

Assessment of the Reliability of a Commercial Maturity Test Kit for Composted Manures

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Stability significantly affects the potential for beneficial utilization of composts but is difficult to measure by farmers and compost producers. A simple four hour test (the Solvita® maturity test) that measures CO₂ evolution and ammonia emission from compost samples was compared to a traditional three-day, 25°C, CO₂ evolution rate procedure and to measurements of ammoniacal nitrogen concentrations in manure composts to assess the reliability of this test. Three composts — 1) Dairy manure amended with wheat straw, 2) The same dairy manure but amended with sawdust and 3) Swine manure amended with sawdust and ground wood pallets — were composted in windrows for 120 days. Samples were removed weekly to biweekly. CO₂ evolution rates of the three composts decreased from initial means (n=6) of 3.41, 3.42 and 9.35 to 0.63, 0.76 and 0.31 mg CO₂-C g⁻¹ VS day⁻¹, for the dairy manure-straw, dairy manure-sawdust, hog manure composts, respectively. The corresponding mean Solvita CO₂ test values for these composts increased from 3.4, 3.0 and 3.2 to 6.8, 6.5 and 7.0, respectively. Correlation analysis between CO₂ evolution rates and Solvita CO₂ test values gave linear correlation coefficients (r) of -0.82, -0.78, and -0.87 for the straw-amended dairy manure, the sawdust-amended dairy and the hog manure composts, respectively. The Solvita NH₃ test gave highly significant correlations (p<0.0001) with ammoniacal-N concentrations (correlation coefficients (r) = -0.43, -0.64 and -0.65, respectively). The Solvita® maturity index, a combination of Solvita CO₂ and NH₃ values, correlated significantly with both CO₂ evolution rate and ammoniacal-N concentrations. However, the Solvita CO₂ index alone was the best predictor of compost CO₂ evolution rate or stability. The Solvita Maturity test, which combines the Solvita CO₂ and NH₃ tests, provided useful information about the potential for the development of a toxic response in plants due to excessive concentrations of ammoniacal-N present in some stable compost samples that would not have been detected if the CO₂ stability test were used by itself. We conclude that the Solvita maturity test provided a simple, inexpensive relative test of compost stability and NH₃ emission for diverse samples of composted manures. Even so, it did not accurately predict their CO₂ evolution rates measured by respirometry nor their ammoniacal-N concentrations. The test would be most useful for on-farm applications.

Introduction

Composting reduces the volume of manure to be applied to farmland (Pecchia *et al.* 2002) and offensive odor emissions during application, thus facilitating utilization on farms (Elwell *et al.* 2001; Louhelainen *et al.* 2001; Nicolai and Janni 2001; Park *et al.* 2001; Walker 1993). Composted manures can be stored easily and marketed as value-added plant disease suppressive products in the potting mix and golf course industries (Boulter *et al.* 2000; Craft and Nelson 1996; Hoitink *et al.* 1997).

The stability of composts, or the degree to which the organic fractions in composts have been stabilized during the process, critically affects compost quality. Unstable composts may be recolonized by fecal pathogens after peak heating (Bohnel and Lube 2000; Parmar *et al.* 2001). They may also generate odors (Elwell *et al.* 2001; Louhelainen

et al. 2001; Nicolai and Janni 2001; Park *et al.* 2001; Walker 1993) and cause phytotoxic responses in plants during utilization (Hirai *et al.* 1993; Warman 1999). Operators of composting plants interested in process control and management as well as compost users, therefore, are very interested in the stability of composts.

Several types of compost stability tests have been developed. They range from elaborate tests which determine the rate of oxygen uptake under process control conditions (Tseng *et al.* 1995; Scaglia *et al.* 2000), to more simple batch tests that either measure O₂ uptake or CO₂ production at a constant temperature (Iannotti *et al.* 1994) or monitor metabolic heat produced by the compost microbiota during incubation in a nearly adiabatic chamber under controlled conditions (Dell'Abate *et al.* 1998). The rate of compost respiration determined over three days by CO₂ respirometry at 25°C, as described by Bartha and Pramer (1965), has been modified (T=37°C) and adopted by the U.S. Composting Council as a standard method of measuring compost stability (Thompson *et al.* 2002; TMECC 05.08-B). Rates of respiration are expressed as mg CO₂-C g⁻¹ dry solids day⁻¹ or mg CO₂-C g⁻¹ -volatile solids day⁻¹. Even though these methods are simple, they are laborious and generally unsuitable for on-farm use.

A short duration, quantitative O₂ uptake procedure has been developed for testing compost stability at industrial scale facilities (Iannotti *et al.* 1994). The test is useful if compost samples are incubated at 37°C because the microorganisms in immature high temperature composts are not active at the lower temperature of 25°C that typically is used for soil respirometry. Low temperature preincubation of samples at 25°C avoids inhibition of microbial activity during the first 24-36 hr of a test in samples collected from high temperature immature composts and, therefore, it also avoids false stability readings (McKinley and Vestal 1984). Unfortunately, this stability procedure is too complex for on-farm use.

In some cases compost stability is determined on the basis of heat output by microorganisms in compost samples incubated in a nearly adiabatic Dewar flask (Jourdán 1982). The increase in temperature over time in the sample provides a measure of stability. Although this method seems simple enough and sound in principle (Finstein *et al.* 1983), it is a four-day test with several pitfalls that prevent it from serving as a reliable on-farm method unless many precautions are taken (Weppen 2002).

Compost maturity, which refers to the ability of composts to support plant growth, critically affects the value-added market potential of composts. It is much more difficult to define than stability. One aspect of compost maturity is compost ammoniacal-N concentration. Composts low in C/N ratio may contain phytotoxic concentrations of ammoniacal N (Hirai *et al.* 1983). This limits the application rate of composts in potting mixes and even in the field if it is applied directly before planting, thus severely limiting marketability of the product in value-added markets. Nitrate-N usually accumulates during curing of composts as a result of nitrification. Thus, a decrease in ammoniacal N concentration over time and an increase in nitrate-N concentration during curing is an indication of maturity (Ouatmane *et al.* 2000; Belete *et al.* 2001; Eggen and Oistein 2001). Thus, it is important to monitor stability based on respirometry as well as ammoniacal N in composts prepared for use in high value crops. This is one of the reasons why the U.S. Composting Council has adopted the Solvita® stability/maturity kit as a simple method for assessment of these properties of composts. It involves the use of colorimetric paddles sensitive to carbon dioxide and ammonia in a jar that contains a fixed volume compost sample. Although this test seems suitable for on-farm use, its accuracy to our knowledge has not been independently verified.

The objective of this research was to test the suitability of the Solvita® Compost Maturity Test for the determination of stability and ammonia toxicity potential of composted dairy and hog manures. The tests were evaluated by comparing Solvita CO₂, Solvita NH₃ and Solvita maturity index values to CO₂-C evolution rates and ammoniacal nitrogen concentrations measured throughout the composting process for three different types of composted manures.

Materials and Methods

Raw Materials and Composting Process

Three types of manures were used, 1) manure from an OSU dairy facility blended with a mixture of sawdust and wood shavings, 2) the same dairy manure blended with wheat straw, and 3) a partially composted hog manure mixed with shredded wood pallets (mostly red oak) and sawdust received from a High Rise Hog® facility (Keener *et al.* 2000; Michel *et al.* 2001). The ratio of dairy manure and bulking agents for the sawdust/wood shavings and wheat straw manure blends was approximately 3:1 (v/v) to produce an initial moisture content of approximately 65% and provide optimum conditions for composting as described previously (Pecchia *et al.* 2002). The partially composted hog manure was collected after three cycles of 1000 hogs and then blended with sawdust (hard wood, primarily red oak) to reduce its moisture content. Two equal sized batches of each of the three types of manures were composted from April 2001 to July 2001 in windrows with a height of approximately 1.5 m and width of 3 m to maintain process temperatures within the range of 55 to 70°C. Initially, the hog manure was turned daily to further reduce its moisture content, avoid leachate formation and reduce odor generation. Thereafter, all windrows were turned weekly or biweekly to maintain adequate porosity. Due to shrinkage of the compost windrow height was readjusted periodically to 1.5 m. Water was added if necessary to maintain optimum process conditions (Rynk *et al.* 1992).

Sample Collection and Preparation

Changes in physical and chemical properties and in stability and maturity of the three manures during composting were monitored using sampling protocols and analytical methods specified by the U.S. Composting Council (TMECC 2002). Three 9 L composite samples were collected from each compost type and batch at weekly or bi-weekly intervals within 1 hr after turning of the windrows. Ten subsamples were removed from five locations (2-3 m apart) within each windrow and composited. Half of these subsamples were removed from the high temperature center and the remainder from the outer zone of each windrow. Each composite sample was then mixed thoroughly to ensure maximum sample homogeneity and placed in a polyethylene bag. One 500 g subsample was cooled over ice and submitted for analysis of the chemical properties to the Service Testing and Research (STAR) Laboratory at The Ohio State University (Wooster, Ohio). A second 500 g subsample was placed in a partially closed polyethylene bag, preincubated overnight at 25°C and then used to determine compost stability based on CO₂ respirometry (Bartha and Pramer 1965) and on the Solvita® Compost Maturity test (TMECC method 05.08-E). The remainder of each sample (approximately 7 L) was stored at -15°C. Sampling of composts in windrows was discontinued after stability values based on CO₂ respirometry were less than 1.0 mg CO₂-C g⁻¹ VS day⁻¹, a value recognized as stable for composts in general (TMECC 2002). Both tests were conducted at a temperature of 25°C.

Compost Stability

The rate of respiration ($\text{mg CO}_2\text{-C g}^{-1}\text{ VS day}^{-1}$) for each compost sample was determined by the standard protocol (TMECC method 05.08-B) except that a temperature of 25°C was used. Briefly, a 25.0 g subsample that had been preincubated overnight at 25°C was transferred into a 1 L Mason jar containing 20 mL of 1 M NaOH in a 100-mL beaker. The lid was closed tightly and the jar was then incubated at 25°C . A jar without compost served as the control. Preliminary measurements of the oxygen concentration revealed that the air to compost volume ratio in the jar was sufficient to avoid O_2 limited respiration conditions for all compost samples used in this work. The rate of respiration expressed as $\text{mg CO}_2\text{-C g}^{-1}\text{ VS day}^{-1}$ was monitored for three days and the mean rate of respiration per day was then calculated.

Compost Maturity by Solvita® Kit Test

Manure compost maturity tests were performed with the Solvita® kit (Woods End® Research Laboratory, Inc., Mt Vernon Maine) following the protocol specified in the Solvita® kit manual (Guide to Solvita® testing for compost maturity index) supplied by the manufacturer. The Solvita® kit measures carbon dioxide evolution and ammonia emission simultaneously. The moisture content of all the samples was within the optimum range (50-55%, w/w) for microbial activity. Samples were allowed to equilibrate at 25°C in partially closed plastic bags as described above and loaded into the Solvita® jars up to the fill line. Solvita® CO_2 and NH_3 test gel-paddles were carefully inserted into the compost without touching the gels after tearing the packs. The sample jars were then closed tightly thereafter. During this process the gel portion of the paddle did not come into contact with the samples and paddle positioning allowed easy viewing of gel color change. To determine Solvita® CO_2 and NH_3 kit values, the observed gel color change after 4-hr incubation at 25°C was matched with the color on charts supplied with the kit. The gel color change was used to determine Solvita® kit CO_2 values on a scale of 1-8 and NH_3 values on a scale of 1-5. Finally, the two values were used to determine the Solvita® maturity index on a scale of 1-8 which then represents the maturity level of the compost samples.

Chemical Properties of Composts

Changes in chemical properties of the three types of manures during composting were monitored according to standard protocols specified by the U.S. Composting Council (TMECC 2002). Samples were ground to the particle size specified by the analytical method for each chemical property. The number of subsamples (3-5) depended on the sensitivity of a particular assay, again as specified for each method in order to obtain means with coefficients of variation less than 30%. Percent dry solids (w/w) were determined after oven drying ($60\text{-}80^\circ\text{C}$) to a constant weight. The pH was determined on a 1:5 dilution of compost with distilled water (TMECC method 04.11-A1:5). Electrical conductivity also was determined on this slurry with a solu-bridge conductivity meter (Beckman Instruments, Cedar Grove, New Jersey; TMECC method 04.10-A). Percent ash was determined after heating for 4 hr in a muffle furnace at 550°C (TMECC method 03.02-A). Percent volatile solids (VS) were determined by subtracting percent ash from 100. Total N analyses were performed using a Dumas combustion method (VarioMax N analyzer, Elementar Americas; TMECC methods 04.02-D and 04.01-A). The detection limit for this instrument was 200 mg N kg^{-1} . Total C was determined using coulometry.

This instrument converts C in the sample to CO₂ by oxidation at 1100°C. The detection limit was 1 mg C kg⁻¹. Inorganic C was determined by coulometry (model 5020, Coulometrics, UIC, Joliet, Illinois). Organic C was determined by subtracting inorganic C from total C. Total NO₃⁻-N and NH₄⁺-N were determined by ion chromatography (TMECC method 04.02-B) and micro-Kjeldahl distillation-titration methods, respectively.

Statistical Analyses and Data Presentation

Means and standard deviations for all values presented in this work are based on two windrows per compost type with three replicates per windrow (n=3). Throughout the composting process, the two windrows of each type of manure used in this work were uniform in appearance and the chemical and biological properties were not significantly different. Therefore, the data for the tests from the two windrows of each compost type were combined (n=6). Because composting of all manures was started in the spring under similar weather conditions for each, mean values for the physical, chemical and biological properties of the manures during composting were plotted on the basis of days of composting rather than the julian date.

Statistical analyses of the correlations between Solvita® test results and the monitored manure properties during composting were performed using SAS statistical analysis software (SAS Institute Inc., Cary, North Carolina release 8.1 for Windows 98 platform) and Minitab (version 13 for Windows, Minitab Inc., www.minitab.com). The linear correlations between Solvita® test values of CO₂, NH₃-N and maturity and: 1) CO₂ respirometry, 2) compost age, 3) % VS, 4) C:N ratio, 5) organic C concentration, 6) total N concentration, 7) ammoniacal-N concentration, and 8) nitrate-N concentration were determined. Absolute Pearson linear correlation coefficients (r) were used to determine significance of correlations based on a level of probability (P-values). Correlation coefficients were declared significant for P-values ≤0.0005 and highly significant for P-values ≤0.0001.

The relationships between Solvita CO₂ value and CO₂-C respiration rate, Solvita Maturity Index and CO₂-C respiration rate and Solvita NH₃ index and ammoniacal-N concentration were analyzed by linear, log transformed linear, log transformed second order polynomial and polynomial second order regression analyses. The 90% prediction intervals and regression line equations were determined using Minitab software (Release 13.1).

Results

Compost Temperature and Moisture Content

Temperature profiles for the three types of composts differed considerably (Figure 1A). The dairy manure/sawdust compost reached temperatures of 60°C within ten days of windrow formation. In contrast, the dairy manure/straw compost did not reach this high temperature until after ten weeks of windrow formation. This may have been due to the very high initial porosity of this material which would be expected to lead to greater heat losses to the environment (Pecchia *et al.* 2002). The hog manure compost did not reach similarly high temperatures until after six weeks. Shortly after formation (1-2 days), leachate drained out of the base of this windrow indicating that its moisture content was too high and that this mixture could not support the same moisture content as the other two composts (65%). Therefore, it was turned several times to promote drying. Thus, the low initial temperature was probably due to low porosity and, there-

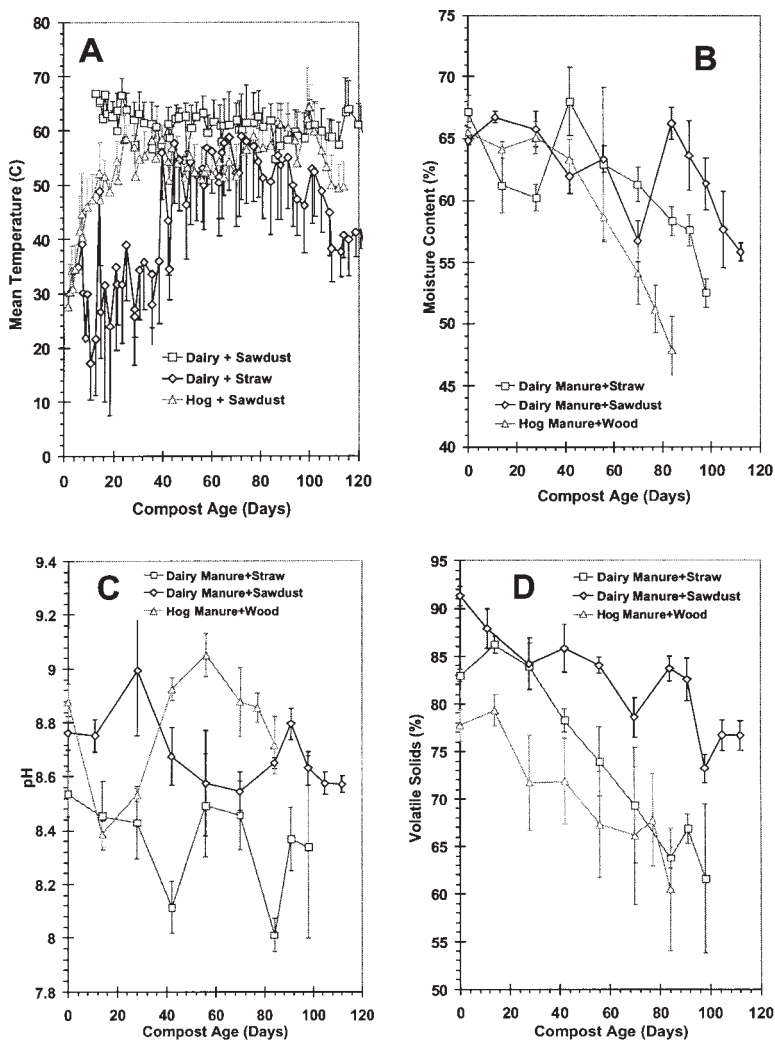


Figure 1. Trends in temperature (A), moisture content (B), pH (C) and volatile solids (D) during windrow composting of dairy manure mixed with straw or sawdust, and hog manure mixed with wood chips. Each value represents the mean of six randomly collected samples harvested at weekly or biweekly intervals from each of two windrows (3 replications per windrow).

fore, low oxygen availability in addition to the relatively resistant to decomposition ground wood used as bulking agent and carbon source in the hog manure compost. All windrows eventually reached mean temperatures within the optimum range (55-65°C) for decomposition and pathogen destruction.

The mean moisture content of the dairy manure/straw compost decreased from an initial value of 67% to 52% after 98 days (Figure 1B). In the dairy manure/sawdust compost it decreased from 65% to 56% after 112 days and in the hog manure compost it decreased from 65% to 48% after 84 days.

Compost pH

In general, mean pH values of the hog and dairy manure/sawdust composts were higher (8.4-9.0) than those of the dairy manure/straw compost (8.0-8.5, Figure 1C). The

pH of the hog manure compost fluctuated from 8.4 to 9 during the process. Large fluctuations in mean pH values also were observed in samples removed from the dairy manure/straw compost. Less variation in pH was observed in the dairy manure/sawdust compost.

Compost % Volatile Solids (VS) and Organic C

Trends in percent volatile solids for the three types of manures revealed significant losses in volatile solids during composting (Figure 1D). The greatest losses were observed for the dairy manure/straw compost where % VS declined from an initial mean value of 83% to 62% after 98 days representing a loss of 67% of the initial VS. Percent VS for the dairy manure/sawdust compost decreased from an initial mean value of 91% to 77% after 112 days representing a loss of 67% of the initial VS. VS% for the hog manure compost declined from 77% to 60% VS after 84 days which represented a 55% loss of the initial VS on a constant ash basis. Similar trends in destruction of dry solids were observed on the basis of changes in mean percent organic C (Figure 2a). In

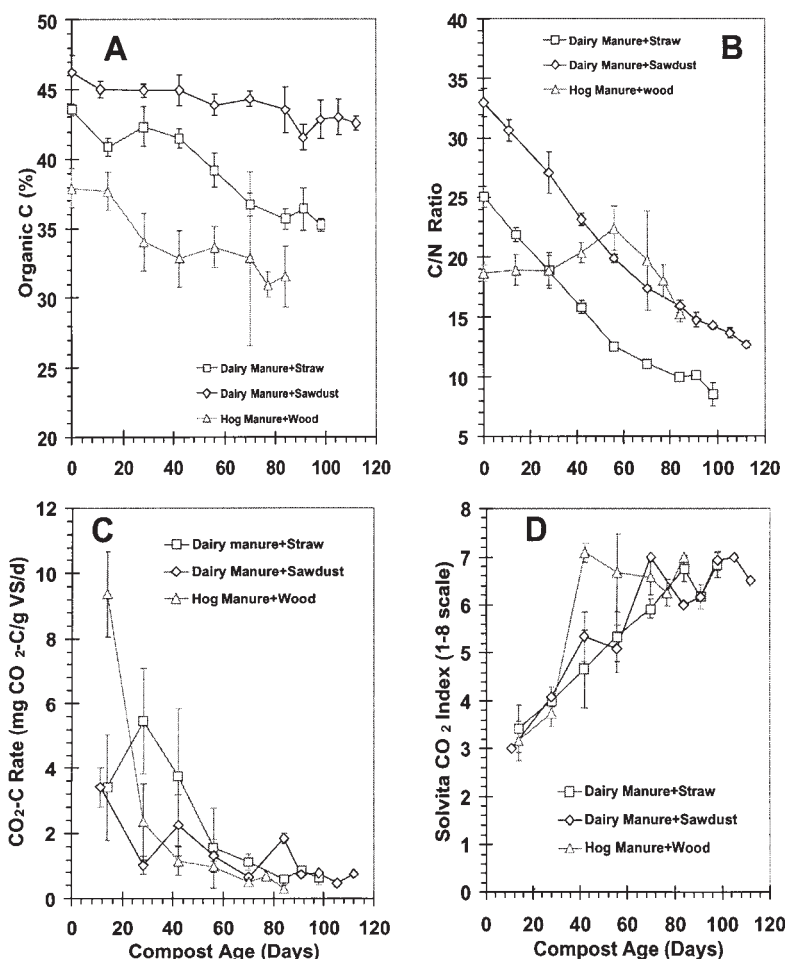


Figure 2. Trends in total percent organic C (A), C/N ratio (B), rate of CO₂ respiration (C) and Solvita® CO₂ index (D) during windrow composting of dairy manure mixed with straw or sawdust, and hog manure mixed with wood chips. Each value represents the mean of six randomly collected samples harvested at weekly or biweekly intervals from each of two windrows (3 replications per windrow).

the dairy manure/straw compost, percent organic C decreased from a mean value of 44% to 35% after 98 days. The organic C value of the dairy manure/sawdust compost declined from a mean value of 46% to 43% and that for the hog manure compost from a mean value of 38% to 32%. These represented losses of 64%, 63% and 52% of the initial carbon, respectively, on a constant ash basis.

Compost Total N, C/N, Ammoniacal N and Nitrate-N

The total percent N for the dairy manure/straw compost increased from an initial mean value of 1.8% to 4.2% after 98 days. Mean total percent N values for the dairy manure/sawdust compost were significantly lower than the sawdust compost and increased from an initial value of 1.4% to 3.4% after 112 days (Figure 3B). The high initial mean total percent N value of 2.1% for the hog manure compost was not

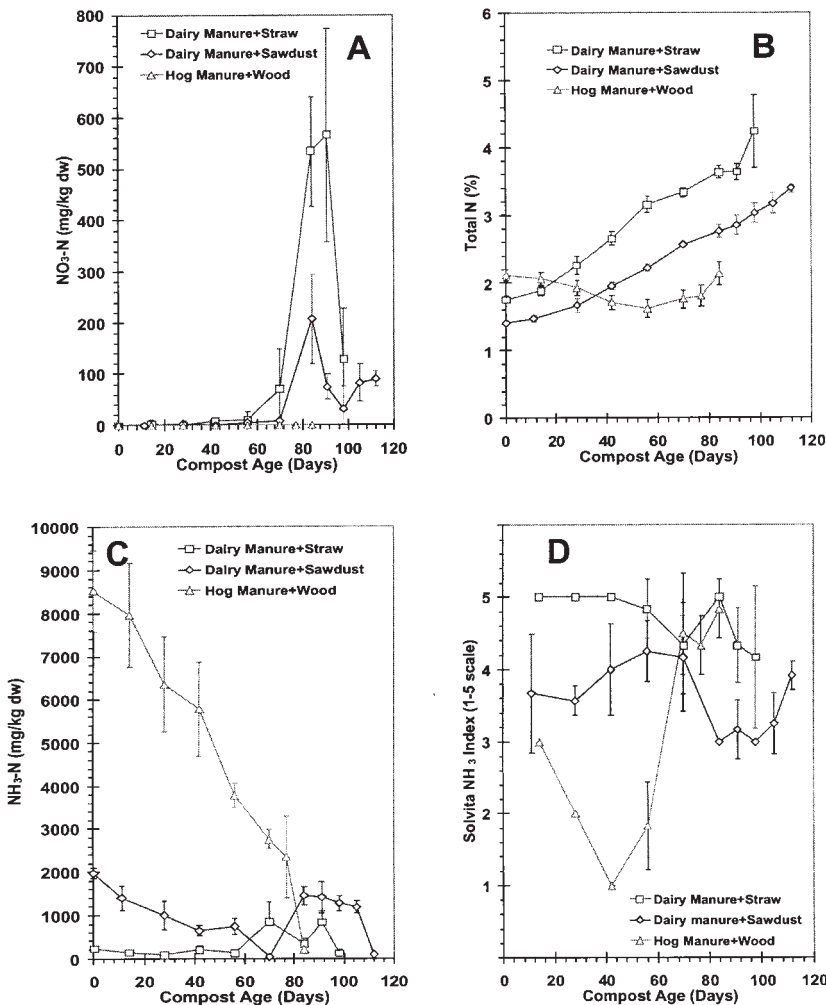


Figure 3. Trends in total nitrogen (A), nitrate-N (B) and ammoniacal-N (C) concentration, and Solvita® NH₃-index (D) during windrow composting of dairy manure mixed with straw or sawdust, and hog manure mixed with wood chips. Each value represents the mean of six randomly collected samples harvested at weekly or biweekly intervals from each of two windrows (3 replications per windrow).

significantly different from the value of 2.1% observed after 84 days, although a significant decrease followed by an increase was observed during the process. This suggests that significant losses of N occurred early during composting of this manure followed by concentration of N thereafter due to organic matter loss. The C/N ratio (Figure 2b) for the dairy manure/straw compost decreased from an initial mean value of 25 to 9 after 98 days. The mean C/N ratio values for the dairy manure/sawdust compost decreased from 33 to 13 after 112 days. The hog manure compost had a low initial C/N ratio. It decreased during composting from an initial mean value of 19 to 15 after 84 days.

The concentrations of ammoniacal-N early during composting of the dairy manure/straw were comparatively low, probably due to losses of ammonia from the porous mixture (Figure 3c). These concentrations increased after 56 days of composting when the straw had lost its physical structure and the bulk density of the compost increased (reported for these specific composts in Pecchia *et al.* 2002). The concentration of ammoniacal-N declined to a mean value of 116 mg kg⁻¹ dw⁻¹ after 98 days when temperatures in the windrow had declined also (Figure 1a). During this period late in the process, the concentration of nitrate-N increased to a value as high as 565 mg kg dw⁻¹ on day 91 but declined to 128 mg kg dw⁻¹ after 98 days (Figure 3a). The concentration of ammoniacal-N in the dairy manure/sawdust compost declined from an initial mean value of 1976 to 89 mg kg dw⁻¹ after 112 days (Figure 3C). Nitrate-N was detected after 56 days and a mean concentration of 91 mg kg dw⁻¹ was detected after 112 days. In the hog manure compost, extremely high ammoniacal-N concentrations prevailed throughout the entire 77-day composting period (Figure 3C). After 84 days, it had decreased to 196 mg kg dw⁻¹ - but nitrate-N was not yet detectable (Figure 3A) in this still high in temperature compost (Figure 1A). Thus, the initial ammoniacal-N concentrations of the three composts ranged over two orders of magnitude (from 100 to nearly 10000 mg kg⁻¹) representing a wide range of initial ammoniacal-N concentrations.

CO₂ Respirometry and Solvita® CO₂ Kit Analysis

The respiration rate based on CO₂ respirometry was measured after overnight preincubation at 25°C followed by slight mixing of the samples to release trapped CO₂. The CO₂ evolution rates of the dairy manure/straw, dairy manure/sawdust, and hog manure plus wood shavings decreased from initial means (n=6) of 3.41, 3.42 and 9.35 to 0.63, 0.76 and 0.31 mg CO₂-C g⁻¹ VS day⁻¹, respectively. This revealed significant changes in mean rates of respiration over time (Figure 2C). The greatest decrease in rate of respiration was observed during composting of the hog manure compost, particularly early during the process. A significant decrease in rate of respiration was also observed early during composting of the dairy manure/sawdust. The greatest decrease in rate of respiration activity in the straw-manure compost occurred between days 42 and 70 when the straw was losing its physical structure. The hog manure compost reached a low mean value of 0.31 mg CO₂-C g⁻¹ VS d⁻¹ after 84 days of composting. The dairy manure/straw compost reached a low value of 0.63 mg CO₂-C g⁻¹ VS d⁻¹ after 98 days. The dairy manure/sawdust compost reached a consistently low mean stability value after 91 days.

The rates of respiration measured on the first day of the three-day respirometry test were on average 50% higher than the CO₂ rate values averaged over the entire three day bioassay period (data not shown). This indicated that the microorganisms in the compost samples were not inhibited in activity due to initial conditions in the com-

post. Thus, a fourth day of measurement was not required for any of the respirometry bioassays performed in this work.

The mean Solvita® CO₂ test values increased from 3.4, 3.0 and 3.2 to 6.8, 6.5 and 7.0, respectively (Figure 2D). Overall, trends in stability observed with the respirometry procedure (Figure 2C) agreed inversely with those based on the Solvita® CO₂ test (Figure 2D). Since the CO₂ values measured by the Solvita® kit were made during the first 4 hours of incubation on the first day, they would be expected to be measuring a higher rate than the 3-day average values determined by the CO₂ respirometry procedure.

Solvita® Ammonia Kit and Maturity Analyses

The Solvita NH₃ index (1-5 scale) for ammonia emission by the three manures at various stages during the composting process showed that little ammonia was emitted by the dairy manure/straw compost (NH₃ index > 4.5 for all samples; Figure 3D). In general, more ammonia was lost from the dairy manure/sawdust than from the dairy manure/straw compost samples. The test indicated that the hog manure compost released much more NH₃ than the dairy manure composts and that the highest quantity of ammonia release occurred after 40 days. Interestingly, early during composting of this manure much less ammonia was detected by the Solvita

NH₃ test (Figure 3D) even though the concentration of ammoniacal-N based on the extraction procedure was high at that time (Figure 3C). The Solvita Test measures the ammonia in the gas phase above the compost while the lab test determines ammoniacal N within the compost itself which may explain the differences.

The Solvita CO₂ test and Solvita NH₃ test values were used to calculate the Solvita maturity index (scale 1-8). The Solvita maturity index values ranged from 2 to 3 initially, which indicates a "raw" or "very active" compost (Figure 4). The hog manure compost had the lowest maturity indices through day 56 (Figure 4) probably

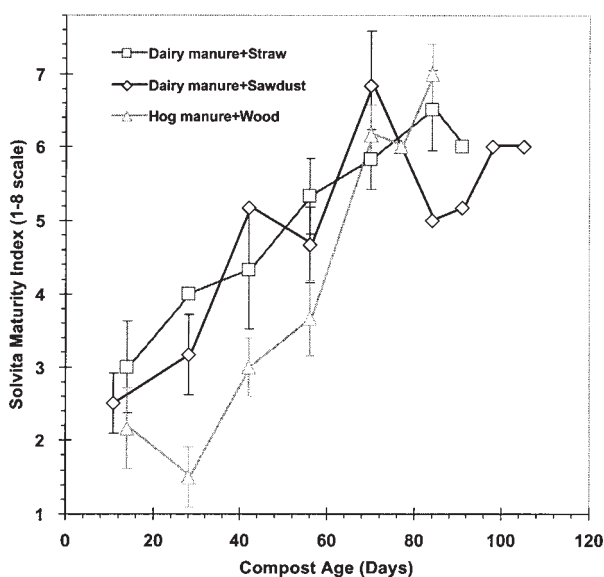


Figure 4. Trends in Solvita® maturity index during windrow composting of dairy manure mixed with straw or sawdust, and hog manure mixed with wood chips. Each value represents the mean \pm one standard deviation of six randomly collected samples from each of two windrows (3 replications per windrow).

due to the contribution of the low Solvita NH₃ index values for this compost (Figure 3D). The two dairy manure composts showed similar Solvita maturity index values during composting (Figure 4). The Solvita maturity index for all three composts rose during composting. After 100 days all three exhibited Solvita maturity values of 6 to 7 indicative of "curing" or "finished" compost according to the Solvita test interpretive booklet.

Correlations Between Solvita® CO₂, NH₃ and Maturity Index Values and Compost Characteristics

The Solvita NH₃ and CO₂ test values as well as the derived Solvita maturity index values were correlated to several compost characteristics including the CO₂ respiration rates and ammoniacal-N concentrations of the individual compost samples. Simple linear correlations between Solvita® CO₂ test values and changes in several individual compost characteristics showed highly significant (P<0.0001) negative correlations with the measured CO₂ evolution rates based on respirometry for each of the three types of composts (Tables 1 and 4). The Solvita® CO₂ test values also strongly correlated with compost age, % VS and organic C for each of the three types of composts (Table 1). Correlations between Solvita® CO₂ test values and total N and C/N ratio of both types of composted dairy manures were also highly significant, while for the hog manure compost they were not significant (P>0.01). There was no significant correlation between Solvita® CO₂ test values and the ammoniacal-N concentration of the three composts (Table 4).

Correlations between Solvita® NH₃ test values and changes in several compost characteristics over time of the three types of composts revealed a significant correlation with ammoniacal-N concentration for each of the three composts (Tables 2 and 4). The Solvita NH₃ test value was also very strongly correlated with compost age and %VS of the hog manure compost (Table 2). The concentration of ammoniacal-N in each of the three composts was the only characteristic that consistently had a significant correlation with Solvita® NH₃ test values.

The Solvita® maturity index, derived from the Solvita® CO₂ and NH₃ test values, was also compared to other measured compost characteristics. There were significant correlations with CO₂ evolution rate, compost age and %VS as well as ammoniacal-N (Table 3). However, use of the Solvita maturity index did not improve the correlations established individually with the CO₂ and NH₃ tests alone (Table 3).

Correlation coefficients for Solvita® test values of all three composts together and various compost characteristics confirmed that Solvita® CO₂ test values were highly correlated with compost age (r=0.82), CO₂ evolution rate (r=-0.79), and percent volatile solids (r=-0.56) but not with ammoniacal-N concentration (r=-0.21) or nitrate-N accumulation (r=0.25) (Table 4). Correlation coefficients for the Solvita® NH₃ kit values with compost ammoniacal-N across all three compost types were highly significant (r=-0.68). However, the Solvita® NH₃ kit values correlated poorly with most other

TABLE 1.
Correlations between Solvita® CO₂ test values and various characteristics of three different manure composts

Characteristic	Dairy Manure/Straw			Dairy Manure/Sawdust			Hog Manure		
	r	n	P-value	r	n	P-value	r	n	P-value
CO ₂ evolution	-0.82	48	<0.0001	-0.78	60	<0.0001	-0.87	42	<0.0001
Compost age	0.93	48	<0.0001	0.88	60	<0.0001	0.78	42	<0.0001
% VS	-0.86	48	<0.0001	-0.77	60	<0.0001	-0.58	42	<0.0001
C/N ratio	-0.92	48	<0.0001	-0.91	60	<0.0001	0.04	42	0.7792
Organic C	-0.82	48	<0.0001	-0.49	60	<0.0001	-0.46	42	0.0019
Total N	0.91	48	<0.0001	0.87	60	<0.0001	-0.38	42	0.0125
Ammoniacal N	0.31	48	0.0333	-0.18	60	0.1807	-0.69	42	<0.0001
Nitrate N	0.57	48	0.0001	0.34	60	0.0078	nd ^z	42	nd ^z

^z-Nitrate was not detected in any of the samples collected from the hog manure composting samples.

TABLE 2.
Correlations between Solvita® NH₃ test values and various characteristics of three different manure composts

Characteristic	Dairy Manure/Straw			Dairy Manure/Sawdust			Hog Manure		
	r	n	P-value	r	n	P-value	r	n	P-value
CO ₂ evolution	0.42	48	0.0027	-0.18	60	0.0400	-0.19	42	0.2326
Compost age	-0.47	48	0.0007	0.27	60	0.0310	0.63	42	<0.0001
% VS	0.53	48	<0.0001	-0.28	60	0.2369	-0.34	42	0.0248
C/N ratio	0.43	48	0.0024	0.16	60	0.0928	-0.61	42	<0.0001
Organic C	0.50	48	0.0003	0.22	60	0.0676	0.32	42	0.0387
Total N	-0.40	48	0.0048	-0.24	60	0.0542	0.40	42	0.0085
Ammoniacal N	-0.43	48	0.0022	-0.64	60	<0.0001	-0.65	42	<0.0001
Nitrate N	-0.15	48	0.3250	-0.39	60	0.0018	nd ^z	42	nd ^z

^z-Nitrate was not detected in any of the samples collected from the hog manure composting samples.

TABLE 3.
Correlation between Solvita® maturity index values and various characteristics of three different manure composts

Characteristic	Dairy Manure/Straw			Dairy Manure/Sawdust			Hog Manure		
	r	n	P-value	r	n	P-value	r	n	P-value
CO ₂ evolution	-0.78	48	<0.0001	-0.71	60	<0.0001	-0.68	42	<0.0001
Compost age	0.90	48	<0.0001	0.79	60	<0.0001	0.95	42	<0.0001
% VS	-0.84	48	<0.0001	-0.71	60	<0.0001	-0.63	42	<0.0001
C/N ratio	-0.90	48	<0.0001	-0.84	60	<0.0001	-0.36	42	0.0191
Organic C	-0.80	48	<0.0001	-0.44	60	0.0004	-0.51	42	0.0006
Total N	0.87	48	<0.0001	0.78	60	<0.0001	0.02	42	0.9224
Ammoniacal N	0.35	48	0.0157	-0.52	60	<0.0001	-0.89	42	<0.0001
Nitrate N	0.54	48	<0.0001	0.20	60	0.1249	nd ^z	42	nd ^z

^z-Nitrate was not detected in any of the samples collected from the hog manure composting samples.

TABLE 4.
Correlations between Solvita® test values and various combined characteristics of three different manure composts

Characteristic	Solvita® CO ₂ Test			Solvita® NH ₃ Test			Solvita® Maturity Index		
	r	n	P-value	r	n	P-value	r	n	P-value
CO ₂ evolution	-0.79	150	<0.0001	0.05	150	0.5093	-0.67	150	<0.0001
Compost age	0.82	150	<0.0001	0.07	150	0.3698	0.82	150	<0.0001
% VS	-0.56	150	<0.0001	0.01	150	0.9312	-0.45	150	<0.0001
C/N ratio	-0.54	150	<0.0001	-0.26	150	0.0012	-0.62	150	<0.0001
Organic C	-0.30	150	0.0002	0.09	150	0.2546	-0.12	150	0.1590
Total N	0.43	150	<0.0001	0.29	150	0.0003	0.57	150	<0.0001
Ammoniacal N	-0.21	150	0.0108	-0.68	150	<0.0001	-0.61	150	<0.0001
Nitrate N	0.25	150	0.0014	0.17	150	0.0356	0.31	150	<0.0001

compost characteristics (Tables 2 and 4). The Solvita maturity index (a combination of the Solvita® CO₂ test and Solvita® ammonium test) correlated significantly with both CO₂ evolution rate and ammoniacal-N concentration and therefore provided a good predictor of compost stability and maturity.

Discussion

Trends in temperature, oxygen concentration, C:N ratio, volatile solids concentration, pH, and other compost characteristics observed in this work (Figures 1-3) were similar to those found for other composts (Michel *et al.* 1996; Rynk *et al.* 1992; Tiquia *et al.* 2002; Elwell *et al.* 1996) and indicate that the conditions in this study were ideal for organic matter decomposition. Under such conditions, the rate of respiration of compost samples serves as a suitable indicator of their stability (Finstein *et al.* 1983; Garcia *et al.* 1993). The highly significant ($P < 0.01$) correlations between the rate of respiration and NH_3 concentration and the Solvita maturity index in the individual compost samples (Tables 1 to 4) and its ease of use suggest that this index would be ideal for on-farm testing of compost stability when a consistent type of compost feedstock is used. This finding is supported by significant correlations between the Solvita maturity index and CO_2 -C evolution rate, compost age, % volatile solids, ammoniacal-N and organic C (Tables 1 and 4) which are known to closely correlate with compost stability (Finstein *et al.* 1983; Garcia *et al.* 1991; 1993).

To more critically evaluate the ability of the Solvita kit to predict compost stability/maturity, the Solvita CO_2 , NH_3 and Maturity index values were compared to CO_2 evolution based on respirometry and to the concentration of ammoniacal-N in the compost samples. Least squares regression analyses were performed using linear, log transformed-linear, second order polynomial and log transformed second order polynomial models. These analyses indicated that the model that gave the greatest coefficient of determination was a linear regression with log transformation of the CO_2 -C rate data ($R^2 = 65.4\%$). The log transformed linear regression model provided a better fit than the linear ($R^2 = 50.9\%$), polynomial ($R^2 = 54.2\%$) or the log transform polynomial regression ($R^2 = 65.2\%$) models of the relationship between CO_2 -C rate and the Solvita CO_2 index. The fact that log transformation of the CO_2 -C rate data provided the best fit indicated that the relationship between CO_2 -C rate and Solvita CO_2 was exponential and not linear. It accounts for the reduced variation in CO_2 -C rate at higher Solvita CO_2 index values (data not shown). This also may explain why the Solvita CO_2 results had a smaller standard deviation (as a % of the mean) than the CO_2 -C evolution rates for immature compost samples (days 0-60, Figure 2C and 2D). Thus, the ability of the Solvita CO_2 test to predict CO_2 evolution rate based on respirometry was better for more stable composts (e.g. Solvita values > 6) than for immature composts (Solvita $\text{CO}_2 < 4$; Table 5, Figure 5A). For example, a Solvita CO_2 index value of 2 had a 90% prediction interval range of 3.0 to 17 mg CO_2 -C/g VS/d, while a Solvita CO_2 index value of 7 had a 90% prediction interval of just 0.25 to 1.9 mg CO_2 -C/g VS/d (Table 5). Finally, the 90% prediction intervals over all three compost samples for CO_2 -C rate data based on the Solvita CO_2 test indicated that the ability of the Solvita CO_2 test to predict CO_2 -C rate was not very good (Table 5). For example, the 90% prediction interval for a Solvita CO_2 index value of 4 was equivalent to a CO_2 -C evolution rate interval of 1.25 to 6.0 mg CO_2 -C/g VS/d (Figure 5A, Table 5).

To determine whether the predictive ability of the Solvita CO_2 test varied among the three different types of composted manures, least squares regression and 90% prediction ranges were determined separately for each compost type. Results showed that the 90% prediction ranges were quite different when the composts were unstable and that they did not even overlap in some cases (Table 5). For example, a hog manure compost Solvita CO_2 value of 3 corresponded to a CO_2 -C rate 90% prediction interval range of 4.7 to 10.7 mg CO_2 -C/g VS/d. For the dairy manure/sawdust compost, the interval was 1.2 to 4.2 mg CO_2 -C/g VS/d. Thus, the relationship between the Solvita CO_2 test and the CO_2 -C respiration rate differed for the three different types of composts.

TABLE 5.

Regression analysis of CO₂-C rate evolution rate (25 C) as a function of Solvita CO₂ test values. Numbers in brackets represent 90% prediction interval for CO₂-C rate based on Solvita CO₂ test values. A logarithmic transformation linear regression analysis was used. nd-no data.

SolvitaCO ₂ Index Value	CO ₂ -C Rate (mg CO ₂ -C/g VS/d)			All Samples
	Hog + Wood	Dairy + Sawdust	Dairy + Straw	
1	nd	nd	nd	nd
2	9.7 (8.0 to 15.0)	nd	11.9 (2.6 to 14)	7.6 (3.0 to 17)
3	5.5 (4.7 to 10.7)	2.8 (1.2 to 4.2)	6.4 (2.5 to 12)	4.6 (2.0 to 12)
4	3.1 (2.0 to 7.5)	2.0 (1.0 to 4.0)	3.4 (1.7 to 7.0)	2.7 (1.25 to 6)
5	1.7 (0 to 5.0)	1.4 (0.7 to 3.1)	1.9 (1.0 to 4.0)	1.6 (0.80 to 4)
6	1.0 (0 to 3.2)	1.0 (0.5 to 2.1)	1.0 (0.5 to 2.0)	1.0 (0.4 to 2.5)
7	0.6 (0 to 2.8)	0.7 (0.3 to 1.3)	0.5 (0.25 to 2.5)	0.6 (0.25 to 1.9)
8	0.3 (0 to 2.8)	nd	nd	0.4 (0.17 to 1.3)
R2	68.0%	53.9%	76.8%	65.4%

The number of Solvita tests that must be performed on a given compost windrow to obtain an estimate of compost stability is an important cost consideration for farmers. Therefore, the 90% prediction intervals were determined for each compost type based on single, averages of three, and averages of six Solvita CO₂ and CO₂ respirometry tests. The predictive ability (i.e. narrowing of the 90% prediction interval) was not improved by using averages of three or averages of six replicates to calculate a correlation equation (data not shown). Therefore, a single test should be sufficient to estimate compost stability for on-farm use purposes.

The poor correlation of the Solvita CO₂ test with respirometry tests may be due to differences in the procedures used to measure CO₂-C evolution rates by respirometry and the Solvita CO₂ test. One difference is that CO₂ rates in the TMECC CO₂ respirometry assay represent means of CO₂ evolution rates collected daily over a three day period while those in the Solvita CO₂ test are for CO₂ evolution over a 4-hour period. Further comparison of the first day CO₂ evolution rate to the three-day averaged rate showed that values on the first day on average were 50% greater than those averaged over three days (data not shown). Therefore, three-day means would be expected to give lower values than a four-hour Solvita measurement. Another difficulty in correlating Solvita test values to CO₂ evolution rates was that the Solvita test is conducted on a fixed volume of compost while the CO₂ evolution rate in the respirometry bioassay is determined on a volatile solids basis. Changes in sample density and volatile solids content during composting, although inversely proportional (Michel *et al.* 1996), would mean that the quantity of volatile solids in the Solvita test would likely change with compost age while being fixed in the CO₂-C evolution test. It is not surprising, therefore, that the Solvita CO₂ test value did not correlate 100% with direct CO₂ evolution measurements based on respirometry. On the other hand, for on-farm use it may make more sense to measure CO₂ evolution on a constant volume basis rather than a constant VS basis since this better represents the properties of the material as it is marketed.

The concentration of ammoniacal-N in composts prepared from low C:N materials has been proposed as an indicator of compost maturity (Hirai *et al.* 1983, Inbar *et al.* 1989). The Solvita® NH₃ test was designed to evaluate compost maturity by measuring volatilized ammonia corrected for compost pH to estimate ammoniacal-N in the

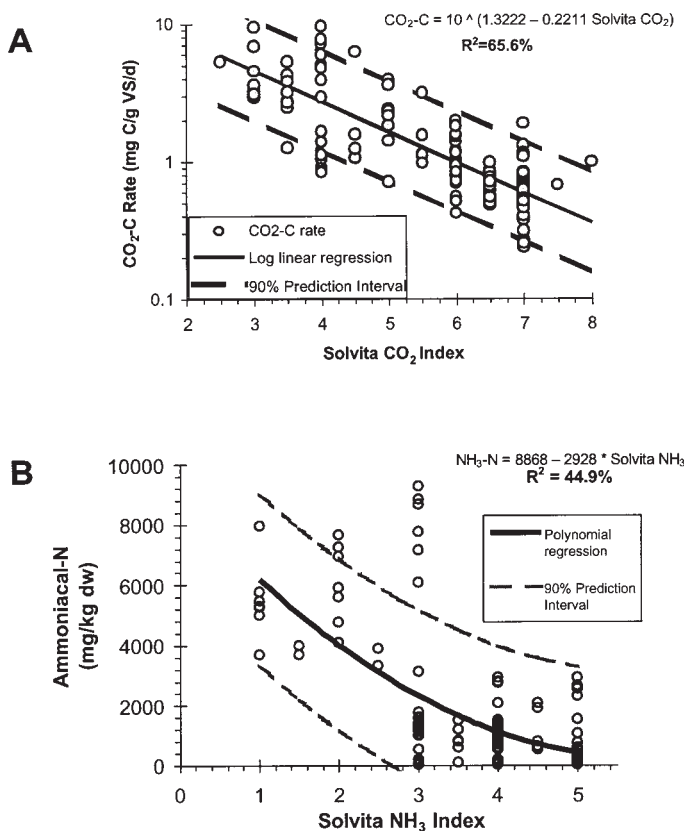


Figure 5. Least squares regression analysis of the relationship between Solvita® CO₂ test values and log transformed CO₂ evolution rates (A) and Solvita® NH₃ test values versus ammoniacal-N concentrations (B) of three composts. Least squares regression fit and 90% prediction interval are shown.

compost itself. In general, the kit provided useful relative information on the concentration of ammoniacal-N in the compost samples used in this work (Figures 3C and 3D). The correlation coefficients presented in Table 2 confirm this. The Solvita NH₃ test correlated strongly with ammoniacal-N in the hog manure compost which had a high initial ammoniacal-N concentration (Figure 3C; Table 2). In some cases, however, this relationship between the NH₃ test values and ammoniacal-N concentration was inconsistent. For example, the fresh hog manure compost samples tested by the Solvita® kit on days 18 and 25 showed Solvita NH₃ test values of 2-3 which did not agree with the very high measured ammoniacal-N concentrations of >5,000 mg kg dw⁻¹ (Figures 3C and D). In addition, while the initial ammoniacal-N concentration ranged over two orders of magnitude for the three composts, the Solvita NH₃ values ranged from only 3-5 (Figure 3D). So the test was not particularly discriminating.

To further evaluate the ability of the Solvita NH₃ index to predict compost ammoniacal N concentration, the measured ammoniacal-N concentrations for all compost samples were compared to Solvita® NH₃ test values. Least squares regression analyses were performed using linear, log transformed-linear, second order polynomial and log transformed second order polynomial models. Unlike the Solvita CO₂ test, the best model fit was provided by a polynomial least squares regression (Figure 5B). However, the ability of the NH₃ test to predict ammoniacal-N was not very strong as indicated by a coefficient of determination (R²) of only 44.9%. For example,

a Solvita® NH₃ test value of 2 had an ammoniacal-N 90% prediction interval of from 800 to 7500 mg/kg (Figure 5B). Since ammonia emission is a strong function of pH, Solvita NH₃ test values can be modified based on compost pH using a table in the Solvita handbook (Woods End Research Laboratory 1999) to give a better estimate of compost ammoniacal-N concentration. Using the Solvita handbook, the estimated ammoniacal-N concentration based on the Solvita NH₃ test and sample pH (Figure 1C) was compared to the measured ammoniacal-N values for all of the compost samples (data not shown). The pH values of the three manure composts, which ranged from 8 to 9 during composting, were typical of manure and some other types of composts (Rynk *et al.* 1991; Michel *et al.* 1996). This indicates that a substantial proportion of the ammonia would not be ionized and therefore volatile (pKa NH₃ @ 55 C = 8.4). The slope of the estimated ammoniacal-N concentrations after pH correction versus the laboratory measured ammoniacal-N values was 0.375 (ideally it should be 1) and the linear correlation coefficient (r) was 0.53. This indicates that the Solvita estimated values of ammoniacal-N using the chart in the Solvita instruction booklet were off by a factor of nearly 3 for the manure composts used in this study. Thus, the ability of Solvita NH₃ test results to predict the concentration of ammoniacal-N was poor, even when corrected for compost pH based on the relationship in the Solvita test booklet (WERL 1999; Figure 5B). This is not surprising because emission of ammonia from compost samples can be influenced by several factors other than pH and ammoniacal-N concentration (Tisdale *et al.* 1985). In addition, the Solvita NH₃ test is performed on a wet volume basis while ammoniacal-N measurements are made on a dry weight basis. Thus, while the NH₃ test may be useful for estimating ammonia volatilization, it would be of limited use to farmers for predicting ammoniacal-N concentrations in composts.

The Solvita Maturity Index values obtained in this work corresponded closely with compost age, CO₂ evolution rate and ammoniacal-N concentration values of the compost samples (Figure 4). To more critically evaluate the ability of the Solvita maturity index to predict compost stability/maturity, the maturity indices from all of the compost samples were compared to corresponding CO₂-C evolution rates based on respirometry. Least squares regression analyses were performed using linear, log transformed-linear, second order polynomial and log transformed second order polynomial models.

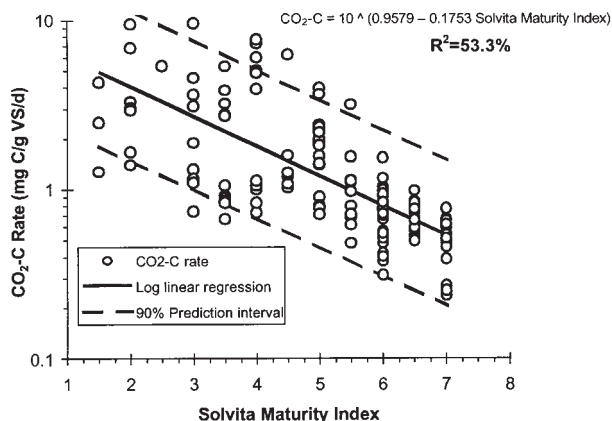


Figure 6. Log transform least squares linear regression analysis of the relationship between Solvita® maturity index value and CO₂-C evolution rate (mg C/g VS/d). Least squares regression fit and 90% prediction interval are presented.

As with the CO₂ index, the log transformed linear model of the relationship between CO₂-C rate and Solvita maturity index had the best coefficient of determination ($R^2=53.3\%$). However, this coefficient of determination was lower than that found with the Solvita CO₂ test alone ($R^2=64.5\%$). This can also be clearly seen in the narrower 90% prediction interval found with Solvita CO₂ test (Figure 5A) as compared to the 90% prediction interval found for the Solvita maturity

index (Figure 6). Therefore, the Solvita CO₂ index alone appears to be the best predictor of compost CO₂ evolution rate or stability. On the other hand, an indication of the superiority of the Solvita Maturity index over the Solvita CO₂ index alone is shown by the dairy manure-sawdust compost in the last half of the composting period. After day 80, Solvita NH₃ test data revealed a sudden increase in concentration and concurrently ammoniacal-N rose to values of ~1500 ppm. This indicates a degree of immaturity for these samples that could lead to phytotoxicity in some applications. The CO₂ evolution rate and Solvita CO₂ values for these samples indicated a stable compost suggesting that they could be used without restrictions. Through incorporation of the Solvita NH₃ value of 3 and the Solvita CO₂ rate of 6 for these specific samples into the Solvita maturity index Table of the Solvita booklet; a Maturity Index of 5 would be obtained. This value does reveal that the compost samples were immature and that they might cause phytotoxicity in some applications. This is consistent with the elevated ammoniacal-N values detected in these samples during this period. Another example where the Maturity Index indicated immaturity is the hog manure compost up to day 70. The two different CO₂-rate tests indicated that the hog manure was "stable" after day 40 while the Solvita Maturity Index showed that it was not mature until day 70 because it incorporates ammonia emissions caused by the high ammoniacal-N levels. Therefore, the Solvita Maturity test provided more useful information to compost users than the CO₂ stability test by itself because it combines an estimate of the CO₂ evolution rate of compost samples with the emission of ammonia from such samples. Finally, even though the Solvita maturity index provided a simple, relatively inexpensive relative test of compost stability and NH₃ emission for diverse samples of composts, it did not accurately predict CO₂ evolution rates determined by respirometry nor ammoniacal-N concentrations in these compost samples. We conclude that the Solvita maturity test would be most useful for quality control purposes in field applications by farmers.

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