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Dan M. Sullivan

Compost maturity is an important determinant of end use for composted municipal yard debris, and generally refers to the effect the compost has on plants. The rate of microbial respiration is an indicator of compost stability. The objectives of this research were to: i) determine whether continuous aeration resulted in more rapid maturity of composted yard debris than windrow turning; ii) determine which maturity indicators distinguish between mature and immature compost; iii) measure rates of CO_2 evolution during active composting and curing; iv) adapt the CO_2 detection tube technique for compost; and v) evaluate rapid compost stability tests (Solvita test, self-heating test and CO_2 detection tubes) for potential use by commercial composters. Land Recovery, Inc. of Puyallup, WA, composted yard debris under careful process control. Two compost piles were studied for 113 d; one was subjected to continuous forced aeration and periodic turning. The other was managed as a turned windrow. We found that forced aeration resulted in mature compost about 20 days

before windrowing. Compost pH, C content and respiration rate were all useful indicators of compost maturity. Carbon fell from 400 k kg^{-1} to 250 g kg^{-1} and pH rose from 5 to 7. The CO_2 evolution rate fell from 16 to 2 mg CO_2-C g C^{-1} d^{-1}. Maturity correlated somewhat with compost odor. Neither percent germination nor an odor/color scale were reliable indicators of maturity for theses composts. All the rapid tests were correlated with alkaline trapping of microbially respired CO_2. The Solvita test took 4 h to administer; values (1 to 8 Solvita scale) were 2 to 4 during active composting, 3 to 6 during early curing and 6 to 7 during late curing. Self-heating test values decreased from 20°C above ambient at the start of composting to ambient (no heat production) at the end of composting. This test took two to six days to administer. We developed a method to measure CO_2 evolution rates of samples in sealed containers using CO_2 detection tubes. This method took 4 h to administer, correlated well with alkaline trapping, was quantitative and had excellent sensitivity at extreme compost maturity. The methods shows promise as a raid test for compost respiration and should be evaluated on a wider range of composts.

Maturity and Stability Evaluation of Composted Yard Debris

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To remember and honor

Oscar G. Brewer

and

Gilbert J. Brewer

MATURITY and STABILITY EVALUATION of COMPOSTED YARD DEBRIS

INTRODUCTION

Variability of compost maturity and stability is a factor limiting its greater use. Stability refers to the recalcitrance or volatility of carbon structures within compost. It is reflected by rates of CO_2 evolution or O_2 uptake. Maturity, as it is used here, refers to plant response to compost. It is generally assessed by indices of germination or by root and shoot mass. The phytotoxic compound content is sometimes reflected by compost pH, as many phytotoxic substances are organic acids, for example acetic acid and propionic acid.

The survival of municipal yard debris composting programs depends on markets for the resultant compost. Large-scale compost users value quality assurance from compost producers, particularly when the end use can affect plant response. Yet many compost producers lack the technical support to assess compost stability and maturity.

This thesis presents a comparison of the end result of composting in traditional turned windrows versus software controlled continuous aeration composting. It also offers a comparison of a number of commercially available tests of compost maturity, including the prototype of a new test developed as a part of the thesis research process.

Chapter 1 reviews the literature pertaining to these topics, including respirometric, chemical and sensory measures of compost maturity, stability and phytotoxicity, and the effects of continuous aeration on compost.

Chapter 2 documents the differences in a number of important parameters between identical composts produced with or without continuous aeration. It will be submitted to a peer-reviewed journal. Chapter 3 assesses the precision and accuracy of a number of low-tech tests of compost maturity, and describes the development of a prototypic method. The Bibliography is a comprehensive listing of the sources sited throughout the thesis.

LITERATURE REVIEW

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COMPOST MATURITY AND STABILITY ASSESSMENT

This chapter reviews the methods of compost maturity and stability assessment. The introductory sections "Compost Stability" and "Compost Maturity" briefly review the common assessment methods. Subsequent sections explore these assessment methods at greater depth.

The composition and character of compost varies with feedstocks, processing methods and degree of maturity. Feedstocks are the materials to be composted. Ideally, composting reduces the volume of the materials, killing pathogens and reducing carbon (C) content in the process. In addition, it concentrates plant nutrients and transforms organic acids and some other environmental hazards (Barker, 1997; Hoitink et al., 1997). Composted materials have been found suitable for horticultural (Hartz et al., 1996) and agricultural applications (N'Dayegamiye et al., 1977; Buchanan and Gliessman, 1991; Barker, 1997). Compost can be used as peat substitute in container applications (Inbar et al., 1993; Rosen et al., 1993; Hartz et al., 1996). Common problems related to feedstock include high boron and soluble salt level (Rosen et al., 1993). Composted yard debris generally contains lower levels of heavy metals than do biosolids, and so is more readily accepted by farmers (de Bertoldi et al., 1989; Hartz et al., 1996).

Compost application can increase soil organic matter, total porosity, aggregate stability and water-holding capacity (Rosen et al., 1993). Due to

the slow rate of release of some plant nutrients from compost, optimal plant response demands supplemental nutrients (N'Dayegamiye et al., 1977; Rosen et al., 1993; Hartz et al., 1996).

Grower demand for compost depends on predictable plant response to the product (Iannotti et al., 1994). Quantitative chemical, biological and physical properties that define compost stability and maturity can promote successful marketing (Rosen, 1993; Grebus et al., 1994). Hartz et al. (1996) believe the compost market will bear the added costs to mature and fully cure compost. This suggests a value-added market niche for compost producers who can quantify product quality.

Sanitization and stabilization are important composting processes that can increase compost value in agricultural applications. Sanitization refers to killing pathogens and weed seeds by heating. It occurs rapidly during the bio-oxidative stage of composting. By contrast, stability is time-dependent (Stentiford and Neto, 1985). Compost becomes stabile as unstable organic C compounds are oxidized to carbon dioxide (CO_2), or converted to more complex organic forms. Unstable compost and the lack of reliable stability ratings discourage growers from using compost. Immature compost will cause more problems in container-grown systems than in field operations (Hoitink et al., 1997). Thus, the ability to rate compost stability is critical in establishing the use of compost by large-scale users like nurseries (Helfrich et al., 1998).

ASSESSING COMPOST QUALITY

Compost Stability

Stability reflects the degree of decomposition of organic matter. Compost is considered stable when the rate of oxygen (O_2) consumption or CO_2 evolution has dropped below some defined level. Poor plant response, odor, and pathogen regrowth are characteristic of compost instability. Ianotti et al. (1994) considered O_2 consumption, CO_2 evolution rate, water soluble organic C in aqueous compost extracts, and the ratio of organic C to organic N in compost to be good indicators of compost stability. They found O_2 consumption rate and organic C concentration decreased with duration of composting.

Bernal et al. (1998) related nitrogen (N) immobilization to carbon: organic nitrogen ratio. Large values suggest high labile C content. Immature organic matter immobilizes N in soil as readily degradable carbon is metabolized.

Lasaridi and Stentiford (1998a, b) noted that end use determines acceptable compost stability and favor stability determinants based on respiration rates. They found increasing stability with age for all composts. They further found that optical density and chemical oxygen demand (COD), a measure of the O_2 required to fully oxidize a sample's organic

matter, did not provide useful information about compost stability (Lasaridi and Stentiford, 1998b).

Inbar et al. (1993) measured electrical conductivity (EC), nitrate (NO_3^-), phosphorous (P), calcium (Ca^{2+}), magnesium (Mg^{2+}), and total alkalinity in water extracts; when these values were stable, compost was judged suitable for container media.

Compost stability is crucial for disease suppressive applications. According to Hoitink et al. (1997), the material must be in the curing stage, able to support desirable microbes, and stable enough to preclude phytotoxicity. The authors note that "excessively" stable materials, for which organic matter has been transformed into humic substances, do not support biocontrol agents. Remaining lignin and humic structures are too low in energy content to support disease suppressive agents.

Several authors have written about the characteristics of a good stability test (Willson and Dalmont, 1989; Frost et al., 1992). Desirable qualities include:

- applicability to a broad range of feedstocks over a wide range of conditions
- employment of large, representative test sample size
- avoidance of false respiration increases from screening or grinding
- validity at moisture content equal to 50%

- cost-effective, on-site testing results in less than a work-day
- reliable equipment that is easy to operate and readily available
- results well correlated with scientifically proven measures.

Respiration, a measure of microbial activity, is often used as an indicator of compost stability (Frost et al., 1992; Grebus et al., 1994; Lasaridi and Stentiford, 1998a, b) as is capacity to reheat (Nakasaki et al., 1985; Gurkewitz, 1989; Brinton et al., 1995) because heat is a by-product of respiration. Other microbial indicators of compost maturity that have been used include microbial counts (Waksman et al., 1931; Waksman et al., 1939) and a multitude of intra- and extra-cellular microbial polymer concentrations (Forster et al., 1993; Helfrich et al., 1998). High respiration rates continue so long as conditions supporting microbial life prevail. These conditions include moisture content, temperature range, nutrient and O_2 supply. When any of these requirements become depleted, respiration slows (Waksman et al., 1931; Miller, 1991; Inbar et al., 1993).

Fresh materials with abundant degradable C content rapidly develop high microbial populations, resulting in strong O_2 demand (Jiménez and Garcia, 1989). Further, high CO_2 evolution rates coincide with thermophyllic processes (Paré et al., 1998). In the presence of degradable C, added N stimulates microbial growth and increases respiration rates (Paré et al., 1998). Stentiford et al. (1985) considered a 50% reduction of COD over the course of processing to be an indicator of maturity.

Mature compost has undergone thermophyllic and mesophyllic cycles, mediated by bacteria, actinomycetes, and fungi (Waksman et al., 1931; Waksman et al., 1939; Forster et al., 1993). Stable temperatures after turning and the coincident decrease in thermophyllic bacteria counts indicate a slowing of bio-oxidation. The absence of reduced compounds (H_2S, NH_3) also may suggest compost maturity. The presence of these compounds indicates anaerobic, low redox-potential conditions (Jiménez and Garcia, 1989).

Compost Maturity

No single test adequately predicts compost maturity for all feedstocks. Nitrate content, cation exchange capacity (CEC), and electrical conductivity (EC) values have been observed to increase with increasing composting duration; soluble organic C content, total carbon to nitrogen ratio (C: N), dissolved oxygen (DO), and phytotoxic effects are reduced (Willson and Dalmont, 1989). Perhaps the definition of "mature" is in the best sense a functional one, formed with respect to plant response or other end-use of a given material (Frost et al., 1992). Generally, maturity tests fall into four categories: plant response (Grebus et al., 1994; Iannotti et al., 1994), chemical (Frost et al., 1992; Henry and Harrison, 1996; Grebus et al., 1994), microbial (Forster et al., 1993), and physical (Grebus et al., 1994).

Plant response to compost

Tests for plant response to compost are most often measures of root and shoot mass of test plants exposed to water extracts of the sample material (Garcia et al., 1992; Inbar et al., 1993; Shiralipour et al., 1997) or with the sample incorporated into a potting mixture (Garcia, et al., 1992; Inbar et al., 1993; Hartz et al., 1996). Inbar et al. (1993) suggested that these biological tests integrate a number of factors, and so address the problem of the lack of a single measure characterizing compost maturity. Recently, Helfrich et al. (1998) by-passed the time delay inherent in such studies by measuring photosynthetic electron transport across specially prepared plant-cell membranes.

Short-term effects of compost on plants have their basis in the degree of organic matter decomposition (Forster et al., 1993). Immature compost inhibits germination or reduces root length because it releases water-soluble phytotoxic compounds into the growth medium (Jiménez and Garcia, 1989; Forster et al., 1993; Hartz et al., 1996), or because it is undergoing reductive decomposition (Jiménez and Garcia, 1989). Low molecular weight organic acids and salt content at any level of compost maturity are considered important phytotoxins (Iannotti et al., 1994). Actively decomposing C compounds may reduce N availability (Forster et al., 1993). Nitrogen deficiency symptoms of plants can be used as an indicator of compost immaturity (Iannotti et al.,1994). Forster et al. (1993)

emphasized the influence of the feedstock in nutrient availability. Mature compost promotes plant growth, in part because a portion of its N is available to plants as NO_3 (Barker, 1997). The formation of metal-organic matter complexes during curing further affects plant responses to compost (Inbar et al., 1993). When these metals are necessary plant nutrients, like copper, zinc and molybdenum, and are applied at agronomic rates, plant response is enhanced; if they are toxic to plants, or if the application rate exceeds safe limits, the plants suffer.

Chemical tests

Many chemical parameters have been considered as potential maturity indicators for compost (N'Dayegamiye et al., 1977; Inbar et al., 1993; Liao, et al., 1994). These contribute to an integrated understanding of the suitability of compost for a specified purpose, and its potential for environmental impact. Among the parameters considered by Inbar et al. (1993) were EC, NO_3^-, P, Ca^{2+}, Mg^{2+} and total alkalinity; their stability indicated compost maturity. N'Dayegamiye et al. (1977) and Liao et al. (1994) considered the concentration of fulvic acids and the low molecular weight non-humic fraction in defining maturity. Additional maturity indicators include humic acid content, humic acid to fulvic acid ratios, C: N ratios, ash content, pH, NO_3^-, N, and CEC (N'Dayegamiye et al., 1977).

High ammonia (NH_3) concentrations and N loss as NH_3 gas are considered indicative of immature compost (Barker, 1997; Paré et al., 1998). In mature materials, NH_3 is oxidized to NO_3^-. The same is true for N originally held in protein molecules. As this N is released through microbial action, nitrifying bacteria convert it to oxidized forms (NO_2^-, NO_3^-). These forms appear after initial labile C content has been metabolized (Jiménez and Garcia, 1989). Mature compost contributes its N to the plant-soil system over extended periods of time (Barker, 1997). As composting progresses, NH_4^+ concentration decreases as it is converted to NO_3^- (Forster et al., 1993).

Cation exchange capacity correlates well with the degree of organic matter decomposition in soils. It increases with the progression of humification of the compost organic fraction. Jiménez and Garcia (1989) noted Harada's finding of a rise in CEC of municipal refuse compost from 40 mol_c / kg to 80-100 mol_c / kg within 12 weeks of processing.

A number of investigators considered pH an indicator of composting progress for low N content materials (Gurkewitz, 1989; Jiménez and Garcia, 1989; Inbar et al., 1993). In the first hours of processing, pH drops, then rises with increasing stability, approaching neutral toward the end of processing. Acidic compost, with pH below 7, may be incompletely processed, or it may have undergone anaerobic processing and have high fatty acid content (Jiménez and Garcia, 1989).

High C: N ratio is considered an indicator of immaturity (Barker, 1997). Jiménez and Garcia (1989) considered solid phase C: N less than 20 as necessary but not sufficient for determining maturity. They cite Morel et al. (1982) who computed final C: N to initial C: N ratio as a compensation for the variation inherent with differing feedstocks. For some feedstocks, the final to initial C: N value does not correlate with time. This ratio is not useful for materials with initial C: N ratio less than 15: 1.

Sensory and physical tests

Odor, color, bulk density and moisture content are commonly monitored physical characteristics of compost. The interpretation of these tests is dependent on feedstocks and composting process control. Fatty acids, alcohols, aldehydes, ketones, and volatile sulfur compounds indicate instability and contribute to odor problems. Geosmine should be the dominant odor after mature compost is turned. Maturing compost assumes a dark color, which may be evaluated directly from the sample (Leege and Thompson, 1997) or from compost alkaline extracts (Jiménez and Garcia, 1989). N'Dayegamiye et al. (1977) considered high bulk density indicative of compost maturity.

MEASURES OF COMPOST STABILITY

Respiration reflects microbial activity. The cost and complexity of most commercial respirometers stimulate the effort to find rapid, accurate and affordable methods of measuring compost respiration. Often, commercial respirometers are not practical for commercial composters, or they are calibrated for soil samples and do not accommodate the higher rate of compost respiration (Lasaridi and Stentiford, 1998a).

Respiration is measured by O_2 consumption (Frost et al., 1992; Grebus et al., 1994; Iannotti et al., 1994; Lasaridi and Stentiford, 1998a, b) or CO_2 evolution (Bartha and Pramer, 1965; Nakasaki, et al., 1985; Forster et al., 1993; Inbar et al., 1993; Robertson and Morgan, 1995). These parameters have been variously measured using alkaline traps, manometers, coulometers, constant pressure respirometers and Clark-type polarographic probes. Lasaridi and Stentiford 1998a, b) used the latter device to measure specified O_2 uptake rates (SOUR). Other related O_2 uptake assays assessed are total O_2 demand in a 20 h period (TOD_{20}), O_2 uptake rate (OUR), and specific O_2 uptake rate for solid compost matrix samples (DSOUR) (Lasaridi and Stentiford, 1998b). Both SOUR and DSOUR measures were closely correlated to compost age, and decreased with increasing time (Robertson and Morgan, 1995). Dissolved oxygen (DO) meters determine respiration rates by measuring O_2 demand, an indicator of sample stability (Frost et al., 1992; Robertson and Morgan, 1995).

Dissolved oxygen probes were found to be easy, fast and inexpensive (Grebus et al., 1994).

Readily degradable C compounds (e.g., soluble sugars, hemicellulose, amino acids, proteins) promote high respiration rates. Composting reduces soluble C as it is oxidized to CO_2 or transformed to insoluble organic matter (Inbar et al., 1993). Frost et al. (1992) asserted that the most volatile fraction of organic solids is metabolized out of actively aerated systems within the first two weeks.

Lasaridi and Stentiford (1998b) observed an increase in respiration in the early portion of the composting process. They hypothesized that as large organic molecules degrade, more C substrate becomes available. Ianotti et al. (1994) identified a similar increase in respiration later in the composting process. They attributed a late flush of microbial activity to increasing the moisture content of low moisture materials. The decomposition of fungal biomass, which increases under lower moisture conditions, may account for some of the C conversion observed upon rewetting the dry compost (Hoitink et al., 1997).

The age, feedstock and elapsed time between sampling and testing all contribute to variability in measured microbial activity levels (Lasaridi and Stentiford, 1998b). Careful sample collection, handling and incubation promote measurement accuracy (Frost et al., 1992). Unless other factors (water, N, O_2) are limiting CO_2 evolution, reduced O_2 consumption and

reduced temperature suggests approaching maturity (Henry and Harrison, 1996).

In summary, the cited literature confirmed:

- O_2 uptake or CO_2 evolution rates are closely related to compost age, and decrease with increasing composting duration.
- feedstocks with higher decomposable carbon content (chicken manure, grass clippings) promote higher rates of microbial respiration
- carbon forms become increasingly recalcitrant with increasing compost time.

Alkaline traps

This is a standard procedure, adapted from soil testing methods. A measured volume of NaOH solution of known molarity is exposed to the headspace developed by a compost sample in a closed vessel. The evolved CO_2 is held in the NaOH as carbonate. The remaining unneutralized base is titrated with HCl, also of known molarity, to determine the amount of CO_2 evolved over the trapping period. This technique was used by Forster et al. (1993) and by Iannotti et al. (1994) to determine CO_2 evolution rates from compost as a measure of stability. The use of strong bases to estimate microbial activity is adapted from a soil test (Frost et al.,

1992; Leege and Thompson, 1997). Bartha and Pramer (1965) adapted the method to determine rate of pesticide mineralization by soil microbes. One disadvantage of this test is its use of as little as 25 mg of compost to represent perhaps hundreds of cubic meters of material (Frost et al., 1992; Forster et al., 1993). Another is that the titration required laboratory facilities and a skilled technician.

Color detection gas sampling tubes

Color detection gas sampling tubes have been used to analyze the gaseous content of the headspace developing above soil columns (Liebig et al., 1996). The gas sample is drawn through a glass tube containing reagents sensitive to the compound of interest. Extent of reagent color change is commensurate with the concentration of the gas in the sample. Liao et al. (1994) used headspace-gas chromatography to determine gases released by compost, in an attempt to judge the material's maturity. Liebig et al. (1996) field-measured CO_2 content of headspace gases above soil using gas sampling tubes. They compared their results with laboratory analyses determined by gas chromatography. They measured respiration rates two to three times higher with the gas sampling tube field method, and attributed these differences to several differences in methodology. Field samples tested by gas sampling tubes may have reflected plant root respiration. The laboratory samples were incubated over far longer periods

(30 minutes in the field versus 10 days in the lab). The laboratory samples were sifted and repacked, while field-testing was conducted on undisturbed soils. The field-test measured respiration within a 7.5 cm soil column, while the in-lab respiration measure was over a 2.25 cm column.

Solvita colorometric gel

The Solvita test is a semi-quantitative test that employs CO_2-sensitive gel to indicate microbial respiration rates. A measured volume of compost and the Solvita test paddle are placed in the reaction vessel. The test is interpreted after four hours by comparing the resultant gel color to a color scale. On the calibrated Solvita color scale, readings of one and two indicate raw compost, three through six indicate active compost, and seven and eight indicate finished materials. It can be administered and interpreted in the field, on freshly sampled compost.

Seekins (1996a) found the Solvita test in the field highly correlated with the Dewar test of self-heating. The Dewar test measures heat production by compost. Seekins stressed the importance of accurately adjusting sample moisture content prior to testing with the Solvita test. Ammonia can interfere with gel color modification, making adequate buffering of high ammonia content samples a necessity for reliable test results. It is not known whether the variability of high pH samples is due to a chemical interaction with the gel or inhibition of microbial activity, or due to

some other reason. Other conditions resulting in unreliable results include highly heterogeneous samples, samples with significant volatile organic content and samples with high C: N ratios.

In another publication of the same year, Seekins (1996b) reported that Solvita was most accurate for the extremes of compost maturity, that is, for readings of three and below or for readings of six and above. For the intermediate states, readings of four and five, the results were much more variable. Fifty-seven percent of the samples tested (n=72) in Seekins' study fell into this range of greater variability. Greater variability for intermediate maturity stages limits the utility of the test. Generally, the extremes of maturity are more readily assessed. McDonnell and Regenstein (1997) expressed some reservations about the use of this test as a regulatory tool, given the variability of results without careful sample preparation and the potential for users to test inadequately prepared samples.

Dewar self-heating test

The potential for compost to reheat is another measure of microbial activity. It is well known that the temperature of fresh organic matter can rise without externally applied heat sources. Self-heating is recognized as a sign of immaturity, regardless of other parameters. The Dewar test outlined by Brinton (1995) allows evaluation of compost self-heating under standardized conditions.

Careful sample preparation is vital for meaningful test results. This test is valid only within a range of moisture contents (35-60%) because of the heat capacity of water and the potential for evaporative cooling (Zucconi et al., 1981; Frost et al., 1992). The test will not produce reliable results for materials falling outside the recommended moisture content range (Brinton et al., 1995). The heat capacity of compost is estimated to be 0.2 times the heat capacity of water. Water contained in a wetter sample will absorb heat and lessen temperature increase. The temperature of such materials will not reflect true heat production.

This test results in easily understood heat units, and it integrates several indicators of compost maturity (Brinton et al., 1995). Henry and Harrison (1996) considered this method a poor maturity indicator because accurate results depend so heavily on the sample's water content. Sifting materials may encourage additional temperature elevation. Fluctuating room air temperature will impact final test result interpretation. The test can require as many as nine days to complete (Brinton et al., 1995).

MEASURES OF COMPOST MATURITY

Seedling Germination and Growth

Compost can have deleterious effects on plants when its chemical profile falls outside the limits that support vigorous growth. Of specific importance in this regard are concentrations of organic acids, salt concentrations and growing medium O_2 levels (Garcia et al., 1992).

Phytotoxicity can be determined with water extracts of compost (Shiralipour et al., 1997; Helfrich et al., 1998; Lasaridi and Stentiford, 1998b). These water extracts are used as germination media or they are evaluated spectrophotometrically. Alternatively, compost commonly is mixed in with other components to make potting mixes (Garcia et al., 1992; Grebus et al., 1994; Iannotti et al., 1994; Hartz et al., 1996).

Germination tests compare the growing medium of interest with a control medium. The assumption is that the percent germination is affected by components of the test medium. The most common tests expose seeds to water extracts of compost, using water as a control, (Hartz et al., 1996; Shiralipour et al., 1997; Helfrich et al., 1998) or mix compost with a potting mixture, and use the mixture without compost as a control (Grebus et al., 1994; Iannotti et al., 1994; Hartz et al., 1996).

The literature gives a number of examples of seeds used to test phytotoxicity. Among them are ryegrass (*Lolium perenne* L.) and barley

(*Hordeum vulgare* L.) (Garcia et al., 1992; Iannotti et al., 1994). Cress seed (*Lepidium sativum* L.), with its short germination time, often is used to evaluate compost phytotoxicity (Grebus et al., 1994; Iannotti et al., 1994; Lasaridi and Stentiford, 1998a, b). Radish (*Raphanus sativus* L.) is used, also presumably because of its short germination time (Grebus et al., 1994; Iannotti et al., 1994). Cucumber (*Cucumis sativus* L.), reputed to be salt-tolerant, is useful for separating the effects of other phytotoxic compounds from salt concentrations (Shiralipour et al., 1997; Helfrich et al., 1998). Tomatoes (*Lycopersicon esculentum* L.) and peppers (*Capsicum annuum* L.) also have been used in greenhouse trials (Hartz et al., 1996).

A number of indices are used to interpret germination data. Percent germination is commonly used (Iannotti et al., 1994). Zucconi (1981) developed the germination index in 1981. This index is the product of the percent germination and the percent of the control root length. Zucconi found this index to be both sensitive at both extremes of concentrations for phytotoxic compounds. Lasaridi and Stentiford (1998a) used it with composts in the later phases of processing. Helfrich et al. (1998) and García et al. (1992) also used Zucconi's germination index. Stentiford and Neto (1985) applied a germination rate emergence time ratio that compared the emergence of the compost seedling to the emergence of the control.

Organic acids, by-products of fermentation, are considered the principal phytotoxic agents in immature compost. (Garcia et al., 1992; Hartz

et al., 1996; Shiralipour et al., 1997; Helfrich et al., 1998). Shiralipour et al. (1997) concluded that poor plant response was a problem of short-chain fatty acid metabolism rather than the result of low pH. A number of researchers have found acetic acid to be associated with phytotoxic responses (Liao et al., 1994; Shiralipour et al., 1997; Helfrich et al., 1998). At low concentrations, acetic acid delays, but does not reduce, germination and root elongation. At higher concentrations, it does both (Shiralipour et al., 1997). Other compounds that contribute to compost phytotoxicity are propionic acid, ethylene oxide and butyric acid. Propionic acid has been observed to work synergistically with acetic acid (Jiménez and Garcia, 1989; Shiralipour et al., 1997). Degradation of immature materials can increase soil temperature and inhibit germination of some seeds (Jiménez and Garcia, 1989).

Oxygen competition between plant roots and microbes is another potential source of poor plant response (Jiménez and Garcia, 1989; Inbar et al., 1993). This competition could be due to rapid organic matter decomposition or lowered O_2 gradients in the growing medium.

Nitrogen effects on plants can be of several types. Ammonia hinders germination, and injures seedlings and soil fauna. Often, ammonia damage is confused with saline damage (Henry and Harrison, 1996; Barker, 1997). Fresh compost, with insufficient C oxidation, contributes to net N immobilization (Jiménez and Garcia, 1989; Hartz et al., 1996; Henry and

Harrison, 1996). When fresh organic matter is added to plant-soil systems, N may be immobilized by actively growing microbes.

Salt reduces water's matric potential in compost. Soluble salts inhibit germination and depress yield. In addition, common compost ions like boron, sodium, and chloride have specific plant toxicity levels (Rosen et al., 1993).

Without exception, researchers observed that phytotoxic effects decrease with duration of composting (Garcia et al., 1992; Grebus et al., 1994; Helfrich et al., 1998). This is true whether water extracts were used or whether compost was added to a potting mix. As compost matures, phytotoxic substances are metabolized (Lasaridi and Stentiford, 1998a), NO_3 content increases, and soluble organic C compounds are decomposed (Grebus, et al., 1994). The inhibitory effects of immature compost on plant growth subside as the materials mature (Helfrich et al., 1998).

Chemical Measures

Carbon, and to a lesser extent N, are released by the composting process; therefore, the concentration of other elements increases (Inbar et al., 1993). Any single chemical analysis of compost will provide only partial information; no single test is universal for all feedstocks. Further, O_2 or water compromised materials may give misleading test results (Frost et al., 1992; Forster et al., 1993). Included among the tests referred to in the

literature are those which measure the reduced to oxidized states of N (Jiménez and Garcia, 1989; Garcia et al., 1992; Forster et al., 1993; Inbar et al., 1993; Robertson and Morgan, 1995; Lasaridi and Stentiford, 1998a), C parameters such as total C, C: N, humic and fulvic acids (Jiménez and Garcia, 1989; Garcia et al., 1992; Forster et al., 1993; Liao et al., 1994; Robertson and Morgan, 1995; Paré et al., 1998), and CEC (Jiménez and Garcia, 1989), EC (Inbar et al., 1993), pH (Liao et al., 1994), DO (Lasaridi and Stentiford, 1998a) and ash (Henry and Harrison, 1996).

Oxygen uptake

Low rates of O_2 uptake suggest compost stability unless O_2 is limited. Low CO_2 evolution rates likewise suggest compost stability (Stentiford and Neto, 1985; Stentiford et al., 1985; Frost et al., 1992; Iannotti et al., 1994; Lasaridi and Stentiford, 1998a;b). A number of procedures have been employed to determine this rate:

- Specific O_2 uptake rate (Iannotti et al., 1994; Lasaridi and Stentiford, 1998a; b)
- Chemical oxygen demand (Stentiford and Neto, 1985; Stentiford et al., 1985; Lasaridi and Stentiford, 1998b)
- Oxygen partial pressure in a closed system (Frost et al., 1992)

Lasaridi and Stentiford (1998a) found SOUR to be a useful measure of compost stability, providing consistent information significantly correlated

with compost age. It had the additional advantage of low time and labor requirements. In another paper published the same year (1998b), they found SOUR, TOD_{20} and DSOUR to correlate highly with one another and to show similar patterns of change over time. To review, TOD_{20} is the total O_2 demanded by microbial respiration in a 20-hour period. The specific O_2 uptake rate of as-received compost is DSOUR. Chemical oxygen demand, a test adapted from wastewater testing, has not been shown a useful assessment for compost (Stentiford and Neto, 1985).

pH

Compost pH is highly dependent on feedstocks, and conclusions about compost maturity based on pH must consider them. The buffering capacity of fresh compost is low, with a CEC near 30 $mol_c\,kg^{-1}$ as-received weight. Therefore, abundant organic acids reduce the pH of young compost (Iannotti et al., 1994). Stentiford et al. (1985) attributed high buffering capabilities to municipal solid waste and sewage sludge (pH 7.0-8.3) processed in aerated static piles. These materials experienced slight pH change over the course of composting. Mature yard debris compost pH values are generally near seven (Gurkewitz, 1989). Likewise, García et al. (1992) found pH ranges just above neutral for a selection of mature municipal solid waste (MSW) composts.

Compost pH often varies with the processing stage (Stentiford et al., 1985; Inbar et al., 1993; Iannotti et al., 1994). Iannotti et al. (1994) worked with MSW and observed a drop in pH from 7 to 5.7 in the first 10 days of composting. By day 80, pH rose to a peak of 7.8, then dropped again to a value of 7.5 by day 175. During curing, these materials slowly approached neutral. In general, the tendency is for pH to approach a steady value during curing (Stentiford et al., 1985; Inbar et al., 1993; Iannotti et al., 1994).

Compost pH also may reflect composting progress. A number of authors have associated an apparent change in microbial activity with low pH (Rinzema and Klapwijk, 1990; Iannotti et al., 1994). Rinzema and Klapwijk (1990) urged careful pH control for consistent processing results. Of interest were the observations of Waksman et al. (1931) regarding the increased decomposition of lignin at pH levels above 7, and at higher temperatures.

Nitrogen

Compost's ability to enhance or to inhibit N availability within the soil-plant system is a key concern to growers (N'Dayegamiye et al., 1977; Inbar et al., 1993; Barker, 1997; Bernal et al., 1998).

As composting progresses, NH_4^+ is oxidized to NO_3^- by the action of nitrifying bacteria (Iannotti et al., 1994). The general pattern of N release

during decomposition is the conversion of labile organic forms into microbial biomass (Waksman et al., 1931; 1939; Grebus et al., 1994; Barker, 1997). After the exhaustion of the degradable C supply, oxidized N forms appear (Waksman et al., 1939). Young compost does not accumulate mineral N. Rather, N is incorporated into microbial biomass (Stentiford et al., 1985). This would suggest that NO_3 accumulation is an indicator of compost maturity (N'Dayegamiye et al., 1977; Grebus et al., 1994). Ammonium nitrifying bacteria are inactive at temperatures above 40°C (Waksman et al., 1939). For this reason, Stentiford and Neto (1985) considered the increase in nitrification a secondary maturity indicator, evidence of falling temperatures. Nitrate may be lost from the compost matrix by the action of denitrifiers at work in pockets of low O_2 concentration in heterogeneous materials (Grebus et al., 1994).

For high C: N ratio feedstocks, composting reduces the C: N ratio. Composting also reduces concentrations of unstable N forms like amines and urea for all feedstocks (Waksman et al., 1939). Sludge proteins are significant sources of degradable N (Barker, 1997; Bernal et al., 1998). As the stable N fraction increases, N becomes linked to humic materials. The partitioning of compost organic N into various hydrolyzable and non-hydrolyzable fractions suggests the vulnerability of organic N compounds to microbial degradation, and may be indicative of the level of compost maturity (Paré et al., 1998).

N'Dayegamiye et al. (1977) characterized N mineralization by compost in soil incubation studies as a brief, rapid exponential initial phase followed by a longer, slower, linear phase.

Compost processors must avoid environmentally hazardous large-scale ammonia releases that draw odor complaints (Rinzema and Klapwijk, 1990; Barker, 1997). If C: N of the parent material (e.g., manure) is low, then there is high NH_4^+ production, high pH, and NH_3 gas released (Zwart, 1990; Barker, 1997). For compost with C: N less than 15: 1, reduced decomposition rates, by any mechanism during the early stages of composting, result in N loss as NH_3 (Waksman et al., 1931; 1939; Barker, 1997). For composts with higher C: N, less N is lost.

Oxidized forms of N, NO_2^- and NO_3^-, appear when the decomposable C supply has diminished. Ammonia released by decomposition and protein N are oxidized into these forms (Jiménez and Garcia, 1989; Grebus et al., 1994). Nitrogen mineralization in more mature composts is slowed by the lack of readily degradable C source for nitrifier use. Robertson and Morgan (1995) attributed linear decline in C and N mineralization after two weeks of compost incubation in soil columns to increased C and N stability.

To summarize, the fate of N in compost is loss as NH_3, consumption by microbes to increase biomass, or oxidation to NO_3.

CEC

Cation exchange capacity is related to soil fertility. It is a measure of a material's ability to adsorb positively charged ions. An increase in CEC is correlated with increased compost age (Grebus et al., 1994). It is positively correlated with percent humic substances found in compost. Humic content is a function of the degree of organic matter degradation (Jiménez and Garcia, 1989; Forster et al., 1993). Humus, with its high CEC, buffers soil acidity (Barker, 1997). Finer sized feedstocks often show a higher CEC, probably due to greater surface area. Forster et al. (1993) stated on the basis of experimental evidence that it is only valid to compare the CEC of materials of the same feedstock. Henry and Harrison (1996) stated that the ratio of CEC to total organic matter correlates well with other chemical measures of compost maturity.

Volatile solids

Volatile solids (VS) are the non-ash portions of compost feedstock. Low VS indicate low organic matter content (Iannotti et al., 1994). Heat production is associated with the rate of VS degradation (Stentiford and Neto, 1985). Lasaridi and Stentiford (1998b) considered relative changes in VS a good non-specific indicator of the degree of decomposition when absolute values are not considered. Stentiford and Neto (1985) cautioned

that this parameter is substrate specific and not valid as a universal test of maturity, although VS measures do decline with time for all composts (Lasaridi and Stentiford, 1998b). Reduction in VS is significantly correlated to compost age and respirometric parameters (Stentiford and Neto 1985). Reduction of VS by as much as 40% from the initial value is cited in the literature (Stentiford et al., 1985).

Carbon

Many authors have investigated the transformation of C during composting (Liao et al., 1994; Robertson and Morgan, 1995; Paré et al., 1998). Carbon concentration in compost drops consistently to equilibrium as feedstock biodegradability is reduced (Lasaridi and Stentiford 1998a, b). Paré et al. (1998) found about one-third of the initial C was lost as CO_2. Much of that C was released during the early thermophyllic processes. Water soluble and acid hydrolyzable C, the fractions accessible to microbes, make up most of that third. Reduction of water-soluble organic C concentration has been suggested as an indicator of stability (Iannotti et al., 1994). A low fulvic acid-to-humic acid ratio suggests mature compost, while a high fulvic acid-to-humic acid ratio indicates degradable organic C content (Forster et al., 1993).

Carbon to nitrogen ratio

Sugars, starches, cellulose, and lipids are high in easily decomposable C and low in N. They impart a wide C: N to feedstocks when they predominate. Such materials immobilize N and other plant nutrients as they decompose (Grebus et al., 1994; Barker, 1997). Composting narrows C: N of the original materials, and is highly correlated with age of the compost (Buchanan and Gliessman, 1991; Grebus et al., 1994; Barker, 1997; Lasaridi and Stentiford, 1998a). The more rapid loss of CO_2 – C than NH_3 –N results in a net relative reduction in C: N during composting (Barker, 1997). Carbon to nitrogen ratio cannot be considered an infallible measure of C stability. Immature compost may, of itself, have low C: N, but have significant N sequestered in microbial biomass (Hartz et al., 1996). Consider chicken litter, which may have initial C: N as low as 10: 1. A number of authors suggest absolute C: N values indicative of maturity relative to starting materials (Jiménez and Garcia, 1989; Zucconi and de Bertoldi, 1989; Forster et al. 1993). To compensate for variability among feedstocks, Morel et al., (1982), cited by Jiménez and Garcia (1989), recommended the ratio of final C: N to initial C: N. Some C: N for finished compost reported in the literature are:

- composted yard debris - 10:1 (Hartz et al., 1996),
- household waste – 12:1 to 20:1 (Forster et al., 1993),
- sewage sludge and paper - 20:1 to 35:1 (Forster et al., 1993),

- cattle manure with straw – 15:1 (N'Dayegamiye et al., 1977),
- horse manure with paper – 20:1 (Paré et al., 1998),
- composted chicken manure – 11:1 (Robertson and Morgan, 1995),
- mixed manures with paper – 20:1 (Paré et al., 1998).

Electrical conductivity

Electrical conductivity (EC) indicates salt content, and so is an important element of plant response to compost. Often, cattle manure is characterized by high EC. Barker (1997) suggested further evaluation of material testing at 4 dS/m from 2:1 (w:v) or saturated paste extracts before using in growing media. Forster et al. (1993) did not consider EC an indicator of maturity per se, but rather an indicator of the initial feedstocks. They did note that EC varies with time. By contrast, Inbar et al. (1993) followed EC through 147 days of composting and observed a steady increase of EC with NO_3^- and ash, as the compost matured. Hartz et al. (1996) found that EC varied with feedstock and between composted yard debris samples from two distinct eco-regions of California.

SENSORY AND PHYSICAL MEASURE OF COMPOST MATURITY

Sensory Measures

Odor is neither objective nor quantifiable, but odor control is an important aspect of composting process control, since yard debris composting facilities are often near housing developments. Grass clippings commonly are fermenting when they arrive at the composting site (Grebus et al., 1994). Fatty acids, alcohols, aldehydes, ketones, and volatile sulfur compounds indicate instability and contribute to malodorous compost (Jiménez and Garcia, 1989; Lasaridi and Stentiford, 1998b). Odor problems can be reduced or eliminated with careful process control. Water and aeration are important compost process parameters noted for odor control. Adequate water content promotes rapid degradation (Frost et al., 1992). Sufficient aeration avoids fermentation (Grebus et al.,1994). Mature compost lacks objectionable odors (Henry and Harrison, 1996).

The most common tests rate odors according to written descriptions (Leege and Thompson, 1997).

Physical Characteristics of Mature Compost

Bulk density and moisture content are commonly monitored compost physical characteristics. The interpretation of these tests is dependent on feedstocks and composting process control (Waksman et al., 1931).

Composting reduces initial moisture content of yard debris (Inbar et al., 1993). Hence, water content monitoring is an important aspect of process control if optimal microbial activity is to be supported (Stentiford et al., 1985; Hoitink et al., 1997; Touart, 1999; Sikora and Sullivan, In Press). Inbar et al. (1993) observed an increase of bulk density and a decrease of total porosity in batch-processed cattle manure solids (Inbar et al., 1993). Increased bulk density and reduced total porosity sometimes are characteristic of mature compost (N'Dayegamiye et al., 1977; Inbar et al., 1993).

AERATION EFFECTS ON THE COMPOSTING PROCESS

Forced Aeration

Mechanically augmented aeration during composting has a number of advantages for the final product. It is an efficient way to ensure optimal air supply. Forced aeration increases the decomposition rate by removing heat, promoting maximum microbial activity (Stentiford et al., 1985; Bernal et al, 1998). Aerated static compost piles can sustain temperatures sufficient to kill pathogens and weed seeds (Stentiford et al., 1985; de Bertoldi et al., 1989; Rosen, 1993; Sikora and Sullivan, In Press). Finally, these systems are shown to control effectively the odor problems

associated with fermentative by-products (Stentiford et al., 1985; Touart, 1999).

In comparing the traditional turned windrow management style on these points, Lasaridi and Stentiford (1998b) found O_2 levels in turned windrows drop within an hour of turning. Piles greater than 3 m high are difficult to sufficiently aerate in order to kill pathogens. Further, all materials must be rotated into the interior and exposed to higher temperatures within the compost pile (de Bertoldi et al., 1989). Sustained high temperatures reduce microbial numbers, and thus the rate of microbial respiration (Stentiford et al., 1985; Bernal et al., 1998).

The main effects on materials processed under forced aeration over turned windrows are:

- faster reduction of organic C and O_2 demand
- faster reduction of carbohydrate and protein content, and
- faster increase of compost CEC (Stentiford et al., 1985).

Further enhanced aeration effects on compost, noted by de Bartoldi et al. (1989) include a rapid decrease in soluble organic C and a reduction in C: N. Whatever the processing technique, compost produces NH_3 whenever excess N is available. Forced aeration compost loses more N as NH_3 than non-aerated static piles, though physical turning also releases trapped gases from compost piles (Rynk, 1998). Greater odor problems might be associated with NH_3 from non-aerated static windrowed materials

than from forced aeration materials. Turning events release large volumes of NH_3 gas compared to the constant release through forced aeration systems. Further, increased NH_3 release is associated with lower initial C: N of feedstocks, presumably because C availability limits biomass increase and N uptake (Hansen et al., 1993; Michel et al., 1996; Rynk, 1998). Compost cured under forced aeration showed lower concentrations of phytotoxic compounds, including NH_3, than non-aerated compost of the same age (Liao et al., 1994). Lasaridi and Stentiford (1998b) found longer treatment under forced aeration increased initial C stabilization rates, but over time, the difference between treatments diminished, and disappeared within six months.

Temperature Effects on Composting

A number of attempts have been made to define optimal processing temperatures for composting. Hoitink and Stone (1997) tracked chemical changes with temperature. They found a marked reduction in VS as process temperatures rose to 40 to 50°C within the first 48 hours of processing. Cellulose content dropped during the thermophyllic phase, defined by temperatures between 50 and 70°C. Finally, during the curing phase, temperatures dropped below 40°C as readily decomposable C content diminished. Other parameter changes with temperature cited in the literature:

- VS reduction is optimal at 40 to 55°C (Nakasaki et al., 1985; McKinley et al., 1989; Walker et al., 1989; Bernal et al., 1998).
- Temperatures from 40 to 60°C are most closely associated with low odor conditions (Walker et al., 1989; Inbar et al., 1993).
- Pathogens are eliminated between 40 and 60°C (de Bertoldi et al., 1989; McKinley et al., 1989; Walker et al., 1989; Miller, 1991).

Above 60°C, aerobic decomposers are heat-killed and decomposition slows (Walker et al., 1989). Inbar et al. (1993) recommended long, slow curing as ideal for maximum C stabilization.

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CHAPTER 2

ASSESSING MATURITY OF YARD DEBRIS COMPOSTED VIA TURNED WINDROW AND FORCED AERATION METHODS

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ABSTRACT

Compost maturity is an important determinate of end use for composted municipal yard debris. Highly technical composting facilities represent a huge financial investment, yet composting in densely populated urban areas demands careful process control. The objectives of this study were to: (i) determine whether continuous aeration resulted in more rapid maturity of composted yard debris than windrow turning and (ii) determine which maturity indicators or indices distinguish between mature and immature compost. We sampled two identical compost piles of source-separated municipal yard debris through 35 d of active composting and 78 d of in-vessel curing. The treatment consisted of continuous forced aeration (FA) during active composting or air supply renewed through pile porosity or free airspace that was reestablished by periodic turning of the windrow (TW). Materials composted under forced aeration continued to receive bottom aeration throughout curing; the TW materials were neither aerated nor turned during curing. We determined chemical (pH, CEC, total C and NH4: NO3 ratio), sensory (odor and color), respirometric (alkaline traps) and biological (percent germination and shoot mass) measures of compost maturity. We found that compost maturity was strongly correlated with pH, C and respiration. Carbon (C) fell from 400 g kg^{-1} to 250 g kg^{-1} and pH rose from 5 to 7. The CO_2 evolution rate fell from 16 to 2 mg CO_2 – C d^{-1}. Maturity was somewhat correlated with odor. Neither biological nor sensory

measures were reliable indicators of maturity for these composts. We conclude that both aeration treatments resulted in mature compost, with a low, stable respiration rate. The FA materials reached this point about 20 d sooner than the TW materials.

INTRODUCTION

The viability of municipal yard debris composting programs depends in large measure on the maturity and stability of the resultant compost, and on the demand for it by large-scale users. The possibility of a value-added market niche for quality compost drives the current research to establish chemical, biological and physical properties that define stability and maturity. (Grebus et al., 1994; Helfrich et al., 1998; Rosen et al., 1993).

Composting reduces the volume of feedstocks, kills pathogens, reduces C content, concentrates non-volatile plant nutrients such as P and K, and transforms troublesome compounds like organic acids (Barker, 1997; Hoitink et al., 1997). Composted materials are suitable for horticultural (Hartz et al., 1996) and agricultural (Barker, 1997; Buchanan, 1991; N'Dayegamiye et al., 1977) applications and can be used as a peat substitute in container applications (Inbar et al., 1993).

Lasaridi and Stentiford (1998) defined stability as the extent to which biodegradable organic matter has decomposed (Lasaridi and Stentiford, 1998b). Compost becomes stable as organic C is oxidized to carbon

dioxide. Respiration is a measure of microbial activity and an indicator of compost stability. Respiration is measured by CO_2 evolution rate (Bartha and Pramer, 1965) or O_2 uptake rate (Frost et al., 1992; Grebus et al., 1994; Lasaridi and Stentiford, 1998a, b). The conditions supporting microbial life -- appropriate moisture, temperature, nutrient, C and oxygen supply -- are necessary to maintain high respiration rates (Inbar et al., 1993; Miller, 1991; Waksman et al., 1931).

Desirable characteristics for a stability test (Frost et al., 1992; Willson and Dalmat, 1989) include:

- applicability to a broad range of feedstocks
- large sample size
- cost-effective, on-site testing in less than a work-day
- reliable, easily operable, readily available equipment
- results correlate well with established measures.

A decreasing CO_2 evolution rate implies a reduction in biodegradable C and increasing C stability (Paré et al., 1998). Grebus et al., (1994) found a variety of tests highly correlated with compost age. Nitrate concentration, cation exchange capacity (CEC), and electrical conductivity (EC) values increased with process time; soluble organic C concentration, C to nitrogen ratio (C: N ratio), dissolved oxygen (DO), and phytotoxic effects were reduced with process time (Grebus et al., 1994).

No single test assesses compost maturity for all feedstocks. Further, the term "mature" is best formed with respect to the compost's intended end-use (Frost et al., 1992). Generally, maturity tests fall into four categories: biological (Grebus et al., 1994; Iannotti et al., 1994), chemical (Frost et al., 1992; Grebus et al., 1994; Henry and Harrison, 1996), microbial (Forster et al., 1993), and physical (Grebus et al., 1994).

Biological tests, tests for phytotoxicity, are most often root- and shoot-mass measures conducted with water extracts of the sample material (Inbar et al., 1993; Lasaridi and Stentiford, 1998b; Shiralipour et al., 1997) or with the sample incorporated into a potting mixture (Garcia et al., 1992; Hartz et al., 1996; Inbar et al., 1993). Immature compost inhibits germination or reduces root length because it releases water-soluble phytotoxic compounds into the growth medium (Forster et al., 1993; Hartz et al., 1996; Jiménez and Garcia, 1989), or because it is undergoing reductive decomposition (Jiménez and Garcia, 1989). Low molecular weight organic acids are important phytotoxins. Nitrogen deficiency symptoms of plants can indicate compost immaturity (Iannotti et al., 1994).

Multitudes of chemical indicators have been considered as potential maturity indices for compost. These include humic acid concentration, humic acid to fulvic acid ratios, C: N ratios, ash concentration, pH, nitrate (NO_3^- N), and CEC (Inbar et al., 1993; Liao et al., 1994; N'Dayegamiye et al., 1977).

High ammonia (NH_3) concentrations in compost and nitrogen loss as NH_3 gas usually indicate immaturity (Barker, 1997; Paré et al., 1998). As composting progresses, ammonium (NH_4^+) concentration decreases by conversion to NO_3^- (Forster et al., 1993). Cation exchange capacity increases as compost organic content humifies (Jiménez and Garcia, 1989). Composting progress for feedstocks with low initial N concentrations can be indicated by pH. (Gurkewitz, 1989; Inbar et al., 1993; Jiménez and Garcia, 1989). Wide C: N ratio is considered an indicator of immaturity (Barker, 1997), although for feedstocks with low initial C: N ratio this rule does not hold true.

Compost maturation is a microbially mediated decomposition process (Paré et al., 1998). The presence of highly resistant C compounds, low rates of CO_2 evolution (Iannotti et al., 1994; Paré et al., 1998), and stable temperatures after turning (Jiménez and Garcia, 1989) characterize compost maturity.

Odor, color, bulk density and moisture commonly are monitored physical characteristics of compost. The interpretation of these tests is dependent on feedstocks and composting process control (Sullivan and Miller, 2000).

Composting under optimal oxygen supply enhances mineralization of organic compounds, releases labile C as CO_2, and promotes oxidation of phytotoxic compounds in compost. State-of-the-art composting facilities can

exceed regulatory standards while producing a consistent product (Touart, 1999). We believed such a facility would provide the ideal controls for a compost maturity study. We were interested in determining whether materials processed under controlled continuous aeration and those processed in traditional turned windows displayed difference in maturity indicators. In this study, our objectives were to: (i) determine whether continuous aeration resulted in more rapid maturity of composted yard debris than windrow turning and (ii) determine which maturity indicators or indices distinguish between mature and immature compost.

MATERIALS AND METHODS

Composting Facility

Land Recovery, Inc. conducted composting and curing at their indoor Compost Factory in Puyallup, WA, USA. This is a highly technical facility producing yard debris compost under generally optimal conditions. In-floor air vents supply variable volume and directional aeration as software-controlled temperature probes in each compost pile monitor temperature conditions within the pile (Touart, 1999).

Preparation of Compost Feedstock

A Universal Refiner Super Contender (Universal, Montesano WA) grinder and trommel/blender was used to prepare the yard debris for composting. It ground, screened and mixed the source-separated materials. The initial substrate was a roughly 50/50 (v/v) mix of grass clippings and woody prunings. All the materials were received from curbside collection within 24 h of the initiation of processing. Front-end loaders stacked the prepared yard debris into windrows approximately 15 m long by 5 m wide by 2.5 m high on the composting hall floor, for an approximate 185-m^3 volume subjected to each aeration treatment. The experimental compost piles were turned and mixed twice with a SCAT 4932 (Scat Engineering, Division of ATI Incorporated, Delhi, IA) after initial stacking to promote homogeneity of the materials and to establish consistent porosity in the

Active Composting

Composting proceeded in a two-stage process (active composting and curing) described in Tables 2.1 and 2.2. For our study, some yard debris was processed in turned windrows under forced aeration (FA), and some was processed in turned windrows (TW) without additional aeration. The FA treatment provided yard debris with continuous aeration at positive or negative pressure. Air supply valves serving the floor supporting the TW

treatment were closed during active composting. Substrate was actively composted from 0 d to 35 d, with an additional curing phase from 35 d to 113 d.

TABLE 2.1. As-Received Physical Properties of Compost Feedstock

Parameter*	Sample Moisture	Value	Units
Initial moisture content	as-is	620	g kg^{-1}
Wet bulk density	as-is	231	g L^{-1}
Air-filled porosity	as-is	52	mL L^{-1}
Ash content	dry	380	g kg^{-1}
Dry bulk density	dry	108	g dm L^{-1}

*Parameter values are means of six composite subsamples.

The compost was turned and watered by the SCAT 4932 on the same schedule regardless of aeration treatment. This equipment lifts, waters and moves compost, but does not effect appreciable grinding. Compost was tested for moisture levels the day before turning; the target moisture level after turning and watering was 500 g kg^{-1}. Samples were collected on 0, 7, 14, 21 and 27 d of active composting.

Process temperatures were monitored using two Tele-Probes (Green Mountain Technologies, Seattle, WA) per treatment. Each wireless temperature probe radioed thermal information from two sensors 0.9 meters apart, vertically, on the probe to process control software every five

minutes. These sensors monitored temperatures within the piles. In the FA windrows, damper actuators altered blower direction from positive to negative to remove heat and hold temperature and oxygen gradients in the compost to a minimum. Temperature data for 28 to 43 d were lost due to equipment failure.

TABLE 2.2. Process Control Protocol for Compost and Curing Phases

Active composting phase		
Chipping procedure	Rotary disk mill	
Mixing method	Self-propelled windrow turner	
Residence time	35	d
Turning frequency	Weekly	
Target compost moisture after water addition	500	g kg-1
Windrow dimensions (l*base*h)	15 m * 5 m * 2.5	m
Curing phase		
Residence time	89	d
Mixing or turning method	None	
Initial and final moisture content	590 and 660	g kg^{-1}
Water addition	None	
Curing bin volume	FA: 30 m^3; TW: 38	m^3

As compost piles were turned, they moved laterally across the concrete facility floor. Active composting continued for 35 days from the start date, after which time the materials went into curing vessels.

The temperature of the materials rose rapidly after the compost piles were assembled, and remained greater than 55°C during active composting.

Curing

Curing phase materials were sampled on 43, 56, 70, 85, 98, and 113 d. Forced aeration materials cured in a 30-m^3 tarp-covered NaturTech Curing Bin (St. Cloud, MN), with an air line connected to a plenum in the container floor. Software-controlled temperature data collection continued for these materials throughout the curing phase. Turned windrow materials went into a 38 m^3 hard-topped NaturTech Digester (St. Cloud, MN). The curing bin for the TW materials was incapable of collecting temperature data. Materials were not turned through the duration of curing. Curing continued until the final sampling on 113 d.

Compost process control

Moisture was monitored before every turning and adjusted as needed during the active composting period, but not during curing. Figure 2.1a

illustrates total solids, which leveled out after 35 d while materials were curing. The low total solids figures (high moisture) for the last two sampling dates are consistent with the saturated condition of the samples for those dates. Moisture carried by convective currents within the outdoor curing vessels condensed against the colder curing bin covers, adding moisture to the upper layer of compost. The average December temperature range for the Puyallup, WA area is 0 - 10°C. December 1 was day 99 of our study.

Sampling procedures and sample preparation

Actively composting yard debris was sampled immediately after mixing on 0, 7, 14, 21 and 27 d, and an additional six times during curing on 43, 56, 70, 85, 98 and 113 d. Composite samples were taken from three locations within each aeration treatment. Sampling was in accordance with protocols described by Leege and Thompson (1997) and is detailed in Table 2.3. Each composite sample represented approximately 60 m^3 of compost during the active composting phase and 10-12 m^3 of compost during the curing phase.

A portion of each composite sample was shipped on ice to the authors at the Soil Chemistry Laboratory at Oregon State University for analysis, and another to portion to Agricheck of Umatilla, OR. Iced samples arrived at the laboratories within 24 to 48 h of collection.

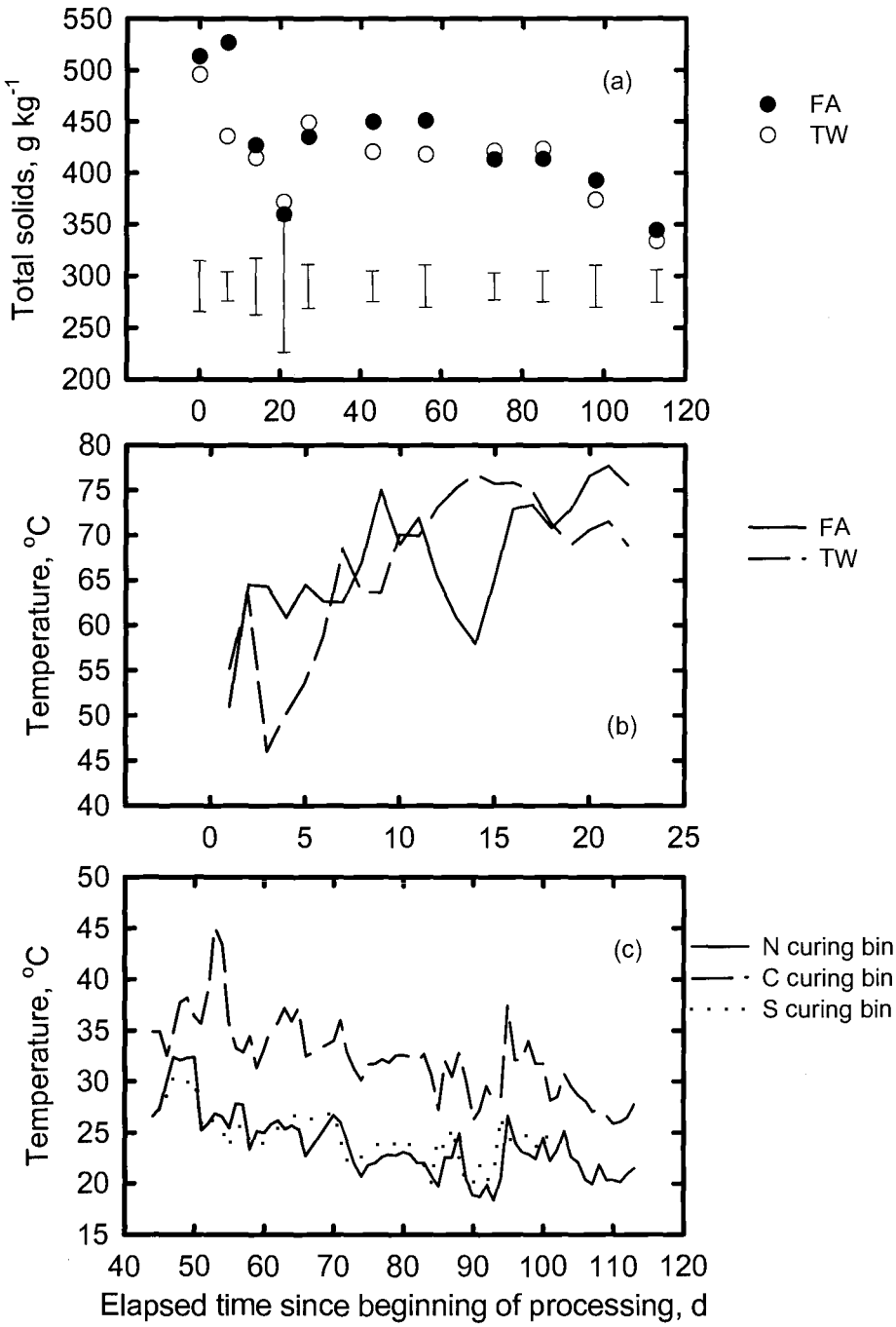

Figure 2.1. Compost Total Solids (a), Active Composting (b) and Curing Phase Temperatures (c). Effect of processing duration on total solids for yard debris composted under forced aeration (FA) or as turned windrows (TW), and observed temperatures for 0-35 d active composting and 38-113 d in-vessel curing. Curing data only from FA treatment; curing bins for TW treatment not capable of data collection. Missing data for 26-43 d represents equipment failure.

TABLE 2.3. Sampling Protocol for Yard Debris Compost During Composting and Curing Phases

Active composting phase	
Sampling days	0, 7, 14, 21,27
Sampling unit size	185 m^3
Number of sampling locations (N, C, S)	3
Number of grab samples per location	30
Sample collection timing relative to turning	Immediate
Composite volume of grab samples per location	20 L
Reduced volume of composite sample per treatment	9 L
Curing phase	
Sampling days	43, 56, 70, 85, 98, 113
Sampling unit (curing bin) size	FA: 30 m^3; TW: 38 m^3
Composite samples per curing bin	3
Number of grab samples per composite sample	30
Collection depth from compost surface	0.3 – 0.6 m
Volume of each grab sample composite	20 L
Reduced volume of composite sample per treatment	9 L

Upon arrival at Oregon State University, samples were removed from their packaging. "As-received" aliquots from each subsample were set aside for total solids and bulk density measurements. The remainder of each sample was picked over by hand for large (>1.5 cm diameter) sticks, stones and all foreign matter, but was not screened. In preparation for incubation, the samples were sprayed to renew moisture concentration to approximately 500 g kg^{-1}. All samples were re-packaged in their original one-liter sealable plastic bags, left unsealed, and held at 37°C for 36 h to promote microbial activity.

ANALYSIS OF COMPOST SOLIDS

We examined numerous chemical, physical, biological and respirometric measures to judge the stability of compost. Table 2.4 summarizes the tests, the methods used, and the testing locations.

Rate of respiration

We used vials with NaOH solution to measure the CO_2 evolution rates from the compost samples. The procedure was similar to one used by Ionatti, et al., (1994) and by Forster, et al., (1993). Twenty-five g samples were placed in 0.5 L (pint) glass canning jars with airtight lids. A 20 mL or 30 mL vial of 0.11 *M* NaOH was placed in the jars before sealing. The

TABLE 2.4. Summary of Compost Chemical, Sensory, Biological and Respiration Test Methods

Laboratory	Chemical Measures	Method	Reference
CAL†	Total nitrogen	Combustion analyzer	SPAC‡
Agricheck§	Total carbon	Combustion analyzer	SPAC
Agricheck	Soluble salts	Conductivity meter	ASA Monogr. 9
Agricheck	Total solids	07.02-C Unmilled Material Ignited at 500°C ± 50°C with Inerts Removal	TMECC¶
Agricheck	CEC	Sodium acetate at pH 7	ASA Monogr. 9
Agricheck	pH	2:1 water: compost volume addition	TMECC
	Sensory Measure		
By author	Odor and color	09.03-A Quick-Test for Field Assessment of Compost Color and Odor	TMECC
	Biological Measure		
By author	Seed Germination	09.05-B, Quick-Test for Emergence and Relative Growth (Direct Seeding)	TMECC
	Respiration Measure		
By author	CO_2 evolution	09.09-C, Carbon Dioxide Evolution Rate	TMECC

† Analyses by Central Analytical Laboratory, OSU.
‡ Soil and Plant Analysis Council, Inc. (1999).
§ Analyses by Agricheck, Umatilla, OR.
¶ Leege and Thompson (1997)

larger quantity was used for the first two sampling periods while respiration rates were high. The sealed jars went into a water bath at 37°C. Carbon dioxide was trapped for two periods: 0-24 h and 24-48 h. The jars were opened briefly at 24 h to exchange vials. Triplicates of each composite compost sample were incubated in this manner. Each incubation included a blank, consisting of a sealed jar containing a NaOH trap, but no compost.

The amount of respiration was calculated as:

$$\text{mg } CO_2\text{ - C } = J\ L\ M^{-1}\ N\ [P - Q] \qquad \text{Eq. [1]}$$

Where:

J = millequivalent weight of CO_2-C, 6 mg meq^{-1}

L = NaOH trap volume, mL

M = volume of NaOH trap aliquot titrated, mL

N = molarity of HCl to titrate NaOH, mmol mL^{-1}

P = volume of HCl used to titrate the trap aliquot from the no-compost blank, mL

Q = volume of HCl to titrate aliquot from trap exposed to compost respiration, mL

Note the adjustment for C represented by the compost in the trap in the following equation, resulting in the respiration rate:

$$\text{mg } CO_2\text{ - C g } C^{-1}\ d^{-1} = \text{mg } CO_2\text{ - C } R^{-1}\ S^{-1} \qquad \text{Eq. [2]}$$

Where:

R = mass of carbon in the sample, g

S = time, d

Phytotoxicity

We prepared a 1:1 yard debris compost sample: potting soil mix by a procedure similar to Method 09.05-B, Quick-Test for Emergence and Relative Growth (Direct Seeding) (Leege and Thompson, 1997). The potting soil mix was Filthy Rich™ medium grade potting soil (Rexius Forest By-Products, Inc., Eugene, OR). Filthy Rich™ potting soil includes composted bark fines, peat moss, mature composted yard debris, and pumice. Three replicates per seed type were prepared by filling 10 cm (800 mL) pots with the compost/potting mix mixture with enough deionized water to promote germination. In addition, three controls of Filthy Rich™ potting soil and no composted yard debris were held under the same conditions for each seed type.

Twenty rye, (*Secale cereale*) barley (*Hordeum vulgare L.*), or zucchini (*Cucubita pepo*) seeds were placed in a pot and covered lightly with the potting medium. The pots were held at 18°C, and exposed to fluorescent light for 16 h daily. Pots were watered with tap water as needed throughout the trial.

The number of sprouts visible in each pot was counted and recorded on trial day 5.

Odor and Color Analysis

Odor and color were evaluated according to TMECC, Method 09.03-A, Quick-Test for Field Assessment of Compost Color and Odor, prior to incubation (Leege and Thompson, 1997). Color was evaluated outdoors in bright shade. The samples were compared to Munsell Chart color chips. Samples were viewed through the hole in the chips to determine the closest color match. Odor was rated by comparing the odor to written odor descriptions (Leege and Thompson, 1997).

STATISTICAL ANALYSIS

The data were subjected to factorial analysis considering the significance of the effects of time and air, and their interaction. In this experimental design, if the interaction of the factors is significant, the effect of the interaction only should be considered in data interpretation. The calculations were made using Microsoft (Microsoft, Inc., Redmond, WA) Excel's "two factor ANOVA with replication." Table 2.5 summarizes the statistical significance of the chemical measures of compost maturity.

The number of replicate samples varied among test procedures. In Figures 2.1a, 2.2, 2.3, 2.4 and 2.5, data presented as FA or TW are the averages of three observations each per sampling date. Respiration data, Figure 2.6, is an exception with nine subsamples for each observation..

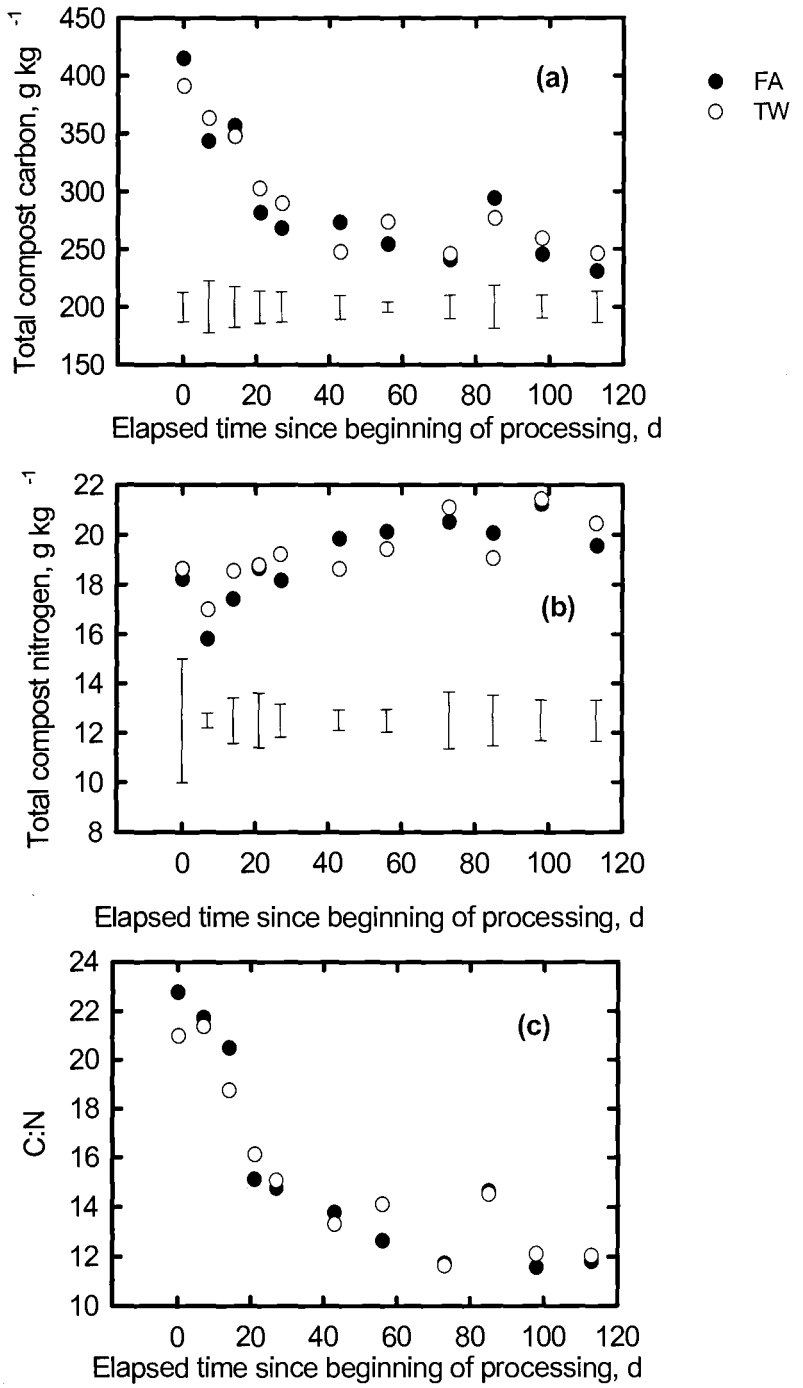

Figure 2.2. Compost Total Carbon (a), Total Nitrogen (b), and Carbon to Nitrogen Ratio (c) Changes with Composting Duration. Effect of composting on these chemical parameters of yard debris processed under forced aeration (FA) or as turned windrows (TW). Error bars represent the standard error of the mean.

Table 2.5. Statistical Significance, Determined by Analysis of Variance, of Chemical Measures of Compost Maturity

	Total solids	Soluble salts	CEC	NO_3-N	NH_4-N	NH_4-N: NO_3-N	Total N	Total C	C:N	pH	Respiration rate
Time	**	**	**	*	**	**	**	**	**	**	**
Air	*	**	*	ns	**	ns	ns	**	ns	**	**
Time* air	ns	ns	ns	ns	**	*	ns	*	ns	**	ns

ns, *,** not significant, significant at the 0.05 and 0.01 probability levels, respectively.

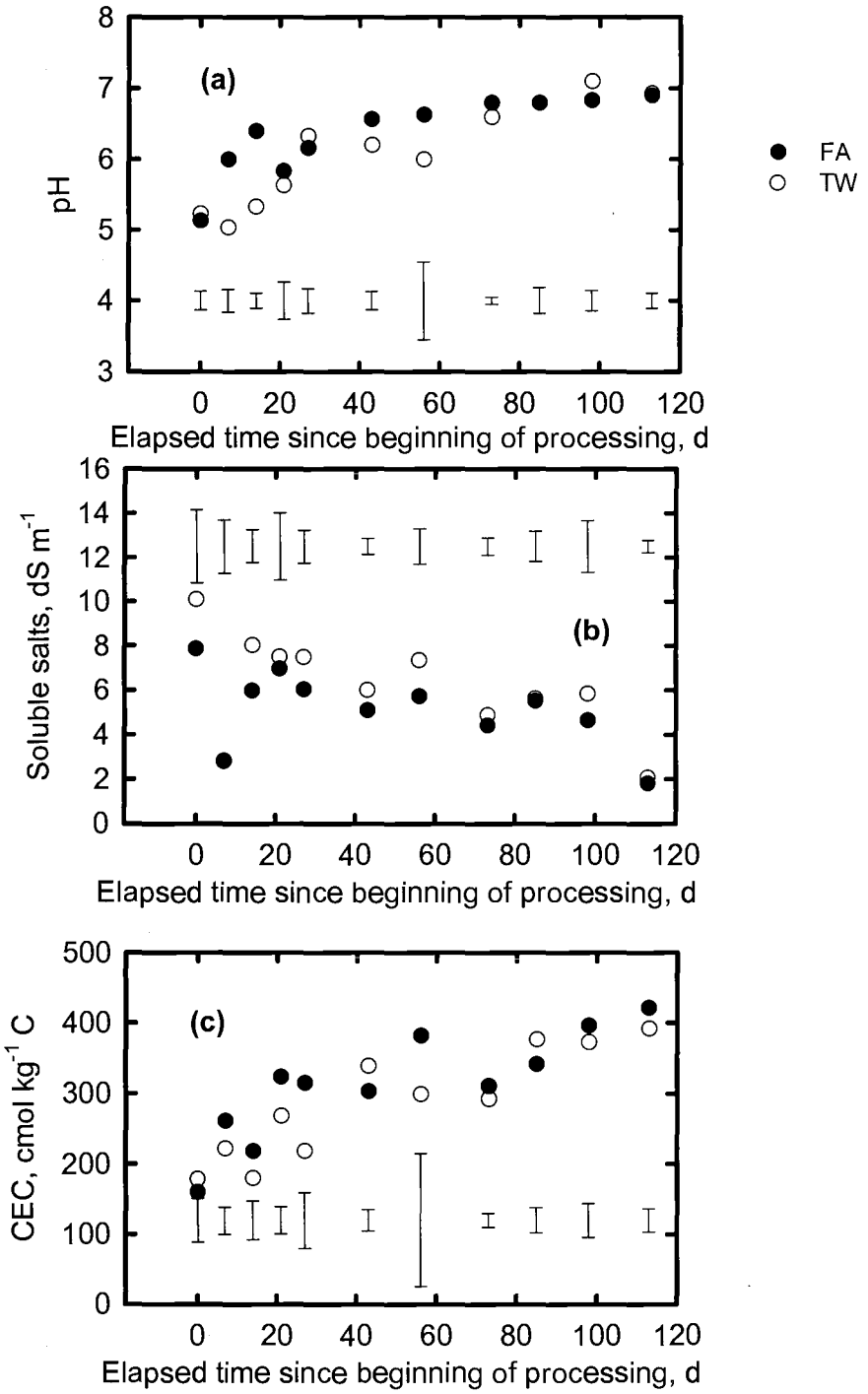

Figure 2.3. Compost pH (a), Soluble Salts (b), and Cation Exchange Capacity (c). Effect of composting on chemical parameters for yard debris processed under forced aeration (FA) or as turned windrows (TW). Error bars represent the standard error of the mean.

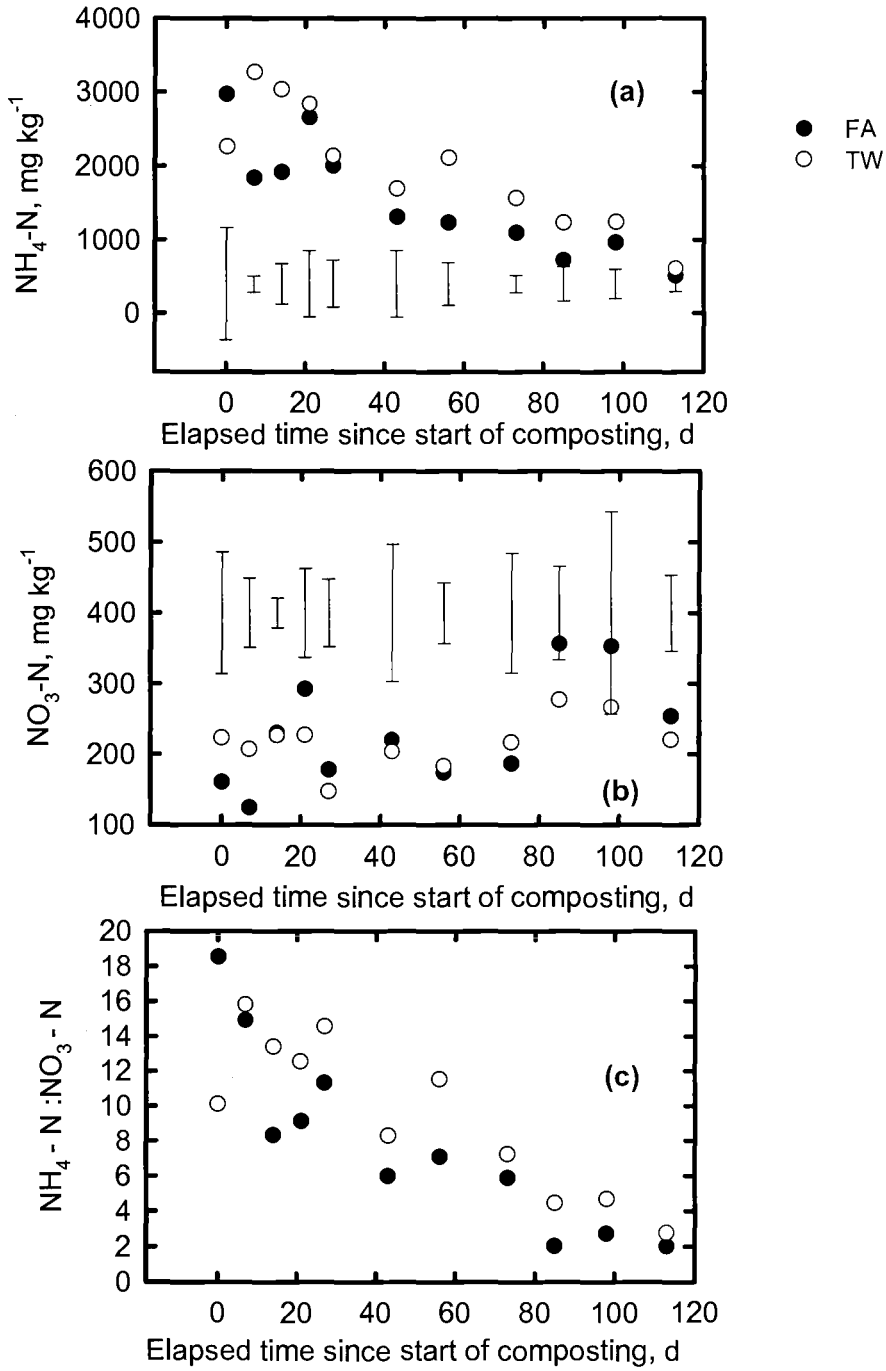

Figure 2.4. Compost Ammonium (a), Nitrate – N (b), and Ammonium – N : Nitrate – N (c). Effect of composting on nitrogen species for yard debris processed under forced aeration (FA) or as turned windrows (TW). Error bars represent the standard error of the mean.

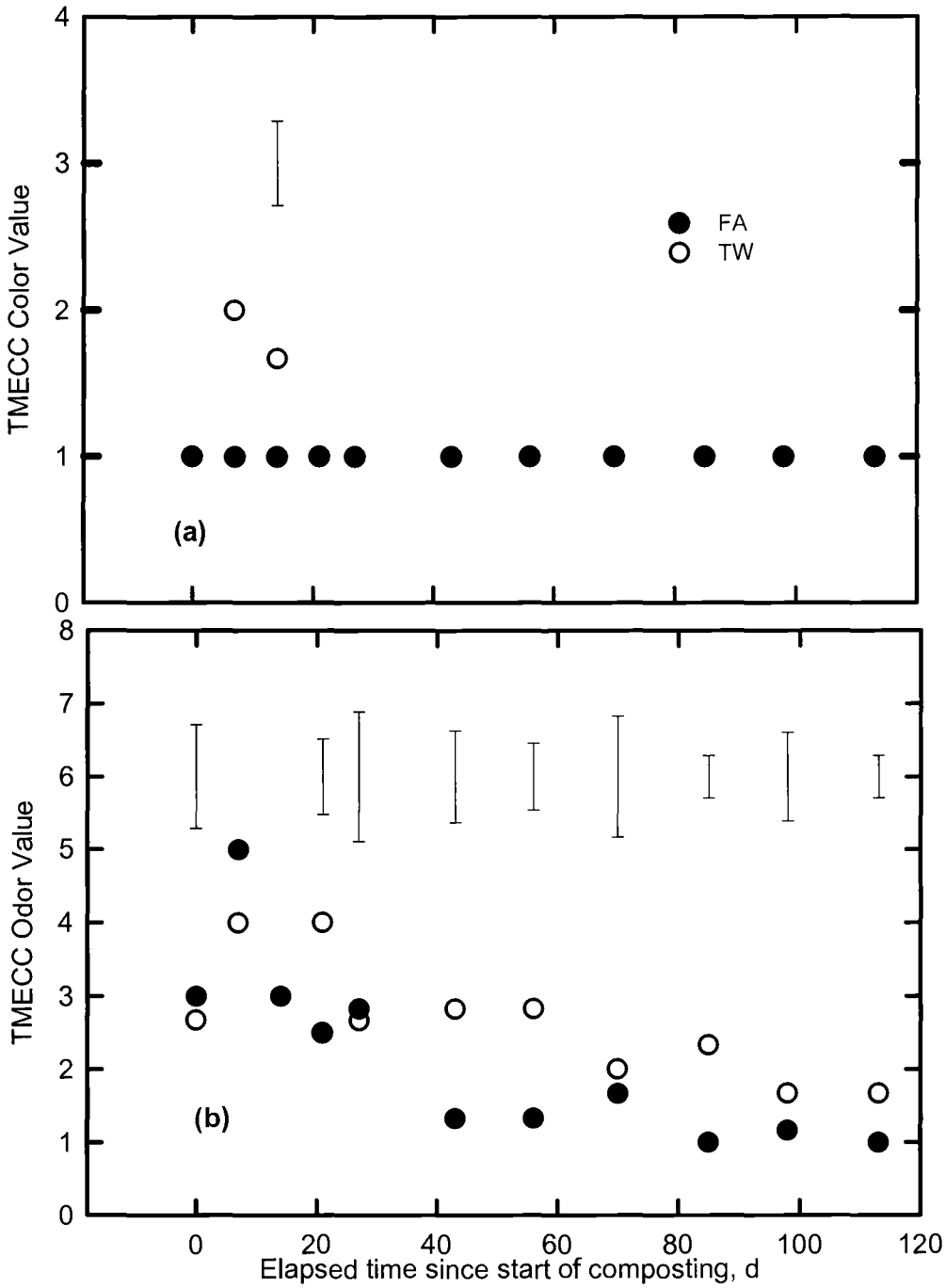

Figure 2.5. Compost Color and Odor. The effect of processing duration on compost color (a) and compost odor (b) for yard debris processed under forced aeration (FA) or as turned windrows (TW). Numerical color and odor ratings from TMECC Method 09.03A (Leege and Thompson, 1997). Error bars represent the standard error of the mean. Missing error bars indicate identical measures for the sampling date.

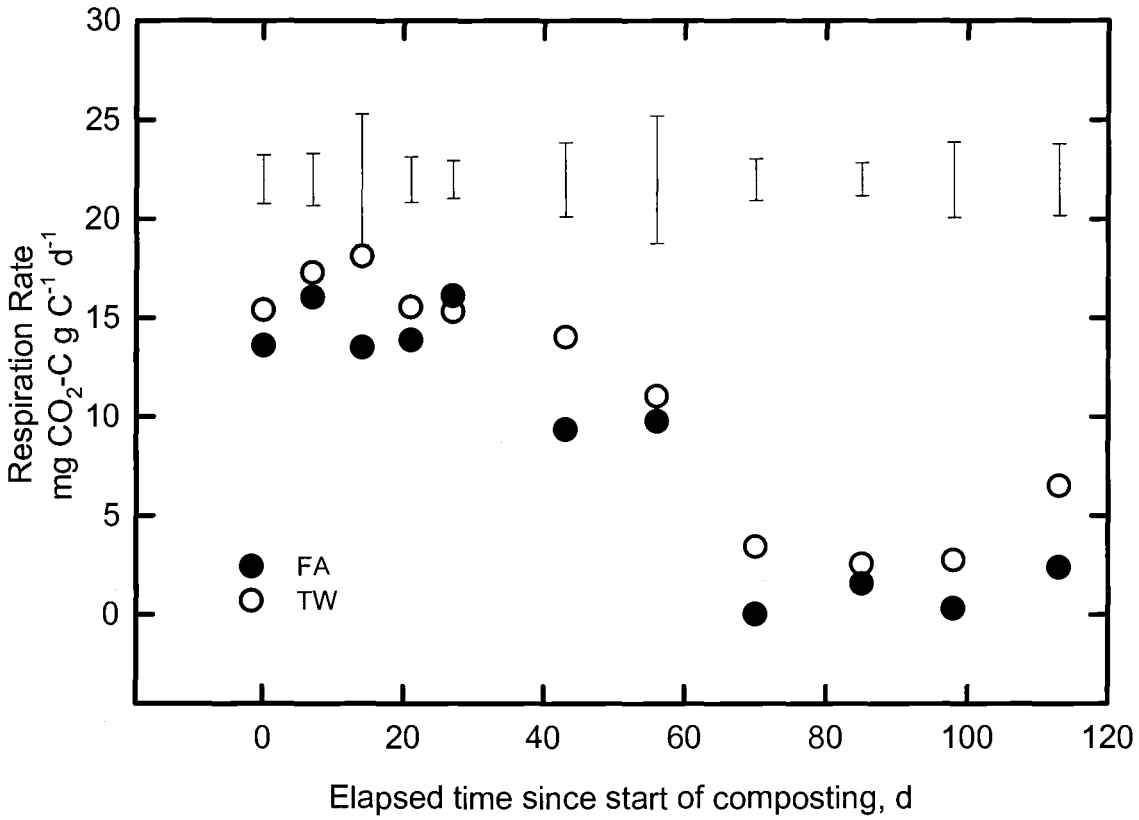

Figure 2.6. Compost Respiration Rate. Effect of processing duration on the rate of CO_2 evolution by yard debris composted under forced aeration (FA) or as turned windrows (TW). Error bars represent the standard error of the mean.

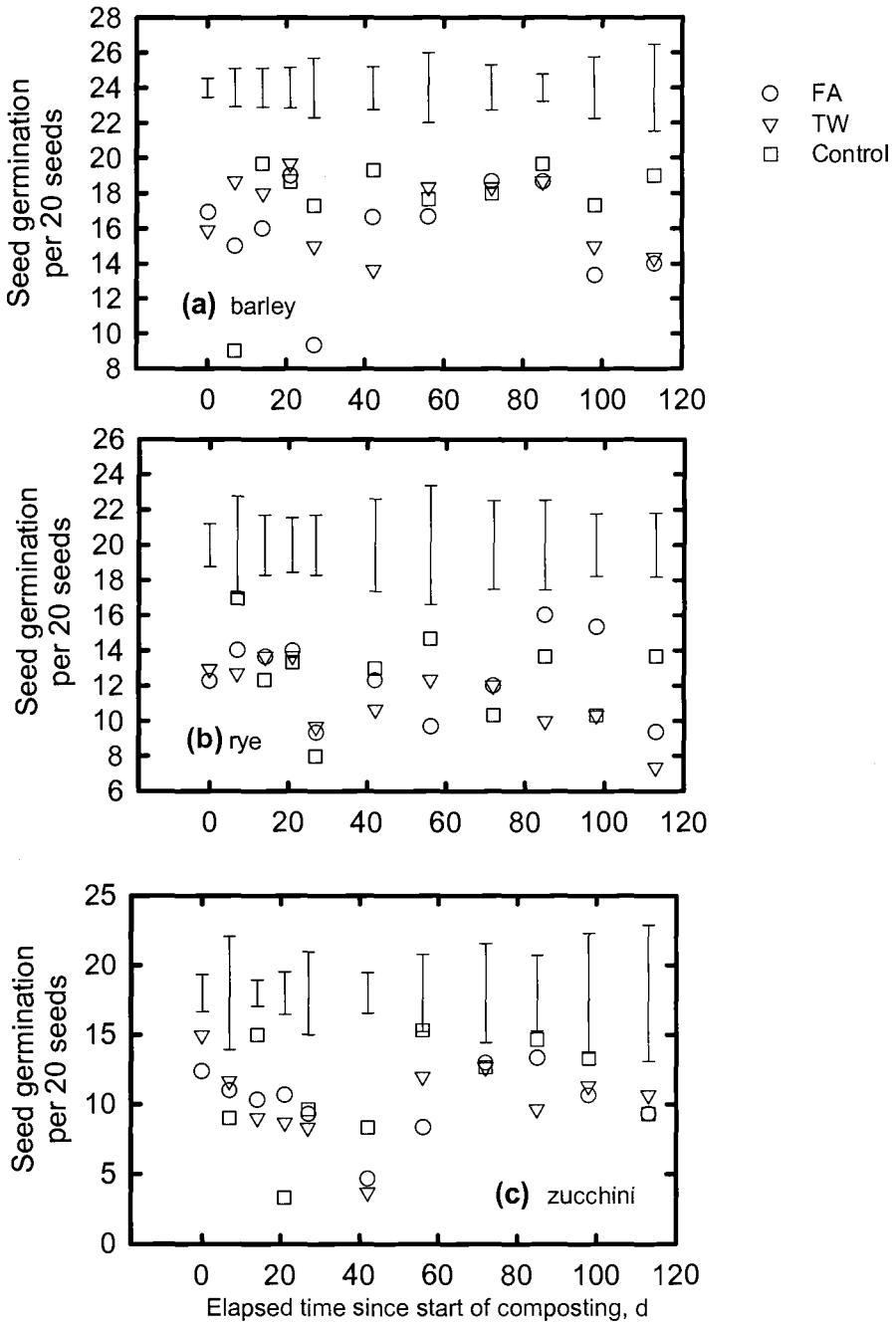

Figure 2.7. Effect of compost maturity on germination after 5 d for yard debris processed under forced aeration (FA) or as turned windrows (TW) for barley (a), rye (b), and zucchini (c). Twenty seeds were planted per container. Growing medium in treatment containers was 50% compost – 50% commercial potting mix. Control containers were filled with 100% potting mix. Error bars represent standard error of mean.

Germination data, Figure 2.7, were three observations per treatment per each of 3 species and 3 controls

RESULTS

These materials were composted under conditions of relatively precise process control. Moisture did not limit compost decomposition rate (Figure 2.1a). Rapid initiation of active composting, as evidenced by temperature data (Figure 2.1b and c) commenced within 12 h, with temperatures rising, and remaining above 55°C, until the compost was placed in curing bins on d 35. Total C reduced over the course of the active composting phase from approximately 400 g kg^{-1} to less than 250 g kg^{-1} (Figure 2.2a). Yard debris progressed to mature, stable compost under both aeration treatments, though total C values for FA treatment reached a plateau about 20 d before the TW treatment. Further, parameters measured for the TW treatment showed greater variability throughout curing.

In this study, indicators of chemical and microbial respiration change proved most useful in determining compost maturity, while biological and physical indicators were less valuable.

Effect of continuous aeration

Continuous aeration had little effect on the ultimate maturity of composted yard debris. Our samples assumed the same, or very nearly the same, values for a number of important maturity markers by d 113. Compost C (Figure 2.2a) declined exponentially. Values for both treatments became level below 250 g kg^{-1}, representing a loss of more than 150 g kg^{-1} over the duration of processing. The C: N ratio values closely paralleled for the two treatments through the curing phase and ended at the same value (Figure 2.2c). Other parameters, including total solids, pH, soluble salts and NH_4, converged by the end of composting (Figures 2.1a, 2.3 and 2.4a). Further, CEC values for both treatments (Figure 2.3c) showed significant effects ($p=0.05$) related to aeration and approached 400 meq g^{-1} C. This value approximates the CEC of soil organic matter (Stevenson, 1994) and suggested a humified product with increased buffering capacity and C stabilization as the result of both treatments.

Continuous aeration had a significant effect on the uniformity of chemical parameters. Data from TW samples expressed greater variability. For example, pH values for FA samples rose sharply, more than a full pH unit, during the first 14 d of composting; TW values reached the same level only by 27 d (Figure 2.3a).

Continuous aeration had a significant effect on respiration (Figure 2.6), an important indirect measure of C stability. For the first 56 d of

processing, CO_2 was released at more than 12 mg CO_2-C g C^{-1} d^{-1}. A sharp drop in CO_2 evolution occurred just prior to 72 d. After this time, respiration rates stabilized, and fell to the same level by the end of processing for both treatments. The slight increase in respiration on d 113 may have been related to the high moisture present in the compost samples, 650 g kg^{-1} (Figure 2.1a).

The TW samples tended to show greater variability in respiration rates during both composting phases. For three of the five sampling dates during active composting, TW materials showed greater standard error of the mean; this was true for four of six sampling dates during the curing phase,.

The data suggest that a respiration rate below 5-mg CO_2-C g^{-1} C d^{-1} indicates yard debris compost stability. This value falls within the "stable" rating published by Leege and Thompson (1997). Brinton et al. (1995) defined "finished" compost as having a CO_2 respiration rate of 2-4 mg CO_2-C g^{-1} C d^{-1}.

Indicators of compost maturity

Significant indicators of compost maturity lend strong evidence of compost maturity independent of other parameters. Examples include pH, CEC, and respiration rate, as shown in Table 2.5. Useful indicators of compost maturity, such as C, NO_3 –N concentration, and compost odor,

suggest compost maturity when several are considered together. Compost maturity indicators with little value, like compost color and seed germination, do not distinguish between mature and immature compost.

Carbon to nitrogen ratio, pH, CEC, and respiration rate were significant indicators of compost maturity. As composting proceeded, pH approached neutral, 7.0. The data suggest that fatty acids and the conditions that produce them were not present by the end of our experiment. Cation exchange capacity ($p=0.01$) approached 400 cmol kg^{-1}, the value for soil organic matter, suggesting the OM in the compost was as stable as typical soil OM. Like respiration, C: N ratio declined exponentially and was significant for time ($p=0.01$). The values decreased by half over the course of processing, and stabilized at 12:1.

The respiration data showed a slowing of microbial metabolism over time (Figure 2.6). Because the compost samples were incubated at optimum moisture and temperature (37°C), the drop in respiration rate is attributed to an exhaustion of readily decomposable organic C.

These parameters offer some evidence of compost maturity: C, total N, NH_4-N, NO_3 –N, NH_4 : NO_3 ratio, and compost odor. Carbon and NH_4-N (Figures 2.2a and 2.4a) show a steady downward trend over time, but the error in test values within a sampling date is of similar magnitude to the change in average test values from 43 to 113 d. Nitrate -N and total-N (Figures 2.4b and 2.2b) generally rose over time but both measures had

high variability. The ratio of NH_4 –N to NO_3-N (Figure 2.4c) changed over time, falling from 20:1 to 12:1 from 0 – 27 d, from 12:1 to 7:1 from 43 –56 d, and from 6:1 to 2:1 from 73 – 113 d. The measures were marked by large variability. This final value NH_4-N: NO_3-N value is higher at maturity than cited by other authors. Bernal, et al. (1998) rated a wide range of farm wastes mature for NH_4-N: NO_3-N less than 0.2; Larney (2000) rated composted feedlot manure mature at 0.9. The value of nitrate as a maturity indicator is brought into question upon consideration that nitrifying bacteria do not function above 40°C (Jiménez and Garcia, 1989). Thus, NO_3 may reflect prevailing compost temperature rather than compost maturity.

Germination (Figure 2.7) did not provide significant information about compost maturity in this study. In general, either aeration treatment performed about as well as the control for all sampling dates. The presence of organic acids, indicated by low pH values for the TW treatment at 7 and 14 d (pH 5 to 5.5; Figure 2.3a) did not correspond with reduced seed germination (Figure 2.6).

This test identified a lack of phytotoxic response by the seed species evaluated. It simulated greenhouse conditions, and did not attempt to stop biological processes in the compost. Presumably, degradation of organic acids that may have been present in the compost pile took place rapidly during compost sample handling.

Salinity appears not to have affected germination rates. All the seed species tested exhibit moderate to good salt tolerance. The electrical conductivity threshold producing a 50% reduction in yield for barley is 16 dS m^{-1}, 10 dS m^{-1} for rye and 4 dS m^{-1} for zucchini (Thorne and Peterson, 1954). The average EC value for the control medium was 1.2 dS m^{-1}. The EC of the compost samples varied from 2 to 10 dS m^{-1} throughout the course of the study, but remained between 4 and 8 dS m^{-1} for 14 to 98 d. Both the treatment and control media were below the salinity threshold for the species tested, though a 50/50 mix of these materials would approach the 4 dS m^{-1} salinity tolerance threshold for zucchini.

Compost color (Figure 2.5) was not a significant indicator of compost maturity. This measure did not differentiate between fresh and mature compost. Values ranged from one to two on the TMECC color rating system (Leege and Thompson, 1997) for 0 d. One is the darkest color on a scale of one to five. All samples scored one on this scale from 7 d onward. When considered together, compost color and compost odor provided a rough indicator of compost maturity, differentiating among three levels of maturity (Table 2.6). The compost was rated "immature" on the TMECC odor and color scale for 0 and 7 d. The compost was rated "moderately mature for 14-56 d and "very mature" from 70 d onward.

TABLE 2.6. Compost Maturity Assessment Based on Combined Color and Odor Rating[a]

Sample day	Forced Air Treatment	Turned Windrow Treatment
0	immature	immature
7	immature	immature
14	moderately mature	moderately mature
21	moderately mature	moderately mature
27	moderately mature	moderately mature
43	moderately mature	moderately mature
56	moderately mature	moderately mature
70	very mature	very mature
85	very mature	very mature
98	very mature	very mature
113	very mature	very mature

[a]Leege. and Thompson (1997)

CONCLUSIONS AND SUMMARY

This investigation determined that composted yard debris reaches the same levels of stability and maturity whether provided with forced aeration or managed as turned windrows. Materials processed under controlled continuous aeration reach stability and maturity about 20 days

before materials processed in traditional turned windrows.

This investigation further found that CEC, pH, C: N and respiration rate were significant indicators of compost maturity. For composted yard debris, these parameters stand alone as accurate maturity markers. It further found that C, total N, NH_4 –N and NO_3 -N concentrations were useful maturity indicators. Individually, these parameters do not establish maturity, but numbers of them, when considered together, strongly suggest it. The compost color and odor scale served as a rough indicator of compost maturity. Finally, seed germination and compost color were of little value and did not distinguish among the degrees of compost maturity.

LITERATURE CITED

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CHAPTER 3

COMPARISON OF COMPOST STABILITY ASSESSMENT TESTS

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Prepared for
Compost Science and Utilization

ABSTRACT

A variety of stability measures have been proposed for use with compost. Our study evaluated four measures of compost stability (the Solvita test, alkaline traps, capacity for self-heating and carbon dioxide detection tubes). We evaluated these measures for accuracy, precision, and sensitivity in measuring stability of municipal yard debris from the initiation of composting to 113 d. Over the course of the study, respiration rates decreased ten fold, from 18 to 2 mg CO_2-C g C^{-1} d^{-1}. Respiration rates developed by use of alkaline trapping allowed us to divide the composting process into three phases, active composting (0 to 27 d), and early (43 to 56 d) and late (72 to 113 d) curing. All "quick tests" were correlated with alkaline trapping, a standard measure of respiration rate. Solvita test values (1 to 8 scale) were 2 to 4 during active composting, 3 to 6 during early curing and 6 to 7 during late curing. Solvita test results of 6 to 7 during late curing are interpreted as active and finished compost, respectively, according to the product insert. Self-heating test values decreased from 20°C above ambient at the start of composting to ambient (no heat production) at the end of the composting period. However, self-heating tests took 2 to 6 d to complete. We developed a method for measuring CO_2 evolved from a compost sample (500 g) in a sealed 3.8 L vessel, using CO_2 detection tubes. The tubes were used to measure CO_2 concentration in the container headspace after 4 h incubation. We found that an approximation of compost solids volume (1 g moist

compost = 1 cm^3 compost solids) was adequate for our CO_2 detection tube method. The CO_2 detection tube method was rapid, quantitative, and had excellent sensitivity, even at extreme compost maturity. We used the Cate-Nelson method to estimate critical test values for stable yard debris composts: 6 mg CO_2 – C g C^{-1} d^{-1} for alkaline trap method, 2 mg CO_2 – C g C^{-1} d^{-1} for gas detection tubes, between 5 and 6 color units for Solvita test, and for the self-heating test, not more than 2 °C temperature rise. We recommend the CO_2 detection tube method evaluated in this study should be investigated on a wider range of composts. It shows promise as a rapid test for quantitative determination of compost respiration rates.

INTRODUCTION

Municipal yard debris composting programs must have a strong market for their compost if they are to continue. Large-scale compost consumers want quality assurance and product consistency (Iannotti et al., 1994). Many authors have investigated measures of compost maturity, although no measure or group of measures has been accepted by the industry. Small-scale compost producers often lack laboratory support, presenting difficulty in quantifying stability of their products. Thus, their lack of access to technology becomes a disadvantage in the market (Rosen et al., 1993; Grebus et al., 1994).

Compost maturation is a continuous process of carbon (C) reduction (Paré et al., 1998). Typically, the plot of this microbially mediated process describes an exponential decay curve, with the curing rates approaching some value as an asymptote. For well-cured compost, the CO_2 release rate may differ by as much as 100 fold between the initiation of composting with fresh materials and the end of curing.

Immature compost can injure plant roots or inhibit germination. It can deprive plant roots of sufficient oxygen, tie up nitrogen, or increase potting medium temperatures. Unstable materials continue to lose C via continued microbial action. Container grower profits could literally disappear if unstable materials are used in the potting mix. The effects of unstable compost and the lack of stability ratings discourage growers from using compost (Hoitink et al., 1997). Thus, the ability to rate compost stability is critical in promoting compost use by large-scale users (Helfrich et al., 1998).

An ideal stability test for these operators would be reliable, affordable, require minimal training to administer, give results within a workday, and result in easily understood units. An ideal stability assessment should also be good science, and its results should correlate well with established measures (Willson and Dalmat, 1989; Frost et al., 1992). Hartz et al. (1996) asserted that the compost market would bear the

added cost to mature and cure compost. This suggests a value-added market niche for compost producers who can quantify product quality.

Actively composting materials may exceed the capacity of commercial respirometers calibrated for soil samples. In addition, their expense and complexity place them beyond the reach of many compost producers (Lasaridi and Stentiford, 1998b). This need stimulates the effort to find rapid, accurate, and affordable methods of measuring compost respiration.

Carbon dioxide evolution (Bartha and Pramer, 1965; Forster et al., 1993) and capacity to self-heat (Frost et al., 1992; Iannotti et al., 1994) have been established as two microbial indicators of compost maturity. The use of alkaline traps to determine the rate of CO_2 evolution is a standard procedure, adapted from soil testing (Frost et al., 1992). Heaped-up organic matter has long been observed to generate heat without additional thermal inputs. This tendency, when it is present, is recognized as a sign of compost immaturity, regardless of other parameters. The Dewar test outlined by Brinton et al. (1995) allows evaluation of compost self-heating under standardized conditions, although some consider this method a poor maturity indicator because accurate results depend so heavily on the sample's water concentration (Henry and Harrison, 1996).

Testing the headspace gases taken from compost incubated in sealed reaction vessels also has been used as a measure of compost C

stability. Liao, et al. (1994) used headspace-gas chromatography to determine concentrations of volatile organic acids and phenols released by compost as a stability measure. Liebig, et al. (1996) measured CO_2 concentration of headspace gases above soil using CO_2 detection tubes, and correlated their results with gas chromatographic CO_2 analyses. We are interested in further extending this technique to compost C analysis.

The Solvita test is a semi-quantitative test that employs CO_2-sensitive gel to indicate microbial respiration rates (Seekins, 1996a). A measured quantity of fresh compost is closed in a reaction vessel with a gel-coated paddle. The gel changes color commensurate with to its exposure to CO_2. A value from 1 (raw compost) to 8 (finished compost) is assigned by comparing the paddle color to a color chart. Variance in sample moisture, ammonia (NH_3) concentration and C: N ratio, three factors that contribute to microbial life support and respiration rate, can contribute to unreliable Solvita test results (Seekins, 1996a).

McDonnell and Regenstein (1996) found on-site use of the Solvita test by secondary school teachers highly correlated with the Dewar test of self-heating. He further reported that the Solvita test was most accurate for the extremes of compost maturity, that is, for Solvita CO_2 color chart readings of three and below or for readings of six and above. For the intermediate states, readings of four and five, the results were variable. This tendency limits the utility of the test. Generally, the extremes of maturity are

readily assessed by established methods. McDonnell and Regenstein (1997) expressed some reservations about the use of this test as a regulatory tool, given the variability of results and the potential for inadequate sample preparation.

In this study, our objectives were: i) to measure rates of CO_2 evolution from yard debris compost samples during active composting and curing; ii) to adapt the CO_2 detection tube technique for compost; and iii) to evaluate a number of rapid compost stability tests for potential use by commercial composters.

MATERIALS AND METHODS

This study examined approximately 185 m^3 of source-separated municipal yard debris as it was composted in a commercial indoor facility. Composting proceeded in a two-stage process described in Table 3.1. The study followed the compost for 113 d. Processing was divided between 35 d of active composting under software-controlled forced aeration and 78 d of aerated closed vessel curing.

Composting Facility

Land Recovery, Inc. (LRI) conducted composting and curing at their indoor Compost Factory in Puyallup WA, USA. This is a highly technical

facility producing yard debris compost under optimal conditions. In-floor air vents supply alternate positive and negative forced aeration as software-controlled temperature probes in each compost pile monitor temperature conditions deep within the pile (Touart, 1999).

TABLE 3.1. Process Control Protocol for Compost and Curing Phases

Active composting phase		
Chipping procedure	Rotary disk mill	
Mixing method	Self-propelled windrow turner	
Residence time	35	d
Turning frequency	Weekly	
Target compost moisture after water addition	500	g kg^{-1}
Windrow dimensions (l*base*h)	15 m * 5 m * 2.5	m
Curing phase		
Residence time	78	d
Mixing or turning method	None	
Water addition	None	
Curing bin volume	30	m^3

Preparation of Compost Feedstock

A Universal Refiner Super Contender (Universal, Montesano WA.) grinder and trommel/blender was used to prepare the yard debris for composting. It ground, screened and mixed the source-separated materials. The initial substrate was a roughly 50/50 (v/v) mix of grass clippings and woody prunings. All the materials were received from curbside collection within 24 h of the initiation of processing. Front-end loaders stacked the prepared yard debris into a windrow approximately 15 m long by 5 m wide by 2.5 m high on the composting hall floor, for an approximate 185 m^3 pile volume. The experimental compost piles were turned and mixed twice with a SCAT 4932 windrow turner (Scat Engineering, Division of ATI Incorporated, Delhi, IA) after initial stacking to promote homogeneity of the materials and to establish consistent porosity in the piles.

Active Composting

LRI's technology provided compost with continuous aeration at positive or negative pressure from beneath the composting hall floor during 35 d of active composting. A windrow turner (Model 4932, Scat Engineering, Division of ATI Incorporated, Delhi, IA) turned compost and added water prior to every sampling event without effecting appreciable grinding. Compost was tested for moisture the day before turning; the target

moisture concentration after turning and watering was 500 g kg^{-1}. Samples were collected on 0, 7, 14, 21 and 27 d of active composting.

Compost process temperatures were monitored by two Tele-Probes (Green Mountain Technologies, Seattle, WA). Each wireless compost temperature probe radioed thermal information from two sensors 0.9 vertical meters apart on the 1.5 m probe to process control software every five minutes. The temperature probes were removed from the compost prior to turning and replaced, perpendicular to the floor, afterwards. Damper actuators altered blower direction from positive to negative to remove heat and hold temperature and oxygen gradients to a minimum.

Curing

Curing proceeded in a 30-m^3 tarp-covered NaturTech Curing Bin (St. Cloud, MN), with an air line connected to a plenum in the container floor. Bins were neither turned nor emptied during curing. Curing phase materials were sampled on 43, 56, 70, 85, 98, and 113 d.

Compost Moisture Content

Compost was sampled for gravimetric moisture content the day before every turning during the active composting period and adjusted with

every turning. No moisture adjustment was made during the curing phase. Figure 3.1a illustrates total solids, which reached a plateau after 27 d.

Sampling Procedures

Actively composting yard debris was sampled immediately after mixing on 0, 7, 14, 21 and 27 d, and an additional six times during the curing on 43, 56, 70, 85, 98 and 113 d. Composite samples were taken from three locations within the mass of compost. Sampling was in accordance with protocols described by Leege and Thompson (1997) and is detailed in Table 3.2. Each composite sample represented approximately 60 m^3 of compost during the active composting phase and 10-12 m^3 of compost during the curing phase.

Sample Handling and Pretreatment

Composite samples from the compost pile were divided into thirds. One subsample was shipped on ice to the author at the Soil Chemistry Laboratory at Oregon State University for analysis, a second was shipped to Agricheck of Umatilla, OR, and the third was frozen and retained at LRI. Iced samples arrived at the laboratories within 24 to 48 h of collection. Upon arrival, samples were removed from their packaging. Each sample was picked over by hand for large (>1.5 cm diameter) sticks, stones and foreign

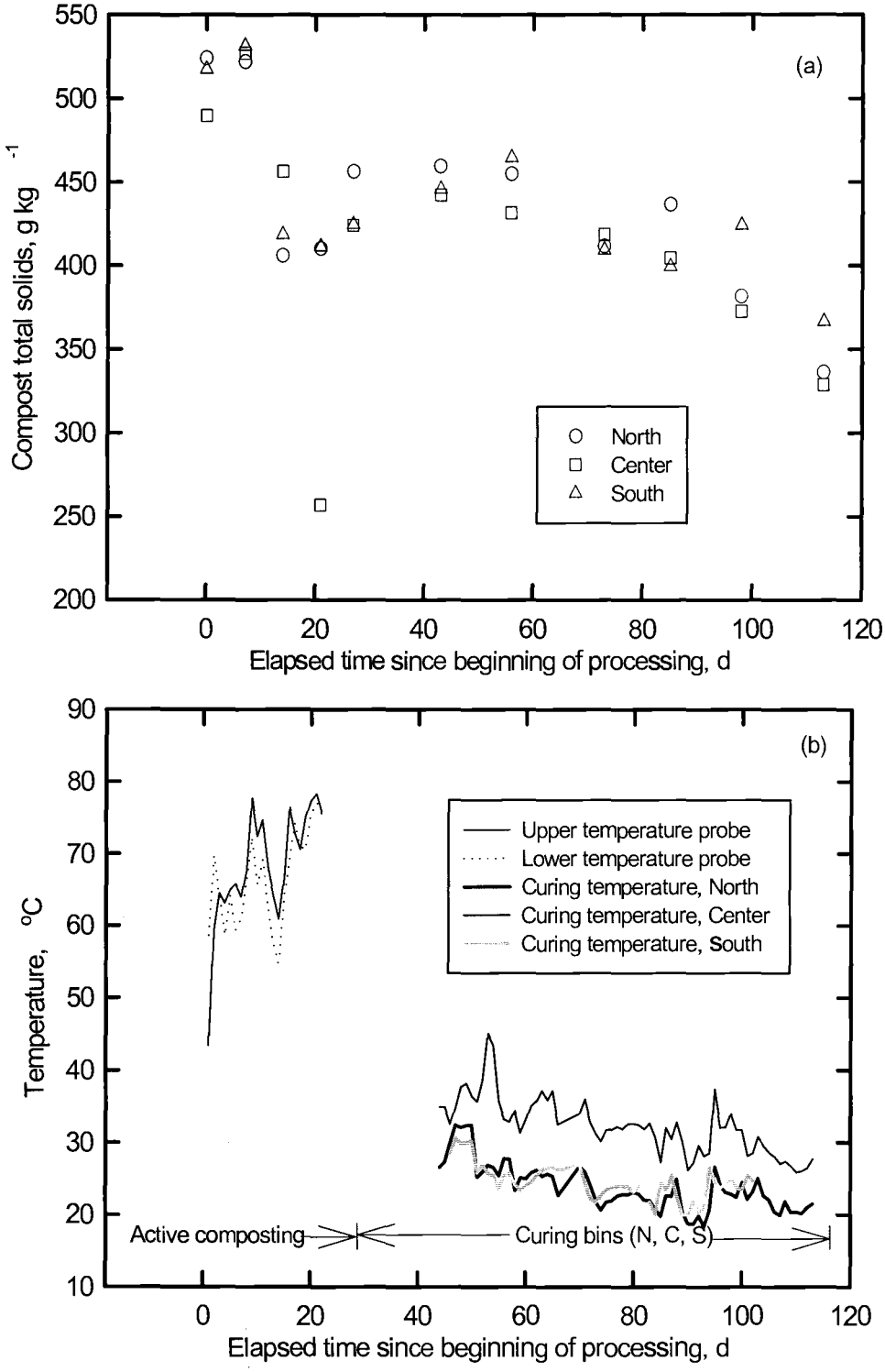

Figure 3.1. Compost Total Solids (a) for three locations in Compost Pile N (north), C (center) and S (south) and Compost Processing Temperatures (b). Temperature data from 0 to 35 d represents active composting; curing phase was 35 to 113 d. Missing temperature data due to equipment failure.

matter such as plastic film and glass shards, but was not screened. In preparation for incubation, the samples were sprayed to approximate the 500 g kg^{-1} moisture concentration target. Samples from the final sampling date did not receive additional water. All samples were then re-packed in

TABLE 3.2. Sampling Protocol for Active Composting and Curing Phases

Active composting phase	
Sampling days	0, 7, 14, 21,27
Sampling unit (pile) size	185 m^3
Number of sampling locations (North, Center and South)	3
Number of grab samples per location	30
Sample collection timing relative to pile turning	Immediate
Total volume of each compost sample	20 L
Curing phase	
Sampling days	43, 56, 70, 85, 98, 113
Sampling unit (curing bin) size	30 m^3
Composite samples per curing bin	3
Number of grab samples per composite sample	30
Collection depth from compost surface	0.3 – 0.6 m
Total volume of each compost sample	20 L

their original one-liter zip-lock bags, left unsealed, and held at 37°C for 36 h to reestablish microbial activity.

Air-filled porosity (AFP) is the percentage volume of compost filled with air just after it has stopped draining after saturation. We measured AFP of incubated samples using Handreck and Black's (1994) saturation method. This test was designed to indicate the amount of air available to roots growing in container media. The procedure involves catching and measuring drainage from a sample that has been thoroughly saturated. Apparatus for taking the measurements was constructed from lengths of 760 mm inside diameter drain and waste pipe (DWV), capped at one end. Four evenly spaced 10 mm holes were drilled into the end-cap, to allow for drainage.

With the four drainage holes in the end-cap covered with the fingertips, the apparatus was removed from the water. Water was allowed to drain freely from the outside of the apparatus, but care was taken to retain all the water held within. The apparatus was placed on a small rack, held above the drainage water, and allowed to drain for 30 minutes into a beaker of adequate size. Volume of drainage water was measured and recorded. AFP was computed according to the following equation:

$$AFP = A\,B^{-1} \qquad \text{Eq. [1]}$$

Where:

A = volume of drainage, cm^3

B = volume of end-capped pipe length, 345 cm^3

Bulk density (ρ_b) was computed according to the following equation:

$$\rho_b = X\ C^{-1} \qquad \text{Eq. [2]}$$

Where:

X = mass of incubated sample aliquot, 500g

C = volume of the aliquot, cm^{-3}

ANALYSIS OF RESPIRATION

For this investigation, we examined four respirometric measures to judge the stability of compost. Table 3.3 summarizes test methods A, B, C, and D. We used vials with sodium hydroxide (NaOH) solution as alkaline traps, CO_2 detection tubes, the Solvita test and the capacity to self-heat to judge the stability of the C in our compost samples.

TABLE 3.3. Summary of Compost Test Methods

Test ID	Measurement	Apparatus	Reference
A	CO_2 evolution	Alkaline vials	Leege and Thompson (1997)
B	CO_2 evolution	CO2 detection tubes	Liebig, et al. (1996)
C	CO_2 evolution	Solvita colorimetric gel	Seekins (1996a)
D	Capacity to self-heat	Insulated flask	Leege and Thompson (1997)

Respiration Test A: Alkaline Traps

For the alkaline traps, 25-g incubated compost samples were placed in 0.5 L (pint) glass canning jars with airtight lids. A 20-mL or 30-mL vial of 0.5 M NaOH solution was placed in the jars before sealing. The larger quantity was used for the first 2 sampling periods while respiration rates were high. The jars went into a water bath at 37°C. CO_2 was trapped for two 24 h periods: 0-24 h and 24-48 h. The jars were opened briefly after 24 h to exchange vials. We incubated triplicates of each sample. Blanks, sealed jars with alkaline traps but no compost, were included with each incubation.

The amount of respiration was calculated as:

$$D = E\ F\ G^{-1}\ H\ [I - J] \qquad \text{Eq. [3]}$$

Where

D = respired carbon, mg CO_2 - C

E = millequivalent weight of CO_2-C, 6 mg meq^{-1}

F = NaOH trap volume, mL

G = volume of NaOH trap aliquot titrated, mL

H = molarity of HCl to titrate NaOH, mmol mL^{-1}

I = volume of HCl used to titrate the trap aliquot from the no-compost blank, mL

J = volume of HCl to titrate aliquot from trap exposed to compost respiration, mL

Respiration rate was calculated as:

$$K = D\ L^{-1}\ M^{-1} \qquad \text{Eq. [4]}$$

Where:

K = respiration rate, mg CO_2 - C g C^{-1} d^{-1}

D = cumulative C respired in 48 h, mg CO_2 – C (from Eq. 3)

L = mass of carbon in the sample, g

M = time, d

Respiration Test B: CO_2 Detection Tubes

This test measures the CO_2 concentration in the headspace of a 3.8 L incubation vessel (Figure 3.2). Our use of CO_2 detection tubes (Dräger CO_2 Detection Tubes 0.1-6 vol %, Drägerwerk, Lübeck, Germany) as a C stability test is adapted from work done by USDA-ARS staff (Liebig et al., 1996). Five-hundred-gram aliquots of pre-incubated compost, containing approximately 500 mL H_2O L^{-1} compost, was placed into 3.8 L glass jars with airtight lids. Each vessel lid was equipped with two tight-fitting rubber septa (#210074-9, Aldrich Chemical Co., Milwaukee, WI), inserted into holes cut with a drill bit.

A: Needle to prevent vacuum
B: Needle to access air sample
C: Rubber tubing
D: 0.1-6% Gas sampling tube
E: 120 cc Syringe
F: Syringe plunger
G: Rubber septa
H: Reaction vessel lid
I: Glass reaction vessel
J: Compost sample

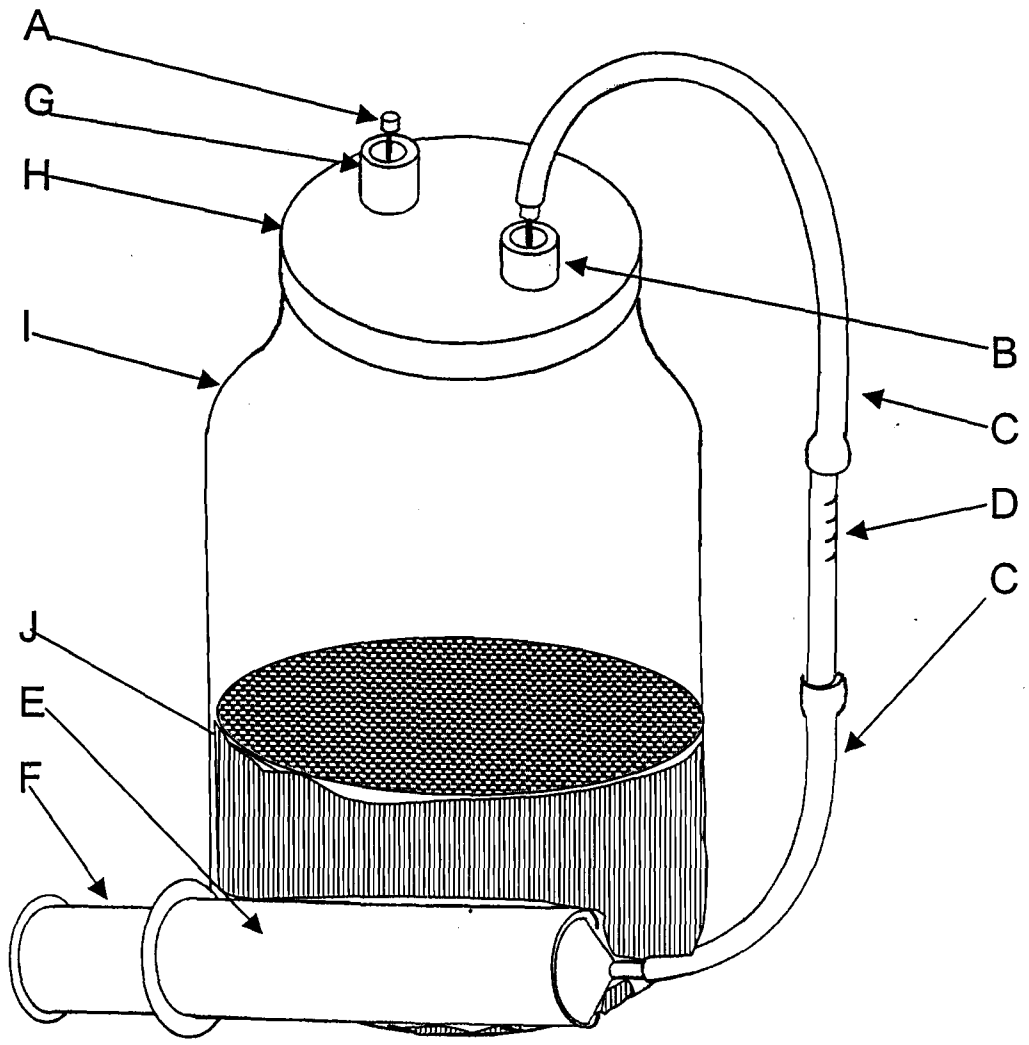

Figure 3.2. Test Method B, gas detection tube headspace sampling apparatus.

We measured CO_2 concentration in the vessel headspace after a four-hour equilibration period. The ends of the CO_2 detection tube were snapped off immediately before drawing the headspace gas sample. The tube was placed in-line with rubber tubing attached to a 140 mL syringe at one end and a #14 hypodermic needle at the other. The needle was inserted through one septum. Another needle inserted through the other septum avoided partial vacuum development. A 0.1 L headspace sample was drawn through the CO_2 detection tube over a fifteen-second period. Results were read directly from the tube and recorded. We began collecting data from this method on 27 d.

The reading from the gas detection tube, percent CO_2, was converted to mg CO_2-C g C^{-1} d^{-1} through a series of steps. The first step was to determine the net headspace (volume not occupied by compost solids) in the reaction vessel, as in equation 5:

$$N = O - [P\ (1\text{-}AFP)] \qquad \text{Eq. [5]}$$

Where:

N = headspace volume, cm^3

O = total reaction vessel volume, 3800 cm^3

P = compost volume, cm^3, from measurement of volume of 500 g sample

AFP = air-filled porosity, expressed on a volume basis as a decimal fraction, $cm^3\ cm^{-3}$

The second step converts percent CO_2 in the reaction vessel to a volume of CO_2:

$$Q = (R - 0.035)\ (\ N\ ) * 0.01 \qquad \text{Eq. [6]}$$

Where:

Q = volume CO_2 in reaction vessel, cm^3

R = reading from gas detection tube, percent CO_2

0.035 = ambient concentration atmospheric CO_2, percent CO_2

N = headspace volume in reaction vessel, cm^3, from Eq. 5

The volume of CO_2 computed is then converted to a mass of CO_2 produced:

$$S = Q\ T\ U^{-1}\ (V + 273)\ 273^{-1} \qquad \text{Eq. [7]}$$

Where:

S = amount CO_2 –C evolved, mg

Q = volume CO_2 in reaction vessel, cm^3

T = mass of CO_2 – C in a mole of gas, 12,000 mg

U = volume of a mole of gas at STP, 22,400 cm^3

V = ambient temperature, °C

Finally, the amount of CO_2 – C produced is converted to a respiration rate:

$$W = S\ Y^{-1}\ Z^{-1} \qquad \text{Eq. [8]}$$

Where:

W = rate of CO_2 release adjusted for sample C content,

mg CO_2 – C g compost C^{-1} d^{-1}

S = amount CO_2 – C evolved, mg

Y = carbon content of the sample, g

Z = reaction time, d

Respiration Test C: The Solvita Test

We administered the Solvita test (Woods End Research Laboratory, Mt. Vernon, ME) according to the kit directions by placing 250 mL (1 cup) of compost in the reaction vessel provided. Carbon dioxide and NH_3 test paddles were unwrapped and inserted into the compost, and the vessels were sealed. After four hours, the jars were opened and the results read by comparison to the color charts provided with the test kit.

Respiration Test D: Self-Heating Test

Compost self-heating was tested by placing 1-L samples into open-topped insulated vacuum bottles (Compost Self-Heating Flask #2119, Woods End Research Laboratory, Mt. Vernon, ME). Digital minimum/maximum indoor-outdoor thermometers (#63-1021, Tandy Corporation, Fort Worth, TX) measured maximum temperatures inside the

flask and the room temperature. Temperatures were recorded daily, for two days beyond the maximum temperature measured in the Dewar bottle. The test period in this study was not longer than six days. The flasks were held at room temperature (18°C). Because of the cost of the vacuum flasks, this test was not replicated.

RESULTS AND DISCUSSION

Moisture and oxygen were not limited during composting and curing (Figure 3.1). Compost total solids, indicative of compost moisture content, dropped from initial values near 500 g kg^{-1} during the first eight days of processing to values between 400 – 450 g kg^{-1} for the duration of active composting. During the curing phase, compost total solids declined to 350 g kg^{-1} by 113 d.

Process temperatures indicated active aerobic composting. Immediately after piles were formed, compost temperature rose rapidly, and remained above 60°C throughout active composting (Figure 3.1b). Curing phase temperatures remained between 20 - 40°C. The north (N) and south (S) curing bin temperatures were close in value; temperature in the center (C) bin was nearly 10°C higher throughout the curing phase.

The pile size and compost sample collection protocols used in our study reflect those used by commercial composters. Test results for three compost samples taken from sections of a large pile (approximately 185

m^3) on each sampling date are shown individually (Figure 3.3). There is no clear trend in respiration measurements from any third of the compost pile. Careful process control and relative uniformity of the materials from the study's onset may have contributed to the uniformity of measurements from different sections of the pile. Further, it suggests that the sampling protocol, based on Leege and Thompson (1997), resulted in generally representative samples.

One objective of this study was to evaluate the suitability of quick tests of compost maturity for compost producers with limited support. Our definition of a "suitable" test was one that was accurate and precise, low-cost, gave results in less than a work day, could be administered after brief training, and provided an answer in easily understood units.

Establishing Compost Respiration Baseline: Test A, Alkaline Traps

We used alkaline traps to quantify a baseline respiration rate for these materials. This rate became the standard against which we compared the other tests. Alkaline trap testing (Figure 3.3a) provided data to divide the 113 d processing and curing period into three distinct phases: active composting, early curing and late curing. Active compost initiated on 0 d and continued to 35 d, when compost was moved into curing bins. Carbon

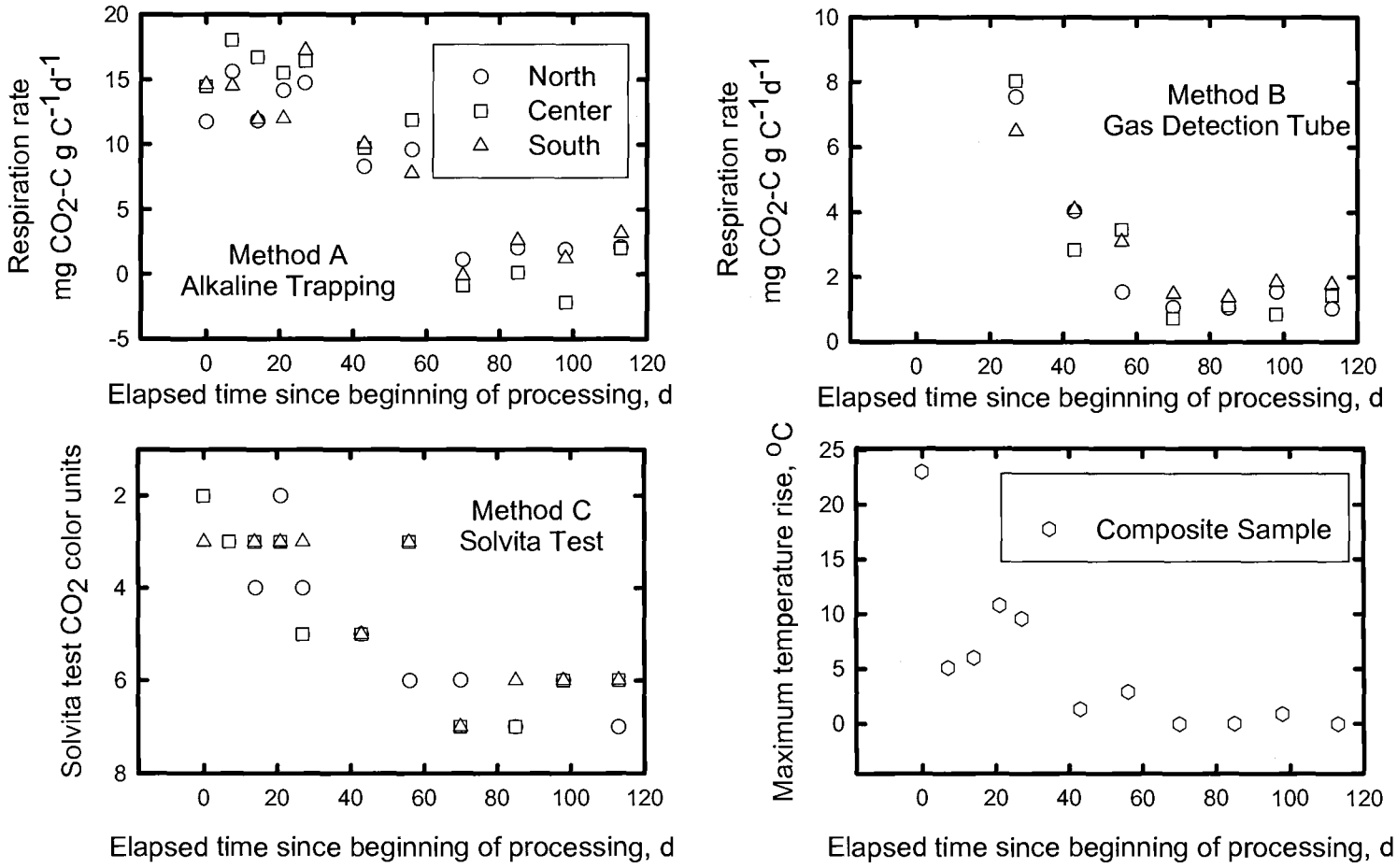

Figure 3.3. Effect of Duration of Composting on Yard Debris Stability as measured by NaOH Traps (Test Method A), Gas Sampling Tube (Test Method B), Solvita Test (Method C), and Self-heating (Test Method D). Compost samples from different sections of the pile (North, Center and South), were measured via Test Methods A, B and C at each sampling date. One compost sample per date was tested via Method D.

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dioxide release rates greater than 12 mg CO_2-C g C^{-1} d^{-1} characterized this process phase. Early curing samples were collected on 43 d and 56 d. Release rates near 10 mg CO_2-C g C^{-1} d^{-1} characterized this period. Finally, late curing phase, from 56 to 113 d, was characterized by CO_2 release rates below 5 mg CO_2-C g C^{-1} d^{-1}.

Table 3.4 shows testing precision by compost processing phase for the alkaline trapping test (Method A) and the gas detection tube test (Method B). Coefficient of variance (CV) for alkaline trapping was 0.14 for active composting and 0.16 for early curing. During late curing, the pooled error, 1.3, is greater than the mean respiration rate, 1.1, suggesting that the sensitivity of the test has been exceeded by the low rate of respiration during this process phase.

The alkaline trap method provided concise, quantified information through the use of a time-tested method. Circumstances permitting, we prefer this method to any of the quick tests because it has been shown as accurate and reliable and to give results in recognized technical units. However, according to our definition of the term, it is not "suitable" for compost producers without technical support. The technique requires titration of the alkaline trap, demands specialized equipment and a skilled technician, and so is costly. In addition, the test requires 48 hours to complete. Further, its apparent loss of sensitivity for samples having low

TABLE 3.4. Sampling Precision by Composting Process Phase

Process phase[a]	Measured value				Standard deviation		
	Max	Min	$\bar{X}$	Median	Max	Min	Pooled
	mg CO_2-C g C^{-1} d^{-1}						
Method A: Alkaline trapping							
Active composting	18.1	11.7	14.6	14.6	2.8	1.3	2.0
Early curing	11.9	7.8	9.6	9.7	2.1	0.9	1.5
Late curing	3.1	-2.2	1.1	1.6	2.2	0.6	1.3
Method B: CO2 detection tubes							
Active composting[b]	-	-	7.4	-	-	-	0.8
Early curing	4.1	1.5	3.2	3.3	1.0	0.7	0.9
Late curing	1.9	0.7	1.3	1.2	0.5	0.2	0.4

[a]Active composting: 0 to 27 d; active curing: 43 to 56 d; late curing 72 to 113 d.
[b]Respiration rate for 27 d for test method B

respiration rates limits its value for accurate measurements from very stable composts.

Assessing Quick Tests of Compost Carbon Stability

Respiration test B: CO_2 detection tubes

Headspace determination. This test measures CO_2 concentration in reaction vessel headspace. Since compost solids (organic matter, ash and water) occupy part of the incubation vessel volume, it was necessary to estimate the headspace remaining after compost addition.

To estimate headspace volume, we first measured the volume of the 500 g of moist compost added to the incubation vessel. This compost volume (solids and air) was adjusted using an estimate of air-filled porosity (AFP), equation [5], to estimate the volume of compost solids added (Figure 3.3c).

As composting proceeded, compost particle size decreased and moisture content increased (Figure 3.1a). These changes in compost physical properties are reflected in reduced AFP (Figure 3.4a) and increased compost bulk density (Figure 3.4b) with composting time. The change over time in estimated volume occupied by compost solids is shown in Figure 3.3c. Compost solids (500 g sample) occupied an average of 1.10 $cm^3\ g^{-1}$ from 27 to 113 d (standard deviation = 0.14). This range of compost

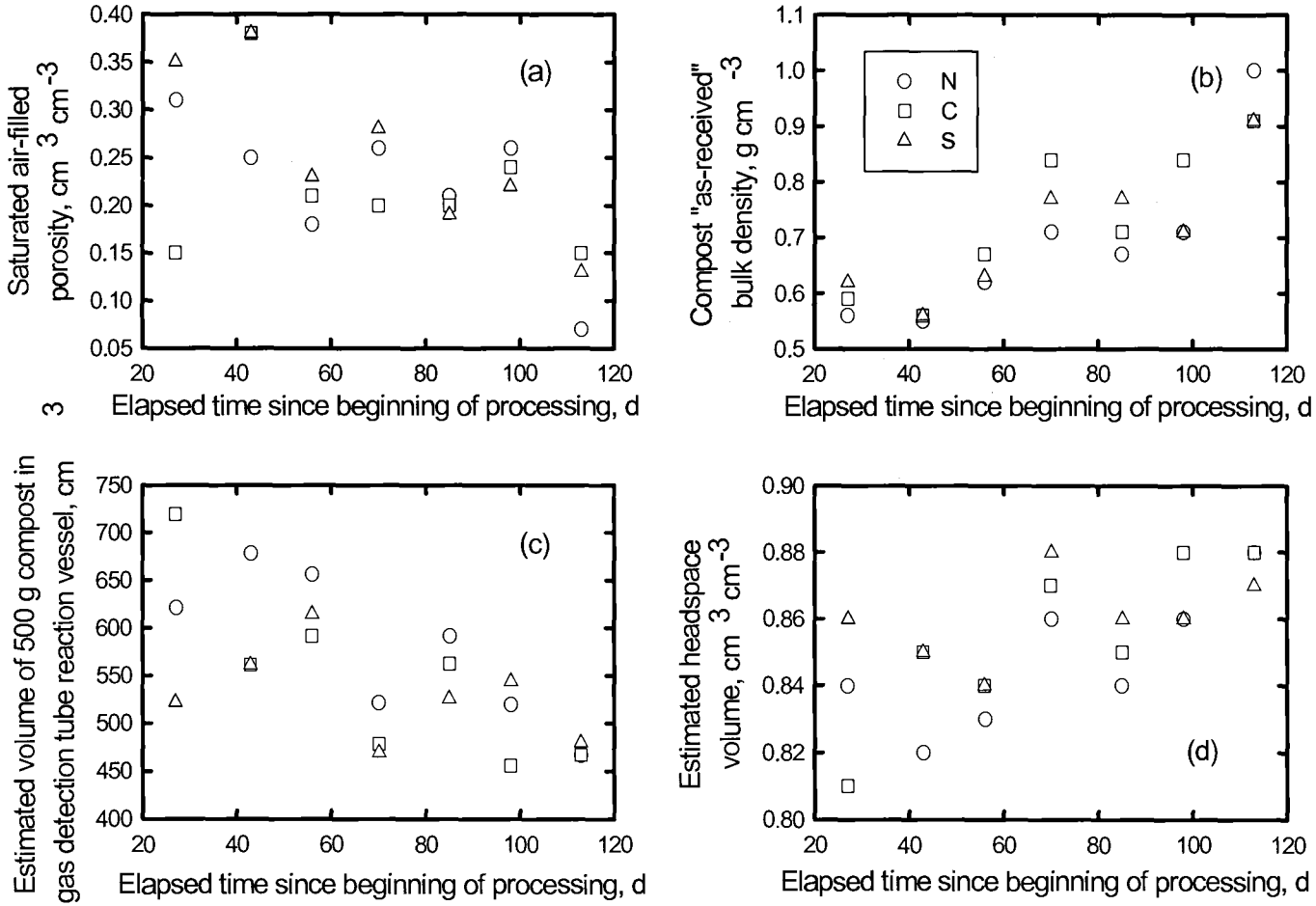

Figure 3.4. Compost saturated air-filled porosity (a), bulk density (b), estimated volume of 500 g compost sample (c) and estimated headspace volume (d) in 3800 cm^3 glass jar used in Compost Respiration Test B.

solids volume is relatively small relative to the total volume of the incubation vessel (Figure 3.4d). Estimated headspace volume ranged from 3100 to 3300 cm^3 during composting. Because headspace volume change varied less than 10% across all sampling dates, compost producers could simplify this technique by assuming headspace volume is approximately equal to sample mass (500 g).

Converting percent CO_2 to a mass of CO_2 – C. Gas detection tubes, as discussed in the methods section, measured the concentration of CO_2 gas released during incubation. Equation [6] converts the concentration of gas, adjusted for ambient atmospheric concentration, into a volume of gas. Investigations undertaken at altitudes significantly higher than sea level could include a factor to correct for atmospheric pressure variance as well.

Equation [7] converted volume into mass of CO_2 – C. Finally, equation [8] developed a rate of CO_2 release. To maximize utility for compost producers, we considered a number of compost fractions in developing the rate. Figure 3.5a shows the percent CO_2 in the incubation vessel headspace. Figures 3.5 b and c show respiration rate adjusted for fresh and dry compost, respectively. Figure 3.3b shows the respiration rate adjusted for compost C.

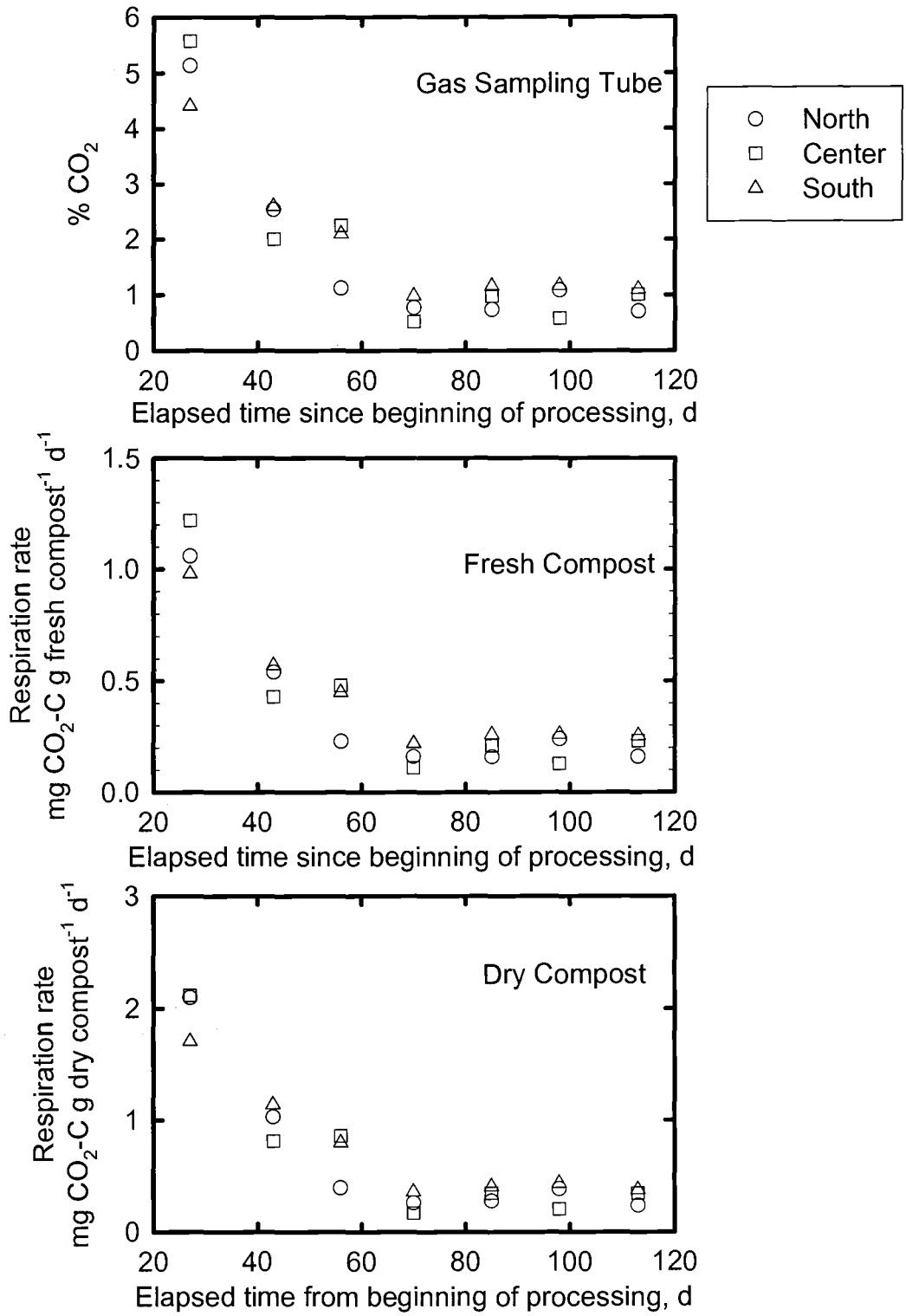

Figure 3.5. Effect of Processing Duration on Percent CO_2 and Compost Respiration Rate Measured by Gas Sampling Tube and Adjusted for Mass Fresh or Dry Compost.

Regardless of the compost fraction considered, the results provide similar information about compost respiration: early, high and highly variable respiration rates that drop off exponentially, with stable compost respiration rates by 72 d. This is the same date alkaline trapping indicated late curing.

Method sensitivity. Table 3.4 lists mean and standard deviation for the three processing phases identified during this study. Mean respiration rate magnitude compared favorably with pooled error; for early curing, the coefficient of variance (CV) was 0.28, and for late curing it was 0.31. This comparative consistency in CV, even into late curing indicates the technique provided reliable information even at low respiration rates.

Respiration measured by CO_2 detection tube (Figure 3.3b) was always lower than alkaline trapping (Figure 3.3a), probably at least in part because the alkaline trap reaction vessels were held at 37° C, in comparison to 23° C for CO_2 detection tube vessels. Higher temperatures support higher microbial respiration rates. In addition, the alkaline trap aliquot, 25 g, was much smaller than the 500 g CO_2 detection tube aliquot. The larger sample probably contained more recalcitrant materials (sticks and stones) than the alkaline trap sample.

We believe this test shows promise as a measure of compost maturity. It was accurate, reliable, low cost, and could be completed in less than a workday by a minimally trained technician. The units, volume percent

CO_2, were readily converted to units consistent with the alkaline traps by spreadsheet, allowing direct comparison between the two tests. We encourage further investigation and refinement of this method for compost producers.

Respiration test C: the Solvita test

Possible results for the Solvita test range from 1 ("raw compost") to 8 ("finished compost"). In these trials, values increased commensurate with increasing compost maturity. Like the alkaline trap test, the Solvita test showed the general trend toward maturity and stability after 56 d (Figure 3.3c).

The values of the Solvita test results, 6 or 7, for the late curing plateau fall within the active or mature compost class, respectively, according to test literature (Woods End Research Laboratory, Mt. Vernon, ME). The "active compost" interpretation seems unlikely for yard debris compost at 72 - 113 d. It suggests that the test calibration is not well correlated to lower levels of microbial respiration. The test effectively measured the difference between compost in active composting and late curing, but was much less effective at pinpointing the transition from active curing to late curing.

In attempting to understand this test's lack of value in assessing curing phase compost, we considered the variables taken into account by the gas detection tube method. Compost volume, rather than mass, determines the

Solvita test aliquot. Thus, the test lacks a correction for the changes in compost moisture, bulk density and C concentration as compost matures. Given the small aliquot size, 250 mL, these factors may be significant.

We found the Solvita CO_2 test suitable for compost processors without laboratory support, although some may consider the per-test cost somewhat high. A worker with minimal training could complete the test within a workday, assuming samples of suitable moisture concentration. The resultant units are unique to the Solvita test system, though an estimated value for mg CO_2 g C^{-1} d^{-1} can be judged from a table provided with the test kit (Woods End Research Laboratory, Mt. Vernon, ME).

The Solvita NH_3 test was less effective in showing a change over time for these feedstocks (data not shown). Significant NH_3 would not be expected to form at pH below 7.0 to 7.5 (Miller, 1991). Our compost sample pH values ranged from 5.5 to 7.0 during composting. Sample testing consistently indicated the lowest NH_3 levels on the Solvita ammonia scale from 56 d.

Respiration test D: capacity to self-heat

Microbial respiration of composting materials is expressed in the capacity of these materials to self-heat. Consistent reduction in self-heating was observed starting at 43 d. Negligible self-heating occurred after 72 d. According to Brinton et al. (1995), these compost samples would be judged

stable and well aged from 42 d, equivalent to a respiration rate of 0 – 2 mg CO_2-C g C^{-1} d^{-1}. Yet the respiration rate measured by alkaline trapping on 42 d was 9.4 mg CO_2-C g C^{-1} d^{-1} ±1.9. The self-heating test indicated compost was stable about 30 days before the alkaline trapping test.

This test of self-heating capacity is suitable for small-scale composters. Though the initial equipment investment can be prohibitive, additional per-test costs are negligible. Koenig and Bari (2000) substituted less expensive equipment, common thermos bottles, with good results. In addition, the results are in readily understood heat units. Disadvantages are that test completion requires up to 6 days, that the test may indicate maturity well in advance of the fact, and that temperature controlled laboratory conditions result in the most accurate temperature measurements.

Estimating Critical Values for Compost Stability

Because of the limited number of sampling events in this study, linear correlations of quick tests with standard techniques like the alkaline traps provided unimpressive coefficients of correlation. One goal of this study was to determine when compost was stable in terms of respiration rates. We adapted a technique by Cate and Nelson (1965) to these correlations, rather than fitting them with regression lines (Figure 3.6).

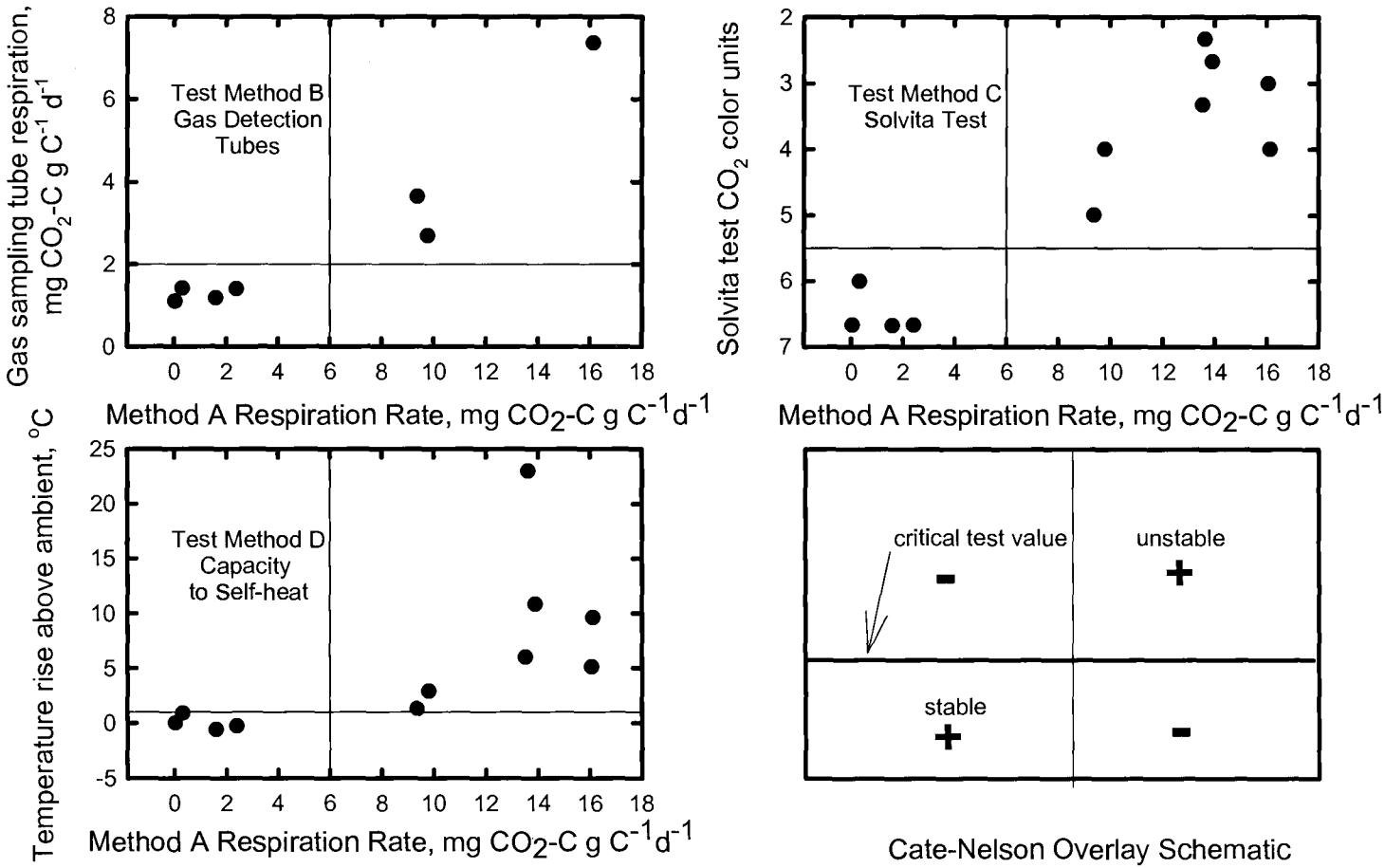

Figure 3.6. Correlation of Respiration Test Method A (NaOH Trapping) against Respiration Test Methods B, C, and D. The vertical and horizontal lines are based on a Cate-Nelson analytical technique, and placed to maximize points falling into the positive quadrants. Points falling within the quadrant closest to the origin are stable materials; farthest from the origin are unstable materials. Points falling into the negative quadrants indicate measurement errors.

A transparent overlay divided scatter plots into four quadrants. The intersecting dividing lines on the overlay were parallel to the graph's axes. The dividing lines were placed so as to maximize the number of points falling into the positive (upper right-hand and lower left-hand) quadrants. In effect, this determined the least sum of squares for the two point sets. The intersection of the dividing lines with the x- and y-axes divided the correlated respirations into two groups, "stable" and "unstable." Above these values, there was a high probability of the materials undergoing further meaningful stabilization; below these values was a reduced probability.

The points falling outside the positive quadrants were interpreted as errors of the predictive method. These errors were of two types. Type I errors, falling in the lower right-hand quadrant, would occur when the quick test predicted mature respiration rates, but the compost was not mature as indicated by alkaline trapping. Type I errors represent the risk of poor compost product performance because it is not as stable as desired.

Type II errors would fall in the upper left-hand quadrant, and would occur when the quick test predicted an immature respiration rate for compost that is, in fact, mature. Type II errors could result in excess processing time for already stabilized materials and potential economic loss to the compost processor.

In an effort to partition the axes into active composting, early curing and late curing, the process was repeated, attempting to divide the "unstable" range into two groups of points. Unfortunately, the distribution of points was such that none fell into the transitional zone. For researchers this indicates the need for continued intensive study of compost after the end of the active composting phase. For compost producers, it suggests that care be used in defining potentially transitional materials as mature or immature. Further, compost producers should consider that the two dividing lines on the graphs are actually intersecting *zones*. Compost maturity is not a single value of respiration rates, but rather a range through which maturing materials pass.

We suggest the following critical test values as dividing mature from immature yard debris compost:

- Test method A, alkaline trap method, 6 mg CO_2 – C g C^{-1} d^{-1}
- Test Method B, gas detection tubes, 2 mg CO_2 – C g C^{-1} d^{-1}
- Test Method C, Solvita test, between 5 and 6 Solvita units
- Test Method D, capacity to self-heat, not more than 2°C temperature rise.

CONCLUSION

We found that composting yard debris released CO_2 at a rate one order of magnitude greater during active composting than during late

curing. Late curing was characterized by low, stable rates of respiration. During active curing, an intermediate phase occurred between 40 and 60 d. Composting yard debris released CO_2 at lower rates, and showed reduced variability than during active composting. The data show the importance of verifying compost maturity with repeated tests, regardless of the test method used. We found that the sampling protocol recommended by Leege and Thompson (1997) was effective in producing representative samples from very large compost piles.

We evaluated three low-technical tests of compost: the Solvita test, capacity for self-heating, and CO_2 detection tube. We judged all these tests to be suitable for compost producers without technical support. These tests were compared with a standard laboratory method of determining respiration, alkaline trapping.

All tests were capable of distinguishing between fresh and well-cured compost. They differed in their sensitivity to changes during active curing. The Solvita test results were more variable, and the CO_2 detection tube data were less variable. This prototypic technique offers opportunities for further refinement and research.

The results of the self-heating test were not replicated, but the data described the same general pattern of microbial respiration as did the alkaline trapping results. With measurements indicating of stability at 42 d, this test estimated compost maturity earlier than the other methods, at 70+

d. This test has the obvious disadvantage of taking up to a week to complete.

Our data suggest that a value below 6 mg CO_2-C g C^{-1} d^{-1}, measured by alkaline trapping, could be established as a standard for composted yard debris stability. Brinton et al. (1995) defined compost mature at 0-2 mg CO_2-C g C^{-1} d^{-1} and Ianotti, et al. (1994) defined compost mature at 1.2-4.5 mg CO_2-C g C^{-1} d^{-1}.

Commercial composters might find it helpful to develop "stability curves" for their feedstocks and process procedures over time. This could contribute to an understanding of the most appropriate time for testing stability for marketing purposes.

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CONCLUSION

This thesis addressed compost maturity indicators and low-tech compost stability tests. We studied source-separated municipal yard debris. The study was somewhat unique in that the compost was produced under working conditions in a commercial compost facility. Thus, our results and conclusions may be more applicable to situations observed by large-scale compost producers.

Chapter two compared the effect of continuous aeration on compost maturity to the effect of windrow turning. We followed an array of chemical, respirometric, sensory and biological (germination) parameters, looking for those indicating maturity. Our study indicated that the ultimate maturity of these materials was no different for the two aeration treatments, although the forced aeration treatment resulted in mature compost about 20 days earlier than the turned windrow treatment. We found compost maturity strongly associated with compost C, pH and respiration. Neither sensory nor biological parameters were useful in determining maturity of these composts.

Chapter three compared "quick" tests of compost stability, suitable for compost producers lacking analytic support. We evaluated the Solvita test, the self-heating test, and a new test using CO_2 detection tubes as a measure of compost respiration rate. This test was developed in our lab as part of the thesis work. These tests were compared to respiration data

developed using alkaline traps. We found all the tests useful in distinguishing between stable and unstable compost. The Solvita test is packaged as an affordable, readily available kit. It is administered in a four-hour period, and the results are easily interpreted. This test was most sensitive to respiration rate changes during active composting and late curing. The self-heating test takes four to six days to complete, but the resulting temperature units are intuitively understood and easily interpreted. Although the initial equipment investment can be high, additional per-test costs are negligible, and less-expensive equipment has been substituted with good results.

Finally, we found gas detection tubes a useful tool for measuring CO_2 released during compost respiration. These tubes are readily available, affordable, and the test can be administered in four hours. Because this test measures the same parameter as the alkaline trap test, results of the two tests indicated similar change over time. A minimally trained worker could administer the CO_2 detection tube test, while the alkaline trap test requires a trained technician. This test will undergo further development.

Source separated municipal yard debris compost has characteristics that differentiate it from other commonly composted materials, like manure or biosolids. Its initial N content effects parameters like C: N ratio and NH_3 content, and thus, indirectly, pH, possibly setting it apart from other feedstocks. It is difficult to generalize beyond the conclusions generated

during the course of this project to other feedstocks. Future research is indicated to determine maturity indices of a broader range of feedstocks. Studying other feedstocks from agronomic and municipal sources would enhance the value of the quick stability test study. In addition, the CO_2 detection tube test requires refinement and streamlining to become a practical test for use under working conditions.

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