THE SCIENCE OF COMPOSTING

ELIOT EPSTEIN

President, E&A Environmental Consultants, Inc.
Canton, Massachusetts
Adjunct Professor of Public Health
Boston University School of Public Health

TECHNOMIC
PUBLISHING CO., INC.

LANCASTER · BASEL

The Science of Composting

a TECHNOMIC ® publication

Published in the Western Hemisphere by
Technomic Publishing Company, Inc.
851 New Holland Avenue, Box 3535
Lancaster, Pennsylvania 17604 U.S.A.

Distributed in the Rest of the World by
Technomic Publishing AG
Missionsstrasse 44
CH-4055 Basel, Switzerland

Printed in the United States of America
10 9 8 7 6 5 4 3 2 1

Main entry under title:
The Science of Composting

A Technomic Publishing Company book
Bibliography: p.
Includes index p. 483

Library of Congress Catalog Card No. 96-61583
ISBN No. 1-56676-478-5

Epstein, 1997

The science of Composting

CHAPTER 5

Stability, Maturity, and Phytotoxicity

INTRODUCTION

The ultimate goal in composting is to produce a humus-like product that can be used for soil improvement and plant growth. Analytical procedures for determining inorganic elements and organic compounds that can affect plant growth have been well defined. Soil and plant analytical procedures are known and accepted (*Methods of Soil Analysis,* American Society of Agronomy, 1982).

It has been much more difficult to assess and quantify the biological manifestations that occur during composting, however. In lieu of definitive chemical methods, the composting industry for decades relied on bioassays that determined plant growth response. At the same time, there was a constant search for chemical methods that could provide quick results and could be related to the state of decomposition of the compost. Some of the early literature relied on techniques taken from soil science. Others sought to examine chemical changes that occurred during the decomposition of organic matter while being composted.

Soil science has long recognized that from a microbiological view, the measurement of total carbon in a soil was a poor representation of the potential activity. Methods by Schollenberger (1945), Walkley and Black (1934), Walkley (1947) and Mebius (1960) attempted to measure available carbon in soils. The Walkley-Black method is still readily accepted and used in the evaluation of available carbon in soils.

Using these techniques and adapting wet chemistry, Epstein (1956) studied the decomposition of organic matter in soil and its effect on soil aeration. Figure 5.1 depicts carbon dioxide evolution while Figure 5.2 shows the

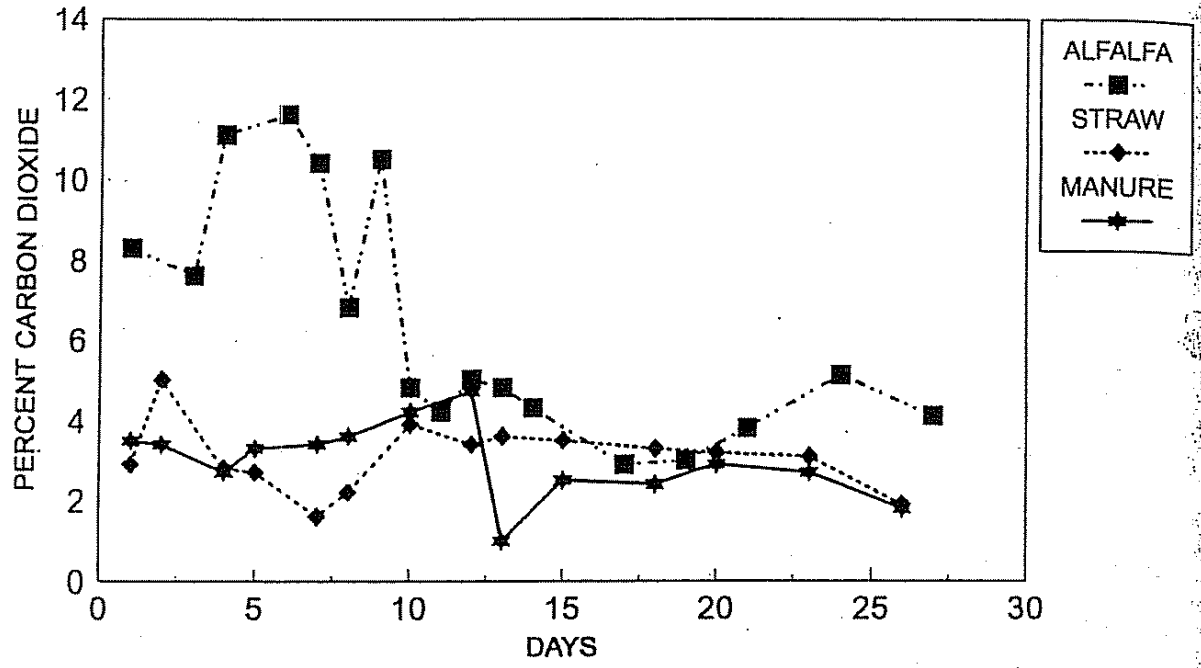


FIGURE 5.1. Percent carbon dioxide at 20 cm soil depth with incorporation of different types of organic matter. (From Epstein, 1956.)

oxygen content in soil as a result of incorporating different types of organic matter into soil. When fresh organic matter, alfalfa or an unstable compost, is incorporated into a soil, the rate of CO_2 evolution is high. Percent CO_2 increases and percent O_2 decreases. As the microbial community consumes the readily available carbon, the rate of CO_2 production decreases; the percent CO_2 decreases and, if the soil pore space is free (water does not

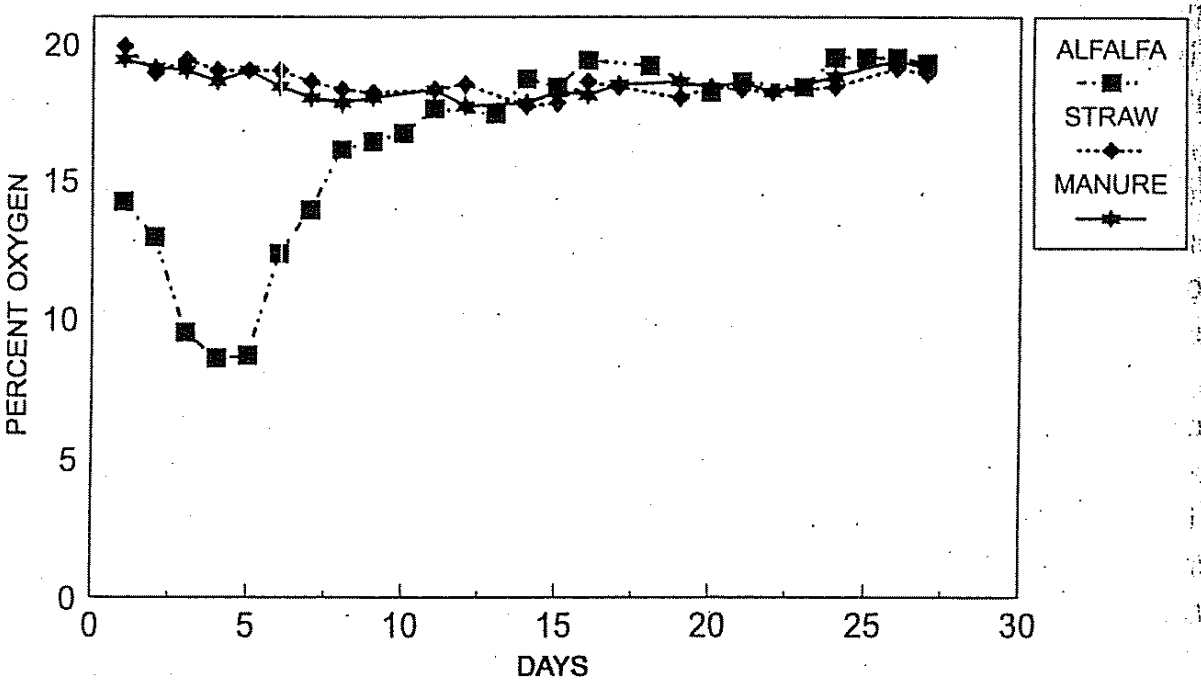


FIGURE 5.2. Percent oxygen at 20 cm soil depth with incorporation of different types of organic matter. (From Epstein, 1956.)

occupy the pore space), oxygen diffuses into the soil and the percent O_2 increases. If the soil pores are blocked, however, anaerobic conditions can set in and plants suffer. Soil aeration can affect plant water relations and nutrient uptake (Chang and Loomis, 1945; Lawton, 1946; Epstein, 1956; Epstein and Konke, 1957).

As early as 1924, Starkey (1924) reported that CO_2 evolution in the soil can serve as an indication of the process of decomposition. This was substantiated by Allen et al. (1934) and Bodily (1944). It was difficult to establish a relationship between microbial counts and CO_2 production (Engle, 1934; Vandecavey and Katznelson, 1938).

Other researchers delved into the chemical makeup of organic matter and the changes that occurred during the decomposition process. Waksman's (1936) proximate analysis of organic matter attempted to evaluate the organic components through fractionation of organic matter. These compounds consisted of sugars, starches, and other simple carbohydrates, fats, fatty acids, cutins, sterols, hemicellulose, cellulose, and lignin. It was argued that if one could follow the changes that occurred in such compounds as sugars, hemicellulose, cellulose, and lignin, or evaluate the formation of humus, it would be possible to identify the path of degradation and determine a stage where the rate of decomposition is very slow. Scientists involved in composting research attempted to use these techniques to identify the state of decomposition during composting. Table 5.1 provides a comprehensive list of the methods used to assess compost stability and maturity.

Two terms subsequently appeared in the literature, "stability" and "maturity," and these were often used interchangeably. The two terms are not synonymous, however. *Stability is a stage in the decomposition of organic matter and is a function of biological activity. Maturity is an organo-chemical condition of the compost which indicates the presence or lack of phytotoxic organic acids.* It must be noted that the term "stabilization" is used in many different contexts. For example, USEPA classes biosolids stabilization as related to pathogen reduction. Biosolids stabilization has also been used to indicate odor and volatile solids reduction (Bruce and Fisher, 1984).

Figure 5.3 illustrates the organic-matter decomposition curve during composting. At the peak of decomposition when microbial activity is greatest, the compost is highly unstable; that is, it is undergoing rapid changes. These changes are principally the result of microbial utilization of the easily decomposable compounds. As these compounds are utilized, the organisms still seek other sources of carbon for energy. They proceed then to attack the more complex-structured carbonaceous compounds. As a result, activity begins to decrease. When the rate of decomposition becomes very low, the compost is "stable." Stable does not mean that no further change will occur, but rather that the rate of decomposition is stable at a very low rate. In fact,

TABLE 5.1. Methods Used to Assess Compost Stability and Maturity.

1. Chemical Methods
   a. Carbon/nitrogen ratio
   b. Nitrogen species
   c. pH
   d. Cation exchange capacity
   e. Organic chemical constituents
   f. Acetic acid
   g. Starch-iodine
   h. Reactive carbon
   i. Humification parameters
      —Humification index
      —Relative concentrations of fulvic acid to humic acid
      —Humic substances
      —Functional groups
   j. Optical density
2. Physical Methods
   a. Temperature
   b. Color, odor, specific gravity
   c. Fluorescence
3. Plant Assays
   a. Cress seed
   b. Wheat and rye grass germination
   c. Root color
4. Microbiological tests and activity
   a. Respiration—oxygen depletion
   b. Respiration—carbon dioxide evolution
   c. Microbial changes—content of fungi, actinomycetes, etc.
   d. Enzyme activity

the rate is often so low that it is difficult to detect changes over short periods of time.

Maturity is a function of the organo-chemical properties of the compost as related to phytotoxicity to distinguish between phytotoxic effects due to inorganic chemicals and salinity. The organo-chemical phytotoxic effects are primarily attributed to fatty acid formation. However, other organic compounds are present in immature compost, which could also result in phytotoxicity.

Factors other than organo-chemicals that can cause phytotoxicity or inhibit germination and plant growth include salinity, trace elements, heavy metals, ammonia, carbon dioxide, soil compaction, soil moisture, and soil aeration.

Why should compost be stable and is a stable product always necessary?

An unstable product continues to decompose rapidly. Unless the compost is cured under aeration, anaerobic conditions will occur in the center of piles. Anaerobic conditions generate reduced compounds of C, N, S and P. Amines, sulphamines, mercaptans, skatoles, and H_2S are malodorous (Mather et al., 1993b).

In addition, methane and phosphine can be produced from C and P, which are inflammatory gasses (Mathur et al., 1993a). Fires in immature biosolid compost have occurred at the Baltimore composting facility and others. Similarly, in Riverside, California, fires have occurred in large piles of immature manure compost. Mather et al. (1993b) also indicated that stockpiles of immature compost may release methane and nitrous oxide to the atmosphere and that these gasses are considerably more effective than CO_2 as greenhouse gasses. Mather et al. (1993b) reported that bagged immature compost erupted as a result of gasses.

A stable product, on the other hand, does not produce odors in storage. If the product is bagged at the proper moisture content, opening the bag should not release putrescible odors. Further, when incorporated into the soil, a stable product does not decompose rapidly and utilize nitrogen required for plant growth. When a compost that has a high C/N ratio is added to soil, the microbial population competes with plants for soil nitrogen. In this case, plants typically exhibit chlorosis, yellowing of the leaves, indicating nitrogen deficiency. If organic materials with low C/N ratios are added to soil, ammonia can be released, which can cause phytotoxicity (Dowdy et al., 1976). Ammonia in refuse extracts has been shown to reduce germination and root elongation (Wong, 1985).

The decrease in oxygen in soil can result in reduced oxygen levels or anaerobic conditions, which not only affect plant growth but also soil chemical species, heavy metal solubility and uptake of nutrients.

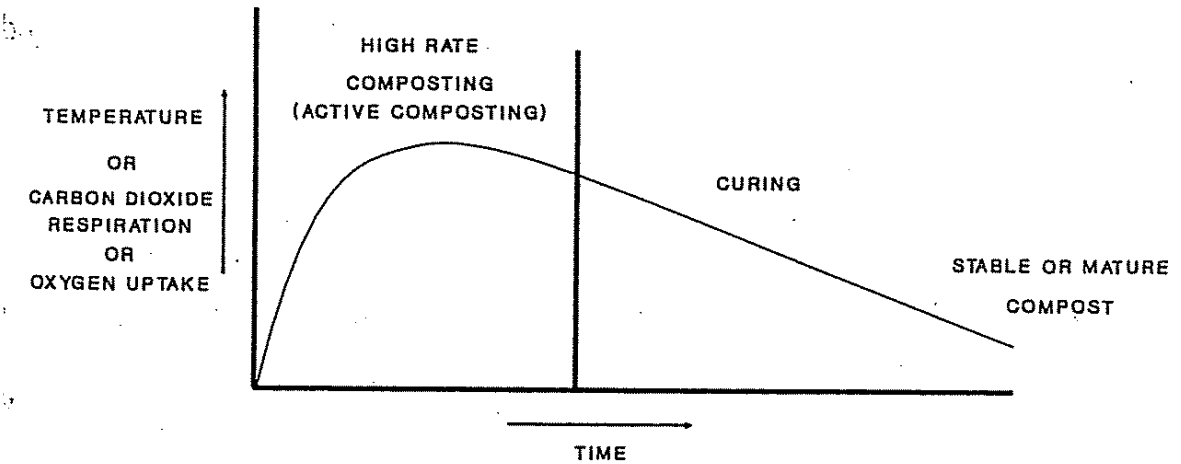


FIGURE 5.3. Phases during composting as related to temperature, and carbon dioxide respiration or oxygen uptake.

Composting to the point of stability often requires considerable time, particularly if cellulolytic feedstocks (e.g., MSW) are used. Stability with high cellulolytic materials can be achieved by proper feedstock preparation such as particle-size reduction and C/N ratio adjustment. Many composting operators want to market material as soon as possible in order to reduce storage space requirements and materials handling.

In certain situations, an unstable product could be used. For example, in remote land-reclamation areas, unstable compost could be applied and the amended soil could be planted at a later date. However, even this practice should be avoided since storage and transportation might release odors. Further, E&A Environmental Consultants, Inc. (1987) found that using uncured compost resulted in depressed growth of jack pine, red pine, white spruce, Siberian pea shrub, and chokecherry seedlings, which were to be used for mine land reclamation. In a subsequent application of cured compost to a taconite mine tailing, the composted plots maintained vegetation for two growing seasons whereas the fertilized plots had no vegetation. Applying uncured compost to land without planting for one to two months would reduce potential phytotoxic effects.

One objective of this chapter is to discuss the various methods that have been used to measure stability and maturity of composts. To be valid, a stability method must relate to physical changes in the compost as a result of microbial degradation. These physical parameters include color, odor, and inability to produce heat if bagged or minimal heat in large piles. Furthermore, a stable compost product should not produce excess CO_2 in the soil or utilize soil nitrogen, which would affect plant growth.

A mature compost should not reduce germination or result in decreased plant growth. Tests for maturity should distinguish between biological impacts on plant growth and chemical effects such as salinity. The stability method should be valid for composts of different feedstocks.

Several recent reviews of the literature focused on stability and maturity; for example, Jimenez and Garcia (1989), Beck & Associates (1990) and Mathur et al. (1993b).

STABILITY AND MATURITY

Many methods have been suggested and evaluated to assess the state of decomposition and the suitability of the compost as a medium for plant growth (Table 5.1). Not all these methods will be discussed here, since several of them have had limited success and were abandoned after initial evaluation.

One of the major early centers of research on composting in the United States was the University of California's Sanitary Engineering Department

at Berkeley. A 1953 Sanitary Engineering Research Project Report stated, "A compost is considered finished when it may be stored in large piles indefinitely without becoming anaerobic or generating appreciable heat and may safely be put on agricultural soil because of its low C:N ratio or the poor availability of its carbon." After 42 years this statement is still valid.

An early review of the methods of measuring maturity as related to raw refuse and/or sewage sludge was made by Keller of the Swiss Water Control Federation (Keller, 1961). Many of Keller's observations are currently being revisited. For example, he stated that first of all a raw refuse-biosolids compost must be hygienic. He also questioned whether short-time decomposition can destroy resistant organisms such as spores and cysts as well as weed seeds. Further, Keller (1961) stated that the most important purpose of applying compost is to raise or maintain the humus content of soils and that the production and use of fresh compost does not result in an increase of humus. Furthermore, he indicated that the use of fresh compost can result in crop failures. He does point out, however, that Dutch experiments have shown favorable results with immature compost on clay soils. This may have resulted from the interaction of the organic matter and the clay particles, yielding increased water permeability and improved soil aggregation.

Chemical Methods

More effort and research have gone into chemical methods for determining stability and maturity than into the biological or physical evaluations. In general, chemical methods require less time and are often more rapid.

CARBON/NITROGEN RATIO (C/N)

C and N are the building blocks of plant and animal cells and, therefore, are impacted by microbial activity. Hence they are the most studied parameters during the decomposition process. One of the most difficult aspects of C determinations is the evaluation of what fraction of the total C is readily available C for microorganisms.

The C/N ratio has been used to indicate the stability of compost. Ratios below 20 were assumed to be indicative of a stable compost. Keller (1961) noted that the C/N ratio was not a reliable indicator of stability due to the large variability. This was further substantiated by Hiari et al. (1983), who found that the C/N ratio varied from 5 to 20 for different feedstocks. Mathur (1991) indicated that a mature compost should have a C/N ratio of about 10 as in humus. This is not readily achieved since different compounds decompose at different rates.

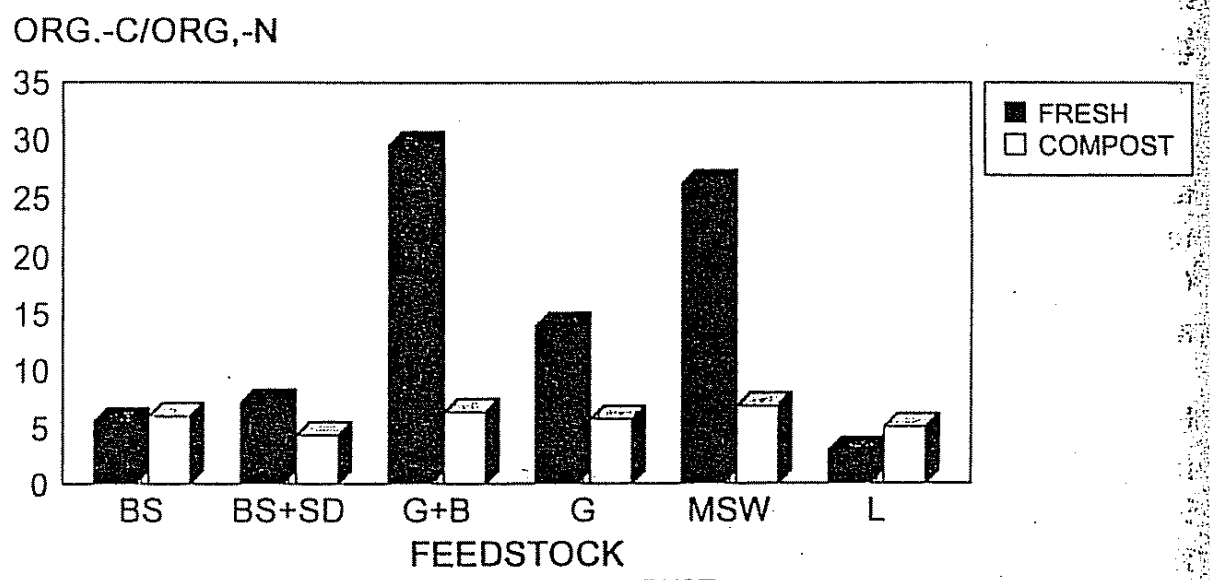
Chanyasak et al. (1983) suggested that the ratio of organic C to organic N

(org.-C/org.-N) of water extracts from compost was indicative of maturity. Evaluating the ratio of org.-C/org.-N in water extracts, Hiari et al. (1983) found that with the exception of biosolids, this ratio was almost 5 to 6 regardless of material (Figure 5.4). The reason that this parameter was not applicable for biosolids was the low initial org.-C/org.-N ratio. Hiari et al. (1983) also found a good correlation between total-C and the ratio of organic-N to total N in water extracts, but not with solid material.

Morel et al. (1985) proposed that the final C/N to initial C/N ratio was a better indicator of maturity or stability, based on the finding that nitrogen-rich feedstocks often resulted in low C/N ratios. No specific values were given for the ratio, which would indicate stability or maturity.

Jimenez and Garcia (1989) utilized data in the literature to determine if this concept was valid. The data indicated that the final C/N to initial C/N ratio ranged widely (0.49 to 0.85) for different composting times. Some of the lowest and highest values were found for the same duration of composting. As a result, Jimenz and Garcia (1985) concluded that the final C/N ratio to initial C/N ratio could be used as a guide but not as an absolute indicator of the degree of compost maturity.

Inbar et al. (1990) found that the C/N ratio decreased rapidly from 27 to 10 during the first 60 days of composting separated cattle manure (Figure 5.5). After 60 days the C/N ratio decreased slightly, to 8.7. The C/N ratio was highly correlated with composting time ($r^2 = 0.991$). Since the data were not related to plant growth, it is difficult to assess when after the 60-day period the compost was considered stable or mature.



BS = BIOSOLIDS; BS+SD = BIOSOLIDS AND SAWDUST
G = GARBAGE; MSW =MUNICIPAL REFUSE;
L = LEAVES.

FIGURE 5.4. Changes in the ratio of organic carbon to organic nitrogen during composting. (Reprinted with permission from Hirai et al., 1983.)

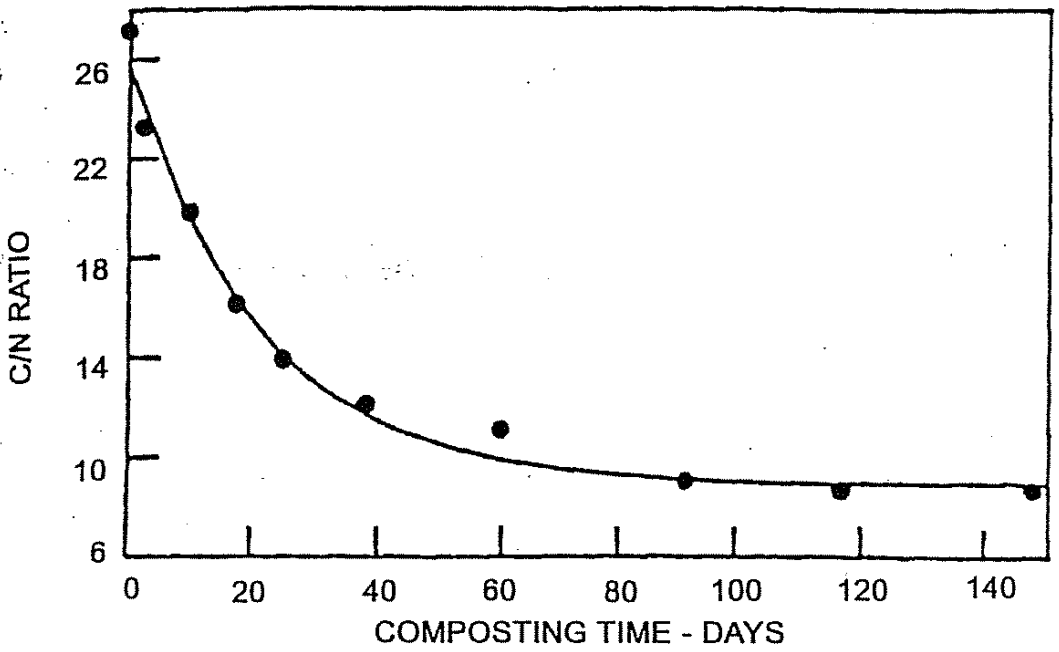


FIGURE 5.5. Changes in C/N ratio during composting of separated cattle manure. (Reprinted with permission from Inbar et al., 1990.)

NITROGEN SPECIES

Changes in nitrite (NO_2), nitrate (NO_3) and ammonia (NH_4) have also been suggested as indicators of maturity.

Spohn (1978) reported that the presence of ammonia indicated that the compost was not cured (ripe), whereas the presence of nitrate indicated that it was well "ripened." Spohn (1978) indicated that N tests alone were not sufficient and that they should be complemented with a sulfide test and a cress seed germination test.

Keller (1961) reported that in some samples of unripe compost, large amounts of NO_2 in relation to NO_3-N were found. However, the ratio of NO_2/NO_3 tests gave only an indication of maturity.

Finstein and Miller (1985) related maturity to the amount of NO_2^- and NO_3^-. The appearance of considerable quantities of these radicals during composting was a sign that the compost was mature. In aerated static pile methods with composting of biosolids, NO_2^- appeared after 86 to 113 days; NO_3^- appeared after 96 to 123 days.

PH

Changes in pH have been noted to occur during the composting period and, therefore, have been considered as a possible indicator of biological activity. Generally, the pH drops during the very early stages of composting

and then increases to a range of 6.5 to 7.5. A typical pH curve was shown in Chapter 3, Figure 3.28. However, exceptions to this "typical" curve exist.

Jimenez and Garcia (1989) noted that acid pH values indicate a lack of maturity due to short composting time or the occurrence of anaerobic conditions. Often with very acid food processing wastes (grape pomace, cranberry waste), the initial pH is low and even under aerobic conditions over long periods of time it remains acid.

Jann et al. (1960) found that when an aerobic stable compost is subjected to anaerobic conditions, there is no further change in pH, and odors are not produced. The pH of the material was slightly alkaline at a pH of 7.5. In general, pH is not a good indicator of stability.

CATION EXCHANGE CAPACITY (CEC)

CEC is a measure of an inorganic or organic particle's ability to sorb or retain cations on its surfaces. Since many cations (K, Ca, Mg, etc.) are important plant nutrients, the higher the CEC, the greater the particle's ability to retain these nutrients so that they may be available to plants.

Harada et al. (1981) found that during aerobic composting, the CEC increased from approximately 40 me/100 g to 70 to 80 during five to eight weeks and then remained essentially the same. A highly significant negative correlation ($r = -0.94$) was found between CEC and the C/N ratio.

Inbar et al. (1990) noted that the CEC increased rapidly with composting time and that over a period of 150 days it was threefold that of the original material (Figure 5.6). A correlation coefficient, $r^2 = 0.990$, was obtained. Similar data were obtained in other studies. A minimum value of 60 meq/100 g is an acceptable state of maturity. Mathur et al. (1993b) indicated that the CEC is not a reliable indicator of maturity since humic substances may vary in CEC partly as a result of the blocking of their exchange sites by complexing ions such as Cu, Fe, and Al, partly due to interaction with amorphous Fe and Al compounds.

ORGANIC CHEMICAL CONSTITUENTS

During composting, changes take place in the major organic constituents that make up the feedstock. One of the earlier attempts to analyze these constituents and follow their changes during composting was carried out by Waksman (1936) using the proximate analysis to evaluate sugars and simple carbohydrates, fats and waxes, hemicellulose, cellulose, and lignin. This was discussed in Chapter 4.

Cellulose content yields a good index of the degree of maturity of the compost (Keller, 1961). Figure 5.7 shows that cellulose decreased with

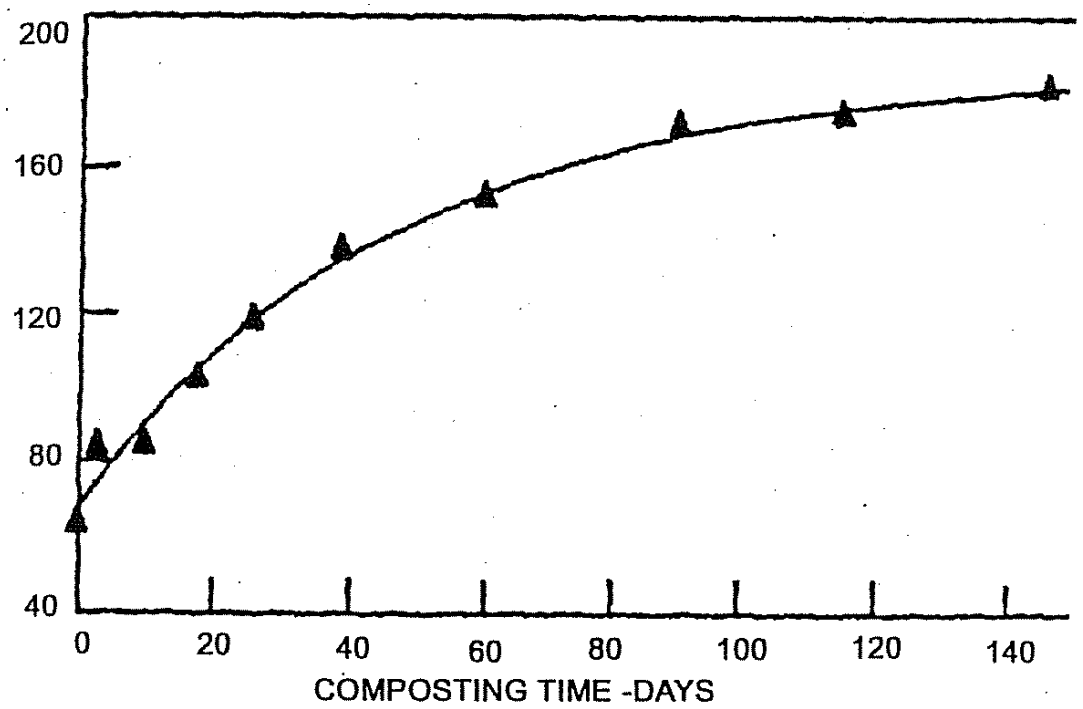


FIGURE 5.6. Changes in cation exchange capacity during composting of separated cattle manure. (Reprinted with permission from Inbar et al., 1990.)

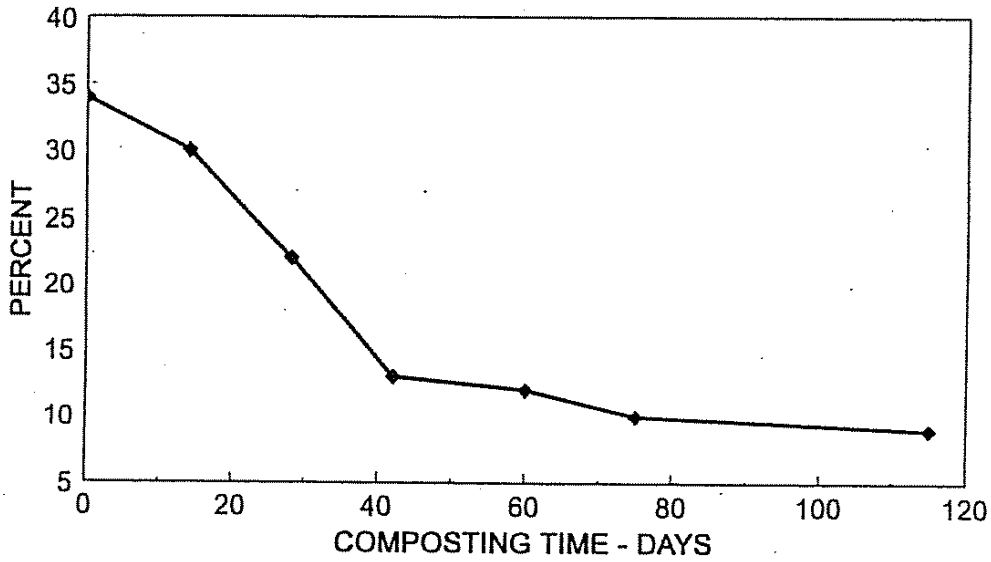


FIGURE 5.7. Changes in percent cellulose during the windrow composting of refuse. (Data from Keller, 1961.)

duration of composting. Several methods have been suggested to determine cellulose.

Inoko et al. (1979) studied the changes in hemicellulose and cellulose (reducing sugars) during composting of city refuse. They reported that the content of these polysaccharides decreased from approximately 36% of the total dry weight to about 20% after 60 days. A positive correlation was found between the polysaccharides and the C/N ratio (Jimenez and Garcia, 1989). With nine samples, the regression equation was:

$$\text{Reducing sugars} = (1.749\ \text{C/N}) - 6.424r = 0.909$$

Microbial metabolic activities on organic matter take place in the water film on the surfaces of particles. Hirai et al. (1983), therefore, studied the changes of water soluble components during composting. Amino acids, low fatty acids, and polysaccharides greatly decreased during the composting of refuse and garbage; however, composting of biosolids resulted in a decrease of amino acids and low fatty acids but not polysaccharides or peptides. In fact, polysaccharides and peptides increased. Peptides also increased during composting of garbage. Finally, total organic C decreased during the composting of refuse, garbage, and biosolids (Figure 5.8).

Recently, Zhang et al. (1992) suggested that reactive carbon could be used to assess maturity. Reactive-C measurement is an attempt to quantify the available C, which microorganisms utilize for energy. The approach modi-

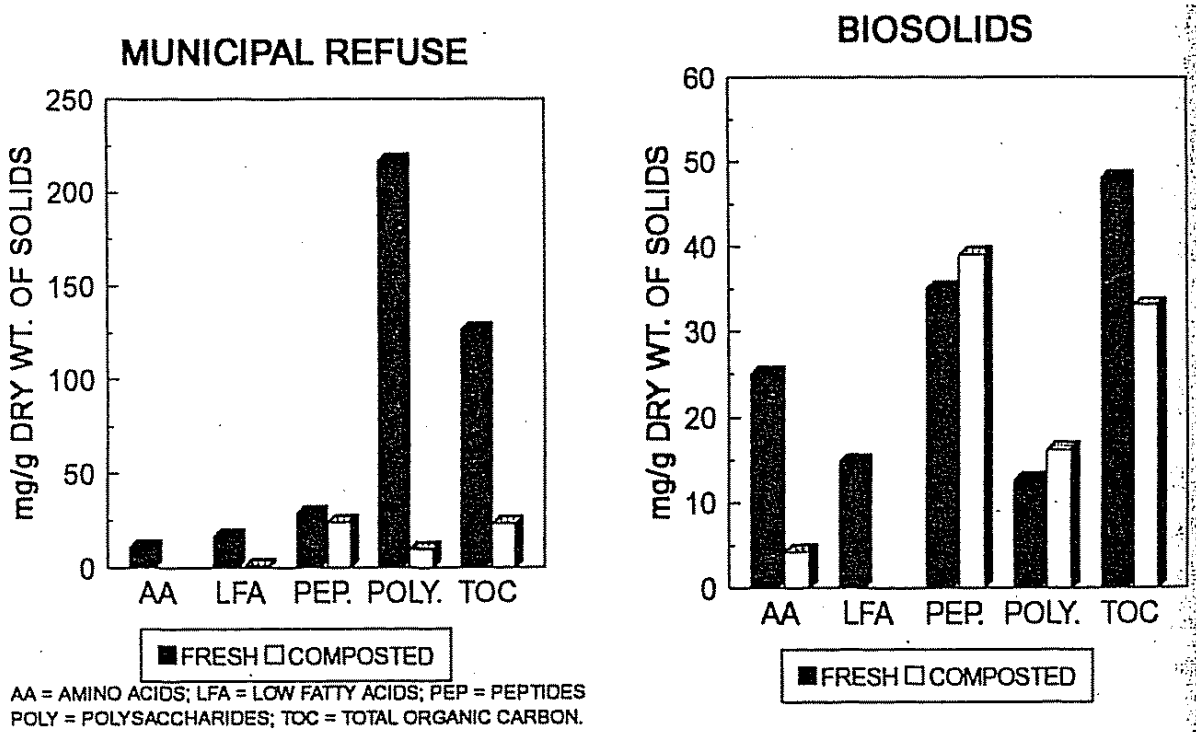


FIGURE 5.8. Changes in several chemical components during composting of refuse and biosolids. (Reprinted with permission from Hirai et al., 1983.)

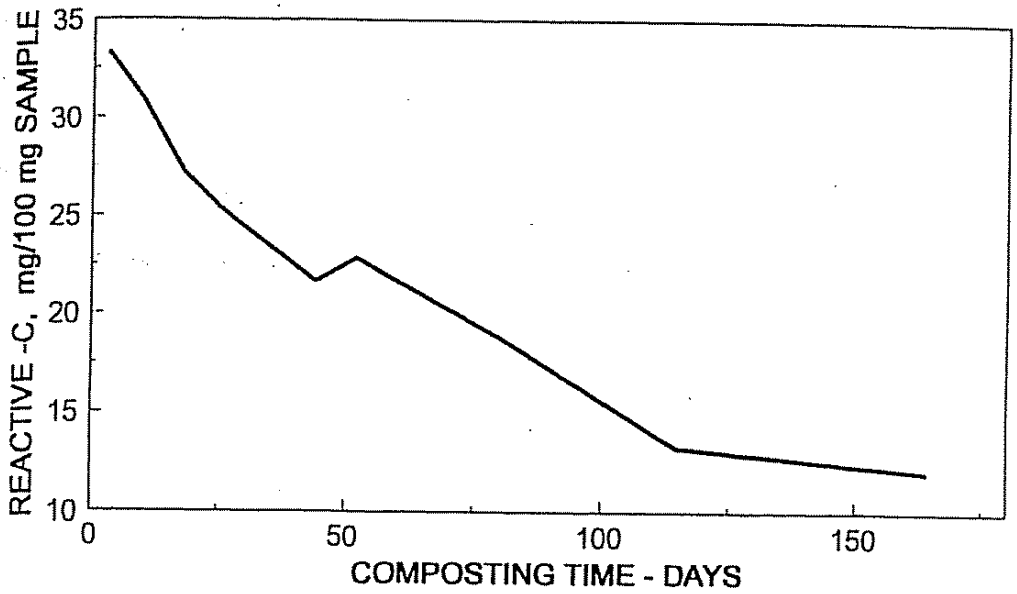


FIGURE 5.9. Changes in reactive-C during composting of MSW. (Data from Zhang et al., 1992.)

fied the Walkley-Black methods used in soils for measuring available C. Changes of reactive C during composting are shown in Figure 5.9.

As illustrated, the initial values of approximately 33 mg reactive-C/100 mg sample and final values of approximately 11 mg/100 mg were similar to 12 to 16 mg/100 mg obtained with yard waste. However, in the case of a biosolids-MSW co-compost, the final value remained near 30 mg/100g. This may indicate that the method does not apply to all organic materials to be composted or that in the case of biosolids or other material, some factor may interfere with the determination.

The authors indicated that since the MSW tested retained some phytotoxic properties, reactive-C is not a good indicator of maturity. One of the difficulties with this method is the small sample size of 200 mg. In fact, the authors stated that the sample size must be less than 200 mg dry weight per assay. Above this size, the results were not linear. This method may require a larger number of samples to ascertain its reproducibility. Data for other materials did show good reproducibility.

HUMIFICATION PARAMETERS

The changes in the constituents of organic matter represent a potential for evaluating the degree of stabilization. Several studies have looked at changes in humic acid, fulvic acid and other products of decomposition.

Humification Index

Roletto et al. (1985) coined the terms "humification ratio" and "humifi-

cation index." Humification ratio (HR) was the percentage of total extractable humic-C (C-ext) as related to the total organic-C (C-org) (i.e., HR = C-ext × 100/C-org). The humification index (HI) was defined as the percentage humic acid C (CHA) as related to the C-org (i.e., HI = CHA × 100/C-org).

As a result of the extraction procedure, the authors indicated that the method overestimated the extent of humification in the early stages of composting. No comparisons were made at different stages of composting with other parameters.

Relative Concentrations of Humic Acid to Fulvic Acid

Saviozzi et al. (1988) attempted to follow the changes in decomposition (i.e., maturation process) by evaluating various humification parameters. They used a different "humification index," which was based on the ratio between the organic C of the non-humified fraction and that of the humic acid (HA) + fulvic acid (FA). The HI seemed to be appropriate for evaluating stability but was deemed to be complicated and slow. The authors recommended that considerably more analyses with different materials needed to be tested before the methodology could be accepted.

Humic Substances

Another approach has been to evaluate the total content of humic substances (HS). Inbar (1989) reported that the total content of humic material extracted from separated cattle manure compost increased from 377 to 710 g/kg OM (see Figure 4.14, Chapter 4). Humic material increased rapidly during the first 60 days and from 60 to 140 days a very gradual change was noted.

Functional Groups

The advent of sophisticated organic chemical methods provided scientists with tools to evaluate changes in specific C compounds. Two more recent methods include solid-state cross-polarization magnetic angle spinning ^{13}C-nuclear magnetic resonance (CPMAS^{13}C-NMR) and infrared spectroscopy. Distribution of C in several organic compounds using CPMAS^{13}C-NMR for fresh and composted manure is shown in Figure 4.13, Chapter 4 (Inbar et al., 1990). This method reflected the changes in various C compounds during decomposition of cattle manure.

The humification methods require sophisticated expensive equipment and, therefore, are not suited for routine evaluation of stability for field

operations. However, they can be extremely valuable by furthering our knowledge on the transformations that occur during composting. They may also provide validation of simple techniques that could be used for routine stability evaluations.

OPTICAL DENSITY

Mathur et al. (1993a) and Schnitzer et al. (1993) proposed the use of optical density, or colorimetry, to evaluate maturity. The method is based on absorption by water abstracts of composts at 665 nm of visible light. Data presented compared the results to temperature, % O_2, biological oxygen demand (BOD), dissolved organic carbon (DOC), NH_4^+, NO_3^-, and cress germination tests. The optical density data (Mathur et al., 1993a) only showed lower adsorption (E665) at the end of 59 days of composting. Variation between replicates was great. For three of the four treatments, the difference in optical density between 40 and 59 days of composting was significant at a 95% confidence level. Average cress germination tests for four manure treatments at 40 and 59 days were 78% and 102%. The coefficient of determination (R^2) between absorption at various optical densities and DOC was low (<0.73).

No other statistical data were provided. At this time, limited testing on composted manures using passive aeration in bins cannot justify the use of this method to determine what the authors termed "biomaturity" or "maturity" as a result of biological activity.

Schnitzer et al. (1993) indicated that optical density of water extracts was due to many intermediate products of decomposition. Optical density decreased during composting as a result of the formation of "new" humus. Composting does not produce humus, but rather a state leading to the ultimate production of humus.

Physical Methods

TEMPERATURE AND HEAT OUTPUT

Temperature is a reflection of the microbiological activity during composting. Depending on the feedstock and its physical state, the temperature usually rises within the first few days of composting from ambient to 60°C to 70°C. It remains at this level with minor fluctuations for several days and then gradually decreases to a constant state near ambient. The point at which temperatures approach ambient may be considered the state of stability of the product.

Heat output is a function of microbial activity. Niese (1963) used Dewar flasks to measure heat production as related to respiration. It was found that the temperature increased to a maximum and then declined as the process progressed. Heat loss could not be prevented even with Dewar flasks when using small amounts of organic matter. When heat was not dissipated temperatures increased.

Maximum temperatures of about 75°C occurred. The maximum temperatures were dependent on the ambient temperature. Unless the surrounding temperature of the flask was controlled, inaccurate results were obtained. Dewar's data indicated that temperatures of self-heating, with large temperature differentials between flask and ambient temperature, were not the same as those present during spontaneous self-heating and were, therefore, inaccurate.

Niese (1963) indicated that with a high bacterial count, the temperature rose immediately; but at low bacterial counts, there was a delay in temperature increase. In 8 of 10 experiments, the number of mesophilic bacteria were between 2×10^9 and 15×10^9/g dry weight. Self-heating temperatures increased rapidly, reaching 45°C in 7–15 hours. The maximum temperature ranged from 73.5°C to 77.5°C. Based on these results, it was concluded that self-heating resulted in maximum temperatures if sufficient nutrients were available to the microorganisms.

From these studies, Niese stated that a judgment of decomposition of refuse and refuse compost can be made using several stages of temperature (Table 5.2). However he cautioned that this is only a guide and that comparisons with plant growth need to be made. Spohn (1978) stated that heating in a pile or a well-insulated aerated vessel is indicative that the compost is unstable or "unripe," but that the lack of temperature does not indicate that the compost is "ripe" or stable.

TABLE 5.2. The Relationship of Degree of Decomposition to Temperature as Determined by Self-Heating in a Dewar Flask (Niese, 1963).

Maximum Temperature Achieved	Degree of Decomposition
Above 70°C	0 Raw refuse, very slight decomposition
60–70°C	1 Moderate decomposition
45–60°C	2 Medium decomposition
30–45°C	3 Good decomposition
Under 30°C	4 Decomposition mostly or completely finished

Recently, the Dewar flask-heat output method was reintroduced by German and U.S. scientists (Brinton et al., 1993; Woods End Research Laboratory, Inc., 1993). Currently there is little information on the relation of this method to other stability measurements or plant growth.

Jann et al. (1960) felt that temperature was not a good criterion by which to evaluate maturity because "a low temperature could be the result of loss of aerobic conditions and of loss of moisture and the production of excessive heat during the high plateau could inhibit microbial activity." This has been observed at numerous composting facilities; temperatures drop because of inhospitable conditions for microbial activity, and material is considered stable. Later, rewetting or long-term storage of the material results in reactivation and subsequent anaerobic conditions.

COLOR, ODOR, STRUCTURE AND SPECIFIC GRAVITY

Keller (1961) indicated that the physical properties of color, structure, odor, and specific gravity were not specific enough to assess stability. The following were some of his criteria. A mature compost should be dark brown to black regardless of the feedstock. Mature compost should have "smells like forest soil (typical soil odor is caused by actinomycetes)."

Recently two USDA scientists (Becker, 1995) determined that the smell of soil is primarily the result of two gasses, geosmin and 2-methylisoborneol, which are by-products of fungi and actinomycetes. The scientists are developing an odor-based soil test as a barometer of organic activity. If these two gasses are present in compost, it is possible that they could be used to determine stability.

Odor and color are too subjective to provide accurate assessment of stability, and structure is too difficult to describe and measure accurately. The specific gravity increases during composting. Ranges in a mature compost are from 0.5 to 0.9 g/cc. Because of this wide range, this parameter has not been deemed accurate.

PLANT ASSAYS

Plant assays are used to evaluate maturity but have not been used to determine stability. Keller (1961) used plants to determine phytotoxicity in field trials. However, he felt that these tests were subject to error and recommended they only be used in conjunction with other tests. Keller (1961) studied the relationship between wheat growth and age of compost. With 100% compost, yield was depressed for 45-day-old compost but 60-day-old compost produced a 49% increase over the control.

In 1969 the cress seed germination and elongation tests were described along with two analytical methods (Spohn, 1969). Prior to that time, other plant tests were used. Zucconi et al. (1981a) studied the cress seed germination test and established a germination index, obtained by multiplying the percent germination by the percent root growth as related to control. The presence of phytotoxic compounds indicated that the compost was not stabilized.

Windrow and static piles were compared. Toxicity disappeared much more rapidly in the static piles than in windrows. This is not surprising since within a very short time after turning the windrow it becomes anaerobic, and under these conditions organic acids are produced, which can be phytotoxic.

Studies by E&A Environmental Consultants, Inc., found a correlation between poorly stabilized compost and cress germination, but highly stable compost did not relate to cress germination. As indicated earlier, the confounding effects of other chemical parameters including salinity, C/N ratio, and pH can affect germination and provide erroneous conclusion regarding the maturity of the compost.

Other plants, cucumber, ryegrass and radish have been used. Iannotti et al. (1994) found that these plants differed in their response to MSW compost treatments.

No single plant bioassay has been identified as related to maturity of compost. Several germination and growth tests may be needed using different plants to assure users of the maturity of compost. Alternatively, a method that would remove the confounding effects of salinity and other factors could be valid.

MICROBIOLOGICAL TESTS AND ACTIVITY

Since stability represents the state of microbiological activity, measurements of respiration either through CO_2 evolution or O_2 uptake should provide the best indication of this state. The problem with respiration measurements, as well as most chemical measurements, is the use of small, disturbed samples. If a material is homogeneous and represents the entire mass, then the measurement would indicate the state of stability. However, many compost products are far from uniform. For example, biosolids are often composted with wood chips, where a single wood particle can offset results. MSW often includes inerts, plastics, and other contaminants that affect the results. Yard waste also may contain woody particles that skew the data. Pressel and Bidlingmaier (1981) indicated that sample conditions and preparation could significantly affect measurements of oxygen uptake. Moisture content of the sample was directly related to respiratory activity.

Frost et al. (1992) pointed out that a good assay avoids excessive screening or grinding as it will increase the surface area and provide for an increase in

microbiological activity and an indication of instability of the compost. Their data confirmed Pressel and Bidlingmaier's (1981) finding that moisture content of the sample can affect stability determinations. Frost et al. (1992) indicated that stability measurements must be made on samples having a moisture content of 50% to 65% on a weight basis. The major microbial-related tests are:

(1) Respiration—carbon dioxide evolution
(2) Respiration—oxygen depletion
(3) Microbial changes—content of fungi, actinomycetes, etc.
(4) Enzyme activity

Respiration—Carbon Dioxide Evolution

The methodologies for CO_2 have been derived from respiration studies in soils (Epstein, 1957; Bartha and Pramer, 1965; Anderson, 1982). Two principal methods may be used to determine the carbon dioxide respiration rate. One method (Bartha and Pramer, 1965) is based on a single point in time. CO_2 is trapped in an alkaline solution and alkaline solution is titrated to determine the extent of the reaction. CO_2 is determined over a four-day period. Respiration is expressed as mg/CO_2 C per gram of compost per day, or mg CO_2 per kg of biological volatile solids (VS) per hour. The term "biological VS" is used to distinguish from non-biological material such as plastics.

High respiratory activity indicates greater microbial activity as C is being transformed to CO_2. A low respiration activity indicates that the available C has essentially been utilized. E&A has established a compost stability index based on a large number of samples for different feedstocks in relation to their decomposition time. Different stages of stability as related to CO_2 evolution are shown in Table 5.3. Compost is considered relatively stable when the respiration rate is less than 5 mg CO_2-C/g compost C. Rates over this amount reflect different stages of instability. The advantage to this method is its simplicity and low cost.

Another approach that measures continuous CO_2 evolution has been used to measure soil organic matter decomposition (Epstein and Kohnke, 1957). This method allows for continuous monitoring of CO_2 and determining the rate of respiration over time.

Respiration—Oxygen Uptake

Oxygen uptake as a result of microbial activity has been used for many years (Epstein and Kohnke, 1957; Pressel and Bidlingmaier, 1981). Pressel

TABLE 5.3. Compost Stability Index Based on Carbon Dioxide Evolution.

Respiration Rate (mg CO_2-C/g compost C-day)	Rating	Characteristics
<2	very stable	well cure; no malodors; earthy odor
2–5	stable	cured compost; minimal impact on soil dynamics
5–10	moderately stable	uncured compost; some malodor potential; addition to soil may immobilize N; high phytotoxicity potential; not recommended for growing compost from seed
10–20	unstable compost	very immature compost; high malodor and phytotoxicity potential; not recommended for growing plants from seed
>20	very unstable compost	extremely unstable material; very high malodor and phytotoxicity potential; not recommended for use

Source: E&A Environmental Consultants, Inc., 1994.

and Bidlingmaier (1981) stated that the specific biological oxygen consumption or respiratory activity in a sample of compost was indicative of the compost's state of decomposition. Willson and Dalmat (1986) determined oxygen consumption rate by measuring the decrease in partial pressure of oxygen. A 75% decrease in respiration was observed during curing of biosolids composting.

Frost et al. (1992) and Iannotti et al. (1994) evaluated a dissolved O_2 test, which requires only several hours in contrast to much longer times for CO_2 evolution determinations. Again, this method determines a single point in time. The method provides for on-site measurement of respiration and compost stability. As Frost et al. (1992) noted, sample drying and anaerobic samples give false results. Samples must be pre-incubated overnight. The change in % O_2 in air is converted to an O_2 based on VS as follows:

$$\text{Mean } O_2 \text{ uptake} = \frac{-CVS60D}{KW_tVS}$$

where

C = oxygen content by volume in the air, which is usually 20.8% and expressed as a fraction of 0.21
V = volume of air in flask (mL)
S = slope of relative O_2 uptake rate (% saturation per minute)
60 = factor to change minutes to hours
K = constant factor based on the calibration value corrected for elevation above sea level based on the dissolved oxygen recommendations of the instrument manufacturer
W_t = compost dry matter weight used in grams

Figure 5.10 shows data obtained by Iannotti et al. (1994) and compares the O_2 uptake and CO_2 evolution data. A correlation coefficient of -0.80 was obtained between composting time and O_2 respirometry. In comparison, CO_2 respirometry data had a correlation coefficient of -90. Both were highly significant. Oxygen respirometry correlated well with maturity as determined by ryegrass growth (Figure 5.11). The index for O_2 is shown in Table 5.4.

E&A Environmental Consultants, Inc., has used the CO_2 respirometry method for several years applied to a wide variety of feedstocks. Based on the large data base, an index was developed as shown in Table 5.3.

MICROBIAL CHANGES

During composting the microbial populations change (see Chapter 3, Microbiology). Several researchers indicated that these changes can be indicative of the state of stability or maturity (Keller, 1961; Citernesi and De Bertoldi, 1979). Keller (1961) noted that actinomycetes appeared at the later stages of composting. Citernesi and De Bertoldi (1979) found that thermophilic bacteria decrease as the compost approaches maturity and that a total count of microorganisms may be indicative of the state of compost maturity. Microbiological methods are more cumbersome and not suited for routine evaluation of stability.

ENZYME ACTIVITY

Microbial enzymes' activities may indicate changes in carbon substrates and may, therefore, be good indicators of the status of the composting process (Herrmann and Shann, 1993).

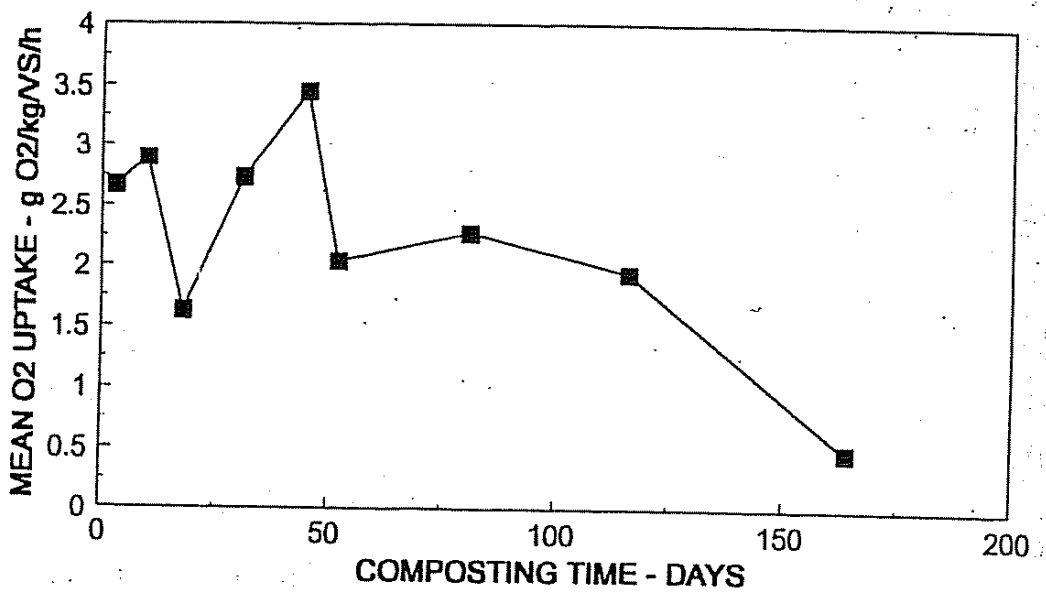
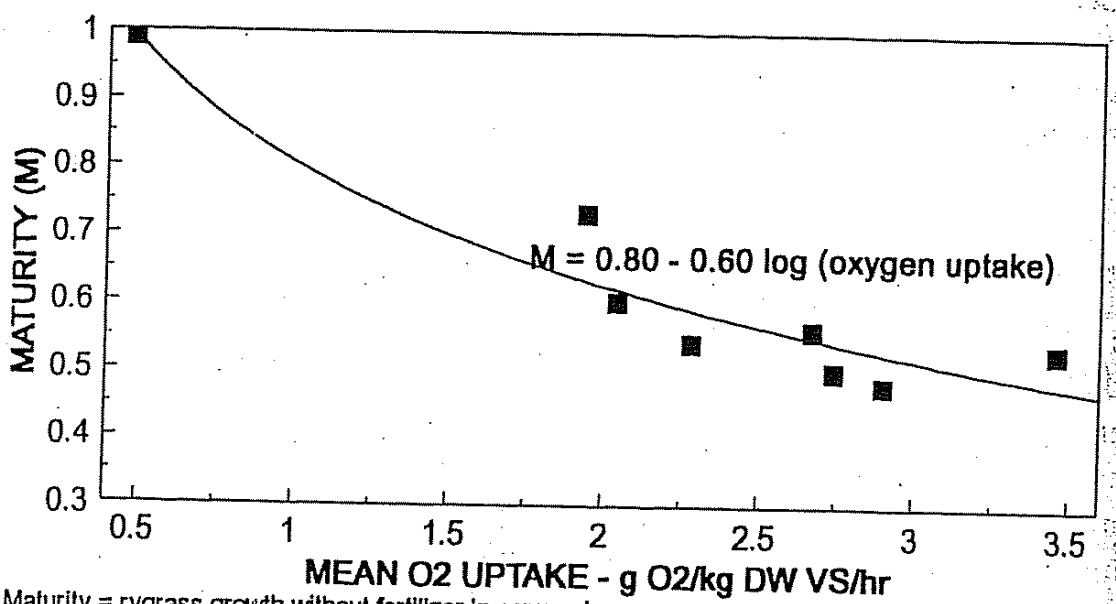


FIGURE 5.10. Changes in rates of respiration based on oxygen uptake per gram of volatile solids during MSW composting. (Reprinted with permission from Iannotti et al., 1993.)



Maturity = rygrass growth without fertilizer in compost divided by growth in fertilized peat.

FIGURE 5.11. Relationship between rate of respiration as measured by oxygen uptake and growth of ryegrass. (Reprinted with permission from Iannotti et al., 1993.)

TABLE 5.4. Compost Stability Index Based on O_2 Uptake.

Respiration Rate (mg O_2/g *VS* × hr)	Rating	Characteristics
0–0.5	very stable	—well cure —no odors —no continued decomposition
0.5–1.0	stable	—cured compost —limited odor potential —minimal impact on soil carbon and nitrogen dynamics
1.0–1.5	moderately stable	—uncured compost —minimal odor production —addition to soil may result in nitrogen immobilization —high phytotoxicity potential —not recommended for growing plants from seed
1.5–2.0	unstable compost	—very immature compost —high odor and phytotoxicity potential —not recommended for growing plants from seed
>2.0	unstabilized material	—extremely unstable —very high odor and phytotoxicity potential —not recommended for use

Source: E&A Environmental Consultants, Inc., based on Ionnatti et al. (1994).

Keller (1961) evaluated the reductase enzyme activity proposed by Buck-steeg and Thiele (1959). It was reported that reductase activity in biosolids was related to oxygen consumption and the number of organisms. However, Keller (1961) did not find that the method was appropriate for compost.

A more recent study evaluated several enzymes including endo-cellulase, glucosidase, lipase, and phosphatase (Herrmann and Shann, 1993). For both endo-cellulase and glucosidase activity, there was relatively little change during the first 80 days of composting. Peak activity occurred during the curing phase at approximately 112 days and then decreased rapidly. This peaking was believed to be the result in a shift towards utilization of the more recalcitrant carbon sources of cellulose, lignocellulose and lignin. The activity of these enzymes does not appear to be a good indicator of changes occurring during composting. With the alkaline and acid phosphatase activi-

ties, which make organic phosphorus available, a very rapid decrease was noted during the first few days. Subsequently, for the next 40 to 50 days the activity level remained low. After the compost was removed from the bins to be placed into curing, the activity level rose. No correlations were given between enzymatic activities and other changes occurring during the composting period.

Based on the above reports, it does not appear that enzymatic activity is a good indicator of compost stability.

Phytotoxicity

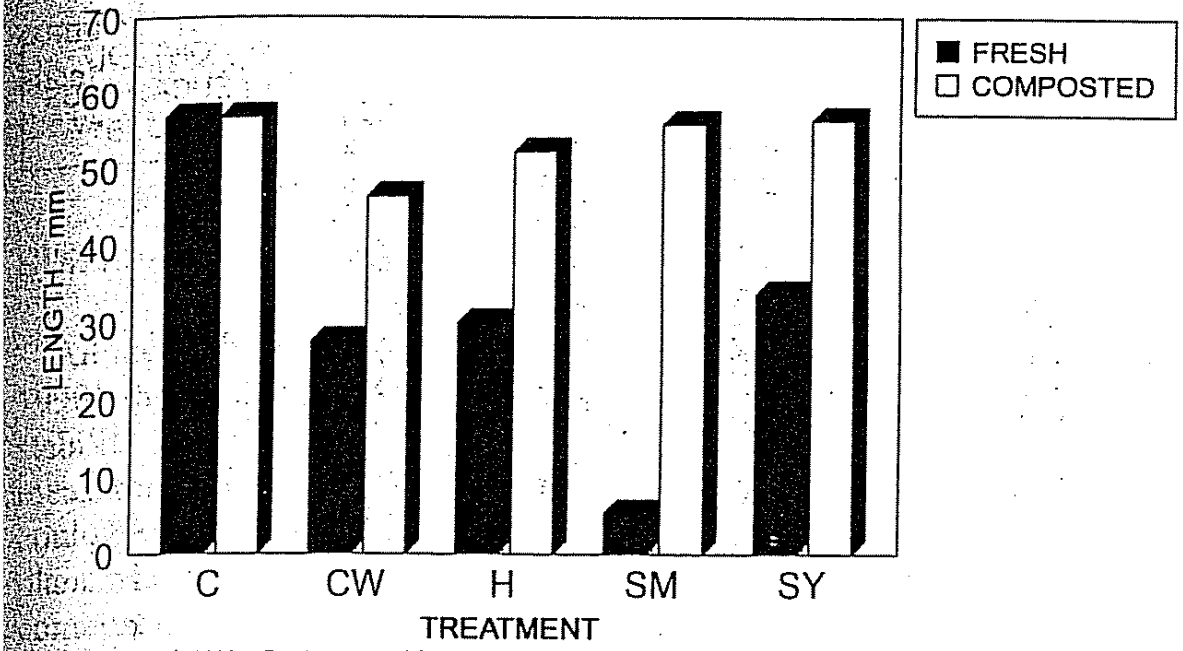
Phytotoxicity can occur from heavy metals, other inorganic elements, soluble salts and organic compounds. In this chapter only phytotoxicity from organic compounds will be discussed. Phytotoxic compounds during composting may be produced during composting as a result of anaerobic conditions, which arise from insufficient aeration or excessive moisture. A result of anaerobic metabolism is the production of low- molecular-weight organic acids such as acetic, propionic, and butyric acids. Phytotoxicity caused by organic compounds generated during composting can be remedied by increasing the period of aerobic decomposition. The formation of fatty acids during composting was presented in Chapter 4, Biochemistry.

Still et al. (1976) found that composting bark for 30 days reduced or eliminated phytotoxic substances that inhibit growth of cucumber roots (Figure 5.12). Zucconi et al. (1981a) reported that olive tree stunting was a function of the amount of compost. This was the result of partial destruction of the root system. This damage appeared to be transitional, however. Cress seed (*Lepidium sativum*, L) was selected to determine the phytotoxicity of compost. Zucconi et al. (1981a) established a "germination index" by multiplying germination and root elongation.

DeVleeschauwer et al. (1981) found numerous organic acids in fresh compost and only small amounts of acetic acid in five-month-old compost. Cress seed germination was inhibited until the compost had been composted for 120 days. They found little difference in germination between aerated and non-aerated MSW compost.

Wong (1985) found that dry weight of *Brassica parachinensis* Bailey was inhibited for over 75 days. Highest yields occurred after 105 days. A minimum of four months is needed to avoid phytotoxicity of MSW compost. Ammonia and ethylene oxide appeared to inhibit root growth. The author did not investigate the presence of other compounds that have been shown to inhibit germination and root elongation.

Manios et al. (1987) found that phytotoxicity was positively related to



C= Control; CW= Cottonwood bark extract; H= Hackberry bark extract; SM= Silver Maple bark extract; SY= Sycamore bark extract.

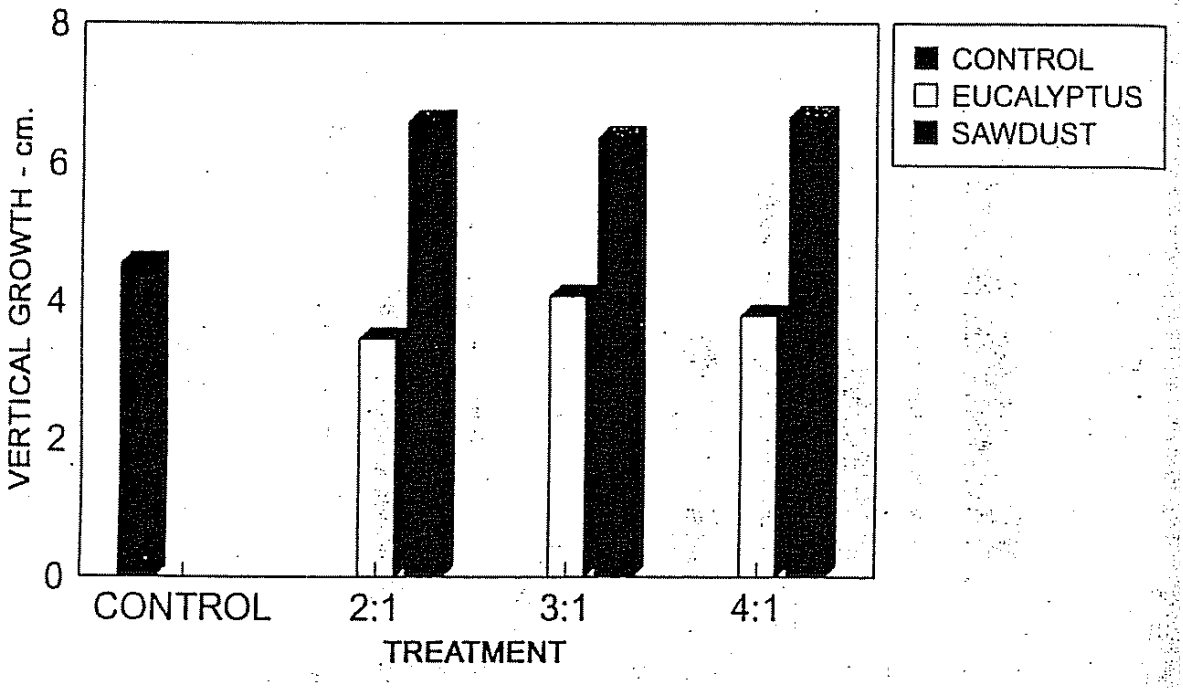
FIGURE 5.12. Effect of composting on phytotoxicity from several bark extracts. (From Still et al., 1976.)

organic acid production during composting of olive tree leaves. Organic acids decreased with composting time and germination of lettuce increased. It took 80 to 180 days for the phytotoxic effect to disappear. Shiralipour and McConnell (1991) found that the presence of a water-soluble substance in the compost inhibited seed germination.

Phenolic acids are the primary phytotoxic compound in eucalyptus. These compounds were degraded after 84 days in the laboratory but required 300 days for complete degradation in the soil (Ratcavek, 1989). E&A Environmental Consultants, Inc. (1990) conducted a study using compost produced from municipal biosolids with eucalyptus or sawdust. Rooted plant cuttings of *Pittosporum tovira* were transplanted into pots containing compost soil mixtures.

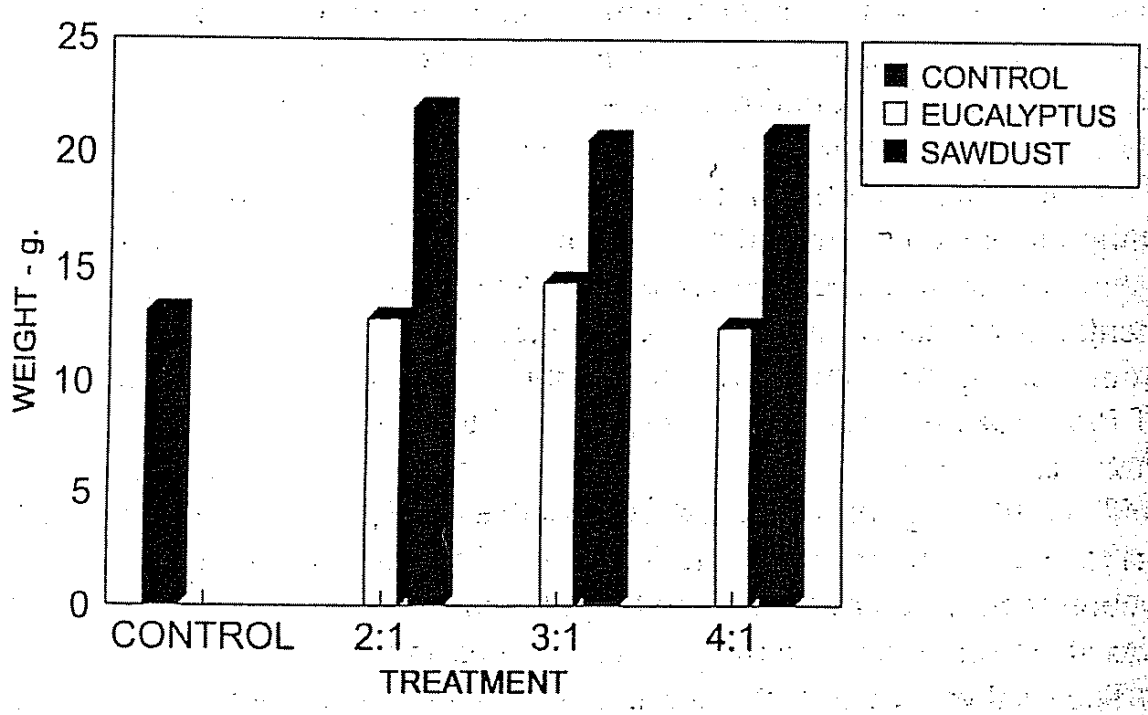
The following six treatments were used: eucalyptus compost:soil 2:1, 3:1, 4:1; sawdust compost:soil 2:1, 3:1, and 4:1. In addition to these treatments, a control consisting of a 3:1 mixture of a commercial organic mix and soil was also used. Each treatment was replicated 15 times.

The final vertical growth measurements depicted in Figure 5.13 show that plants grown in the sawdust compost treatments grew to almost twice the height of plants grown in the eucalyptus compost treatment. However, the growth of eucalyptus treatments was similar to that in the control. This indicated that the eucalyptus compost probably did not have a toxic effect on plant growth. Orthogonal contrasts determined that the eucalyptus compost treatments were significantly lower ($p < 0.01$) than the sawdust



Treatments consist of soil as control and ratios of Eucalptus-biosolids compost to soil or sawdust - biosolids compost to soil.

FIGURE 5.13. Effect of eucalyptus-biosolids compost and sawdust-biosolids compost on the growth of *Pittosporum tovira*. (From E&A Environmental Consultants, Inc., 1990.)



Treatments consist of soil as control and ratios of Eucalyptus-biosolids compost to soil or sawdust-biosolids compost to soil.

FIGURE 5.14. Effect of eucalyptus-biosolids compost and sawdust-biosolids compost on the weight of *Pittosporum tovira*. (From E&A Environmental Consultants, Inc., 1990.)

compost treatments. No significant differences were found between the eucalyptus compost treatments and the control. Similar results were obtained for wet weight measurements (Figure 5.14).

SUMMARY

Although there is no one single method to evaluate maturity (Inbar et al., 1990), the producer and user of compost has several good methods to assess stability and maturity. For stability, it is recommended that respiration, as measured by CO_2 evolution or O_2 uptake, be used. A seed germination test could be used for maturity. The test should be carried out on the least tolerant plant where the compost is to be used or on a similar plant species. If the compost is to be used for lawn, sod, or turf production from seed, grass seed germination test would be most appropriate. Combination of grass, cucumber and other plants may be the best indicators for general use of the compost. The maturity test should be used in conjunction with a test for soluble salts, since a high salt content is phytotoxic to most plants.

The use of sophisticated chemical/physical methods may provide direction to the changes that occur during composting and relate these changes to simpler stability and maturity methods.

A reliable stability test must be applicable to composts prepared from different feedstocks. It should require minimal preparation so as not to alter the physical characteristics of material, which could affect the respiration rate. This includes grinding or excessive screening (Frost et al., 1992). Sample size should be sufficiently large to represent the matrix tested.

Stability tests should be easy to perform by staff at composting facilities and be inexpensive to allow for frequent testing. The latter is important because the margin of error is reduced by increasing the number of samples. When a material is heterogeneous, more samples are needed to obtain a more realistic average.

Three predominant methods are currently in use, CO_2 and O_2 respirometry and the self-heating Dewar-flask method. The CO_2 method had been used for a considerably longer time and is based on a much larger data base than the other two techniques. It is recommended that at present the CO_2 respirometry method be used unless a facility develops a reliable data base for a specific feedstock using the O_2 or Dewar self-heating method.

Phytotoxicity can result if an immature compost is used. Under anaerobic conditions phytotoxic compounds can be formed, but they can disappear after long periods of curing. Some natural compounds found in bark or wood chips can be phytotoxic in fresh or immature compost. Composting under aerobic conditions reduces the phytotoxic effects.

REFERENCES

Allen, O. N., F. A. E. Abel, and O. C. Magistad. 1934. Decomposition of pineapple trash by bacteria and fungi. *Trop. Agr. (Trinidad).* 11:285–292.

Anderson, J. P. E. 1982. Soil respiration, pp. 831–871. In A. L. Page et al. (eds.). *Methods of Soil Analysis. Part 2.* 2nd ed. *Chemical and Microbiological Analysis.* ASA and SSSA. Madison, WI.

Bartha, R. and D. Pramer. 1965. Features of a flask method for measuring the persistence and biological effects of pesticides in the soil. *Soil Sci.* 100:68–70.

Beck, R. W. & Associates. 1990. *Evaluation of Methods for Determining Compost Maturity. Report to the Solid Waste Composting Council,* Alexandria, VA.

Becker, H. 1995. Good earth. *Agr. Res.* 42(6):16. U.S. Dept. Agr., Agr. Res. Serv.

Bodily, H. L. 1944. The activity of microorganisms in the transformation of plant materials in soil under various conditions. *Soil Sci.* 57:341–349.

Brinton, W. et al. 1993. *Compost Maturity Assessment.* Report at the BioCycle Annual Compost Conf. Albany, NY.

Bruce, A. M. and W. J. Fisher. 1984. Sludge stabilization—methods and measurement. In A. M. Bruce (ed.). *Sewage Sludge Stabilization and Disinfection.* Ellis Harwood Ltd. Chichester, UK.

Bucksteeg, W. and H. Thiele. 1959. *Die Beurteilung von Abwasser und Klarschlamm Mittels TTC* (2,3,5, Triphenyltetrazoliumchlorid). *Gas- und Wasserfach.* 100, 1.

Chang, H. T. and W. E. Loomis. 1945. Effect of carbon dioxide on absorption of water and nutrients of roots. *Plant Phys.* 20:221–232.

Chanyasak, V., A. Katayama, M. F. Hirai, S. Mori, and H. Kubota. 1983. Effects of compost maturity on growth of komatsuna (*Brassica Rapa* var. *pervidis*) in Neubauer's pot. *Soil Sci. Plant Nutr.* 29(3):251–259.

Citernesi, U. and M. De Bertoldi. 1979. Il compostaggio dei fanghi miscelati alla frazione organica dei rifiuti solidi urbani. *Inquinamento.* Anno XXI, 2:3–8.

DeVleeschauwer, D., O. Verdonck, and P. Van Assche. 1981. Phytotoxicity of refuse compost. *BioCycle.* 27(1):44–46.

Dowdy, R. H., R. E. Larson, and E. Epstein. 1976. Sewage sludge and effluent use in agriculture. In *Land Application of Waste Material.* Soil Conservation Soc. of Amer. Ankeny, IA.

E&A Environmental Consultants, Inc. 1987. *The Potential of Composting Combined Municipal and Paper Mill Sludge as a Product for Mine Spoil Reclamation.* Report to Iron Range Resources and Rehabilitation Board. Calumet, MN.

E&A Environmental Consultants, Inc. 1990. *Results of a Growth Trial Examining the Phytotoxicity of Eucalyptus-Sewage Sludge Compost and Sawdust-Sewage Sludge.* Report to Las Virgenes Municipal Water District. Las Virgenes, CA.

E&A Environmental Consultants, Inc. 1994. In-house data.

Engle, H. 1934. Kritische Bemerkungen zur "Bodenatmung." *Centra. für Bakt. Parasitenk II. Abt.* 90:156–161.

Epstein, E. 1956. The effect of organic matter on soil aeration with particular reference to nutrient uptake. Ph.D. Diss. Purdue Univ.

Epstein, E. and H. Kohnke. 1957. Soil aeration as affected by organic matter application. *Soil Sci. Soc. Amer. Proc.* 21(6):585–588.

Finstein, M. S. and F. C. Miller. 1985. Principles of composting leading to maximization of decomposition rate, odor control, and cost effectiveness, pp.13–26. In J. K. R. Gasser (ed.). *Composting of Agriculture and Other Wastes.* Elsevier Applied Sci. Pub., New York.

Frost, D. I., B. L. Toth, and H. A. Hoitink. 1992. Compost stability. *BioCycle.* 33(11):62–66.

Harada, Y. A., A. Inoko, M. Tadaki, and T. Izawa. 1981. Maturing process of city refuse compost during piling. *Soil Sci. Plant Nutr.* 27(3):357–364.

Herrmann, R. F. and J. R. Shann. 1993. Enzyme activities as indicators of municipal solid waste compost maturity. *Compost Sci. & Util.* 1(4):54–63.

Hirai, M. F., V. Chanyasak, and H. Kubota. 1983. A standard method for measurement of compost maturity. *BioCycle.* 24:54–56.

Iannotti, D. A., M. E. Grebus, B. L. Toth, L. V. Madden, and H. A. J. Hoitink. 1994. Oxygen respirometry to assess stability and maturity of composted municipal solid waste. *J. Environ. Qual.* 23:1177–1183.

Iannotti, D. A., T. Pang, B. L. Toth, D. L. Elwell, H. M. Keener, and H. A. J. Hoitink. 1993. A quantitative respirometric method for monitoring compost stability. *Compost Sci. Util.* 1(3):52–56.

Inbar, Y. 1989. Formation of humic substances during the composting of agricultural wastes and characterization of their physicochemical properties. Ph.D. Diss. Hebrew University of Jerusalem, Israel.

Inbar, Y., Y. Chen, Y. Hadar, and H. A. J. Hoitink. 1990. New approaches to compost maturity. *BioCycle.* 31(12):64–69.

Inoko, A. K. Miyamatsu, K. Sugahara, and Y. Harada. 1979. On some organic constituents of city refuse composts produced in Japan. *Soil Sci. Plant Nutr.* 25:225–234.

Jann, G. J., D. H. Howard, and A. J. Salle. 1960. Method for determining completion of composting. *Compost Sci.* 1(3):31–34.

Jimenez, E. I. and V. P. Garcia. 1989. Evaluation of city refuse compost maturity. *Biol. Wastes.* 27:115–142.

Keller, P. 1961. Methods to evaluate maturity of compost. *Compost Sci.* 2(7):20–26.

Lawton, K. 1946. The influence of soil aeration on the growth and absorption of nutrients by corn plants. *Soil Sci. Soc. Amer. Proc.* 13: 311–317.

Manios, V. I., P. E. Tsikalas, and H. I. Siminis. 1987. Phytotoxicity of olive tree leaf compost. In M. De Bartoldi, M. P. Ferranti, P. L'Hermite, and F. Zucconi (eds.). pp. 296–301. Elsevier, London, New York.

Mathur, S. P. 1991. Composting processes, pp. 147–186. In A. M. Martin (ed.). *Bioconversion of Waste Materials to Industrial Products.* Elsevier, New York.

Mathur, S. P., H. Dinel, G. Owen, M. Schnitzer, and J. Dugan. 1993a. Determination of compost biomaturity. II. Optical density of water extracts of composts as a reflection of their maturity. *Biol. Agric. and Hort.* 10:87–108.

Mathur, S. P., G. Owen, H. Dinel, and M. Schnitzer. 1993b. Determination of compost biomaturity. I. Literature review. *Biol. Agric. and Hort.* 10:65–85.

Mebius, L. J. 1960. A rapid method for the determination of organic carbon in soil. *Anal. Chim. Acta.* 22:120–124.

Methods of Soil Analysis. Part 1 and 2. 1982. 2nd edition. Agronomy No. 9. Amer. Soc. of Agronomy, WS.

Morel, J. L., F. Colin, J. C. Germon, P. Godin, and C. Juste. 1985. Methods for the evaluation

of the maturity of municipal refuse compost, pp. 56–72. In J. K. R. Glasser (ed.). *Composting of Agricultural and Other Wastes.* Elsevier Applied Sci. Pub., New York.

Niese, G. 1963. Experiments to determine the degree of decomposition of refuse compost by its self-heating capability. International Research Group on Refuse Disposal. *International Bull. No. 17.* Agric. Microb. Institute, Justice-Liebig-Universität, Giessen, Germany.

Pressel, F. and W. Bidlingmaier. 1981. Analyzing decay rate of compost. *BioCycle.* 22:50–51.

Ratcavek, B. 1989. Composting eucalyptus leaves. *Fine Gardening,* July/August.

Roletto, E., R. Berberis, M. Consiglio, and R. Jodice. 1985. Chemical parameters for evaluating compost maturity. *BioCycle.* 26(2):46–47.

Saviozzi, A., R. Levi-Minzi, and R. Riffaldi. 1988. Maturity evaluation of organic wastes. *BioCycle.* 29:54–56.

Schnitzer, M., H. Dinel, S. P. Mathur, H. R. Schulten, and G. Owen. 1993. Determination of compost biomaturity. III. Evaluation of a colorimetric test by ^{13}C-NMR spectroscopy and pyrolysis-field ionization mass spectrometry. *Biol. Agric. and Hort.* 10:109–123.

Schollenberger, C. J. 1945. Determination of soil organic matter. *Soil Sci.* 59:53–56.

Shiralipour, A. and D. B. McConnell. 1991. Effects of compost heat and phytotoxins on germination of certain Florida weed seeds. *Soil and Crop Sci. Soc. Fla. Proc.* 50:154–157.

Spohn, E. 1969. How ripe is compost? *Compost Sci.* 10(3):24–26.

Spohn, E. 1978. Determination of compost maturity. *Compost Sci./Land Util.* 19(3):26–27.

Starkey, R. L. 1924. Some observations on the decomposition of organic matter in soils. *Soil Sci.* 17:293–314.

Still, S. M., M. A. Dirr, and J. B. Gartner. 1976. Phytotoxic effects of several bark extracts on mung bean and cucumber growth. *J. Amer. Soc. Hort. Sci.* 101(1):34–37.

Vandecavey, S. C. and H. Katznelson. 1938. Microbial activities in soil: V. Microbial activity and organic matter transformation in Palouse and Helmer soils. *Soil Sci.* 46:193–197.

Waksman, S. A. 1936. *Humus.* The Williams & Wilkins Co. Baltimore, MD.

Walkley, A. 1947. A critical examination of a rapid method for determining organic carbon in soils: Effect of variations in digestion conditions and or inorganic constituents. *Soil Sci.* 63:251–263.

Walkley, A. and I. A. Black. 1934. An examination of the Degtareff method for determining soil organic matter and a proposed modification of the chromic acid titration method. *Soil Sci.* 37:29–38.

Willson, G. B. and D. Dalmat. 1986. Measuring compost stability. *BioCycle.* 24:25–27.

Woods End Research Laboratory, Inc. 1993. *Compost Self-Heating Flask.* Woods End Res. Lab. Mt. Vernon, ME.

Wong, M. H. 1985. Phytotoxicity of refuse compost during the process of maturation. *Environ. Poll.* (Series A). 37:159–174.

Zhang, L., F. Chuang, and M. A. Cole. 1992. *A Simple Chemical Assay for Estimating Compost Maturity.* Poster presented in ASA Annual Meeting. Minneapolis, MN.

Zucconi, F. A. Pera, M. Forte, and M. De Bertoldi. 1981a. Evaluating toxicity of immature compost. *BioCycle.* 22(2):54–57.

Zucconi, F., A. Pera, M. Forte, A. Monaco, and M. De Bertoldi. 1981b. Biological evaluation of compost maturity. *BioCycle.* 22(4):27–29.