac{100}{1.8} = 56$). This method agreed with the more quantitative method within 2 to 10 percent. Other recent methods for determining compost carbon have been developed by Springer and Klee (142) and also Torok and Csonkareti (143). These are colorimetric and titrimetric procedures involving wet combustion with acid-dichromate.

Relying only upon the amounts of ammonium and nitrate nitrogen without considering the C/N ratio can also lead to erroneous conclusions. Since nitrate does not necessarily appear directly after the cessation of ammonia (Section IIA, 7) production, the compost could be usable before nitrate appears, but only a measurement of the C/N ratio could establish this.

The determination of starch, which has been completely utilized by the time composting is finished, is a simple qualitative test with an iodine reagent as described by Lossin (65). However, this determination must be used in conjunction with others at later stages, because starch disappers early in the process.

Biological tests involving oxygen consumption and carbon dioxide evolution, microorganism counts, and plant growth tests are also useful indicators and serve as complementary tests to physical and chemical methods. Since unfinished compost will continue its decomposition by utilizing soil nitrogen, which might lead to nitrogen deficiency, it is conservative to perform several tests, such as one chemical and one biological test, before assuming the compost is a finished product.

IV. Soil Improvement and Economic Considerations

A. Soil Conditioning

The application of compost to soil serves a double purpose, as it is both a soil conditioner and a fertilizer. The former property is probably the more important of the two, since compost improves the aeration and water-holding capacity of the soil (21, 144), while its fertilizer value is limited.

Many have investigated the role of organic matter in soil. Quastel and Webley examined the effect of adding various organic substances, including compost, to the soil (145). Using a manometric apparatus to investigate the availability of soil oxygen to microorganisms, they found that the addition of organic matter increased the available oxygen and water-holding capacity of the soil. They observed increases of approximately 100 percent in water-holding capacity when they added 1.0 percent of straw to soil. Straw composts were more effective than composts of household refuse and sewage sludge, but were not as effective as uncomposted straw. Downs *et al.* (146) found an increase in water-holding capacity of soils receiving organic matter from green manure on a rotational basis. Studies by the Tennessee Valley Authority and the Public Health Service also concluded that municipal compost added to soil improves aeration and water-holding capacity (147). Banse, using 50 to 400 tons of compost per hectare in vinyards, noted an increase in moisture retention, pore volume, and aeration of the root areas (148). A 10-year field study, cited by Trinel (149), showed an improvement in humus content, hygroscopic moisture, water-retention capacity, and absorption capacity when organic matter was added to the soil. Springer (150), in an excellent discussion, points out that these improvements are primarily the result of alteration of the physical properties of the soil, in that compost improves soil structure and increases pore volume.

B. Fertilization and Trace Elements

Composts have a low content of the elements N-P-K; the dry weight percentages of nitrogen (N), phosphorus (P), and potassium (K) are at most 4.0-1.3-2.1 (Table VI, (21), (29), (33), (55), (114)). Since most of the nitrogen and some of the phosphorus are in organic form, the nutrients are released gradually. This lessens the possibility of leaching and extends the availability of nutrients over the growing season. Because of its low nutrient content, compost is more effective when it is amended with mineral fertilizers (21, 144, 151, 152-155).

Several essential and non-essential trace elements are found in municipal compost. Composts prepared by the Beccari, Vuil-Afvoer-Maatschappij, and Dano processes (Section VB) were found to have the following dry-weight percentages of trace elements (133); magnesium (Mg) : 0.06-0.18, copper (Cu) : 0.04-0.06, manganese (Mn) : 0.002-0.01 cobalt (Co): 0.005-0.007, boron (B): 0.001-0.005, molybdenum (Mo): 0.002-0.003, zinc (Zn): 0.001-0.003, and chromium (Cr): 0.003. Plant damage from these metals can result under certain soil conditions. Garden compost would not likely create such a problem, but municipal compost could, especially if sewage sludge were added. Analyses and field tests would be required to determine whether the metals would be toxic to plants (56).

C. Economic Considerations

Compost, compared to other fertilizers of similar nutrient value, has increased yields as much as 10 percent (146, 147, 151, 152, 153, 156, 157, 158). However, these yield increases were probably insufficient to pay the costs of application (147). Moreover, increases in yield are highly variable, as certain soils benefit more from compost than others. Kortleven (152) found the yield increased when compost was used on light sandy soils. Inamatsu (157) found yield increases with soil that was rich in humus, had a high C/N ratio and low nitrifying activity. Nagata and Muramatsu (158) found decreases with sand dune soils with 1:1 type clays (kaolinates), but increases for soils with 2:1 type clays (illites and bentonites).

Compost is used successfully in hotbeds, greenhouses, bulb production, and on park land. Fully 75 percent of the compost sold in the Netherlands was so used (159). Other potential uses for special problems are suggested by recent research. Hart cites a use in viniculture, where 60 tons of compost per hectare were applied as a mulch on slopes, causing a 25-fold reduction in erosion (159). Another useful application was reported from Germany, where 90,720 kg. of compost per hectare helped establish vegetation (159).

Markets for compost are presently found among bulb growers, nursery operators, and gardeners, but not among many commercial farmers. Since chemical fertilizers are cheaper to buy and to apply than compost, thus limiting markets, composting as a means of solid waste disposal may well be decided by the economics of waste management rather than by demands of agriculture (61, 160). In addition, the recycling of plant nutrients, rather than allowing them to be lost to waterways from dumps, is a consideration. Also, phosphate reserves are limited and may well be exhausted eventually.

One municipal venture, which appears to have been decided by the economics of waste management, is operating successfully in Scarsdale, New York (161, 162). There, leaves are composted on a 4-acre site. Windrows initially contain 30,000 cubic yards of leaves, which are reduced to 6,000 cubic yards when the compost is finished. The composting operation in Scarsdale results in an annual savings, largely because the trucking costs to the village composting site are less than to a more distant landfill.

V. Summary of Composting Methods

A. Compost in the Home Garden

1. Introduction

Basically there are two methods for preparing garden compost, the traditional Indore method that requires 3 months, and the faster Berkeley or "Two Week" method.

2. Indore Process

Many refinements and changes have occured in the traditional Indore process since it was first established (3, 4, 5, 6, 55, 144, 163, 164, 165, 166, 167, 168). All these variations have been examined and will be summarized here.

The basic Indore pile is built about 7 feet wide at the base, 5 feet high, and 7 feet or longer in length. The sides are tapered so that the top is about 2 feet narrower in length and width than the base. If it is located on level, well-drained ground it will not so likely become soggy, and if it is located in a southern exposure it will be warmer. Protection from the wind slows drying, but a nearby water supply is convenient for wetting. A container is sometimes built around the pile to conceal it and protect it from the wind. This may be chicken-wire fencing, cinder blocks, an open-ended box, or slat fencing; a loose-fitting container facilitates aeration (Section IIA, 4).

Indore compost is started at almost any time, but the fall is favorable because many materials, such as leaves and garden wastes, are readily available. Compost started in the fall is completed in the early spring, even though decomposition slows over winter, and it can then be applied to the garden prior to spring planting.

Many materials may be incorporated into the pile. They consist primarily of two classes, carbonaceous and nitrogenous, and both are needed for decomposition to occur as described in Section IIA, 5. Carbonaceous materials include leaves, hay, straw, sawdust, wood chips, shredded or torn newspaper (no more than 10 percent), and cornstalks (chopped). Nitrogenous materials may be green grass clippings, green weeds, fresh plant residues from the garden, garbage, manures (fresh or dry), digested sewage sludge, or to a much lesser degree, soil.

Often the foundation consists of a 6-inch layer of brush (hedge, shrub or light tree cuttings) to facilitate aeration of the heap (see figure 1). This is usually covered with a 1-foot thickness of a mixture of carbonaceous and nitrogenous materials. Unshredded leaves are usually mixed with other materials, so they are less likely to cause slower or even anaerobic decomposition by matting when wet. This and subsequent mixed carbonaceous-nitrogenous layers are roughly composed of three-fourths (by volume) carbonaceous wastes and one-fourth nitrogenous materials; this balanced ratio is necessary for efficient decomposition. Layers are normally wetted so that they feel damp but not soggy. To ensure effective decomposition the carbonaceous-nitrogenous mixed layer is generally covered with an additional nitrogenous source such as 2 inches of manure (fresh or dry), sewage sludge (see Section IIB, 5 for the Connecticut Department of Health guidelines on using digested sewage sludge), or a sprinkling of blood, bone, or cottonseed meal. About 1 inch of soil is commonly sprinkled over this and moistened. Subsequent additions of mixed carbonaceous and nitrogenous materials are frequently reduced to 6-inch layers, followed by manure, soil, and wetting, and this pattern is normally repeated until the pile is 5 feet high. A depression is ordinarily pushed into the top surface to catch rainwater, and the pile is covered with soil, hay, or burlap to retain heat. Moisture at all times aids microbial activity. Thoroughly mixing the pile at 6- and 12-week intervals aids decomposition. The composting process is usually completed in 3 months if started in the spring or early summer, or in the following spring if started in late summer or fall.

There are a few variations. Layering is the usual way of assuring that the proper proportions of materials are incorporated into the pile. If materials are limited, layers of mixed carbonaceous-nitrogenous wastes and manure can be added in sections as they become available. However, all of the materials may be mixed together in the pile if one is careful to maintain the proper proportions. Shredding speeds the composting rate considerably (Section IIA, 3). The home gardener may shred most material by running over it several times with a rotary mower. If unshredded material is used, some materials, such as newspaper or wood chips will decompose slowly, and an additional amount of a high nitrogen source such as blood meal or cottonseed meal may be necessary.

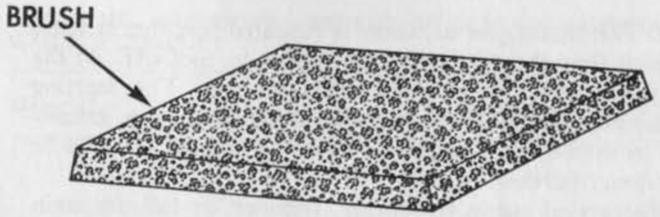
3. Berkeley or "Two Week" Method

Slowness is the disadvantage of the Indore process. The Berkeley method (21, 55, 169) can produce compost in 2 weeks; however, it requires several turnings on a fairly rigid schedule.

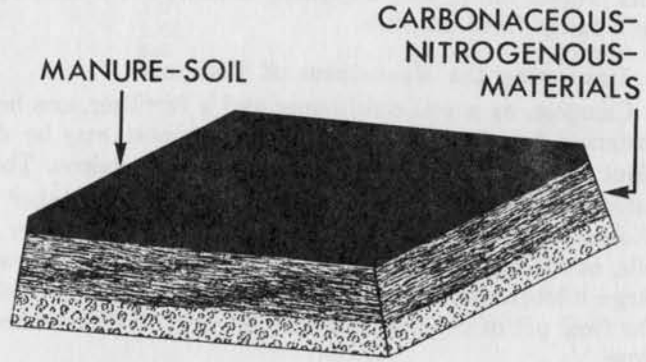
Again a mixture of wastes in a ratio of 2 or 3 parts carbonaceous materials to 1 part nitrogenous materials is used, although the mixture should not contain more than 10 percent of paper. A typical mixture is leaves, grass clippings, and dry manure, since leaves can be stored from the fall, grass clippings are readily available during the growing season, and dry manure can be purchased. The rapidity of the Berkeley method requires that these mixed materials be shredded with a mechanical shedder or by making several passes over small piles with a rotary mower. The material is composted in heaps about 5 feet high by 8 feet by 4 feet which are kept moist for 2 weeks.

By the second or third day, the pile usually heats up. If not, the C/N ratio is probably too high for decomposition. It can be lowered by mixing a high nitrogen source such as blood meal into the pile. The heap should be turned with a spading or pitch fork on the fourth day so that it

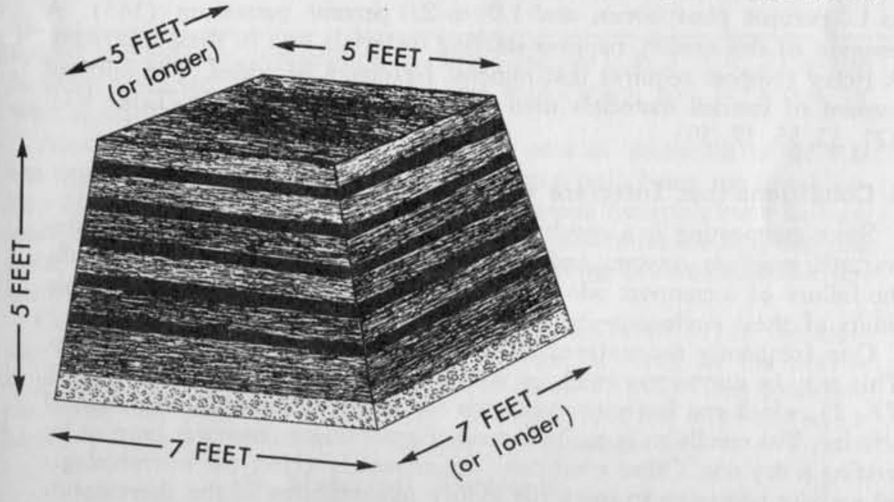
Figure 1. Diagramatic Illustration of an Indore compost pile.



1. The base usually consists of a 6-inch layer of brush.



2. This is followed by a 1-foot thickness of mixed wastes, 2 inches of manure or a substitute, and 1 inch of soil.



3. Remaining layers are a repeated pattern of 6 inches of mixed carbonaceous-nitrogenous wastes, 2 inches of manure or a substitute, and 1 inch of soil. The final pile is tapered, 5 feet high, and completely moist. A depression is commonly formed on top to catch rain and the pile is often covered with burlap, hay, or soil to conserve heat. Microbiological activity is aided by keeping the pile moist and the decomposition is speeded by thoroughly mixing the pile at 6 and 12 weeks.

is thoroughly mixed. The turning or aeration is repeated on the seventh and tenth day, at which time the pile normally begins to cool off. At the end of the 14 days, the compost is generally ready for use. The starting materials will be somewhat recognizable, but should appear coarse, crumbly, and dark brown in appearance. If finer humus is desired, it may be sifted or allowed to decay further.

This method can be carried out in the spring, summer, or fall. Its main advantage is speed, since large quantities of compost can be produced by this process throughout a growing season; but it does require more labor on a fairly fixed schedule.

4. Improving the Usefulness of Compost

Compost, as a soil conditioner and a fertilizer, can be altered in some instances for specific uses. An acid compost may be desired for some plant species, such as azalea, laurel, or rhododendron. This can be accomplished by using oak leaves in the pile (55). On the other hand, soil acidity should be neutralized by adding lime to the soil, rather than the compost pile, as studies at Berkeley (21) indicated that liming compost piles causes large nitrogen losses (Section IIA, 7). These studies also indicated that the final pH of compost is usually slightly alkaline without the addition of lime.

Although compost is a useful soil conditioner, its value as a fertilizer is limited. Dry compost commonly contains 1.5 to 3.5 percent nitrogen, 0.5 to 1.0 percent phosphorus, and 1.0 to 2.0 percent potassium (145). A compost of this quality requires starting materials rich in these nutrients. A richer compost requires that mineral fertilizers be added. The nutrient content of various materials used in composting is given in Table VII (21, 53, 55, 57, 59).

5. Conditions that Interfere with Composting

Since composting is a result of microbiological activities, it requires warmth, moisture, oxygen, and a mixture of carbon and nitrogen. Usually the failure of a compost pile can be traced to variance from acceptable limits of these environmental conditions.

One frequently encountered difficulty is failure of the pile to heat up. This may be due to too much or not enough moisture (Section IIA, 2, VA, 2), which can lower or even stop the heat-generating microbiological activity. The condition is easily corrected by drying an overwet heap or by wetting a dry one. Other conditions can adversely affect the microbiological activity necessary to reach the higher temperatures of the thermophilic stage. These include insufficient aeration (Section IIA, 4; VA, 2), which can be corrected by turning the pile; carbon-nitrogen ratio too high (Section IIA, 5; VA, 2), which can be altered by adding nitrogenous materials (green grass clippings, blood meal, etc.); pile too small (Section VA,2), which can be corrected by enlarging the pile to provide more insulation; and external temperature too low (Section IIA, 2; VA, 2), which is often corrected by insulating the pile with burlap, soil, or leaves or waiting until the weather warms up.

TABLE VII. NUTRIENT CONTENT OF COMMON MATERIALS USED IN HOME GARDEN COMPOST

Material	Percent (Dry Weight)		
	Nitrogen (N)	Phosphoric Oxide (P_2O_5)	Potash (K_2O)
Blood Meal	10–14	1–5	–
Bone Meal (steamed)	2.0	23	–
Coffee Grounds	2.08	0.32	0.28
Cottonseed Meal	6.6	2.0–3.0	1.0–2.0
Eggshells	1.19	0.38	0.14
Fish Scraps	2.0–7.5	1.5–6.0	–
Garbage	2.0–2.9	1.1–1.3	0.8–2.2
Grass Clippings	2.41	–	–
Grass Clippings /Weeds	2.03	1.09	2.03
Leaves (freshly fallen)	0.5–1.0	0.10–0.15	0.4–0.7
Manure (dry)			
Horse	1.2	1.0	1.6
Cattle	2.0	1.0	2.0
Poultry	5.0	1.9	1.2
Meat Scraps	5–7	–	–
Salt Marsh Hay	1.10	0.25	0.75
Seaweed (dry)	1.68	0.75	4.93
Sewage Sludge (digested)	2.00	1.5	0.18
Wood Ashes (unleached)	–	1.0–2.0	4.0–10.0

Another problem commonly found is the odor of ammonia or of rotten eggs. The first is due to the carbon-nitrogen ratio being too low (Section II5, V2). It is raised by adding carbonaceous materials such as hay, sawdust, leaves, etc. The second results from anaerobic decay; the pile must be aerated (Section IIA, 4; VA, 2) by turning to restore aerobic decomposition.

Occasionally, an abrupt drop in temperature may occur during the heating up or thermophilic stage. This results from the death of the microorganisms by temperatures over 160° F (Section IIA, 2). This condition can occur with piles that are too large. Eventually the pile will recover, or heat can be dissipated by turning the pile with a garden fork.

B. Municipal Processes

1. Windrowing Method

Windrows, or open piles, are probably the oldest form of composting and the most widely used by municipal composters. They can be any convenient length, about 8 to 12 feet wide, and 4 to 6 feet high. Gotaas (40) has pointed out that the height is critical, since a pile too high will compress and reduce pore space. This will require increased turning to combat anaerobic conditions or excessively high temperatures (see Section IIA, 2, 4). If the pile is too low, the insulation effect will not retain sufficient heat to provide a suitable environment for biological decomposition. Windrows will lose between 20 and 60 percent of their initial volume, depending on the starting materials and the amount of compaction. The weight loss can be as high as 50 percent.

This method of composting has been successfully used in many municipal operations; a few of the better known operations are listed below. Studies at the University of California at Berkeley utilized the windrow method (21), and showed it to be satisfactory for composting of municipal refuse. The windrow was employed in studies at Johnson City, Tennessee, conducted by the Tennessee Valley Authority and the Public Health Service (32). Municipal composting of leaves at Scarsdale, New York, also utilizes the windrow system (162).

2. Beccari Process

As originally designed, the Beccari process (11-16, 55) utilizes a cell equipped with air valves which loads from the top and unloads from the front. Initially, the material is digested anaerobically. The vents emit air at 150°F and the process becomes partially aerobic after about 18 days. Compost is ready in 35 to 40 days. This process is presently used in Italy and France, and was used in the United States during the 1920's. Bordas (55) improved the method by utilizing a continuous loading chimney. Another process improvement resulted in the Verdier method (55), where the drainage liquid is recirculated through the composting materials.

3. Vuil-Afvoer-Maatschappij (V.A.M.) Process

This process has been used for some time in the Nethherlands. Refuse is delivered to composting areas by rail. In some composting plants, but not all, it is shredded by rasping. Compost is prepared in windrows and takes 3 to 5 months for completion. The final product is improved in quality by screening and then sold (45, 55).

4. Dano Process

This method was developed in Denmark. Sorted refuse is delivered into a rotating cylinder where it is moistened with sewage sludge or water. Air is blown in at low pressure. A compost is produced in 5 days which is then cured in windrows. This method is used in Europe and was used in the United States for a short time (45, 55).

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