Compost quality attributes, measurements, and variability

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I. WHAT IS COMPOST QUALITY?

Compost testing is used by both compost producers and users. This chapter is designed to assist compost producers and users in collecting representative compost samples, requesting compost analyses, and in understanding and interpreting compost analytical data.

The most critical compost quality factors depend on the planned compost end-use (Table 1). For most applications, plant growth response is the ultimate indicator of compost quality. Compost nutrient content, especially plant-available nitrogen (N), is most important for field crops where compost is applied as a supplement or replacement for other nutrient sources. The pH and soluble salt content of compost is a key characteristic where compost is used at high rates, such as in potting media or compost sold to the general public. Successful marketing to the general public requires a mature, well-decomposed, dark brown to black compost with an earthy odor. Compost maturity and biological stability are most important for compost use in potting media, for bagged products, and for compost-mediated disease suppression. Consistent particle size is needed for soil-less potting media and other high-value applications like amendment of athletic turf or golf greens.

II. COMPOST QUALITY SPECIFICATIONS OR GUIDELINES

Compost industry organizations have recently adopted suggested compost specifications for a variety of uses. These specifications are usually based on consensus among experts. They are often not specific enough for a given end use in a particular location. The guidelines developed by the U.S. Composting Council (Table 2) were evaluated by several groups of professional end-users in the Seattle, WA area (E & A Environmental Consultants and Stenn, 1996). Horticultural professionals considered the guidelines too general to apply to their specific

situations. The study concluded that the Compost Council guidelines are best used by compost producers as a minimum quality standard.

Voluntary or regulation-driven compost quality assurance programs have recently emerged in North America (California Compost Quality Council, 1999; Compost Council of Canada, 1999) and in Europe (Bildingmaier, 1993; Verdonck, 1998). Generally, there are rigid standards for essential quality parameters such as minimum organic matter content, maximum levels of trace elements, maximum levels of man-made inerts, and freedom from human pathogens. Beyond these minimal standards, most compost quality assurance programs have a list of other parameters that must be reported for the product.

A few quality assurance programs include periodic verification of product quality by a third-party laboratory or an oversight agency. In voluntary programs, the compost producer obtains the right to advertise with an organizational "seal of approval" (California Compost Quality Council, 1999; Woods End Research Laboratory, 1999a). However, only a few of the parameters that may be important to high-value horticultural use (Inbar et al., 1993) are evaluated in most current quality assurance programs.

A major problem in compost guideline development or the development of quality assurance standards for compost is the difference in perspective between researchers, compost producers and compost users (E & A Environmental Consultants and Stenn, 1996). Research studies typically focus on how the use of a specific compost product affects the growth of specific plant species in a particular application. Compost users and producers have much broader information needs. Typically, they are interested in efficient methods for compost handling, how compost can be used on a variety of soils and plant species, and how compost use affects other crop maintenance activities (e.g., fertilization, disease and weed control).

Guidelines and quality assurance standards will continue to improve as more experience is gained on compost use in different environments.

One of the first steps towards standardization of compost quality is the standardization of laboratory analysis procedures. The U.S. Composting Council has developed a comprehensive publication describing procedures for compost sampling and testing, *Test Methods for the Examination of Composting and Compost* (TMECC; Leege and Thompson, 1997). The format for TMECC is designed primarily for laboratory use. Quick tests for approximation of compost product quality are also included. Detailed instructions are given for carrying out each test, using a format similar to that used by the American Society for Testing Materials.

Most of the chemical and physical test methods listed in TMECC were adapted from existing standard methods for soil and plant material analysis, and are unlikely to change significantly with time. Many of the biological methods for assessing compost stability and maturity were recently developed by researchers, and are likely to be refined as they are adopted by the compost industry. The current version of TMECC (Leege and Thompson, 1997) is undergoing extensive peer review by laboratory personnel, compost users, scientists, and regulatory officials. Future editions of TMECC will reflect the collective expertise of the peer review group. In this chapter, we will frequently reference TMECC methods from the 1997 edition.

III. COMPOST SAMPLING

Compost sampling is perhaps the most critical phase of compost analysis. A compost sample that accurately represents the compost product is essential. Best results from compost testing come from carefully planned sampling.

Deciding what tests are needed and what laboratories will do the analysis is the first step in designing a sampling plan. For evaluation of horticultural use potential, compost tests can be performed by a laboratory that routinely does analyses for other organic growing media. Other tests, such as those required by regulation (e.g., human pathogens or trace elements), should be performed by a laboratory that specializes in such testing. Some agricultural soil and plant tissue testing laboratories can perform many of the horticultural and environmental tests.

We suggest working backwards from the interpretation of test results to determine when and how to sample. If compost is purchased, tell the supplier what components of compost quality are essential for the intended use. Discuss how and when the compost is sampled, to make sure the analysis reflects "as delivered" quality. If one is producing compost, compost test results can be used to adjust the composting process to meet one's specific needs. To assist in producing quality compost, a producer may want to sample compost feedstocks and actively composting piles, as well as the finished compost.

The generalized sampling protocol described in Table 3 is applicable to samples collected for all analyses except for microbiological analyses. A sterile sample collection and preservation technique is needed for microbiological testing (US Environmental Protection Agency, 1992). Composite sampling, where individual samples are combined into one sample submitted to a laboratory, is the recommended protocol for representing average compost quality. When information is needed on the variability of compost analyses within a pile, a variety of other sampling techniques can be used (Leege and Thompson, 1997).

The best time to collect a composite sample is immediately after a pile has been thoroughly turned or mixed. Within days or hours after turning, a pile develops gradients in moisture, aeration, biological stability, and bacterial populations. Even after turning, piles may

not be thoroughly mixed, so many small samples from different locations in the pile must be combined to reflect average compost quality.

The most common sampling situations are sampling from windrows or sampling from curing piles. For windrow sampling, it is important to take samples from random locations representing the entire length of the windrow. This is especially important when windrows are built gradually from end to end, and may have substantial variation in compost feedstocks and processing time. Curing piles are often extremely variable in moisture, maturity, and bulk density. Frequently, curing piles are very large and contain material from several active composting piles, and are not turned or mixed. In sampling large static windrows and curing piles, it is essential to break into the center of the pile with a front-end loader or other equipment to get a representative sample.

IV. PHYSICAL PROPERTIES OF COMPOSTS

A. Moisture Content

Compost moisture content is easily determined, but may fluctuate widely due to differences in feedstocks, processing, and storage conditions. Moisture content can be expressed on a weight or volume basis. Moisture is most often expressed as a fraction of total compost weight (Table 4). As moisture content increases, dry matter per unit weight decreases. Moisture content may also provide some understanding of processing or storage conditions. Composts with moisture contents of less than 35 percent may not have been fully stabilized due to low moisture, or may have been stored for excessively long periods leading to moisture loss. Composts with less than 35 percent moisture are often dusty and unpleasant to handle.

B. Bulk Density

Bulk density, the weight per unit volume of compost, is affected by moisture content, inorganic (ash) content, particle size distribution, and the degree of decomposition. Bulk density is used to convert nutrient analyses from dry weight to an "as-is" basis.

Bulk density on an "as-is" basis (Table 4) mainly indicates water content. Most composts with an "as-is" moisture content of 35 to 55 % will have a bulk density of 500 to 700 kg m^{-3}, or about 900 to 1200 lb per yd^3.

Bulk density on a dry weight basis is an indicator of particle size and ash content. Dry bulk density usually increases with composting time as ash content increases and as particle size is reduced by decomposition, turning, and screening (Raviv et al., 1987). The dry bulk density of compost is most important when compost comprises a large proportion of the growing media (e.g., potting media). As bulk density increases, drainage and air-filled porosity of growing media are reduced, and water-holding capacity is increased.

Compost users use bulk density and moisture analyses to calculate volume-based application rates (e.g., m^3 compost per 100 m^2) that are approximately equal to a given compost dry weight per unit area (e.g., kg dry matter per m^3). The measurement of "as-is" bulk density in the laboratory (Table 4) simulates a small pile of compost. Compost in big piles, or packed into a truck, may have higher bulk density values.

C. Water Holding Capacity

Water-holding capacity is the amount of water held in pores after gravitational loss for a specified time. This test is used to assess the utilization of compost for potting media. Water-holding capacity (Table 4) is a measure of the water retained by a compost sample after free

drainage for 4 hours. This procedure is container-specific. Water retention after free drainage is strongly affected by the height of the measurement vessel (Inbar et al., 1993).

Water-holding capacity measurements are of limited importance for field compost use. Composts applied to soil, even at high rates, may not increase the net amount of water that is readily available to plants between soil matric potentials of –0.2 and -0.8 bars (Chang et al., 1983). Compost addition to soil increases net water availability at matric potentials near saturation (0 to –0.2 bars; Chang et al., 1983, McCoy, 1992), but this water is drains away rapidly in a field soil.

D. Particle size and man-made inerts

Particle size provides a number of critical indicators for the potential user. Large particles (e.g., those retained by 12 mm screen) prevent efficient spreading for some field applications. Screening can remove larger compost particles, but it is difficult to remove small particles. Small particle size may also limit use for applications such as potting mixes or golf greens, where rapid drainage is important. Too many fine compost particles are undesirable in a mulch product, because they can retain enough water to promote weed seed germination.

Man-made inerts, such as glass or plastics are seldom a problem except for composts derived from municipal solid waste (MSW). Plastics can be a problem with urban yard debris composts, especially if grass is collected in plastic bags.

V. CHEMICAL PROPERTIES OF COMPOSTS

A. Total Organic Carbon

The total organic carbon (C) concentration of a compost is an indicator of its organic matter concentration. Total organic C is generally measured by two laboratory methods: combustion (Method 9.08B in Table 5) and Walkley-Black (Schulte, 1988). The combustion

method relies on high temperature furnace oxidation and subsequent direct measurement of C by an infrared detector. Combustion is the preferred procedure because it is more accurate and precise than the Walkley-Black determination. The Walkley-Black method provides an estimate of organic C, based on partial chemical oxidation of total organic C. The Walkley-Black test is calibrated for soil organic matter, which is not completely similar to compost organic matter. Another disadvantage of the Walkley-Black method is its use of dichromate, a chemical classified as a hazardous waste.

Both the combustion and Walkley-Black methods do not discriminate between organic and inorganic C (e.g., carbonates). Testing for inorganic C is recommended for composts that have a saturated paste pH above 7.3, or composts that have been amended with alkaline materials such as lime.

B. Volatile Solids (Volatile Organics)

The volatile solids (volatile organics) method estimates organic and ash concentrations. The portion of the sample lost in high temperature combustion (550 ^{o}C) estimates organic matter; the portion remaining after combustion is ash. Because organic matter is not determined directly, the volatile solids content of a sample is only approximately equal to its organic matter content. The volatile solids estimate includes non-organic matter sources of weight loss, including rubber, plastic, and "bound" water. This method is also referred to as Loss-On-Ignition (LOI).

C. Cation Exchange Capacity

Cation exchange capacity (CEC) is a measure of the capacity of compost to hold exchangeable cations such as potassium (K), calcium (Ca), magnesium (Mg) and sodium (Na), to negatively-charged surfaces. Sources of negative charges in compost include dissociation of acidic functional groups found in organic matter (e.g., OH, COOH). As pH increases, the CEC

of organic matter increases. Most composts have a pH of 6 to 8, which is similar to that used in most CEC test methods (pH 7).

CEC test methods recommended for compost (Table 5) saturate the compost with a single cation such as NH_4^+, Na^+ or Ba^{2+}, then subsequently displace and determine the saturating cation.

Compost CEC measurements are used in formulating potting media for container plants, and as an indicator of compost maturity (Table 6). A potting medium with a relatively high CEC provides more buffering capacity against changes in pH and is more easily managed in container plant production. Compost CEC increases with composting time, as the compost organic matter becomes more humified.

D. Total Nitrogen

The total N content of composts can vary substantially based on feedstocks, processing conditions, curing and storage (see "Chemical indicators of maturity" in this chapter and Sikora and Szmidt chapter in this book for more interpretive information).

Total N is the sum of inorganic + organic N forms in compost. Total N is measured by two laboratory methods, total Kjeldahl and combustion.

For the Kjeldahl method, strong acid is added to digest the sample, and ammonium-N (NH_4-N) in the digested sample is subsequently determined via colorimetric analysis. Some Kjeldahl procedures do not include nitrate-N (NO_3-N) in the total N determination. For most composts, omitting NO_3 from total N analyses is insignificant, since composts usually contain less than 0.2 % NO_3-N.

The combustion method is a direct measurement of total N. The sample is oxidized in a high-temperature furnace, and N is determined by an infared detector. The combustion method is generally more accurate and precise than the Kjeldahl method. Samples containing large

quantities of lignin will have lower quantities of N by the Kjeldahl method versus the combustion method. The Kjeldahl method does not digest N present in heterocyclic ring compounds like those found in lignin; the combustion method detects all N forms.

E. Inorganic Nitrogen

Inorganic N includes NH_4-N, NH_3-N, and NO_3-N. A number of extractants and colorimetric determination methods are acceptable for NH_4 and NO_3 analyses (Gavlak et al., 1994).

Laboratory procedures for NH_4-N, and NH_3-N are identical. Laboratories differ in how they report test results. Usually, soil testing labs report NH_4-N, while environmental laboratories report NH_3-N. From a chemical perspective, NH_4-N is the more accurate representation. Ammonia (NH_3) is usually a very small proportion of compost NH_4 + NH_3-N.

Sample preservation techniques and holding time can affect inorganic N test results. Ammonium and NO_3 can change rapidly due to drying and unrefrigerated storage. Poorly-stabilized or immature composts will often contain significant quantities of NH_4-N that can be rapidly lost to the air during handling and storage. It is best to rapidly freeze samples that will be submitted for NH_4 or NO_3 analysis.

The form and amount of N present in inorganic forms can be a useful indicator of compost maturity (see "Chemical indicators of compost maturity" in Table 6). Compost inorganic N is also important as an estimate of plant-available N supplied with the compost.

F. Acidity/Alkalinity (pH)

The pH range for most finished composts is from 6.0 to 8.0. The final pH of the compost is highly dependent on the feedstock, the compost process and the addition of any amendments. Excessive acidity or excessive alkalinity can injure plant roots, inhibiting plant growth and

development. Compost feedstocks such as wood may be quite acidic, while others (e.g., lime-treated biosolids) may be a significant source of alkalinity.

Where compost accounts for sizable portions of a potting medium mix, attention must be paid to matching the final pH of the potting medium to plant requirements. In potting media, compost pH can be increased by lime addition, and reduced by elemental sulfur (S) addition. Some composts with high pH may be unsuitable for acid-loving plants because of the difficulty in lowering compost pH with elemental S. To be rapidly effective in reducing pH, elemental S must be of very fine particle size (Marfa et al., 1998). As compost CEC increases, the amount of lime or elemental S needed to change the pH also increases.

Compost pH is measured by two methods in the laboratory: saturated paste and volume addition. For the paste method, water is added to the sample until its moisture content just exceeds water-holding capacity. Then, pH is measured by immersing an electrode into the paste. The volume method involves mixing a specified volume of compost with a specified volume of water (e.g., 1:1 or 1:2 compost:water). Then, pH is measured by immersing the pH electrode into the slurry mixture. Compost pH determined by the volume method usually results in a value 0.1 to 0.3 pH units higher than that determined by the saturated paste method. Traditionally, the saturated paste method has been used to assess compost for landscape applications, while the volume addition method has been used for potting media assessment.

G. Electrical Conductivity (Soluble salts)

Salinity is estimated from measurement of electrical conductivity (Table 5). Like pH measurement, soluble salts can be measured via saturated paste or volume addition methods.

Electrical conductivity does not provide information on the type of salts present. Some cations or anions are nutrients such as Ca, Mg, sulfate-S (SO_4-S), or NO_3-N. Salts containing

Na, chloride (Cl) or boron (B) can be toxic to plants at elevated concentrations. These elements are usually determined in a saturated paste extract (Table 5) or volume addition extract.

High salt contents in compost affect seed germination and root health. Crops differ widely in salt tolerance (California Fertilizer Association, 1990). Some vegetable crops, such as beans (Phaseolus vulgaris L.) and onions (Allium cepa L.) are highly sensitive to salts. Repeated application of high-salt composts can lead to soil salinity build-up in field soils in arid climates. Composts containing over 10 meq of Cl per L of a saturated paste extract may limit the growth of grapes (Vitis spp.), and B contents in excess of 1.0 mg L^{-1} of a saturated paste extract may affect sensitive crops such as beans.

H. Phosphorus, Potassium, Calcium, Magnesium and Micronutrients

Total phosphorus (P), K, Ca, and Mg are determined by total digestion of the compost in strong acid, with subsequent analysis by atomic absorption spectrometry or inductively coupled plasma spectrometry.

Only a portion of the total P, Ca and Mg in a compost sample will be plant-available. Essentially all of total compost K is plant-available. The exchangeable (plant-available) fraction of total K, Ca and Mg can be determined via a soil test procedure called "exchangeable bases." Determination of exchangeable bases, including sodium (Na), is recommended for some composts (e.g., compost derived from beef feedlot manure). High quantities of exchangeable Na may indicate water infiltration problems. In these instances, analysis of exchangeable Ca and Mg concentrations will determine if there is need to amend the compost with gypsum.

Soil test methods for extractable P, such as the Bray (dilute acid-flouride), Olsen (bicarbonate) and Mehlich 3 (ammonium nitrate, ammonium flouride, EDTA and HNO_3)

methods are sometimes performed by laboratories on compost samples. Interpretation of these soil test methods for compost samples is difficult, because the tests were primarily designed for predicting plant growth responses on mineral soils.

Micronutrient analyses [i.e., zinc (Zn), manganese (Mn), iron (Fe), and copper (Cu)] are sometimes of value when composts are used in potting media. The usual test method involves saturation of the compost with an 0.005 M DTPA extraction solution, filtration of the extract, and subsequent analysis for the metals of interest (Whitney, 1998). Composts containing more than 25 mg kg^{-1} of Zn and 2.5 mg kg^{-1} of B via DTPA extraction may have a detrimental impact on plant growth.

VI. EVALUATING COMPOST MATURITY AND STABILITY

Compost maturity and stability are critical for compost use in potting media, for bagged products, and for compost-mediated disease suppression. Maturity is a general term describing fitness of the compost for a particular end use, while stability refers to the resistance of compost organic matter to degradation. Mature composts are ready to use; they contain negligible or acceptable concentrations of phytotoxic compounds like NH_3 or short-chain organic acids. The more stable the compost, the less shrinkage occurs during container plant production. Stable composts remain cool when bagged. Different degrees of compost stability are needed for control of specific plant diseases (Hoitink et al., 1997; Hoitink chapter in this book).

The development of a "mature compost" is a continuous process. The first phase, rapid composting, is characterized by high temperatures (55 to 75 ^{o}C), a supply of readily decomposable organic matter, and rapid rates of organic matter decomposition by thermophilic bacteria. Weed seeds and most fungi and bacteria are killed during rapid composting. The

second phase, curing, begins when the supply of readily decomposed organic matter becomes limiting. During curing, pile temperatures are lower (< 40 ^{o}C) and the compost is recolonized by mesophilic bacteria and fungi. The third phase, maturity, is the most subjective. By our definition, a compost is considered mature when it has cured long enough for a particular end-use.

Maturity measurements have a number of purposes. First, indicators of maturity are used by compost producers to evaluate the success of the composting process. From a processor standpoint, processing compost for the minimum time necessary decreases cost and increases product volume. Second, maturity indicators are sometimes incorporated into minimum product standards by government agencies or compost industry organizations. From a regulatory standpoint, a single measurement that is rapid, reproducible, and accurately reflects product quality is desirable. Unfortunately, several tests are often needed to characterize maturity. Often, the most reliable tests are those that are the slowest, most expensive, or least available. Third, maturity measurements are sometimes used by compost users as a check on compost quality for their particular application. Our discussion here focuses on the horticultural compost user, apart from regulatory considerations.

Compost maturity can be evaluated by sensory, chemical, stability, or phytotoxicity methods (Tables 6, 7, and 8). Sensory and chemical methods are the simplest and most readily available. They evaluate maturity indirectly, and are all somewhat feedstock dependent. They rely on correlations between measured parameters and compost respiration rate or plant growth response. Compost stability, as measured by respirometry or self-heating, describes the relative stability of organic C compounds present in the compost. Standards for compost stability are applicable across a wide range of compost feedstocks. Phytotoxicity tests are often the most

difficult tests to standardize and interpret, because of the many variables involved in plant response to compost.

A. Sensory indicators of maturity

Evaluation of compost color and odor are reasonable screening methods for rejecting composts that have obvious problems. A compost with a foul anaerobic odor is unlikely to be rated as mature by any other test. A standardized matrix for color and odor evaluation is available (Leege and Thompson, 1997; Method 9.03A in Table 6). Compost color darkens during composting, and is strongly affected by feedstocks. Mature yard trimmings composts are usually dark black in color, while manure composts usually attain a more brownish color when mature.

B. Chemical indicators of maturity

A wide variety of chemical indicators of compost maturity have been proposed (Henry and Harrison, 1996; Chen and Inbar, 1993; Jimenez and Garcia, 1989). We describe the most widely used chemical indicators here and in Table 6.

1. *Organic matter*

Volatile solids, an estimate of compost organic matter, decrease during composting. Typically, about half of the initial organic matter is lost during composting. Cation exchange capacity generally increases as the compost matures (Chen and Inbar, 1993). This measurement is most meaningful for comparisons within a particular class of feedstocks (e.g., cattle manure composts). Some organic materials have a relatively high CEC prior to composting (Casale et al., 1995). A minimum CEC of 60 meq $100g^{-1}$ of compost volatile solids (ash-free basis) has been proposed as a target for mature MSW composts (Harada et al., 1981).

2. *Carbon and nitrogen*

Compost total N, carbon:nitrogen (C:N) ratio, and inorganic N concentrations are often more related to feedstocks than to maturity. For this discussion, maturity with respect to N cycling occurs when the compost can be incorporated into growth media without causing excessive immobilization of N or NH_3 toxicity. A variety of maturity indicators can be derived from measurements of compost C and N (Table 6).

Potential problems with N are associated with particular feedstocks (Sikora and Szmidt chapter in this book). Nitrogen immobilization is a major problem for immature composts derived from low N content feedstocks such as municipal solid waste (MSW; Jimenez and Garcia, 1989; Ozores-Hampton et al., 1998). Plants grown in composts that immobilize N are often yellow and stunted because of N deficiency. For high N feedstocks such as manures or biosolids, N availability is highest in immature compost. As composting proceeds, inorganic N and readily mineralizable N is lost as NH_3, or incorporated into complex organic forms (Pare et al., 1998). Immature manure or biosolids composts with NH_4-N concentrations above 1000 mg kg^{-1} can produce enough water-soluble NH_3 to be toxic to plant roots (Barker, 1997). The potential for NH_3 toxicity is primarily a concern for composts or compost-amended media that have a pH greater than 7.5 to 8.0.

Ideal compost feedstock mixtures have an initial C:N ratio of about 30:1, decreasing to less than 20:1 as the composting process proceeds. The use of C:N ratio is based on the C:N ratio of stable soil organic matter, which usually ranges from 10 to 15:1. If cured for an extended period, compost C:N will approach that of soil organic matter. For many composting systems, the C:N ratio is not a sensitive indicator of maturity (Lasaridi and Stentiford, 1998b; Forster et al., 1993). For example, in compost production systems with pH > 7.5, the C:N ratio may

change very little during composting, since C loss as CO_2 and N loss as NH_3 occur simultaneously.

The amount or ratio of NH_4-N and NO_3-N is another simple chemical indicator of maturity. Ammonium-N is often highest in the early stages of composting, declining as compost stability increases. The lower respiration rates found in mature compost are more favorable for NO_3 production via nitrification and less favorable for NO_3 loss via denitrification. Also, nitrification is strongly inhibited at temperatures above 40 ºC. Ammonium and NO_3 concentrations are strongly affected by drying and re-wetting in immature composts (Grebus et al., 1994).

C. Compost stability as a maturity indicator

Compost stability is one aspect of compost maturity. Stability, as measured by respirometry or self-heating, describes the relative stability of organic C compounds present in the compost. Standards for compost stability are applicable across a wide range of compost feedstocks (Haug, 1993b; Frost et al., 1992).

1. *Respirometry*

Respirometry is the measurement of O_2 consumed or CO_2 released by a sample. It is used to estimate biological activity in a sample. The measured respiration rate can be used to estimate the rate of compost weight loss over time, and to estimate compost maturity.

Measurement of O_2 and CO_2 from air samples taken directly from an actively composting pile can provide data to guide pile aeration requirements (Haug, 1993a). However, such measurements cannot be considered maturity measurements because the time of air contact with the compost is unknown.

It is important to understand what units the laboratory uses to report the compost respiration rate. The most commonly accepted units, given in Table 7, base the respiration rate on the amount of volatile solids (VS) or the amount of organic C present in the sample. Such units allow comparison per unit of organic matter or C. Compost respiration rates and organic matter contents can be used to estimate "shrinkage" of a compost via organic matter decomposition. For example, for a compost with 50 % organic matter (25 % C) and a respiration rate of 2 mg CO_2-C per g compost C per day, the rate of product loss via decomposition is approximately 0.1 % per day.

There is great variation in the technology used to measure compost respiration rates. Test procedures range from quantitative to qualitative. Most respiratory procedures include a 2 to 3 day sample preconditioning step to achieve uniform moisture (about 50 % total solids) and a compost microbial population dominated by mesophilic micro-organisms. A recently proposed adaptation of the specific oxygen uptake rate (SOUR) test used in wastewater analysis (Lasaridi and Stentiford, 1998a, 1998b) does not require sample preconditioning or moisture adjustment.

Most respirometric procedures require a standardized temperature (25 to 35 ^oC) and repeated measurements over time to determine respiration rate (Table 7). Since the compost sample produces heat, a water bath is often required to hold temperature constant. The simplest of the quantitative respiration measurements is CO_2 evolution rate measured by alkaline trapping. Carbon dioxide trapped in KOH is determined via titration (Method 9.09C in Table 7). Measurements of O_2 consumption using Clark-type polarographic electrodes require repeated measurements every 10 minutes for at least 90 minutes (Frost et al., 1992). Therefore, O_2 uptake measurements are usually coupled with a datalogger or a computer (Ianotti et al., 1994), or reported as a unitless O_2 uptake index (Grebus et al., 1994). Neither CO_2 evolution nor O_2

consumption measurements of compost respiration rate are currently widely available at commercial laboratories.

A rapid semi-quantitative procedure, the Solvita™* test, uses a colorimetric gel determination of CO_2 evolution (Woods End Research Laboratory, 1999b). The Solvita procedure does not rigidly control compost temperature and moisture. The sample is not "pre-conditioned" prior to testing. The measured respiration rate is estimated per unit volume of "as-is" compost at ambient temperature. The interpretive scale provided has eight categories ranging from "raw" compost (categories 1-2), "active" compost (categories 3-6), and "finished" compost (categories 7-8). "Raw" compost is poorly decomposed and probably phytotoxic, and 'finished" compost is ready for most uses. The Solvita test is being used in connection with agency compost specifications for maturity in Washington State, Texas, California, Minnesota, Maine, and Illinois in the U.S., and in Germany and Denmark (Woods End Research Laboratory, 1999a). Eighteen states in the U.S. are currently reviewing the Solvita procedure for inclusion in compost testing protocols.

2. *Dewar self-heating test*

This test is a standardized procedure for measurement of compost heat production (Brinton et al., 1995; Method 9.11 in Table 7). It is an indirect measurement of respiration rate. Moist compost is placed in an insulated vacuum bottle, and the rise in temperature is recorded over a 2 to 9 day period. The maximum temperature increase over ambient is used for interpretive purposes. The test is simple to perform, but time-consuming. Unlike short-term O_2 or CO_2 respirometry, the Dewar test allows development of a natural succession of compost microflora similar to that which occurs in a compost pile. Therefore, sample preconditioning is

* Registered Trademark of Woods End Research Laboratory, Inc., Mt. Vernon, Maine.

not as critical for this test. Also, compost samples often reach a self-limiting temperature in the Dewar procedure, which also simulates the natural behavior of compost piles.

There is debate about the proper level of compost moisture for the Dewar test (Brinton et al., 1995). Earlier guidance was to dry compost to 30 % moisture, which is below the optimum for microbial activity. Current guidance is to moisten compost to the optimum range for microbial activity, usually above 50% moisture. However, at higher moisture levels, more heat is needed for a given rise in temperature; water addition increases the heat capacity of the compost sample.

Dewar self-heating test values (Method 9.11 in Table 7) are correlated with quantitative measurements of respiration (Woods End Research Laboratory, 1999b). "Raw" compost via the Dewar test corresponds with a respiration rate of greater than 20 mg CO_2-C g compost-C^{-1} d^{-1}. A Dewar test of 0 to 4 mg CO_2-C g compost-C^{-1} d^{-1} is usually observed for "finished" compost. "Active" compost via the Dewar test has an approximate respiration rate of 8 to 20 mg CO_2-C g compost-C^{-1} d^{-1}.

D. Phytotoxicity as a maturity indicator

Composts can contain a variety of phytotoxic substances that inhibit or prevent plant growth. Phytotoxicity tests are most interpretable when the test duplicates or represents a specific compost end use. Reducing compost application rates or allowing time after compost application usually is effective in reducing or eliminating phytotoxicity responses tests.

Standardized germination and growth evaluate a combination of phytotoxic factors in compost including, NH_3, soluble salts, short-chain organic acids, and pH (Leege and Thompson, 1997; Method 9.05 in Table 8). Growth of most plant species and cultivars is inhibited with highly unstable composts (Keeling et al., 1994; Garcia et al., 1992; Zucconi et al., 1981a, 1981b).

As compost becomes more stable, variation in plant species susceptibility to phytotoxic factors becomes more important.

Germination and growth tests directly estimate the plant growth inhibition by compost under specified environmental conditions. Most tests are semi-quantitative, with test scores grouped into 2 to 4 inhibition categories, such as none, mild, strong, and severe inhibition of germination and growth. Tests require one to 14 days depending on the method. Tests using compost extracts are usually more rapid and reproducible than direct seeding tests, but require additional time for extract preparation. Compost extracts must be prepared aseptically via millipore filtering to remove bacteria and to prevent rapid degradation of short-chain organic acids.

The choice of plant species can have a large effect on germination and growth test results when the compost is high in soluble salts. Very stable composts with high salt concentrations may inhibit germination of some plant species (Iannotti et al., 1994). We recommend using seeds with higher salt tolerance (California Fertilizer Association, 1990) when evaluating composts with elevated soluble salts.

Short-chain organic acids resulting from decomposition of organic matter can inhibit or reduce seed germination and root growth. Organic acids responsible for growth inhibition include acetic, butyric, propionic, and valeric acids (Brinton, 1998; Liao et al., 1994). These acids also produce the foul odor associated with compost that has been decomposing anaerobically. They are produced as a natural byproduct of the early stages of organic matter decomposition. As compost matures, the short-chain organic acids are lost via decomposition. These compounds can be determined quantitatively with sophisticated laboratory gas or ion chromatography procedures (Brinton, 1998; Liao et al., 1994). Brinton (1998) reported mean

short-chain organic acid concentrations of 4385 mg kg^{-1} and a range of 75 to 51,474 mg kg^{-1} for 626 compost samples from across the United States. Phytotoxic concentrations of acetic acid can be as low as 300 mg kg^{-1} (DeVleeschauwer et al., 1981).

Composts may have one or more quality problems that impose limitations on their use (Table 9). Most quality problems can be traced to either the compost feedstocks or the composting process. Reducing compost application rates or allowing additional time for compost stabilization can minimize most of the common quality problems.

VII. VARIABILITY IN COMPOST ANALYTICAL DATA

The compost testing methods outlined in this chapter are valuable tools for product quality assessment. Laboratory data are most valuable when one is familiar with the accuracy and precision of the data (how closely it reflects reality). This section describes how to choose a laboratory to perform analyses, and what variability is commonly observed in chemical laboratory analysis procedures. There are very limited published data on the variability of compost physical and biological tests; such tests likely have variability considerably greater than listed here for the chemical tests (Tables 10 and 11).

We recommend selecting a laboratory that has compost testing experience and performs the test methods routinely. Generally, any laboratory that performs compost tests several times each month is sufficient. Preference should be given to testing laboratories that participate in a compost analysis proficiency testing program or a sample exchange program. One example is the Compost Analysis Proficiency (CAP) program coordinated by the Utah State University Analytical Laboratory (Logan, Utah, USA). Proficiency testing programs provide a check on laboratory data quality on a regular basis (usually every 3 months). Ask the laboratory to provide

their results from the proficiency-testing program. Compare their analytical values to the mean or median value for all laboratories participating in the proficiency program.

The quality of laboratory data for a specific test has two components: accuracy or bias, and precision. Bias is the deviation of a lab analysis from its true value, while precision describes the reproducibility of a test value. Bias is assessed using a standard reference sample with known analytical values. Precision can be assessed via repeated analysis of a single well-blended sample.

Tables 10 and 11 illustrate intra-laboratory and inter-laboratory precision for well-blended compost samples. Precision between multiple laboratories (inter-laboratory) is generally higher than that within a single laboratory (Table 10). Compost analytical data presented in Tables 10 and 11 does not include sampling error, the failure to collect a truly representative sample.

The precision of laboratory data is method-dependent (Table 10). For example, the pH saturated paste test method may have an intra-laboratory precision of 1.3%, while that of total N is 4.5% and that of total arsenic (As) is 18.5%. This was most notable for As, cadmium (Cd), and selenium (Se) analyses.

VIII. COMPOST QUALITY IN THE FUTURE

This chapter reflects the growing state of compost quality evaluation. Compost quality testing is becoming a more predictable and routine process as compost use expands, and as analytical methods tailored specifically to compost are developed. The development of guidelines, regulations, and quality assurance programs for compost quality is also spurring improvements in compost analysis. However, the quantity of compost analyses performed by

commercial laboratories is still very small compared to the quantity of analyses performed for soil or plant tissue analysis. The recent initiation of a cooperative compost-testing program, the Compost Analysis Proficiency (CAP) program coordinated by the Utah State University Analytical Laboratory, reflects increasing interest in compost analyses.

The greatest current research activity is in the area of rapid determination of compost stability and maturity parameters. Regulations and user demand for "mature" or "stable" compost are pushing the standardization of these tests forward.

The development of interpretive statements based on compost test data is still an art. The interpretation of test data must consider the needs of the compost user and must integrate chemical, physical and biological aspects of the compost. Even with reliable compost analytical data, expert opinions can differ substantially. Recommendations for compost application rates, adjustments in cultural practices (e.g., irrigation, fertilization, pest control), and determination of "acceptable" quality are based on understanding of interactions. Different interactions may occur with each crop, soil or growing medium, and with other components of the horticultural production or marketing system. Refining recommendations for compost quality for specific applications will continue to provide a challenge for the future.

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Table 1. Relative importance of compost quality measurements for horticultural applications.[z]

Kind of quality measurement	Target compost use			
	Greenhouse or nursery crops	Sales to general public; bulk or bagged	Soil amendment for vegetable and fruit crops	Mulch
	----------relative importance----------			
Plant growth response	++	++	++	-
Nutrient content	-	+	+	-
pH and soluble salts	++	++	+	-
Man-made inerts	++	++	+	+
Sensory: color and odor	+	++	-	+
Maturity and biological stability	++	++	+	-
Particle size	++	+	+	+

[z] -, +, ++ indicates low, medium and high importance for specified compost use.

Table 2. Suggested compost quality guidelines for horticultural applications.[z]

Quality Parameter	Soil amendment for turf, vegetable crops, or planting beds	Potting media	Landscape Mulch
Particle size	passes 25 mm screen	passes 13 mm screen	passes 10 mm screen
Soluble salts	maximum in soil blend of 2.5 to 6 dS m^{-1} depending on crop	maximum in mixed media of 3 dS m^{-1}	must report
Stability	stable to highly stable	highly stable	moderately to highly stable

[z]Adapted from: U.S. Composting Council, 1996. Other quality parameters suggested by the Council are the same across horticultural compost use categories: Nutrient content, water-holding capacity, bulk density, and organic matter content must be reported. Must pass germination and growth screening, and must not exceed Part 503 limits for trace element concentrations (USEPA, 1993). Moisture content ("as-is" basis) should be 35- 55%, and pH from 5.5 to 8.0.

Table 3. Generalized protocol for sampling compost from windrows.[z]

Sample size. A 12 L compost sample is usually needed for a complete chemical, physical and biological analysis. Check with your laboratory for optimal sample size for the requested analyses.
Number of sampling locations. Randomly select six locations along the length of the windrow.
Subsample collection. At each location along the windrow, collect three subsamples of equal volume to represent a cross section of the compost pile. Expose the center of the large piles using a front end loader or other equipment. Collect at least a total of 18 subsamples (6 locations * 3 subsamples per location) to represent a windrow. Mix the three subsamples from each sampling location in a 15 L plastic bucket.
Sample mixing and volume reduction. Empty the six composite "location samples" on a large plastic tarp. Mix all samples together on the tarp. Reduce sample size by repeated mixing, quartering and subsampling. Final sample volume to submit to the laboratory = 12 L.
Sample containers and preservation. Transfer a 12 L blended compost sample to three 4 L zippered plastic freezer bags. Cool sample to 4 ^{o}C with ice or refrigeration. Ship in a plastic pail with blue ice packs. The sample should arrive at the laboratory within 24 to 48 hours.

[z]Adapted from *Test Methods for the Examination of Composting and Compost* (Leege and Thompson, 1997).

Table 4. Common analyses for compost physical properties.

Analysis	TMECC Number[z]	Metric units	Common field units	Lab procedure comments
Gravimetric moisture content	7.01A&B	g water per g of "as-is" compost	% w/w "as-is"	Dry weight of compost sample measured at 70 °C. Moisture content can be calculated from total solids content: Moisture content (%) = 100 – total solids (%). Moisture contents for soils are usually expressed in different units (g water per g of dry soil).
Bulk density	7.01A&B	g compost per cm^3 of "as-is" compost	lb per cubic yard	A reproducible method for packing compost in the measurement vessel (2000 cm^3 beaker) is essential for consistent results. This measurement is used to calculate other physical properties on a volume basis.
Gravimetric water holding capacity	7.01A&B	g water per g of "saturated and drained" compost	% w/w "as-is"	Water held after free drainage for 4 h in a 2000 cm^3 beaker with perforated bottom. This procedure overestimates water-holding capacity of compost in the field because some saturated compost will occur at the bottom of the beaker. Data from this procedure can be used to calculate total porosity and air-filled porosity.
Particle size	5.01-B	% passing sieve (dw[y])	% passing sieve (dw)	Percentage (by dry weight) which passes a given sieve mesh opening (e.g. less than 12 mm). Nested sieving yields particle size distribution.
Man-made inerts	5.01-B	g inerts per g compost (dw)	% (dw)	Visual sorting process. Sample size small because the procedure is time-consuming. Includes glass, plastic, rubber, and metal. Usually does not include rocks. Plastics may be a small amount by weight but be a visual concern.

[z] TMECC: *Test Methods for the Examination of Composting and Compost* (Leege and Thompson, 1997).
[y] Dry weight basis

Table 5. Common analyses for compost chemical properties.[zy]

Analysis	TMECC[z] Number	Metric reporting units[x]	Common units[x]	Lab procedure comments
Total organic carbon (TOC)	9.08-B	mg kg^{-1}	%	Measures the total organic carbon (TOC) content utilizing a combustion furnace and infared detector. Organic C via combustion can be inaccurate for high pH composts that contain a lot of inorganic C as carbonate. The sample size used by different commercial combustion analyzers varies from 0.1 to 2.0 g. A larger sample size usually increases analytical precision and accuracy. This measurement for organic C is preferred for estimating C for C:N ratio. Total C and N analysis can be done simultaneously with some instruments.
Volatile solids[w] (VS)	9.08-A	mg kg^{-1}	%	Sample is preheated to remove moisture, weighed, placed in 550 ^{o}C furnace and then reweighed. Weight loss is "volatile solids" or "volatile organics". Material remaining after ignition is ash. Compost C is approximately 50 % of volatile solids content (rough estimate).
Cation exchange capacity (CEC)	8.03-B	cmol (+) per kg	meq $100g^{-1}$	Sample is saturated with a cation such as NH_4^+, Na^+ or Ba^{2+}. CEC is measured by the replacement technique. Compost CEC varies with pH. CEC determined at pH 7 is adequate for most composts.
Total nitrogen	8.09-A 8.09-D	mg kg^{-1}	ppm or %	Measures sum of inorganic plus organic N forms. Two acceptable methods: Total Kjeldahl (TKN) or combustion with infared detector. Some Kjeldahl methods do not include measurement of nitrate-N.
Inorganic nitrogen	8.09-B 8.09-C	mg kg^{-1}	ppm	Inorganic N includes ammonium N (NH_4-N), ammonia N (NH_3-N), and nitrate N (NO_3-N). A number of colorimetric methods are suitable. Cadmium reduction method most accurate for nitrate. Ammonia-N can be determined by the ion electrode method. Sample inorganic N concentrations can change rapidly with sample drying or unrefrigerated storage.
pH	8.07-A 8.07-B	—	—	Saturated paste or volume addition methods. Saturated paste extract useful for other tests (see below). Adding large volumes of water changes pH. Usually, pH by volume addition is 0.1 to 0.3 units higher than saturated paste pH.
Electrical conductivity (EC)	Gavlak et al., 1994[y]	dS m^{-1}	mmhos cm^{-1}	EC estimates soluble salt concentrations. EC determined on saturated paste extract. Sample is saturated with water, vacuum-filtered, and EC of extract is measured (usually with a conductivity probe). Extract also used for determination of some elements like Cl and B.

[z] TMECC: *Test Methods for the Examination of Composting and Compost* (Leege and Thompson, 1997).

[y] *Plant, soil and water reference methods for the western region* (Gavlak et al., 1994).

[x] dry weight basis

[w] Volatile solids test is sometimes called "loss-on-ignition" (LOI) or "volatile organics." Volatile solids are equal to "biodegradable volatile solids" when sample does not have significant quantities of plastics and rubber.

Table 6. Sensory and chemical indicators of compost maturity.

Method	TMECC[z] Method Number or other reference	Trend during composting	Suggested value for mature compost	Comments
Sensory indicators				
Color	9.03A	darkens	black to very dark brown	Subjective. Feedstock dependent
Odor	9.03A	foul anaerobic odor to earthy odor	earthy, soil-like, no odor	Subjective. Not very sensitive for composts during curing stage
Chemical indicators				
Volatile solids reduction	9.10	decrease	45 to 60+ %	Feedstock dependent. Only measurable by compost producer. Calculation is based on the initial ash content of the feedstock mixture (TMECC 9.10-A; Stentiford and Pereira-Neto,1985)
Cation exchange capacity (CEC)	8.03	increase	> 60 meq 100 g^{-1} volatile solids for MSW composts (Harada et al., 1981)	Maximum CEC in mature compost depends on the feedstocks.
C:N ratio	9.02A	decrease or increase depending on C:N of feedstocks	Mature compost: 15 to 20:1. Composts with C:N ratios above 25 to 30:1 usually immobilize inorganic N.	Ratio is meaningful for assessing maturity for composts derived from high C:N mixtures (initial C:N ratio > 25:1).
Inorganic N	9.02C	NH_4 decrease; NO_3 increase	Mature composts contain more NO_3-N than NH_4-N.	Dry, unstable compost piles can give high NO_3 values. Rewetting of dry, immature compost can result in rapid loss of NO_3 via denitrification.

[z] TMECC: *Test Methods for the Examination of Composting and Compost* (Leege and Thompson, 1997).

Table 7. Laboratory and field methods for assessing compost stability.

Method	TMECC[z] Method Number or other reference	Trend during composting	Suggested value for mature compost	Comments
Specific oxygen uptake rate (SOUR); moist compost	9.09B	decrease	very stable < 0.5, stable 0.5-1.5, mod. unstable 1.5-3.5, unstable 3.5-6.0 mg O_2 g VS^{-1} h^{-1}	Requires specialized apparatus. Not widely available at commercial laboratories. Affected by compost moisture and sample pre-conditioning. Short duration test (60 to 90 min). Requires volatile solids (VS) determination.
Specific oxygen uptake rate (SOUR); compost slurry	Lasaridi and Stentiford, 1998a, 1998b	decrease	very stable < 0.5, stable 0.5-1.5, mod. unstable 1.5-3.5, unstable 3.5-6.0 mg O_2 g VS^{-1} h^{-1}	Only respiration measurement not affected by compost moisture content. Reported to give similar data to TMECC 9.09B with greater precision. Method is widely available, since it is adapted from a wastewater procedure for biological oxygen demand (BOD). Requires computer-assisted control of O_2 inputs and measurements of dissolved O_2. Test duration 20 h.
CO_2 evolution (trapped in KOH or NaOH)	9.09C	decrease	very stable < 2, stable 2-8, mod. unstable 8-15, unstable 15-40 mg CO_2-C g VS^{-1} d^{-1}	Standard vessel size is 4L with air renewal every 24 h, temperature 35 °C. Sample preconditioned for 72 h. Requires volatile solids (VS) determination.
CO_2 evolution (colorimetric gel - Solvita™)	Woods End Reseach Laboratory, 1999b	decrease	Semi-quantitative with eight colorimetric categories corresponding to raw, active, and finished compost. Color categories cover the range from 2 to 30 mg CO_2-C g compost-C^{-1} d^{-1}	For on-site testing. Test provides a semi-quantitative assessment of CO_2 evolution rate. Uses a closed vessel (125 mL) for a fixed time period (4 h) with a specified volume of compost. Test done at ambient temperature with no sample preconditioning. Calibrated by manufacturer with relative scale. Colorimetric gel has limited shelf life. The 1999 version of the Solvita™ kit also includes a colorimetric test for ammonia (NH_3).

Method	TMECC[z] Method Number or other reference	Trend during composting	Suggested value for mature compost	Comments
Dewar self-heating	9.11	decrease	maximum self-heating in 2 to 9 day test: 0-20 °C: finished; 20-40 °C active; 40 °C fresh compost (Brinton et al., 1995)	Simple apparatus and interpretation. Simulates natural heating process in a compost pile. Measurements in "field units": heat output per unit volume. Compost moisture affects test result. Self-heating data roughly correlated to O_2 uptake and CO_2 evolution data for some composts.
Pile re-heating	State of Florida regulations	decrease	Mature compost will not reheat more than 20 °C above ambient temperature upon standing (Ozores-Hampton et al., 1998)	Affected by pile size, porosity and moisture content

[z] TMECC: *Test Methods for the Examination of Composting and Compost* (Leege and Thompson, 1997).

Table 8. Methods for assessing phytotoxic substances in compost.

Method	TMECC[z] Method Number or other reference	Trend during composting	Suggested value for mature compost	Comments
Seed germination and root elongation	9.05	increase	Germination index (Zucconi et al., 1985) using garden cress[y] > 60 %. Other procedures: germination index similar to that of a mature compost produced with similar feedstocks.	Plant species vary in sensitivity to compost extracts. Garden cress test too sensitive for many compost end-uses. Composts with high salt concentrations inhibit germination of some seeds at all stages of curing.
Short-chain organic acids (volatile fatty acids)	9.12	decrease	Acetic acid conc. > 300 mg kg^{-1} inhibited garden cress seed germination (DeVleeschauwer et al., 1981).	Unstable compost contains short chain C organic acids such as acetic, butryric, and propionic acids that are phytotoxic. Direct determination of short-chain organic acids is expensive, requiring gas or ion chromatography. Generally not a sensitive test during curing.

[z] TMECC: *Test Methods for the Examination of Composting and Compost* (Leege and Thompson, 1997).
[y] Garden cress = Lepidium sativum L.

Table 9. Diagnosis and management of potential plant production problems in compost-amended media.

Problem	Impact of composting feedstocks and process	Compost analytical characteristics	Compost Use Suggestions
Nitrogen deficiency	Reported problem for composted MSW and woody debris, and some yard trimmings composts. Higher compost stability or higher N feedstocks needed to overcome problem.	Compost C:N ratio greater than 25-30:1. NO_3-N < 100 ppm mg kg^{-1} High respiration rate[z].	Allow additional time for compost stabilization. Apply additional N fertilizer with compost.
Ammonia toxicity	Unstable composts especially those with pH > 8.	NH_4-N > 1000 ppm (mg kg^{-1}) and C:N < 20:1. High respiration rate	Allow additional time for compost stabilization. Reduce pH to 7. Provide aeration to enhance conversion to nitrate.
Short chain organic acids	Unstable composts. Reported for many feedstocks.	Compost phytotoxic in germination test. High respiration rate.	Allow additional time for compost stabilization. Aerate compost to speed decomposition of short-chain organic acids.
Soluble salts	Feedstocks are the source of salts. Elevated salts often associated with composted manure and grass clippings. Composted paper or cardboard can elevate boron concentrations.	E.C. > 3 dS m^{-1} in growing media. Compost phytotoxic in germination test. Above 10 meq Cl L^{-1} of saturated paste extract Above 1 mg B L^{-1} of saturated paste extract.	Leach compost with water before seeding or planting. Avoid use on sensitive crops.

[z] High respiration rate using a stability assessment procedure for CO_2 evolution, O_2 uptake, or self-heating. See Table 7 for stability assessment options.

Table 10. Analytical variability for a chicken manure compost sample analyzed by 42 commercial laboratories.[z]

Analysis	Units[y]	Mean	Relative Standard Deviation (%)[x]	
		All laboratories	Intra-laboratory[w]	Inter-laboratory
pH (saturated paste)	none	7.8	1	3
pH (1:2 v/v)		8.0	1	2
Conductivity	dS m^{-1}	7.9	11	22
Total N (Combustion)	%	1.1	5	6
Total N (Kjeldahl)	%	1.1	5	5
Total Organic C (TOC)	%	19.6	6	9
Volatile Solids (LOI)	%	46.0	10	12
Total P	%	1.0	9	17
Total K	%	1.0	10	15
Total Ca	%	4.4	7	17
Total Mg	%	0.4	7	15
Total S	%	0.3	11	21
Total Zn	mg kg^{-1}	221.0	9	11
Total B	mg kg^{-1}	30.1	13	30
Total Cu	mg kg^{-1}	103.0	10	19
Total As	mg kg^{-1}	14.9	19	35
Total Cd	mg kg^{-1}	1.0	23	149
Total Pb	mg kg^{-1}	9.7	12	60
Total Se	mg kg^{-1}	0.4	32	86

[z] Source: Personal communication, R.O. Miller, Soil and Crop Sciences Dept., Colorado State University, Fort Collins, CO. Data from Western States Proficiency Testing program, 3rd Quarterly Report, Sept. 1997. Laboratories participating in the proficiency testing program received a subsample of a large bulk sample.
[y] Dry matter basis.
[X] Relative standard deviation = standard deviation/mean *100
[w] Intra-laboratory precision for three analyses of the same sample

Table 11. Analytical variability for two compost samples analyzed by six commercial laboratories. [z]

Compost Analysis	Units	Chicken manure compost		Yard trimmings compost	
		Mean	RSD[y] %	Mean	RSD[y] %
pH		6.6	10	6.9	5
Conductivity	dS m^{-1}	25	34	7	36
Total N	%	3.55	12	1.18	16
Total P	%	2.2	16	0.2	15
Total K	%	2.8	9	0.6	37
Volatile solids	%	70	16	37	8

[z] Adapted from Granatstein, 1997. Laboratories received a subsample of a large bulk sample. Laboratories were not told what method to use, or informed that they were part of a "study."
[y] Relative standard deviation (inter-laboratory) = standard deviation/mean *100