-Sept. 1975

THE BIOCHEMISTRY AND METHODOLOGY OF COMPOSTING

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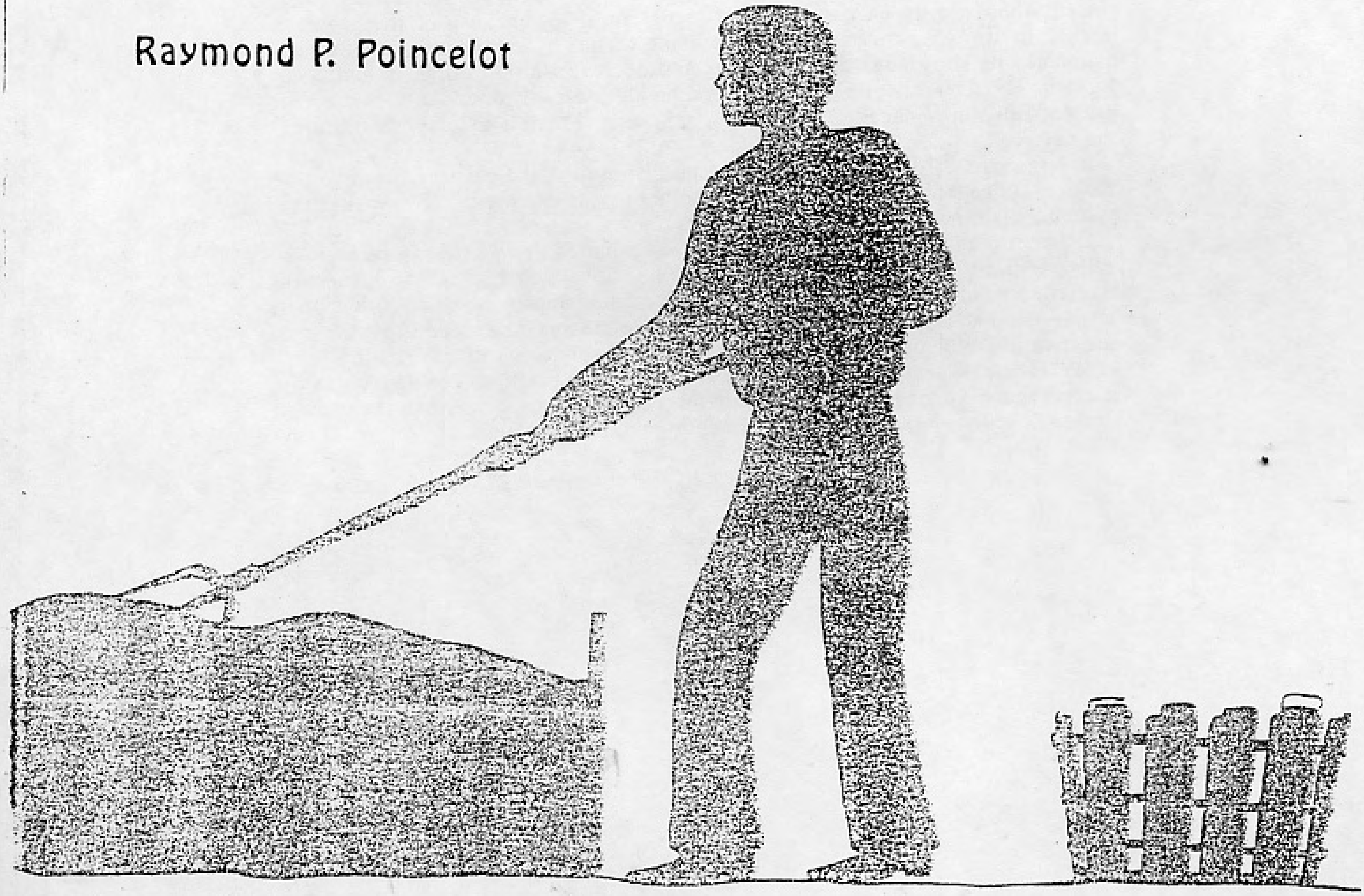

THE CONNECTICUT AGRICULTURAL EXPERIMENT STATION, NEW HAVEN

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

Certainly this Agricultural Experiment Station, now in its Centennial year, has experiments and knowledge accumulating over many decades that can be marshaled when society encounters new needs. In 1972, because of the growing interest in disposing and recycling its organic wastes by composting, the Station marshaled its knowledge of composting and decomposition of organic matter in Bulletin 727. This Bulletin, which proved highly useful, is now out of print. The present Bulletin replaces 727 and reports Station research accomplished during the past 2 years.

A large part of the organic waste to be disposed is the garbage, leaves, and sewage sludge that is commonly disposed by burying or burning. This makes the valuable plant nutrients contained in them unavailable.

Observant gardeners learned long ago that most of this waste can be biologically recycled by composting. The Station has always had scientists concerned with the role of organic materials in maintaining and improving soil fertility. So it is natural that a Station biochemist should relate old knowledge to new and produce this Bulletin on the biochemistry and methodology of composting.

We anticipate that this work by the Station will be useful to people who enjoy gardening, to citizens who must decide on recycling organic waste in their town, and to scientists interested in experimenting with composting.

Paul E. Waggoner, Director

History of Composting

Composting is an ancient practice. The Bible mentions compost several times, and George Washington's diary refers to 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.

Johnson's book, "Essays on Peat, Muck, and Commercial Manures", published in 1859, contained a chapter on composting (2). Most compost was prepared by rotting one part stable manure with two or three parts soil. One farmer in New Canaan used as many as 220,000 whitefish in one year with a compost consisting of one part fish and 12 parts soil. Other materials such as slaughter house wastes, sawdust, corn stalks, and leaves were also mentioned in Johnson's book.

The first important advances in composting were made about 40 years ago in India by Sir Albert Howard, a British agronomist (3-6). The Indore process, named after the state in India where it was formulated, employs a 5-foot high layered pile of garbage, night soil, animal manure, sewage sludge, straw, and leaves. The pile is turned twice, and composting is completed in 3 months.

Howard demonstrated composting as a replacement for burning and dumping of sewage sludge and refuse (7,8,9). One outgrowth of his efforts was the initiation of the organic gardening movement in 1942 by J. I. Rodale.

The Itano process, a mechanized method for large quantities of compost was described in 1928 (10). Another was developed by G. Becari (11-16). An improvement of this process was described by J. Bordas in 1931 (17). More methods followed, including the V.A.M. process (Vuil-Afvoer-Mattschappij) which is still used in the Netherlands (18,19,20).

Attempts to formulate efficient composting methods by improving upon past research began in New Zealand (21). In 1953, an extensive investigation at the University of California produced a straightforward method for aerobic composting of municipal refuse (22).

A 1971 Environmental Protection Agency publication (23) discusses the municipal composting plants in the United States, and cites at least 2,600 facilities in operation outside the United States.

A plant operated jointly by the U.S. Public Health Service and the Tennessee Valley Authority (24,25) in Johnson City, Tenn., was put into operation to study the technology, economics, and marketing of compost. Other plants recently in operation in the United States include those in Houston, Texas and Gainsville, Fla. (26,27).

The current interest at this Station arose from two things. First, Connecticut was faced with disposing of more waste on less land. Second, scientists who work on agricultural problems recognized that the decomposition of organic matter was a familiar problem. They knew about the rapid decomposition of organic matter in the soil from their years of experiments. Also, they were familiar with the biology, biochemistry, and methodology of compost piles.

A Station Bulletin (28) covered published research to September 1971. This revision covers research to September 1974. Other aspects of composting have been reviewed recently (29, 30, 31). No attempt has been made to include composting in the soil (green manuring).

Biochemical and Microbiological Aspects of Composting

Biochemistry

Temperature. A rapid warming occurs as microorganisms multiply in the composting mass. When the temperature moves past 40°C (104°F), the mesophilic stage is replaced by the thermophilic stage. This frequently occurs in 2 to 3 days (22,32). After the temperature in the middle of the pile stabilizes around 70°C (158°F), it gradually cools to ambient temperature. This pattern is typical for garden compost and municipal compost (33-37).

However, there is a larger temperature variation between the center and surface of small as opposed to large piles. In studies (22) of municipal compost in windrows approximately 7 by 7 by 5 feet high, the characteristic temperatures were observed on all four sides midway between the top and bottom at a depth of 1 foot from the outside surface. But in 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 by up to 10°C. Similar results were noted by Wiley (38). With still smaller piles of wheat straw compost in bins 40 by 40 by 40 inches, the temperature difference between the middle and 4 inches below the surface was as much as 20-30°C (36).

Since heat loss is proportional to surface area and heat generation is proportional to volume, the larger piles, having a smaller surface area to volume ratio, lose relatively less heat. In large piles, the temperature increases steadily with time. In small piles there is usually a leveling at 40°C while the transition from mesophilic to thermophilic microorganisms occurs (22). At Berkeley (22) changes in ambient temperature had no effect on this temperature progression. In colder areas, however, winter temperatures may slow or even stop decomposition (39).

Decomposition is fastest in the thermophilic stage (40). The optimal temperature, based on oxidation of organic matter into CO_2 and H_2O, has been found by Wiley (41,42) to be 60°C. Schulze (43) showed a maximal temperature of 71°C was optimal, but more often it is found that temperatures should not exceed 70°C for long because decomposition will be slowed by a "thermal kill" of microorganisms (22,44). More recently Jeris and Regan (45) demonstrated that 59°C was optimal (based on CO_2 consumption) for composting fresh municipal refuse containing 60-70% paper. For composting newsprint alone, the optimal temperature was 48°C.

During turning and aeration, the interior temperature may drop 5-10°C. However, studies with municipal compost indicate that the pile returns to initial temperature within a few hours (22,37,38).

Heat production, as determined by Wiley (41), could be as high as 10,000-12,000 BTU per lb of volatile solids decomposed into CO_2 and H_2O. Up to 75% of the heat was derived from decomposition of lipids.

Moisture. If the amount of moisture in the compost is below 40% (w/w), decomposition will be aerobic but slow. But if the moisture content is above 60%, the prevailing air spaces and the wet strength of the material are often insufficient to prevent anerobic decay and the resulting foul odors (22,46).

The optimal moisture level is often 50 to 60% (22,37,42,43,47,48,49), but municipal refuse with over 40% newspaper and over 30% free air space degrades best at higher (67%) moisture levels (50).

Since some lipids are present as liquids during the thermophilic state, it has been suggested that the term percent liquid

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

is more correct when assessing the optimal wetness for thermophilic decomposition (51).

Grinding. Decomposition can be speeded by grinding because better initial aeration is achieved, and the surface area is increased, making the materials more susceptible to microbial invasion (22,47). Grinding also makes the material easier to handle and moisten. Gray and Sherman (52) observed that grinding might double the amount of evolved CO_2, especially during the thermophilic stage.

Aeration and Gaseous Products. It is apparent from various studies that the rate of O_2 consumption by microorganisms depends upon the temperature, particle size, composition of the material, and the degree of agitation. For example, garbage and sewage sludge mixed (53), municipal waste (48), garbage (42), and municipal refuse containing 60 to 70% paper (45), respectively consumed 5 to 9, 7.3, 9 to 23, and 6 cu ft air per lb volatile matter per day.

Windrows may be aerated either by turning the outer edges into the center of the pile or by mechanical mixing. The turning schedule should be based on the O_2 concentration, although it is often based on temperature and moisture levels (22,37). Wiley and Spillane (38) found that the percentage by volume of O_2 was lower in the interior of the pile. The O_2 concentration was as high as 18.6% at 15 inches and as low as 1 to 2% at 24 inches. An O_2 content as low as 0.5% was observed inside municipal composting windrows without anaerobic symptoms (37).

Schulze suggested a minimum of 5% O_2 in effluent gases of rotating drum composters to ensure aerobic conditions at the thermophilic stage (53). If agitation is used, it should be periodic because constant agitation causes excessive cooling, drying, and disruption of fungal mycelia (29).

Unless there is adequate aeration, a pile turns pale green, and foul smelling gases which might be hazardous in high concentrations are produced. For example, anaerobic composting of cattle manure produces hydrogen sulfide, carbonyl sulfide, and methane (54). If a pile turns anaerobic, it may be returned to the aerobic state by daily turning (22). Two to three turns per week were sufficient for aerobic decomposition of municipal refuse. Turning was done twice a week at the University of California (22) and five times a week at Johnson City, Tenn. (37).

Much organic matter is converted to CO_2 and H_2O during decomposition (55). As much as 4.5 millimoles of CO_2 per gram of volatile matter may be produced during composting of municipal refuse (45). If C is unavailable, for example, when much newspaper is present, or the carbon to nitrogen ratio (C/N ratio) is too low, the smell of ammonia may come from the pile. Ammonia is produced during the thermophilic stage because the pH is slightly alkaline and the temperature favors volatilization.

Carbon: Nitrogen Ratio. The relationship between the dry wt of C and the dry wt of N (C/N ratio) and the rate of decomposition is probably the most important aspect of composting. Microorganisms require C for growth and N for protein synthesis.

As 30 parts by weight of C are used by microorganisms for each part of N, a C/N ratio of 30 would seem to be most desirable for efficient composting (22,56). C/N ratios between 26 and 35 as reported by many investigators (21,22,57-61), provide for rapid and efficient composting. Lower ratios cause increasing loss of N as ammonia, and higher values lead to progressively longer composting.

The N content and C/N ratios for commonly composted materials derived from many sources are presented in Table 1. High C/N ratios are generally caused by paper. An increase of paper content from 16 to 21% can increase the C/N ratio from 40 to 55; more paper may easily produce C/N ratios of 80 (22).

The C/N ratio, and hence the time for composting, can be lowered by adding a N source such as activated sewage sludge (22,37,38,63). In smaller scale composting, as in a home garden, paper can be avoided and the N content can be raised with a variety of materials.

TABLE 1. Nitrogen content and C/N ratio of various materials used in municipal or industrial compost

Material	Nitrogen %N (Dry Wt)	C/N Ratio (Wt/Wt)
Garbage		
Washington, D.C.	2.70	—
Yonkers, NY	2.50	—
Chicago, IL	1.24	—
Canton, OH	2.08	—
Raleigh, NC	1.92	15.4
Louisville, KY	2.90	14.9
Total Raw Refuse (Residential—includes garbage)		
Berkeley, CA	1.07	33.8
Savannah, GA	1.30	38.5
Johnson City, TN	0.6	80
Raleigh, NC	—	51.5
Chandler, AZ	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
Sawdust	0.11	511
Lumber Mill Wastes	0.31	170
Pharmaceutical Wastes	2.55	19

[1] Sources: 22, 29, 37, 38, 62-73.

Changes in Composting. The compositions of typical compost materials are shown in Table 2. Degradative changes described by several researchers are summarized in Table 3.

TABLE 2: Composition of various materials prior to degradation

	Total Municipal Refuse[1]	Garbage[2]	Plant Material	Sewage Sludge (activated)
Component		% (dry wt)		
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.
[8] Sources: 22, 29, 38, 62, 64, 66, 67, 71, 74-77.

Microorganisms rapidly utilize the available sugar and starches, and large losses of water-soluble materials follow. Lipids undergo major, and cellulose and hemicelluloses undergo intermediate decomposition. Lignin is perhaps the most resistant to degradation.

In both municipal and small-scale composting, the dry wt may decrease 26 to 60% (Table 3), and the volume may decrease 66%. The loss of total N (Table 3) appears to contradict the sometimes observed gain in protein, but the increase in protein coincides with a decrease in soluble N.

Changes in pH. The initial pH in compost windrows is usually slightly acid (pH 6) as is the cell sap of most plants. The production of organic acids during the early stages of decomposition causes further acidification (pH 4.5-5.0), but as the temperature rises, the pH increases and levels off slightly (pH 7.5-8.5) alkaline (22,29,37).

Effects of Pollutants. Detergents in sewage slightly accelerate, oil in municipal refuse slightly retard, and herbicides in agricultural residues have no effect (83) on the process of composting. Unless abundant, lim-

TABLE 3. Compositional changes after aerobic composting

		% (dry wt) Loss (−) or gain (+)													
Type of Compost	Age	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
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)	8.8 days	−28	−7.1	−32	−31	−2	−77	−100	−89	−2	—	—	—	—	—
Municipal Refuse[1] (Laboratory)	10-30 days	−40	−30	−45	—	—	−86	—	—	−22	—	—	—	−65	—
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, TN
[3] Chandler, AZ
[4] Savannah, GA
[5] Contains sugar, starch, ammo and aliphatic acids, salts.
[6] Contains sugar, glucosides, and oil.
[7] Sources: 37-39, 76, 78-82.

ited research suggests these pollutants should have little impact.

Nitrogen and Phosphorous Chemistry. The N in plant materials begins to change several hours after harvesting. Severed leaves, for example, gain amino and amide N at the expense of protein N. These changes, which continue for several days and are induced by enzymes, are discussed by Chibnall (84).

Compost microorganisms metabolize both inorganic and organic N. Isotope studies (^{15}N) by Jansson *et al.* with NH_4NO_3 demonstrated a significant preference by microorganisms for ammonium N (85). Mattingly (86,87) found that the percentage of soluble N in straw composts containing sewage sludge or ammonium sulfate decreased during the first 50 days but increased gradually during the next 450 days.

As the soluble N decreased, the insoluble N (presumably protein) and the α-amino and amide N increased. After 3 months, the α-amino N level remained fairly constant, but the amide N gradually decreased. The soluble N was initially soluble organic N and ammonia; after 100 days, these were increasingly replaced by nitrate.

Bremner (88) got similar results using straw-ammonium carbonate composts. He also found that most of the microbially-synthesized N was protein and that the amino acid composition was similar in composted and uncomposted straw. Composted straw differed slightly in containing small amounts of β-alanine and what was tentatively identified as a α-Σ-diamino pimelic acid.

Nitrogen compound changes (86-90) may be summarized as follows:

- Microorganisms metabolize available inorganic N, preferably in the form of ammonium.
- Insoluble N compounds are degraded into solution forms before use by microorganisms.
- Ammonia is produced by oxidative de-amination of protein amino acids.
- Most of the synthesized N is in the protein fraction. α-amino N becomes constant due to concurrent synthesis and degradation after 100 days or more.
- Nitrate begins to form at the expense of soluble organic N and then can be leached or to a lesser degree denitrified by bacteria.

Because nitrate did not increase significantly for the first 120 days under Bremner's or Mattingly's conditions (86,90), leaching or denitrifying bacteria should not be a problem unless compost is wet and stored for a long time.

Limestone or Phosphate as Additives. Studies show that the alkaline pH resulting from addition of calcium carbonate (limestone) or calcium hydroxide accelerated the rate of decomposition of organic wastes while acetic acid slowed the rate (22,29,91). The slight improvement from liming, however, is outweighed by the cost and the extensive loss of N as ammonia because alkaline conditions favor this loss (22).

Several investigators have reported calcium phosphate increases the rate of decomposition and N conservation (92-95), but that more than 2% inhibited decomposition.

Chang found the increased rate of decomposition occurred mainly in the cellulose and hemicellulose fractions (96). Korovkin demonstrated that this resulted from an increase in cellulose-decomposing organisms and claimed that the addition of phosphate conserved N by decreasing the number of denitrifying bacteria (97). Similar results were reported by Tepla (98).

Although N fixation may be increased by adding phosphate (99), there generally is enough phosphate in the waste materials. Microbes need only 5 to 20% as much P as N (39,100).

Humus and Finished Compost. Polymeric reactions that produce humic acids and humus occur after compost has cooled to the ambient temperature. Schnitzer (101), Prat (102), and Kononova (103) give this comprehensive treatment.

Compost should be "ripened" before being applied to the soil, otherwise decomposition will continue at the expense of soil N. Although robbing of soil N will usually occur at C/N ratios higher than 10 to 12 (104), higher ratios are acceptable if the excess C is in a relatively undegradable form, such as paper (22).

The time for ripening is a function of variables such as the C/N ratio, availability of C, shredding, etc. In Berkeley (22), windrows ripened in 2 weeks; in the Netherlands (105) municipal windrows ripened in 7 weeks.

Microbiology

The microfloral population changes continually during aerobic composting. Chang and Hudson (36) and Goleuke (106) have described a typical pattern. Fungi and acid-producing bacteria appear during the mesophilic stage. As the temperature increases above 40°C, these are replaced by thermophilic bacteria, actinomycetes, and thermophilic fungi. Spore-forming bacteria follow at temperatures above 70°C. Finally, as the temperature falls, mesophilic bacteria and fungi reappear. Protozoa, nematodes, ants, springtails, millipedes, and worms are also present during the later mesophilic stage (29,73). Examples of mesophilic and thermophilic bacteria, fungi, and actinomycetes isolated from compost are listed in Table 4. Densities of these microorganisms as a function of temperature are summarized in Table 5. Dead and living microorganisms can be 25% of the weight of compost (31).

TABLE 4. Bacteria, actinomycetes, and fungi isolated from compost

BACTERIA

Mesophilic
- *Cellumonas folia*
- *Chondrococcus exiguus*
- *Myxococcus virescens*
- *M. fulvus*
- *Thiobacillus thiooxidans*
- *T. denitrificans*
- *Aerobacter* sp.
- *Proteus* sp.
- *Pseudomonas* sp.

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*
- *F. roseum*
- *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]
- *Glomerularia* sp.
- *Pullularia (Aureobasidium)*
- *Fusidium* sp.
- *Actinomucor corymbosus*
- *Mucor jansseni*[3]
- *Talaromyces (Penicillium) variabile*[3]
- *Helminthosporium sativum*[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*
- *T. emersonii*
- *T. thermophilus*
- *Sporotrichum thermophile*
- *S. chlorinum*
- C. t. 6 *(Mycelia sterilia)*
- *Stilbella thermophila*
- *Malbranchea pulchella* var. *sulfurea*
  (Thermoidium sulfureum)
- *Dactylomyces crustaceous*
  (Thermoascus aurantiacus)
- *Byssochlamys* sp.
- *Torula thermophila*

[1] Treated separately because of their common occurrence in compost.
[2] Rafaai aggregate (ref. 114).
[3] Probably mesophilic, but not definite with available data.
[4] Sources: 35, 36, 44, 47, 74, 107-119.

Bacteria and Actinomycetes. Many aerobic mesophilic bacteria are initially present (Table 5) and multiply, but after their increased activity raises the temperature, their numbers decrease due to the change in environment. A minimum is reached (33,36) at 55° to 65°C during composting of grass clippings or straw, but their numbers increase again as the temperature drops below 50°C. Thermophilic bacteria follow an inverse pattern (36).

TABLE 5. Microfloral population during aerobic composting[1]

	Numbers per gram wet compost at each temperature		
Ambient →	40°C → Mesophilic (M)	70°C → Thermophilic (T)	Ambient 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 (33), Chang and Hudson (36), using compost prepared from grass clippings and also straw.

The role of mesophilic bacteria is unclear. Their primary purpose may be raising temperature for the thermophilic microorganisms that follow. During the limited time that they flourish, mesophilic bacteria consume the most readily decomposable carbohydrates and proteins (29).

Thermophilic bacteria (120) initially decompose the protein and non-cellulose carbohydrate components in compost. These bacteria also attack the lipid and hemicellulose fractions, but cellulose and lignin appear to resist their activity.

Although Waksman and Cordon (121) concluded that actinomycetes attack hemicellulose but not cellulose, Stutzenberger (122) has recently isolated a thermophilic actinomycete (*Thermomonospora curvata*) that he suggests may be important in cellulose decomposition. *T. curvata* was the most frequently isolated actinomycete in municipal and mushroom compost (111,122).

Because thermophilic actinomycetes can grow at higher temperatures than thermophilic fungi, they become dominant at the warmest stage (36,105,107,111). Over the range 42 to 72°C the initial actinomycete population multiplied 500-fold compared to a 5-fold increase for thermophilic bacteria in wheat straw compost (36).

Fungi. Mesophilic fungi are present as the compost heats (36). Although these organisms, which are usually saprophytic sugar types, are quickly replaced by thermophilic fungi, they reappear in large numbers as the pile cools below 40°C (Table 5). Evidently, they persist in the outer layers during the thermophilic stage, and reinvade when the temperature drops sufficiently. These mesophilic fungi can utilize cellulose and hemicellulose, but not as well as thermophilic fungi (78).

Thermophilic fungi occur when the temperatures are between 40 and 60°C. Like the mesophilic fungi, they survive in the periphery of the pile when the temperature exceeds this level. These reinvade when the temperature declines below 60°C. Thermophilic fungi are important (35,78,121,123) because they decompose hemicellulose and cellulose, and in pure cultures can affect up to half the cellulose.

The most common thermophilic fungi in wheat straw compost and in horse manure-straw compost are *Humicola griseus* var. *thermoideus, H. insolens, H. lanuginosa,* and *Chaetomium thermophile* (36,111). These grow well because of their ability to utilize complex carbon sources (cellulose) and to thrive at high temperatures (36). *H. lanuginosa* is a special case because it uses sugars produced by the cellulases of other fungi (78).

The only detailed study of succession in microfloral populations during composting is work with wheat straw compost in bins by Chang and Hudson (36). They divided fungi into three groups. Group 1 contained initial fungi such as the mesophilic forms *Cladosporium herbarum, Alternaria tenuis, Aureobasidium pullulans, Aspergillus repens, A. amstelodami, A. versicolor, A. candidus, A. nidulans, Penicillium* sp., the thermophilic *Mucor pusillus*, and the thermotolerant *Absidia ramosa* and *Aspergillus flavus*. Group 2, isolated after 2 days, contained only thermophilic fungi, such as *Humicola insolens, H. lanuginosa, Chaetomium thermophile, Malbranchea pulchella* var. *sulfurea*, and *Talaromyces duponti*. Group 3 consisted of the thermophile *Sporotrichum thermophile*, a *Mycelia sterilia* that they designated C. t. 6, and the mesophiles, *Fusarium culmorum, Stysanus stemonitis, Coprinus cinereus, C. megacephalus*, and *Clitopilus pinsitus*.

No apparent succession of fungi was found in municipal refuse during the thermophilic stage (115). *Mucor, Aspergillus*, and *Humicola* were predominant. Lesser numbers of *Chaetomium thermophile, Dactylomyces crustaceous (Thermoascus aurantiacus)*, and *Torula thermophila* were also present.

Most decomposition occurs in the thermophilic phase (78, 124). Whether bacteria, actinomycetes, or fungi cause most of it remains to be answered. In pure cultures *Chaetomium thermophile* caused 40% breakdown of wheat straw in 3 weeks at 45°C (78). Most of the material broken down was hemicellulose or cellulose. Earlier Waksman *et al*. (124) reached a similar conclusion. They indicated a mixed microflora was best, but that thermophilic fungi were most active in decomposing stable manure. However, based on frequency of isolation, Kane and Mullins (115), have shown that fungi account for a lesser part of the thermophilic decomposition of municipal refuse. A thermophilic actinomycete, *Thermomonospora curvata*, was shown to be a major cellulose decomposer of municipal compost (122).

Pure culture studies must be viewed with reservations because of competition and antagonism in natural mixed populations. Also, the contribution of various microorganisms could vary with the material being degraded.

Inocula and Other Additions to Compost. Success with additives was claimed by some investigators (125-129), and negative results were obtained by others (22,64,106,130-133). Because of this, additives do not appear justified except in a few instances.

If the C/N ratio is too high, adding N can speed composting by lowering the ratio. This could account for the apparent success of some additives. Additives may also be beneficial in a pile poor in microorganisms. Although this seldom occurs, it has been observed in sawdust. Inoculation with spores of the fungus *Coprinus ephemerus* (a cellulose decomposer) and addition of ammonia, phosphoric acid and potassium sulfate shortened composting of sawdust from the usual 1 to 2 years to 3 months, and produced a compost that did not rob N from soil as did fresh sawdust (125,126).

Japanese patents for additives to accelerate decomposition of wood products have recently appeared. The addition of nitrohumic acid (humus or complex natural lignoprotein treated with nitric acid) to bark wastes and chicken manure (1:7:100) reduced the decomposition time to 60 days from 180 days (134,135). Decomposition of wood pulp was improved by urea and pyroligneous acid (crude acetic acid distilled from wood).

Pathogens and Parasites. Animal and human pathogens may be present in materials to be composted, especially when sewage sludge is added. Krige (136) lists pathogens in compost and sewage sludge.

The Connecticut State Department of Health does not allow raw or activated sewage sludge to be used for garden composting. Activated sewage sludge may be used in municipal composting, but only with careful monitoring for pathogens. Dried digested sewage sludge may be used in garden composting for above-ground crops or for root crops cooked before eating. If roots are to be eaten raw, the composted sludge should be applied in the fall and dug in before planting. No additional applications are allowed.

Gotaas (47) recommended 60°C for "thermal kill" of common pathogens. Knoll (137,138,139) found that 65°C for one day ensured destruction of *Salmonella* species. Although Strauch (140) found destruction of *S. enteriditis*, *Erysipelothrix rhusiopathiae*, and the *psittacosis* virus under similar conditions, *Bacillus anthracis* was only destroyed by temperatures above 55°C for 3 weeks or longer at 40% or more moisture.

Elevated temperatures may not be the only way to destroy pathogens during composting. Knoll (138,139) concluded that some are killed by competition with other microorganisms. He compared cultures of *S. paratyphi* B and *S. cairo* incubated at 50°C and 50% moisture with duplicates added to compost under the same conditions. Those in the compost died after 7 days, while those in the incubator died after 17 days. An aqueous extract of compost killed these microorganisms in 10 days, whereas those alone in the medium survived beyond 4 weeks.

Scott (141) and Scharff (142) found that resistant forms of parasites, such as *Ascaris* eggs, cysts of *Endamoeba histolytica* and hookworm eggs were destroyed during the windrow composting process. Fly larvae are also killed during composting (22,38). Flies from mechanized composting operations were traced to larvae in refuse arriving at the plant (143). Composting at 49°C or higher appeared to destroy the pathogens causing the main tobacco seedling diseases (144). Wiley has (145) published a thorough review on pathogen survival during composting of municipal wastes.

Composting normally reduces the health hazard posed by pathogens and parasites if the minimal time-temperature conditions prevail. The requirement for windrow composting is apparently 18 to 21 days at temperatures above 55°C, although some pathogenic fungi may survive these conditions (70).

The air at mechanized compost plants contained no more than nine microbes per liter (146). No coliform organisms were present but gram-negative and gram-positive bacilli, fungi, and *Staphylococcus aureus* were found. No reports exist in the literature on sanitation workers being infected by fungi during the handling of compost (23).

Compost and Cellulose Degradation. Cellulose in the form of paper products, which constitutes about half of the typical East Coast municipal refuse (147), produces a high C/N ratio which must be lowered for efficient composting. Even under ideal conditions, 40% of the cellulose in municipal compost is resistant to microbial attack after 8 weeks (74). Regan and Jeris (123) concluded that cellulose decomposition is probably the most serious limiting step in the path of successful composting.

Although many microorganisms have cellulolytic activity, their effectiveness in degrading highly ordered cellulose, such as paper, is often low (115,123) because many lack or nearly lack the C_1 component of the cellulase complex. This component is necessary for the breakdown of highly-oriented cellulose (148). Compost microorganisms reported to possess cellulolytic activity include *Trichoderma* sp. (especially *T. viride*), *Humicola grisea*, *H. insolens*, *Chaetomium thermophile*, *Aspergillus fumigatus*, *A. terreus*, *A. niger*, *Thermomonospora curvata*, *Talaromyces (Penicillium)*, sp., *Chrysosporium pruinosum*, *Fusarium moniliforme*, *F. roseum*, *F. solani*, *Streptomyces* sp., *Myrothecium verrucaria*, *Stachybotrys atra*, *Pestalotiopsis westerdijkii*, and *Cellumonus* sp. (73,78,122,123,149,150).

Of these, the most important are probably *Chaetomium thermophile*, *Humicola insolens*, and *Thermomonospora curvata* (78,111,122,123). But it is difficult from pure culture studies to assess their contribution because they undoubtedly encounter competition in mixed populations.

Hulme and Stranks (151) recently suggested that fungal cellulases are subject to repression by glucose. Catabolite repression of the cellulases of *Trichoderma viride* and *Thermomonospora curvata* has been shown (122,149). Another limiting factor may be the association of cellulose with a protective substance such as lignin (74) which resists attack by microorganisms. The lignin content in paper may be fully 12% (152).

Research at this Station has developed an assay for screening many fungi for cellulolytic activity (153). 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 hydrolysis by fungal cellulases releases this dye, which is then determined spectrophotometrically. This assay was used to determine the difference in cellulolytic activity among several strains of *Trichoderma viride*. The results resembled those obtained by the laborious reducing-sugar assay, which depends upon the determination of glucose released by cellulase from a cellulose substrate.

One waste, which individual Connecticut citizens and municipalities must contend with, is autumn leaves. We (73) examined cellulose decomposition of leaves mixed with several municipal and industrial wastes or other additives (Table 6). The maximal breakdown of cellulose with minimal labor was found with leaves amended with ammonium sulfate, sewage sludge, or dead mycelia from fermentation. A potentially useful agricultural compost was produced from unshredded leaves before the next leaf fall, especially if N was added.

Cellulose, except that from paper pulp, was not detrimental under minimal labor conditions. A thermophilic protozoan was observed in these compost

TABLE 6. Loss of cellulose during composting

Treatment[1]	Initial C/N Ratio	Initial %	% Loss In 200 Days
Leaves	41	26	31
Leaves, bone meal (50)	41	26	32
Leaves, ammonium sulfate (50)	35	26	54
Leaves, sewage sludge[2] (450)	36	24	41
Leaves, mycelial residue (700)	36	28	46
Leaves, paper fiber (900)	45	32	23
Leaves, mycelial residue (900), paper fiber (900)	37	32	23
Leaves, mycelial residue (450), sewage sludge[2] (250)	36	26	36
Leaves, paper fiber (900), sewage sludge[2] (750)	38	28	29

[1] (No.) indicates pounds added to 4200 lb. (dry wt.) leaves.
[2] Digested.
[3] Source: 73.

piles, which we believe is the first to be reported in compost, although they exist in some water sources (154).

We are now working with leaf composts to determine changes in bacterial and fungal flora related to the types of degradative enzymes produced. The enzymes being studied degrade starch, protein, lipid, pectin, cellulose, alkanes, and urea. The changes in flora are also being correlated with temperature, pH, C/N ratio, and losses of starch, protein, cellulose, lipids, pectin, urea, and alkanes.

Preliminary results (119) show that when urea is added to lower the C/N ratio, urease producing bacteria metabolized nearly all of it within 8 days. Most was volatilzed as ammonia. Although urea did not lower the C/N ratio for long, earlier studies showed that ammonium sulfate, sewage sludge or pharmaceutical wastes, effectively lowered the C/N ratio and improved the degradation (73). Cellulose was degraded the least of all substrates studied and only during the thermophilic stage by cellulase-producing actinomycetes. During the latter mesophilic stage, a yeast (*Pullularia*), which can fix atmospheric N (155) was found. This may have value in conserving or increasing N during storage of compost.

Garbage Degradation. Typical municipal refuse contains 12% garbage (71,147). Hankin and Zucker of the Station staff have reported 72% liquifaction of common household garbage in 24 hours using pectate lyase, an enzyme which breaks down the pectin "glues" of plant tissues (156). The liquified garbage is easily handled and may have future uses in agriculture.

Stephens, Hankin, and Zucker (157) showed that 1 inch or 146,000 lb of liquid garbage (from common household vegetable wastes) applied to an acre supplied 300 lb of N, 50 lb of which were available immediately as nitrates and some ammonia. The garbage also supplied 3 lb of P, 19 lb of K, and 8 lb of Ca per acre. When applied as a mulch, it improved yields of corn and beans. The controls received nitrogen fertilizer equivalent to that initially available from the liquid garbage. The increased yield was attributed to the weed control and water conservation by the mulch and to the additional N released during the growing season. Weeds were reduced by 90% or more by an application 2 inches deep. Preliminary tests on forests showed no visible harm from application of 3 inches, and leaves became greener late in the season.

Chemical Analysis of Raw and Finished Compost

Detailed analyses of municipal compost have been made in Europe, particularly in the Netherlands (34,105,158,159,160). These studies include methods for sampling and analyzing for humus, coal, organic matter, moisture, N, P, K, Ca, Mg, Cu, Mn, Co, B, Mo, Zn, and Cr.

A recent publication (161) lists analyses of refuse and compost. Many of the analytical procedures and sampling techniques were developed or adapted for use by the Technical Development Laboratory, National Communicable Disease Center, United States Public Health Service, Savannah, GA.

According to Carnes and Lossin (162), complex buffering in compost can vary the pH as much as one unit when different amounts of water are added. This difficulty is similar to that encountered in soil which has been attributed to the junction effect at the calomel electrode. They proposed that 10 grams should be diluted with 500 ml water to obtain consistent results.

Evaluation of Finished Compost. Many discussions are found in the literature (22,76,105,163-166) on determining when compost is finished, but no method appears adequate.

Physical factors include earthy odor, dark color, fluffy structure, low specific gravity, and cooling. But conclusions based solely on these factors can be erroneous. For example, a cooling could indicate the destruction of microorganisms by heat and insufficient O_2. Cooling, therefore, is a reliable indicator only if the compost does not reheat after turning and moistening.

Chemical tests, such as determination of the C/N ratio, more obviously indicate when compost is finished. If a C/N ratio of 10 to 12 is found, normal compost is finished. However, a higher ratio does not necessarily mean composting is not finished because the C could be unavailable cellulose from paper. Unavailable C would be indicated if the cellulose content remains unchanged for a period of time. Two procedures for determination of cellulose have been presented recently (167); an anthrone colorimetric method, and a gravimetric procedure recommended as easier and quicker.

One shortcoming of the C/N ratio is that C analysis involves the determination of CO_2 in a C combustion apparatus. One simple analysis (21) tested at Berkeley (22) involves only an ash determination. The % C is estimated by the equation

$$\frac{100 - \%\,\text{ash}}{1.8}$$

on the assumption that the dry weight % of organic C averages 56% or 100/1.8. This method agreed within 2 to 10% with the more difficult method. A colorimetric and a titrimetric procedure involving wet combustion with acid-dichromate have been recently developed (168, 169).

Relying only upon the amounts of ammonia and nitrate without considering the C/N ratio can be erroneous. Since nitrate does not necessarily appear directly after ammonia production ceases, the compost could be usable before nitrate appears, but only a measurement of the C/N ratio could establish this.

Although the determination of starch, which has been completely utilized by the time composting is finished, is a simple qualitative test with iodine (76), it must be used with others because starch disappears early.

Biological tests of O_2 consumption (170), CO_2 evolution, microorganism numbers, and plant growth are also useful and complement physical and chemical methods.

Since unfinished compost continues its decomposition by utilizing soil N, which might cause N deficiency, it is conservative to perform several tests, such as one chemical and one biological, before assuming the compost is finished.

Soil Improvement

Soil Conditioning. Compost is both a soil conditioner and a fertilizer. Compost improves the aeration and water-holding capacity of the soil (22,171), but its fertilizer value is limited.

Quastel and Webley examined the effect of adding various organic substances, including compost, to the soil (172). The addition of organic matter increased the available O_2. The water-holding capacity approximately doubled when they added 1% straw to soil. Straw composts were more effective than composts of household refuse and sewage sludge but not as effective as uncomposted straw. Downs *et al.* (173) found an increase in water-holding capacity of soils receiving organic matter from green manure in a rotation. The Tennessee Valley Authority and the Public Health Service concluded that municipal compost improves aeration, tilth, and water-holding capacity of soil (174,175,176). Addition of 50 to 400 tons of compost per hectare in vineyards increased moisture retention, pore volume, and aeration of root areas (177). Humus content, hygroscopic moisture, water-retention capacity, and absorption capacity were increased when organic matter was added to the soil (178). Springer (179) points out that these improvements are primarily caused by improvements in soil structure and increases in pore volume.

About 75% of the compost sold in the Netherlands is used (180) as a soil conditioner in hot-beds, greenhouses, bulb production, and on park land. Other potential uses are suggested by recent research. For example, soil erosion on vineyard hillsides was eliminated by 150 tons compost per acre for 3 years (180, 181). Vegetation was restored on strip mines with 184 tons of compost per acre per year (182). Infertile soil produced good crops with as much as 73 tons compost per acre per year (175). Compost can replace peat moss in potting soils (183). Vegetation was established on ash-ponds of coal-fired electric generating plants with 100 tons compost per acre (184). Land flooded by salt water was reclaimed after an application of 6 tons of compost per acre (185).

Fertilization and Trace Elements. Composts have little N, P or K; the dry wt % of N, P, and K are at most 4.0,1.3,2.1 (Table 7). Since most N is in organic form, it is released gradually. This lessens leaching, and extends the availability of N during the growing season.

Compost is more effective when it is amended with

TABLE 7. 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.

[3] Sources: 22, 34, 38, 64, 133.

mineral fertilizers (22,171,186,187-190). The addition of compost with fertilizer has been claimed to increase the availability of phosphate derived from fertilizer (191).

When compared to other fertilizers of similar nutrient value, compost has increased yields as much as 10% (173,174,181,186,187,188,192,193). Increases in yield are highly variable, however, because certain soils behave differently. Yield was increased when compost was used on light sandy soils (187) and soil rich in humus that had a high C/N ratio and low nitrifying activity (192). Compost decreased yields on sand dunes with kaolinate clays, but increased yields on soils with illite and bentonite clays.

Several essential and non-essential trace elements are found in municipal compost. Composts prepared by the Beccari, V.A.M. and Dano processes had the following dry-weight % of trace elements (159): Mg: 0.06-0.18, Cu: 0.04-0.06, Mn: 0.002-0.01, Co: 0.005-0.007, B: 0.001-0.003, and Cr: 0.003. Plants are damaged by these metals under certain soil conditions. Although garden compost would not likely create such a problem, 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 (65).

Some effects of trace metals in compost upon food products have been studied. Mushrooms grown in compost containing mercury had objectionable levels of Hg (194). Lead was found in plants growing in lead-contaminated compost, but it was not resolved whether the Pb was assimilated by the plant or was in soil on external surfaces (195). Phytotoxic B in some municipal composts was eliminated by leaching (196). Zinc in municipal compost can potentially damage some plants, but a pH greater than 6.0 rendered the Zn unavailable (175). The uptake of Cd by rice in contaminated soil decreased when the soil of ph 7.8 was treated with compost and phosphate fertilizer (197).

Summary of Composting Methods

Compost in the Home Garden

Introduction. The basic methods for preparing garden compost are the traditional Indore method which requires 3 or more months, and the Berkeley method which requires 2 weeks.

Indore Process. All refinements and changes in the Indore process will be summarized (64,73,119,171,198-205).

The basic Indore pile is built about 7 feet wide at the base, 5 feet high, and 7 feet or more in length. The sides are tapered so that the top is about 2 feet narrower in length and width than the base. A container is sometimes built around the pile to conceal it and protect it from the wind which tends to dry the pile out. If the container is loose, aeration is facilitated. The site should be level and well-drained.

If leaves and garden wastes are composted in the fall, the compost can be applied to the garden prior to spring planting even though decomposition slows over winter. Compost will be ready in 3 months if the pile is started in the spring or early summer.

The pile is often started with an 8 inch layer of carbonaceous wastes. Carbonaceous materials include leaves, hay, straw, sawdust, wood chips, shredded or torn newspaper (no more than 10%), and chopped cornstalks. This is usually covered with 4 inches of nitrogenous materials. Nitrogenous materials may be fresh grass, weeds, or garden plant residues, garbage, fresh or dry manures, digested sewage sludge, or, to a much lesser degree, soil.

This pattern of 8 inch carbonaceous and 4 inch nitrogenous layers is repeated until the pile is 5 feet high (Fig. 1). This ratio of layers is necessary for efficient decomposition. Layers are normally wetted so that they feel damp but not soggy. A depression is ordinarily pushed into the top to catch rainwater, and the pile is sometimes covered with soil, hay, or burlap to retain heat. Thorough mixing of the pile at 6- and 12-week intervals aids decomposition.

There are a few variations: If materials are limited, layers of carbonaceous and nitrogenous wastes can be added as they become available. All materials may

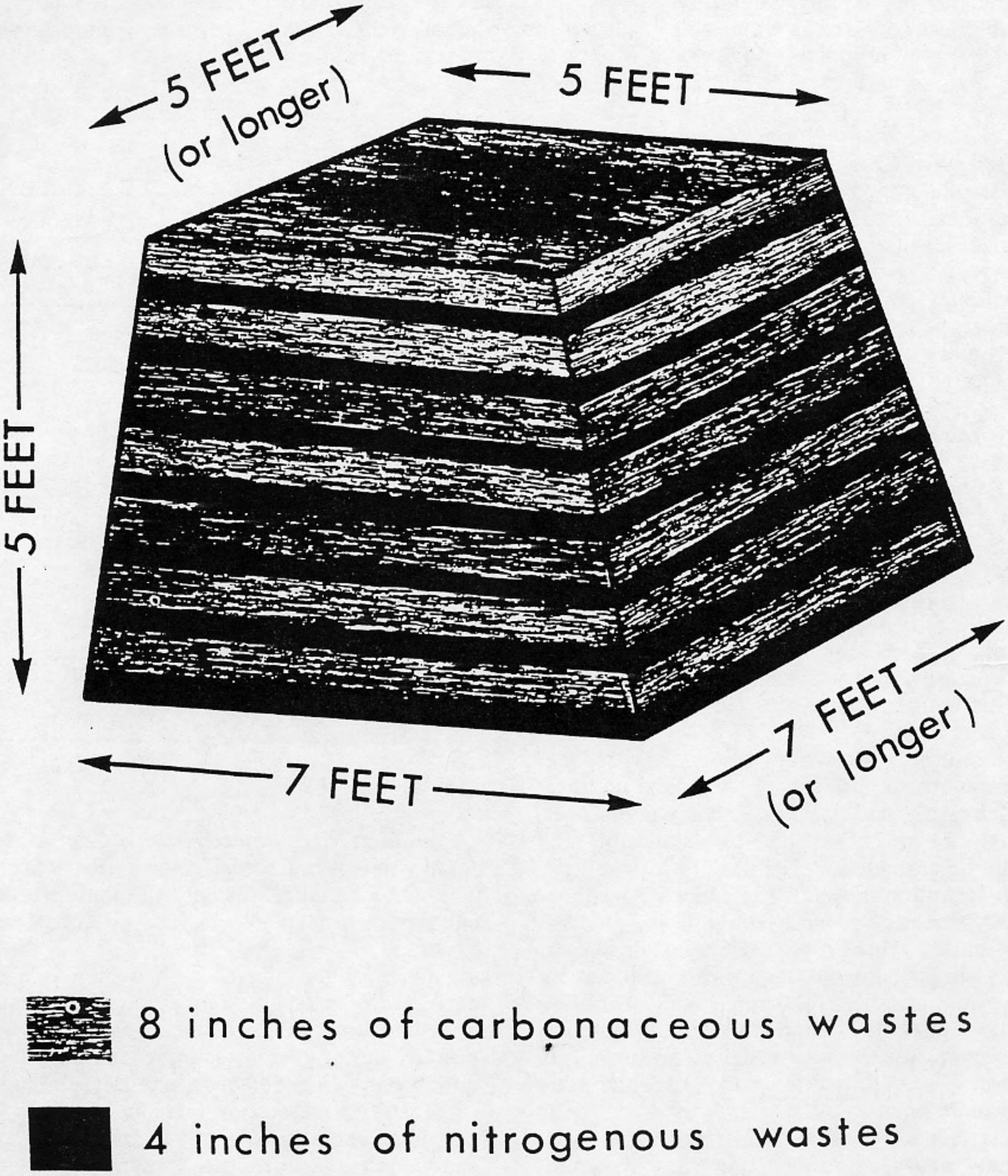

Figure 1. A diagramatic illustration of a garden compost pile. Layers are a repeated pattern of 8 inches of carbonaceous wastes and 4 inches of nitrogenous wastes. The carbonaceous materials include fallen leaves, pine needles, hay, straw, sawdust, wood chips, shredded paper, and chopped cornstalks. Nitrogenous wastes include green grass clippings, green weeds, vegetable wastes, garbage, digested sewage sludge, manure, and soil. The final pile is tapered 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.

be mixed together in the pile if one is careful to maintain the proper proportions. Shredding speeds composting considerably. Most material can be shredded by running over it several times with a rotary mower. Materials such as newspaper or wood chips will decompose slowly if not shredded, so additional N such as from blood meal or cottonseed meal may be necessary.

Experiments at the Station and elsewhere (73,119,205,206) have shown the easiest and most reliable compost pile may be made from tree leaves. Although additional N is not necessary, it will accelerate decomposition if the leaves are unshredded. A pile 7 x 7 x 5 feet high could use as much as 50 lb of ammonium sulfate, 20 lb of urea, or 20 lb of blood meal. The cost of N and the rapid loss of urea through microbial degradation (119) tends to negate their usage. Our studies (73,119) showed that piles of unshredded leaves, neither amended with N nor turned, were ready for agricultural use in the late summer. Leaves amended with N were ready in late spring or early summer, but leaf mixtures containing mostly oak leaves and pine needles take at least twice as long to decompose. Another way of adding N is to alternate 8 inch layers of leaves with 4 inch layers of green weeds, plant residues, or green lawn clippings.

Berkeley or "Two Week" Method. Although the Berkeley method (22,64,207) can produce compost in 2 weeks, it requires several turnings on a fairly rigid schedule. This method can be carried out during the spring, summer, or fall.

Again, a mixture of two parts carbonaceous to one part nitrogenous materials is used. A typical mixture consists of leaves, grass clippings, and dry manure. It should contain no more than 10% paper and the materials should be shredded mechanically or by several passes with a rotary mower. The material is composted in moist heaps 8 x 4 x 5 feet high.

If the pile hasn't heated by the second or third day, the C/N ratio is probably too high. The ratio can be lowered by mixing a rich N source such as blood meal into the pile. The heap must be thoroughly mixed by turning on the fourth day. The turning is repeated on the seventh and tenth day, at which time the pile normally begins to cool off. After 14 days the starting materials will be somewhat recognizable, but should appear coarse, crumbly, and dark brown. If finer humus is desired, it may be sifted or allowed to decay further.

Improving the Usefulness of Compost. Compost can be altered in some instances for specific uses. An acid compost may be desired for plants such as azalea, laurel, or rhododendron. This can be produced by using oak leaves in the pile (64), but soil acidity should be neutralized by adding lime to the soil, rather than to the compost pile because liming of compost piles causes large N losses (22). Finished compost is usually slightly alkaline without the addition of lime (22).

Dry compost commonly contains 1.5 to 3.5% N, 0.5 to 1% P, and 1 to 2% K (172). This quality requires starting materials rich in these nutrients. Mineral fertilizers must be added for a richer compost. The nutrient content of various materials used in composting is given in Table 8.

TABLE 8. Nutrient content of common materials used in home garden compost

Material	% Dry Wt.		
	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

[1]Sources: 22, 62, 64, 66, 68.

Conditions that Interfere with Composting. Since composting is microbial, it requires warmth, moisture, O_2, C, and N. Usually the failure of a compost pile can be traced to a lack of one or more of these essentials.

Failure of the pile to heat, which is a frequently encountered problem, may be due to too much or too little moisture. This is easily corrected by appropriately wetting or drying the compost heap. Other conditions can adversely affect microbiological activity. Insufficient aeration (usually indicated by a smell of rotten eggs) can be solved by turning the pile. If the C/N ratio is too high, sources of N can be added (if the C/N ratio is lowered too much, an odor of ammonia will be present). If the pile is too small, it can be enlarged to retain more heat. If the external temperature is cold, the pile can be insulated with burlap, soil, or leaves. It may be necessary to wait until the weather warms if the outside temperature is too low.

Occasionally in piles that are too large, the temperature may fall abruptly during the thermophilic stage because microbes are killed by temperatures over 70°C. The pile will eventually recover, but heat can be dissipated by turning the pile with a fork.

Municipal Processes

Windrow Method. Windrows, or open piles, are probably the oldest form of composting. They can be any convenient length, about 8 to 12 feet wide, and 4 to 6 feet high.

The height is critical. If a pile is too high, it will compress and reduce pore space (47). A compressed pile requires increased turning to combat anaerobic conditions or excessive temperatures. If the pile is too low, it will not retain sufficient heat for rapid decomposition.

Windrows will lose between 20 and 60% of their initial volume, depending on the starting materials and amount of compaction. Weight losses of up to 50% can occur.

Studies at Berkeley (22), showed the windrow method to be satisfactory for composting of municipal refuse. The windrow was employed in studies at Johnson City, Tennessee (37). Leaves are composted at Scarsdale, New York, by the windrow system (208,209).

In Connecticut the most successful municipal composting has been with leaf windrows (206,208,209). Trucks dump in a straight line and a front end loader is used to shape the windrow. A width of 10 feet and a height of 8 feet is optimal for heat retention (47) but is not so large as to cause compaction. Rain supplies the necessary moisture. Although not necessary, the piles are turned every 4 months. These windrows are finished by late summer or early fall without added N. The material can be shredded and then screened to remove stones and debris and to improve spreadability.

Beccari Process. As originally designed, the Beccari process (11-16,64) utilizes a cell equipped with an air valve which loads from the top and unloads from the front. Initially, the material is digested anaerobically. The vents admit air at 65°C and the process becomes partially aerobic after about 18 days. The compost is finished in 35 to 40 days. This process is presently used in Italy and France, and it was used in the United States during the 1920's. Bordas (64) improved the method with a chimney for continuous loading. The Verdier method (64), in which the drainage liquid is recirculated through the compost, is another improvement.

Vuil-Afvoer-Maatschappij (V.A.M.) Process. The V.A.M. process has been used for some time in the Netherlands. Refuse is delivered by rail. In some plants, it is shredded by rasping. The final product, which takes 3 to 5 months to prepare, is screened before sale (55,64).

Dano Process. The Dano process 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 was used in the United States only for a short time (55,64), but it is still employed in Europe.

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Summary

Considerable interest has recently developed in composting as a means of solid waste disposal. This is in addition to the long-standing interest of home gardeners.

Composting is an ancient practice, but most scientific investigations have been conducted within the past 40 years. This bulletin reviews these investigations and discusses current Station research on improving the composting process.

A thorough examination of the biochemical changes and the microbiological activities during composting helps to establish optimal conditions for the process. The importance of regulating temperature, moisture, grinding, aeration, and carbon-nitrogen ratios in maintaining these optimal conditions is described. Changes in composition and their effect on nitrogen chemistry during composting, as well as the role of bacteria, actinomycetes, and fungi are emphasized as an integral part of composting.

Chemical analyses and other indexes of "maturity" of the finished product are discussed as well as the usefulness of compost as a soil amendment.

Finally, methods for preparing compost are summarized.

Acknowledgments

I wish to thank the following people for their very helpful discussions and editorial remarks: Mrs. S. Anagnostakis, Dr. D. Aylor, Mr. S. Bulpitt, Dr. P. Day, Dr. C. Frink, Dr. L. Hankin, Mr. J. Kosman, Dr. B. Sawhney, Dr. G. Stephens, Dr. H. Vickery, Dr. P. Waggoner, and Dr. I. Zelitch. I also thank J. Marcucci and G. Smith for their library assistance on the original version and Renée Shapiro for her library assistance on the revised version.