Soil Biology & Biochemistry 36 (2004) 767–776

Soil Biology & Biochemistry

www.elsevier.com/locate/soilbio

Maturity indices for composted dairy and pig manures

P. Wang[a], C.M. Changa[a], M.E. Watson[b], W.A. Dick[b], Y. Chen[c], H.A.J. Hoitink[a,*]

[a]*Department of Plant Pathology, The Ohio State University, 1680 Madison Avenue, Wooster, OH 44691, USA*
[b]*School of Natural Resources, The Ohio State University, 1680 Madison Avenue, Wooster, OH 44691, USA*
[c]*Department of Soil and Water Sciences, Faculty of Agricultural, Food and Environmental Quality Sciences, The Hebrew University of Jerusalem, P.O. Box 12, Rehovot 76100, Israel*

Received 10 January 2003; received in revised form 15 August 2003; accepted 3 December 2003

Abstract

Bulking agents and bedding materials used on farms for composting manures affect the time required for composts to mature. The effects of these materials on guidelines for the use of composted manures in potting mixes are not fully known. Several chemical and biological compost characteristics were mentioned and a cucumber plant growth greenhouse bioassay was performed on samples removed from windrows during composting of: (i) dairy manure amended with wheat straw; (ii) dairy manure amended with sawdust (mostly *Quercus* spp.); and (iii) pig manure amended with sawdust and shredded wood (mostly *Quercus* spp.). Dry weights of cucumber seedlings grown in fertilized and unfertilized potting mixes amended with composts (30%, v/v) having stability values of <1 mg CO_2–C g^{-1} dw d^{-1}, did not differ significantly from those in a control peat mix. Only the most mature dairy manure-wheat straw compost samples consistently established sufficient N concentrations in cucumber shoots in unfertilized treatments. For the dairy manure-wheat straw compost, all possible subset regression analyses of compost characteristics versus cucumber plant dry weight revealed that any of several compost characteristics (electrical conductivity-EC, compost age, total N, organic C, C-to-N ratio, ash content, CO_2 respirometry, Solvita CO_2 index and the Solvita® Compost Maturity Index) predicted growth of cucumber in the unfertilized treatments, and thus maturity. In contrast, at least two characteristics of the dairy manure-sawdust compost were required to predict growth of cucumber in the unfertilized treatments. Effective combinations were EC with compost age and the Solvita® maturity index with total N. Even five compost characteristics did not satisfactorily predict growth of cucumber in the non-fertilized pig manure-wood compost. Nutrient analysis of cucumber shoots indicated N availability was the principal factor limiting growth in potting mixes amended with the dairy manure-sawdust compost, and even more so in the pig manure-wood compost even though the compost had been stabilized to a high degree (<1 mg CO_2–C g^{-1} dw d^{-1}). Maturity of the composted manures, which implies a positive initial plant growth response of plants grown without fertilization, could not be predicted by compost characteristics alone unless the bulking agent or bedding type used for the production of the composts was also considered.

Keywords: Compost maturity; Compost stability; Compost quality; Plant bioassay; Dairy manure; Pig manure; Nitrogen immobilization

---

1. Introduction

Changing public perceptions about environmental issues associated with current manure management practices have forced farmers to examine alternative options (Johnson et al., 1998; Jongbloed and Lenis, 1998). The composting process offers the potential to significantly reduce environmental problems associated with manure management (Carr et al., 1995). Unfortunately, the cost of composting relative to utilization of raw manures can be considerably higher (Rynk, 1992). Therefore, composts of high quality must be produced consistently to offset these production costs.

Compost stability is an important aspect of compost quality and it can be assessed with respirometry (Iannotti et al., 1994; Scaglia et al., 2000). It relates to the degree to which the organic matter has been stabilized during the composting process (Chen, 2003). The Solvita® compost maturity kit, which utilizes CO_2-sensitive and NH_3-sensitive paddles in a jar containing a specific quantity of compost (Werl, 1999), can satisfactorily assess the stability of composted manures in on-farm applications (Changa et al., 2003). Heat output as a result of biological activity in composts can also be monitored on farms if several precautions are taken (Weppen, 2002). Thus, adequate

---

* Corresponding author. Tel.: +1-330-263-3848; fax: +1-330-263-3841. *E-mail address:* hoitink.1@osu.edu (H.A.J. Hoitink).

0038-0717/$ - see front matter © 2004 Elsevier Ltd. All rights reserved.
doi:10.1016/j.soilbio.2003.12.012

procedures for testing of stability have been developed. Compost maturity, on the other hand, which implies non-limited plant growth in compost-amended substrates immediately upon their utilization (Zucconi et al., 1981), still is best assessed with plant growth bioassays. This applies even though numerous chemical and biological tests have been proposed to characterize this aspect of compost quality (Hsu and Lo, 1999; Chen, 2003). Much of the literature on stability and maturity does not clearly distinguish between these two properties of composts, however.

The type of animal bedding used on farms (sawdust, wood, straw, etc.) may affect compost quality through its effect on plant growth, presumably through differential effects on N availability (Fauci et al., 1999; Gagnon and Simard, 1999). Similar effects have been described for composted sewage sludge (Bernal et al., 1998). Raw materials used as bedding or bulking agents before composting typically inhibit plant growth and stimulate diseases whereas stabilized mature composts tend to stimulate growth and provide disease control (Hoitink and Boehm, 1999). For these reasons, maturity is one of the most important aspects of compost quality, particularly for composts used in high-value horticultural applications (Gouin, 1998; De Ceuster and Hoitink, 1999).

Some compost maturity tests focus on chemical and physical properties of compost solids. Unfortunately, tests on compost solids such as total N or the C-to-N ratio have long been known to be inadequate for predicting the plant growth response for all types of composts (Golueke, 1975). Therefore, several approaches have been developed to predict compost maturity. For example, Chanyasak et al. (1982) demonstrated that an organic C-to-organic N ratio of 5.6 in the water extract of compost was indicative of maturity for composts prepared from municipal solid wastes. This procedure has been confirmed for this type of compost (Garcia et al., 1993; Iannotti et al., 1994). But it is only partially suitable for composts prepared from separated dairy manure solids (Inbar et al., 1989, 1993). Total water-soluble organic C (Eggen and Vethe, 2001) and several other stability indices have been proposed more recently (Chefetz et al., 1998; Cooperband and Middleton, 1996; Dinel et al., 1996; Forster et al., 1993; Ouatmane et al., 2000). To develop a better understanding of how organic matter transformations during composting affect plant growth, various types of spectroscopic analyses, including NMR and IR spectroscopy have been utilized (Chen, 2003). Unfortunately, all of these tests are costly and unsuitable for on-farm applications. In conclusion, procedures that predict plant growth regardless of compost type are not available to our knowledge.

The objective of this research was to identify characteristics of composted dairy and swine manures that can be used to predict the potential for plant growth in compost-amended potting mixes.

2. Materials and methods

2.1. Raw materials and composting process

Manure solids from The Ohio State University dairy farm at Wooster were blended with: (i) wheat straw or; (ii) a mixture of hardwood sawdust and wood shavings (mostly oak, *Quercus* spp.) and then composted in windrows on a concrete surface. A third type of compost was produced from partially composted pig manure and shredded wood (mostly oak) collected from a High Rise Pig® facility (Keener et al., 2001). Before composting in windrows this partially composted wet manure was amended further with hard wood sawdust (mostly oak) to reduce its moisture content and thus avoid leachate formation. Additional details on the three types of manures used in this work are presented in Changa et al. (2003).

Two different, equal sized batches of each of the three types of manures were composted from April through July 2001 in windrows (height of 1.5 m) with temperatures within the range of 55–70 °C. Initially, the windrows were turned daily, if needed, to reduce the moisture content, avoid leachate formation and reduce odor generation. Thereafter, they were turned weekly or every 2 weeks to maintain porosity and adjust windrow height due to compost shrinkage. Water was added when needed to maintain optimum process conditions for composting of manures (Rynk, 1992). The composting process was continued until the stability of the compost was <1 mg CO_2–C g^{-1} dw d^{-1}, as recommended by the US Composting Council's Test Methods for the Examination of Composting and Compost (TMECC; Thompson et al., 2003).

2.2. Chemical and biological properties of composts

To minimize sample variability, sampling protocols for each type of compost-followed guidelines provided by the US Composting Council (Thompson et al., 2003), as described in Changa et al. (2003). Samples were taken when windrows were first prepared and at 7 or 14 d intervals immediately after turning of the windrows. Ten sub-samples were randomly collected from all locations and depths within a windrow and composited into a single 9 l sample. This was repeated three times for each batch of each type of manure to provide a total of six samples for each compost type. The composted samples were then mixed thoroughly to ensure maximum homogeneity. Changes in some of the chemical properties of the manures during composting were presented in Changa et al. (2003). Electrical conductivity of the compost samples was determined with a Solu Bridge Conductivity Indicator (Beckman Instruments, Cedar Grove, NJ.) according to TMECC method 04.10-A 1:5 Slurry electrical conductivity (EC). Percent Ash was determined after heating (550 °C for 4 h) in a Thermolyne Furnace (model 30400, Thermolyne Corp., Dubuque, IA; TMECC method 03.02-A). The rate of respiration (μg CO_2–C g^{-1} dw compost d^{-1}) for each compost sample was determined according to TMECC 05.08-B (Thompson et al., 2003). The maturity of the compost was determined with a Solvita® Compost Maturity kit (Woods End Research Laboratory Inc., P.O. Box 207, Mt. Vernon, ME 04352) as specified by TMECC, 05.08-E (Thompson et al., 2003). Details of this procedure are presented in Changa et al. (2003). A 4 l quantity of each sample was stored in a freezer (−15 °C) for subsequent use in seed germination and plant growth bioassays.

2.3. Seedling and plant growth bioassays

The effects of compost maturity on seedling emergence and plant growth were determined with a cucumber bioassay according to Iannotti et al. (1994). A sphagnum peat mix that contained 70% peat and 30% perlite (v/v) was used as a control. The percent volumes of fresh and of the most mature compost samples tested in preliminary bioassays for each compost type as substitutes for peat were 0, 5, 10, 15, 30, 40, 50 and 100% (v/v). Dolomitic limestone was added to each mix to adjust the pH to within the range of 5.5–5.8. All treatments, except the control, were fertilized with 12.5 g l^{-1} slow release fertilizer (Osmocote 14-14-14, Grace-Sierra Chemical Co., Milpitas, CA), at the recommended rate for cucumber.

Eight cucumber (*Cucumis sativus* L. cv. Straight Eight, 99% germination) seeds were planted 1.0 cm deep in each of five pots (450 ml potting mix per pot) per compost maturity sample. Plants were grown in a greenhouse at 23–26 °C with 14 h of supplemental illumination d^{-1} (225 μE m^{-2} s^{-1}). Pots were irrigated as needed and the mean percentage of emergence was determined after 7 d. The number of seedlings was then thinned to four per pot and the aerial portion of each plant was harvested and weighed after 21 d and then air-dried (70 °C) to a constant wt. Mean plant fresh wt and dry wt per pot were determined. The air-dried shoots of each pot for each compost maturity treatment (two replicates of five pots per compost type) were pooled and weighed to provide an adequate quantity of shoot sample for analysis. The shoot samples were analyzed at the Ohio State University's STAR analytical laboratory (http://www2.oardc.ohio-state.edu/starlab) to determine the concentrations of plant nutrients.

2.4. Experimental designs and statistical analyses

The chemical and biological properties of the two different batches of each compost type did not reveal significant differences. Therefore, data for the two batches were combined to provide six sample replicates per compost type. Furthermore, plant growth bioassays for each type of composted manure were performed separately because the number of treatments (e.g. compost age, fertilized, non-fertilized and peat controls) applied to each sample was too high to be tested in a single experiment. Individual experimental units were randomized and responses were analyzed using analyses of variance (ANOVA). Where differences in ANOVA tests for treatment were significant at the 0.05 level, means were separated using least significant difference values. Linear correlation analysis and all possible subset regression analysis were performed using SAS statistical software (SAS 8.0) to define predictive relationships between cucumber growth, compost maturity and other chemical properties of the composts.

3. Results

3.1. Compost characteristics

Trends in compost temperature, pH, moisture content, percent volatile solids, organic C, C-to-N ratio, stability, total N, NH_4^+–N, NO_3^- –N and Solvita maturity index were presented in Figs. 1–4 in Changa et al. (2003). A summary of these key compost properties is presented in Table 1 to facilitate interpretation of the plant growth response data presented here.

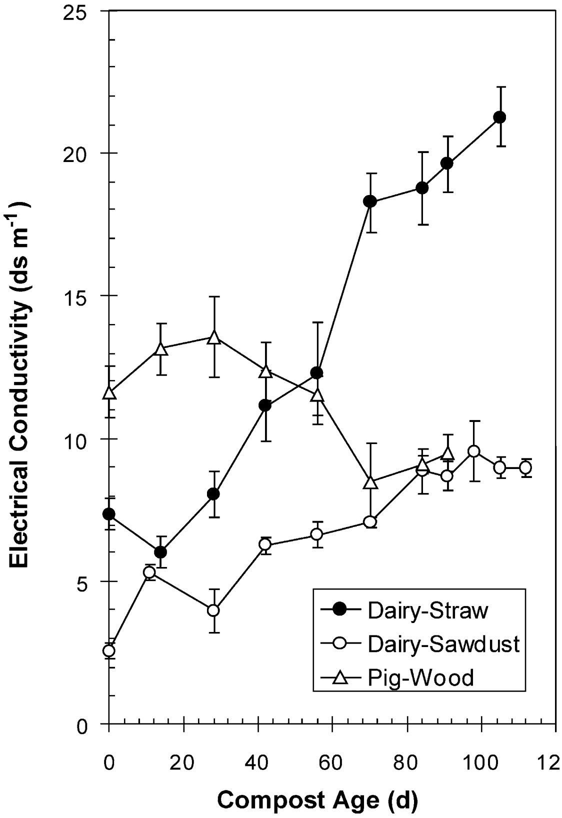

Fig. 1. Changes in electrical conductivity (EC) during composting of three types of materials based on six samples per harvest date. Bars represent standard errors.

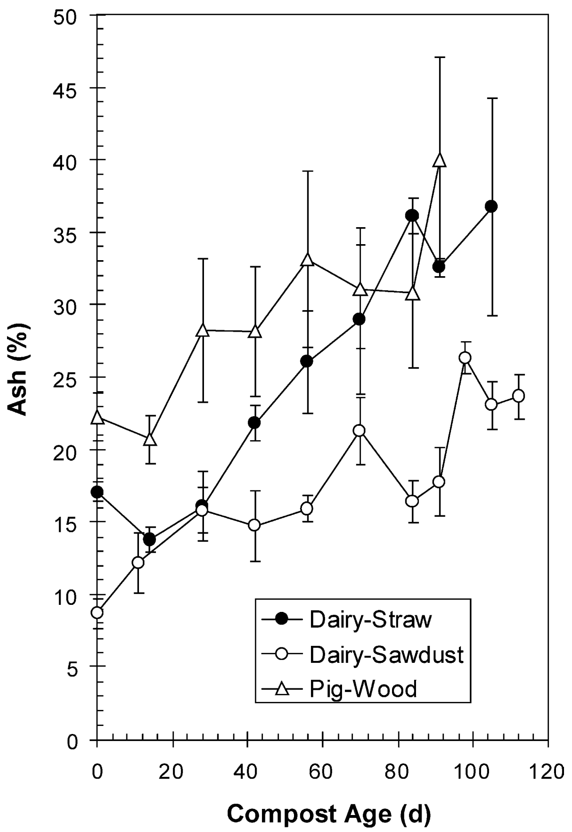

Fig. 2. Changes in ash content during composting of three types of materials based on six samples per harvest date. Bars represent standard errors.

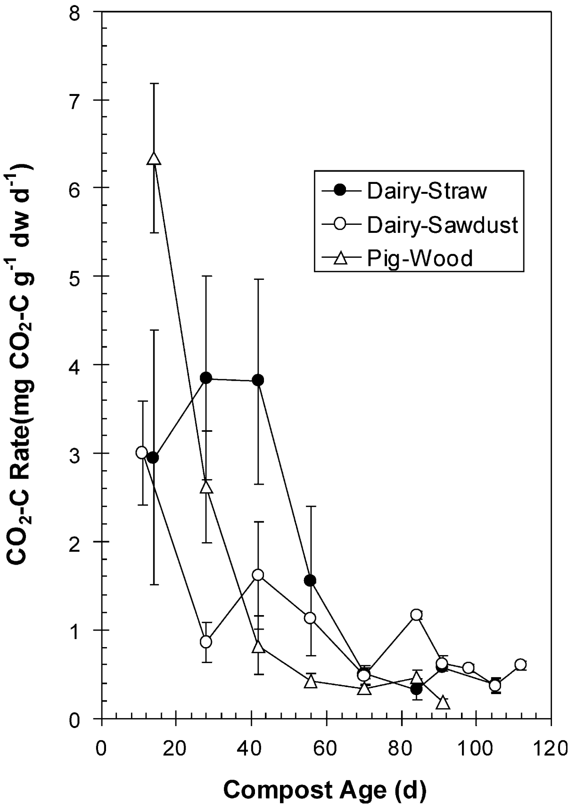

Fig. 3. Changes in rate of CO_2 respiration during composting of three types of materials based on six samples per harvest date. Bars represent standard errors.

3.1.1. EC values of composts

The EC values of the dairy manure-wheat straw and dairy manure-sawdust composts increased significantly during composting (Fig. 1). Towards the end of the process, a very high EC value of 21.3 ds m^{-1} was reached in the dairy manure-wheat straw compost whereas the value in the dairy manure-sawdust compost remained much lower. Trends in EC for the pig manure-wood compost were unusual in that values decreased over time.

3.1.2. Ash content of composts

The ash content of all three compost types increased significantly with time (Fig. 2). After a short lag (28 d), the ash content of the dairy manure-wheat straw compost increased more than 2-fold from 16.1 to 36.7% after 105 d. The ash content of the dairy manure-sawdust compost also more than doubled from a low initial value of 8.7–23.7% after 112 d. The highest initial ash content (22.2%) was observed in the pig manure-wood compost, probably because it contained all the urine from the pigs and also because it had been partially composted in the High Rise® pig facility before initiation of windrow composting. It increased to 40.1% after 91 d. Because leaching was avoided throughout the composting process of all three types of composts, these changes in ash content reflect actual trends in mineralization of organic matter.

3.1.3. Rates of respiration of composts

The rate of respiration for all three compost types decreased during the process until a final stability value in the range of 0.3–0.6 mg CO_2–C kg^{-1} dw d^{-1} was reached after 80–90 d of composting (Fig. 3). Early during the decomposition of the dairy manure-wheat straw compost, when the straw was still largely intact, the rate of respiration of the compost was high and variability among individual samples was considerable. After the physical integrity of the straw was lost later in the process, sample homogeneity increased. In the dairy manure-sawdust compost, rates and variability also decreased with time. The highest initial rate of respiration was observed in the pig manure-wood compost, probably due to decomposition of the fresh sawdust added at the beginning of the process. In conclusion, low rates of respiration indicative of highly stabilized composts were reached towards the end of process in all three compost types.

3.2. Seedling emergence and plant growth response

Cucumber seedlings responded to differences in maturity of all three compost types. The greatest differences in shoot dry weights were observed in potting mixes amended with a compost volumetric ratio of 30%. Only slight differences were observed with the lower volumetric compost

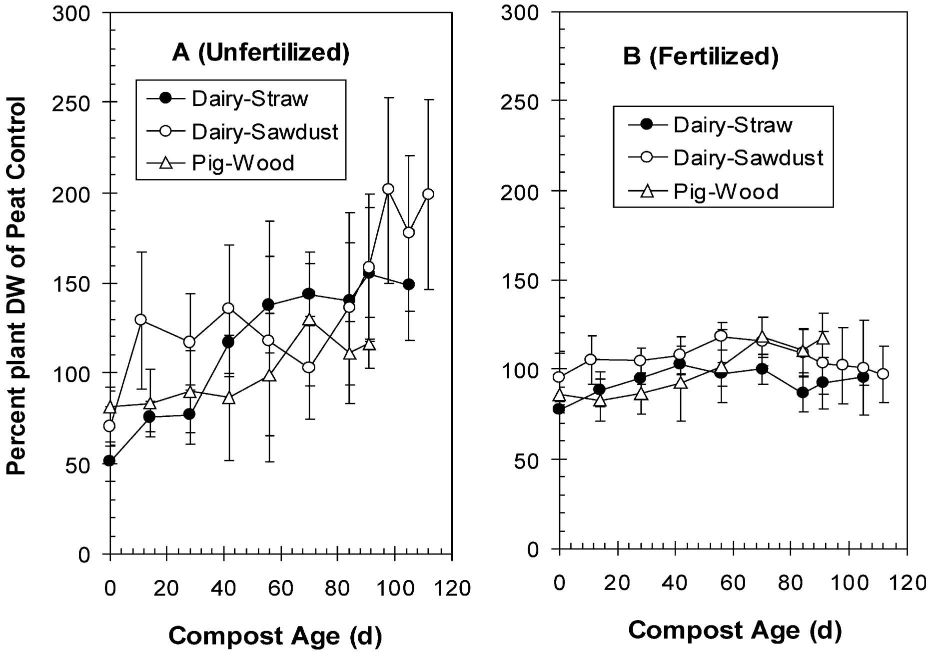

Fig. 4. Effects of compost age on growth of cucumber (*C. sativus* cv. Straight Eight) plants in three different composted materials versus a standard peat potting mix without fertilizer added (A) and with fertilizer added (B).

amendment rates (data not shown). Therefore, the 30% amendment rate was chosen to test the effects of compost maturity on growth of cucumber for all compost maturity levels of all three types of composted manures.

The mean percent emergence of cucumber seedlings in the peat control mix and in potting mixes amended with the three types of composts of all maturity values tested was 95% (data not shown). This percentage was not significantly different from the germination values determined for the seeds prior to being planted in the treated mixes. Therefore, compost age of the three types of composted manures used in this work did not significantly affect the percent germination of cucumber seeds.

3.2.1. Dairy manure-wheat straw compost

The response of cucumber plants to differences in compost maturity was expressed as the percent shoot dry weight of plants grown in compost mixes versus the peat control. Data for the control and fertilized treatments were plotted separately (Fig. 4). Percent plant dry weight of cucumber in the unfertilized (control) dairy manure-wheat straw compost-amended mixes significantly increased with compost age (Fig. 4A). The dairy manure-wheat straw composts sampled at 0, 14, and 28 d inhibited growth compared to the control peat mix. Shoot dry weights increased in mixes amended with older compost samples until a plateau was reached with samples composted 70 d or

Table 1
Changes in chemical and biological characteristics during composting of the three types of manures

Compost type	Compost characteristics								
	Age (d)	pH	Water content (%)	Organic C (%)	Total N (%)	C/N ratio	NH_4^+–N (mg kg^{-1})	NO_3^-–N (mg kg^{-1})	Solvita® MI[a]
Dairy-straw	0	8.54 ± 0.09[b]	67.2 ± 1.31	43.6 ± 0.40	1.76 ± 0.05	25.1 ± 0.85	238 ± 60.3	< 1.0	ND[c]
	56	8.49 ± 0.19	62.9 ± 6.27	39.2 ± 1.27	3.16 ± 0.11	12.5 ± 0.40	123 ± 123	9.71 ± 17.5	5.3 ± 0.5
	105	8.34 ± 0.34	52.5 ± 1.14	35.2 ± 0.45	4.24 ± 0.54	8.5 ± 1.01	116 ± 89.8	128 ± 99.2	6.3 ± 0.8
Dairy-sawdust	0	8.76 ± 0.06	64.8 ± 0.36	46.2 ± 1.23	1.41 ± 0.03	33.0 ± 1.22	1980 ± 121	< 1.0	ND
	56	8.58 ± 0.2	63.3 ± 1.07	43.9 ± 0.74	2.22 ± 0.05	19.9 ± 0.38	738 ± 190	4.63 ± 2.77	4.7 ± 0
	112	8.57 ± 0.03	55.8 ± 0.75	42.5 ± 0.50	3.39 ± 0.06	12.7 ± 0.34	89.0 ± 7.80	90.6 ± 14.6	5.5 ± 0.8
Pig-wood	0	8.88 ± 0.07	65.5 ± 0.86	37.9 ± 1.41	2.21 ± 0.08	18.7 ± 0.66	8510 ± 931	< 1.0	ND
	56	9.05 ± 0.08	58.7 ± 1.86	32.5 ± 3.29	1.62 ± 0.13	21.6 ± 0.93	3780 ± 282	< 1.0	3.7 ± 0.5
	91	8.72 ± 0.11	47.8 ± 2.71	31.5 ± 2.18	2.14 ± 0.17	15.3 ± 0.68	196 ± 46.5	< 1.0	7.0 ± 0

[a] Solvita® MI: Solvita® Maturity Index (1–8).

[b] Each value is the mean of six replicates followed by the standard error.

[c] ND = not determined.

more. The most significant effect on these growth differences was observed after 56 d of composting. Addition of slow release fertilizer avoided inhibition of growth in mixes amended with the 28 d compost samples, but not in the mixes amended with the fresh straw-amended manure (0 d of composting or 14 d compost samples, Fig. 4B).

The effects of dairy manure-wheat straw compost age on the concentrations of essential plant nutrients in the shoots of cucumber plants grown in compost-amended fertilized potting mixes versus the unfertilized control peat mix are summarized in Table 2. The shoot N concentration steadily increased with dairy manure-wheat straw compost age. It increased from a low value of 2.4% in the fresh dairy-straw compost mix, a value that reflects N deficiency, to a value within the sufficiency range (4.0%) after 91 d of composting. All other nutrients, except Ca, were within the recommended sufficiency range for greenhouse cucumber production (see footnote in Table 2). The concentration of Ca was consistently low. It was not affected by compost age.

To further illustrate the response of cucumber growth relative to compost maturity, other variables were plotted against compost age. These included shoot dry weight, total N supplied as compost in the potting mix, and shoot N concentration. Fig. 5A reveals that shoot dry weights of plants produced in the unfertilized dairy manure-wheat straw compost-amended potting mixes increased significantly during the first 70 d of composting. Total N incorporated as compost into this potting mix increased almost linearly with compost age over the entire test period. The shoot N concentration followed a similar trend. Regression analysis confirmed these findings (Table 3). In conclusion, all these factors related well and N availability seemed to be the key compost quality factor that limited growth of cucumber. This effect did not disappear until after 105 d of composting unless fertilizer was applied to the potting mix.

3.2.2. Dairy manure-sawdust compost

Percent shoot dry weight of plants grown in the unfertilized (control) fresh dairy manure-sawdust manure compost (0 d of composting) was significantly lower than that in the unfertilized control peat mix (Fig. 4A). In control mixes amended with older compost samples, shoot dry weights increased with compost age until a plateau was reached after 98 d of composting. A response to compost age was not observed in the fertilized treatments (Fig. 4B) except for in potting mixes prepared with samples composted for 56 and 70 d.

The concentrations of essential plant nutrients in the shoot of cucumber plants in the unfertilized treatments (Table 2) revealed that all nutrients other than N, Ca and Mo were within the recommended sufficiency range (see footnote to Table 2). The concentration of N increased with dairy manure-sawdust compost age, but remained highly deficient even for the most mature compost samples tested. Shoot dry weight related well to shoot N concentration (Fig. 5B). However, total N supplied by the compost did not relate well to shoot N or dry weight. Regression analysis confirmed these findings (Table 3).

Table 2
Effect of compost age on concentrations of nutrients in the shoot of cucumber (*C. sativus* cv. Straight Eight) plants produced in three different types of non-fertilized composted manure-amended versus a fertilized and unfertilized peat potting mix

Potting mix[a]	Compost age (d)	Major nutrients					Micro nutrients					
		N (%)	P (%)	K (%)	Ca (%)	Mg (%)	B (μg/g)	Cu (μg/g)	Fe (μg/g)	Mn (μg/g)	Mo (μg/g)	Zn (μg/g)
Peat − F		2.51	1.00	3.16	1.86	1.09	36.8	3.24	47.46	102.7	0.38	59.1
(Dairy-straw) − F	0	2.40	0.553	3.92	0.833	0.868	49.3	3.66	48.4	89.9	0.270	62.7
	56	3.49	0.804	5.66	0.698	0.606	36.8	8.00	60.9	61.4	1.49	89.0
	105	4.02	0.958	6.88	0.630	0.444	32.8	8.75	57.6	59.1	2.89	93.0
Peat + F		7.36[b]	1.24	5.90	1.86	1.14	26.9	2.13	76.5	94.7	0.250	36.4
Peat − F		2.41	0.15	0.80	2.57	1.96	35.7	4.24	56.9	87.5	0.46	49.4
(Dairy-sawdust) − F	0	1.52	0.581	4.45	0.645	0.631	45.8	3.99	57.1	63.1	0.386	52.1
	56	1.78	0.601	4.83	0.663	0.513	40.8	3.93	46.9	64.0	0.418	50.3
	112	2.07	0.712	5.98	0.713	0.540	43.4	5.77	45.3	70.7	1.02	57.7
Peat + F		7.59	0.976	6.08	1.94	1.02	30.0	2.14	94.5	110	0.346	75.7
Peat + F		2.15	0.14	0.65	2.77	2.02	37.7	3.33	49.8	87.1	1.00	59.1
(Pig-wood) − F	0	4.75	1.39	5.75	0.667	1.07	55.7	14.5	87.5	84.4	3.37	152
	56	2.46	1.05	4.69	0.551	0.963	57.2	7.6	57.4	62.2	5.64	86.8
	91	2.09	0.926	4.30	0.534	0.862	52.3	6.0	47.6	62.5	5.77	78.1
Peat +F		7.11	1.579	4.89	1.69	1.15	29.7	1.6	75.8	84.4	0.407	50.1
Sufficiency range[c]		4.3–6.0	0.3–1.0	3.1–5.5	2.4–4.0	0.35–1.0	30–100	8.0–10.0	50–300	50–300	0.8–5.0	25–200

[a] Fertilized (+F) with 12.5 g Osmocote 14-14-14 (N–P–K) slow release fertilizer L^{-1} potting mix (−F, nonfertilized).

[b] Mean values based on two measured replicates (A and B) per treatment, each replicate had 5 × 4 plants pooled together.

[c] Recommended foliar nutrient sufficiency range for cucumber produced as a green house crop from Mills and Jones (1996).

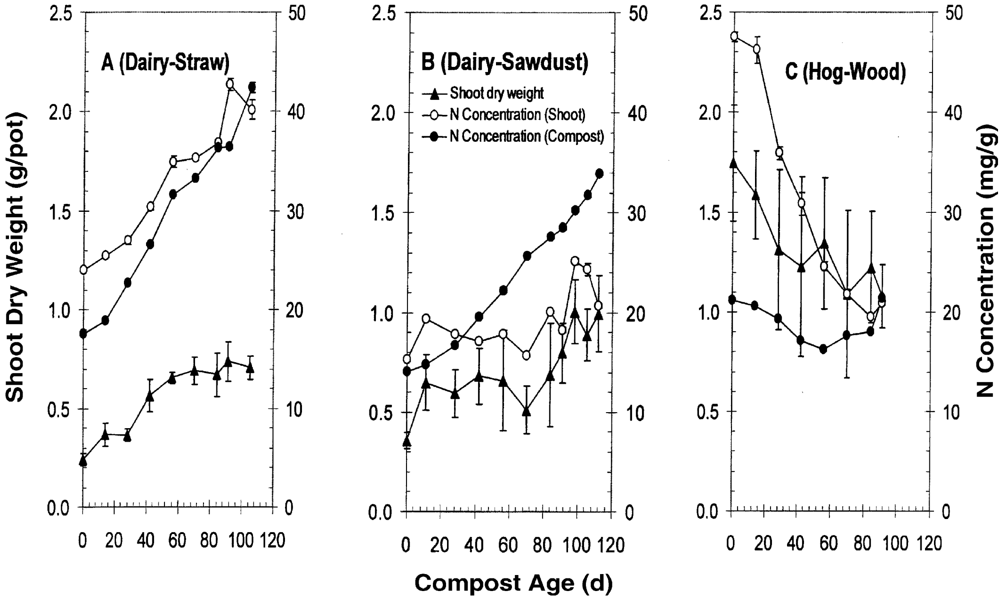

Fig. 5. Effects of compost age on total N supplied by compost, the N concentration in shoots of cucumber (*C. ativus* L. cv. Straight Eight) and shoot dry weight for plants produced in three different composted manure-amended potting mixes.

Ca was consistently low and not affected by compost age. The concentration of Mo reached the sufficiency range after 84 d of composting.

3.2.3. Pig manure-wood compost

Growth of cucumber was inhibited in the unfertilized (control) fresh pig manure-wood compost relative to that in the peat control (Fig. 4A). This effect disappeared after 70 d of composting. The effect of compost age on growth was much more evident in the fertilized treatments (Fig. 4B).

Trends in concentrations of essential plant nutrients in the shoots of cucumber plants produced in the unfertilized pig manure-wood compost mixes revealed that all concentrations except Mo decreased with compost age (Table 2). All, except for N and Ca, were within the recommended sufficiency range. The concentration of N in samples composted 14 d or less was sufficient (>4.3%). However, this concentration declined to a value as low as 2.1% after 91 d of composting. Calcium was not affected by compost age. Neither shoot N nor shoot dry weight related well to compost N (Fig. 5C). Regression analysis confirmed this finding (Table 3). N availability seemed to be the critical factor limiting plant growth for this composted manure, particularly in the older compost samples.

3.3. Relationship between compost characteristics and plant growth

The correlations between shoot N content and compost age for the three different types of composted manures were examined further through linear regression analysis. Significant correlations were established between shoot N content and compost age for each compost type. The R^2 value of the dairy manure-wheat straw regression line ($R^2 = 0.93$) was significantly higher than that of the dairy manure-sawdust regression line ($R^2 = 0.69$). With increasing composting

Table 3
Relationship between N concentration in compost, shoot dry weight and shoot N concentration

Compost type		N concentration in compost	Compost age
	N concentration in compost		$y = 4.17x - 68.8$ ($R^2 = 0.9841$)
Dairy-straw	N concentration in shoot	$y = 0.737x + 11.2$ ($R^2 = 0.9145$)	$y = 0.178x + 23.3$ ($R^2 = 0.9396$)
	Dry weight	$y = 0.020x - 0.030$ ($R^2 = 0.8694$)	$y = 0.005x + 0.298$ ($R^2 = 0.8765$)
	Total N content in shoot	$y = 0.101x - 1.06$ ($R^2 = 0.9067$)	$y = 0.024x + 0.606$ ($R^2 = 0.9265$)
	N concentration in compost		$y = 5.47x - 68.8$ ($R^2 = 0.9888$)
Dairy-sawdust	N concentration in shoot	$y = 0.292x + 12.2$ ($R^2 = 0.4147$)	$y = 0.054x + 15.8$ ($R^2 = 0.4251$)
	Dry weight	$y = 0.023x - 0.167$ ($R^2 = 0.6424$)	$y = 0.004x + 0.447$ ($R^2 = 0.6678$)
	Total N content in shoot	$y = 0.075x - 0.2971$ ($R^2 = 0.6807$)	$y = 0.014 + 0.631$ ($R^2 = 0.687$)
	N concentration in compost		$y = -5.14x + 146$ ($R^2 = 0.095$)
Pig-wood	N concentration in shoot	$y = 2.93x - 24.7$ ($R^2 = 0.2646$)	$y = -0.331x + 46.8$ ($R^2 = 0.9341$)
	Dry weight	$y = 0.049x + 0.407$ ($R^2 = 0.1678$)	$y = -0.006x + 1.63$ ($R^2 = 0.7763$)
	Total N content in shoot	$y = 0.610x - 7.13$ ($R^2 = 0.2646$)	$y = -0.068x + 7.66$ ($R^2 = 0.9081$)

Table 4
Adjusted *R*-Square $(R)^2$ values of all possible subset regression analyses of compost characteristics versus cucumber dry weight

Compost characteristics	Compost		
	Dairy-straw	Dairy-sawdust	Pig-wood
C-to-N ration	0.880[a]	0.295	0.000
Electrical conductivity	0.817[a]	0.443	0.242
Compost age	0.814[a]	0.415	0.117
Solvita® maturity index	0.782[a]	0.059	0.092
Solvita® CO_2 index	0.767[a]	0.164	0.102
Ash	0.754[a]	0.131	0.123
Total N	0.742[a]	0.406	0.000
Organic C	0.680[a]	0.360	0.010
CO_2 respirometry	0.642[a]	0.070	0.167
Solcita® NH_3 index	0.378	0.108	0.000
NO_3^-–N	0.264	0.036	ND
NO_4^+–N	0.209	0.000	0.182

[a] Adjusted *R*-square $(R)^2$ values >0.500 were significant at $P < 0.05$.

time, significantly more N was taken up by cucumber plants grown in the dairy manure-wheat straw compost-amended mixes compared to the dairy manure-sawdust compost mixes. In contrast, a negative correlation was observed for the pig manure-wood compost mixes. Thus, compost age affected shoot N more critically than any other essential nutrient and the effect was specific to compost type.

Adjusted R^2 values of linear regression analyses of compost characteristics versus cucumber plant growth (shoot dry weight), based on all possible subset regression analyses presented in Table 4, revealed that several dairy manure-wheat straw compost characteristics could be used to predict growth of cucumber. Useful compost characteristics (R^2 values > 0.5) for this compost type in decreasing order of R^2 value included C-to-N ratio, EC, compost age, Solvita® maturity index, Solvita® CO_2 index, ash content, total N, organic C, and the rate of CO_2 respiration. In contrast, none of the dairy manure-sawdust compost characteristics by themselves had high R^2 values. At least two characteristics were required to predict plant growth (R^2 values > 0.5, data not shown). The best predictor was EC combined with compost age. The Solvita® Maturity Index and total N combination also was a useful indicator for the dairy manure-sawdust compost. Finally, even a combination of the five highest ranked characteristics of the pig manure-wood compost did not provide an $R^2 > 0.5$ (data not shown). This suggests that no combination of these compost characteristics could serve as a suitable indicator of the growth response of cucumber.

4. Discussion

4.1. N availability in compost for plant growth

The results of our work show that all three types of composts could serve as effective peat substitutes (30%; v/v) for growth of cucumber plants if fertilizer was added and after they reached the stability level recommended by the US Composting Council (<1 mg CO_2–C g^{-1} dw d^{-1}; Thompson et al., 2003). With fertilizer, growth equivalent to that in a standard fertilized peat mix occurred after 40–80 d of composting. Without added fertilizer, however, only the two most mature composted dairy manure-wheat straw samples (after 91 d of composting) established sufficient N concentrations (43 mg N g^{-1} dw; Fig. 5A–C; Mills and Jones, 1996) in cucumber shoots. All other unfertilized treatments were deficient in N.

The type of bulking agent used for composting of the dairy manure clearly affected N released by the composts into the potting mixes, based on plant growth response data and the concentrations essential plant nutrients in the shoots of cucumber. The dairy manure-wheat straw compost seemed to steadily release more N as the organic matter mineralized during the composting process (Table 1, Fig. 5A). Although the dairy manure-sawdust compost supported growth of cucumber without added fertilizer, the shoot N concentration remained in the deficiency range, probably due to the dilution effect caused by plant growth. Thus, the dairy straw compost would be most useful for organic producers who rely on N provided by composts as an important source of fertilizer (Hodges, 1991; Pang and Letey, 2000; Levanon and Pluda, 2002).

The pattern of transformations of N in the pig wood compost was quite different from that of the dairy manure samples. It is more in line with that described earlier for composting of pig manure (Hsu and Lo, 1999; Moller et al., 2000). The decrease in N concentration in cucumber shoots observed for pig manure-wood compost type as composting proceeded (Fig. 5C) probably is best explained by: (i) loss of N due to NH_3 volatilization and (ii) immobilization of N by the wood fraction in the compost. The cucumber shoot N concentration did not increase until the last sampling date when the quantity of N supplied with the compost in the potting mix had also increased. As a result, prediction of plant growth in non-fertilized potting mixes prepared with this pig manure-wood compost, based on chemical properties of the compost alone (Table 1, Figs. 1–3), would appear to be a challenge. No combination of these compost characteristics proved useful for predicting growth of cucumber unless fertilizer was added to the mix. Inhibition of growth in the immature fertilized pig manure-wood compost mixes probably was due to toxicity caused by high concentrations of NH_3 on NH_4^+–N in the compost (Table 1).

4.2. Effect of bulking agent type on compost maturity

The differential effects of wheat straw and sawdust used as bulking agents in this work for composting of dairy manure can be explained on the basis of differences in their biodegradability in soil (Allison, 1973; Blanco and Almendros, 1994). Utilizing ^{13}C CPMAS NMR and DRIFT spectroscopy, Stone et al. (2001) demonstrated that much of the cellulose in sawdust and wood shavings (mostly oak) blended with dairy manure solids indeed are destroyed during 120 d of composting whereas lignin and lignin-protected cellulose are conserved. Thus, differences in C availability between the wheat straw and the sawdust composts probably accounted for differences in N mineralization and plant growth observed.

The significant correlation between any of several chemical or biological properties of the dairy manure-wheat straw compost (i.e. C-to-N ratio, EC, compost age, ash content, total N, organic C, and the rate of CO_2 respiration, or the Solvita® Maturity Index) with cucumber growth was to be expected. Farmers thus could use simple tests such as the EC or the Solvita® maturity index to provide quality control for individual compost batches prepared from wheat straw-amended dairy manures. This is important for many parts of the world because wheat straw is still used widely by dairy farmers. Thus, predictable quality control for value-added utilization of dairy manure-wheat straw composts should be possible as was determined for composted separated dairy manure solids by Inbar et al. (1993) and Hadas et al. (1996).

Recommendations for utilization of composted manures in potting mixes to our knowledge do not consider the type of bulking agent or bedding used on farms even though this has been suspected to have an effect (Fauci et al., 1999; Gagnon and Simard, 1999). Our data show that the wood industry wastes (sawdust, chips, shavings and ground wood) may introduce N nutrition problems for organic farming systems that are not readily apparent from compost characteristics. As mentioned above, the three composts met the CO_2 stability guidelines proposed by The US Composting Council (Thompson et al., 2003). Guidelines for the Solvita® maturity index test (Woods End Research Laboratory, 1999) identified the pig manure-wood compost (value of 7 after 91 d of composting) as stable or as providing few limitations during utilization. In contrast, the dairy manure-wheat straw and dairy manure-sawdust composts only reached Solvita® values of 6 after 70 and 98 d of composting, respectively, even though they released more N as mature composts. Thus, the Solvita® maturity index did not identify the N immobilization potential of this compost type. The only compost characteristic that revealed the potential for N deficiency in plants grown in the pig manure-wood compost was lack of nitrate accumulation in this compost after 91 d. Unfortunately, nitrate may be denitrified quickly in composts under low O_2 concentrations (Kowalchuk et al., 1999). Thus, the concentration of nitrate may not be a suitable compost maturity test, a view supported by a recent review of the composting process (Day and Shaw, 2001).

Although we did not present the data here, we tested the suitability of the water extract organic C-to-organic N ratio for all three compost types used. This procedure also did not yield data that could be used to predict compost maturity which agrees with a previous report for compost produced from dairy manure solids without bedding (Inbar et al., 1993). We suspect that the reason for the difference between the above mentioned studies and that of Chanyasak et al. (1982) mostly result from the presence of bulking agents and lignin-protected materials in composts prepared from manures as opposed to from municipal sewage wastes (MSW). The latter contained low amounts of lignin-protected materials and high quantities of paper. The tree, species specific allelopathy toxins, that are responsible for the selective rate of decomposition of woody materials are removed during the pulping process. It is not surprising, therefore, that mineralization characteristics of MSW composts are as predictable (Levanon and Pluda, 2002) as those of the straw compost were in this work.

5. Conclusions

The types of bedding or bulking agents used for composting of manures must be considered in the development of compost utilization guidelines Wheat straw, as expected, did not pose problems, but wood wastes affected N availability. This will need to be considered, particularly for organic production systems. To the best of our knowledge, methods that adequately assess this potential negative aspect of compost quality are not available. Thus, plant bioassays need to be performed on composts prepared with wood wastes or N fertilization and results must be considered carefully to avoid N deficiency and thus plant growth problems.

Acknowledgements

This research was supported by grants from The Ohio Water Development Authority, Columbus, OH, and by State and Federal funds appropriated to The Ohio State University and The Ohio Agricultural Research and Development Center, Wooster, OH. The authors thank G.L. Reid, C.A. Musselman and T.L. Moore for technical assistance.

References

Allison, F.E., 1973. Soil Organic Matter and Its Role in Crop Production. Elsevier, Amsterdam, pp. 416–444.

Bernal, M.P., Navarro, A.F., Sanchez-Monedero, M.A., Roig, A., Cegarra, J., 1998. Influence of sewage sludge compost stability and maturity on carbon and nitrogen mineralization in soil. Soil Biology & Biochemistry 30, 305–313.

Blanco, M.J., Almendros, G., 1994. Maturity assessment of wheat straw composts by thermogravimetric analysis. Journal of Agricultural Food Chemistry 42, 2454–2459.

Carr, L., Grover, R., Smith, B., Richard, T., Halbach, T., 1995. Commercial and on-farm production and marketing of animal waste compost products. Animal waste and the land–water interface. Lewis Publishers, Boca Raton, pp. 485–492.

Changa, C.M., Wang, P., Watson, M.E., Michel, F.C. Jr., Hoitink, H.A.J., 2003. Assessment of the reliability of the Solvita® maturity test for composted manures. Compost Science and Utilization 11, 125–143.

Chanyasak, V., Hirai, M., Kubota, H., 1982. Changes of chemical components and nitrogen transformation in water extracts during composting of garbage. Journal of Fermentation Technology 53, 215–219.

Chefetz, B., Chen, Y., Hadar, Y., 1998. Water-extractable components released during composting of municipal solid waste. Acta Horticulturae 469, 111–118.

Chen, Y., 2003. Nuclear magnetic resonance, infra-red and pyrolysis studies of solid organic waste composts. Compost Science and Utilization 11, 152–168.

Cooperband, L.R., Middleton, J.H., 1996. Changes in chemical, physical and biological properties of passively-aerated composted poultry litter and municipal solid waste compost. Compost Science and Utilization 4, 24–34.

Day, M., Shaw, K., 2001. Biological, chemical and physical processes of composting. In: Stoffella, P.J., Kahn, B.A. (Eds.), Compost Utilization in Horticultural Cropping Systems, Lewis Publishers, New York, pp. 17–50.

De Ceuster, T.J.J., Hoitink, H.A.J., 1999. Prospects for composts and biocontrol agents as substitutes for methyl bromide in biological control of plant diseases. Compost Science and Utilization 3, 6–15.

Dinel, H., Schnitzer, M., Dumontet, S., 1996. Compost maturity: extractable lipids as indicators of organic matter stability. Compost Science and Utilization 4, 6–12.

Eggen, T., Vethe, O., 2001. Stability indices for different composts. Compost Science and Utilization 9, 19–26.

Fauci, M.F., Bexdicek, D.F., Caldwell, D., Finch, R., 1999. End product quality and agronomic performance of compost. Compost Science and Utilization 7, 17–29.

Forster, J.C., Zech, W., Würdinger, E., 1993. Comparison of chemical and microbiological methods for the characterization of the maturity of composts from contrasting sources. Biology and Fertility of Soils 16, 93–99.

Gagnon, B., Simard, R.R., 1999. Nitrogen and phosphorus release from on-farm and industrial composts. Canadian Journal of Soil Science 79, 481–489.

Garcia, C., Hernandez, T., Costa, C., Ceccanti, B., Masciandro, G., Ciardi, D., 1993. A study of biochemical parameters of composted and fresh municipal wastes. Bioresource Technology 44, 17–23.

Golueke, C.G., 1975. Composting. A Study of the Process and its Principles. Rodale Press, Emmaus.

Gouin, F.R., 1998. Using compost in the horticulture industry. In: Brown, S., Angle, J.S., Jacobs, L. (Eds.), Beneficial Co-Utilization of Agricultural, Municipal and Industrial By-products, Kluwer Academic Publishers, Boston, pp. 131–138.

Hadas, A., Kautsky, L., Portnoy, R., 1996. Mineralization of composted manure and microbial dynamics in soil as affected by long-term nitrogen management. Soil Biology and Biochemistry 28, 733–738.

Hodges, R.D., 1991. Soil organic matter: its central position in organic farming. In: Wilson, W.S., (Ed.), Advances in Soil Organic Matter Research: the Impact on Agriculture and the Environment, The Royal Society of Chemistry, Redwood Press, UK, pp. 355–364.

Hoitink, H.A.J., Boehm, M.J., 1999. Biocontrol within the context of soil microbial communities: a substrate-dependent phenomenon. Annual Review of Phytopathology 37, 427–446.

Hsu, J.-H., Lo, S.-L., 1999. Chemical and spectroscopic analysis of organic matter transformations during composting of pig manure. Environmental Pollution 104, 189–196.

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

Inbar, Y., Chen, Y., Hadar, Y., 1989. Solid-state carbon-13 nuclear magnetic resonance and infrared spectroscopy of composted organic matter. Soil Science Society of American Journal 53, 1695–1701.

Inbar, Y., Hadar, Y., Chen, Y., 1993. Recycling of cattle manure: the composting process and characterization of maturity. Journal of Environmental Quality 22, 857–863.

Johnson, A., Purvis Thurow, A., Vietor, D., 1998. Dairy manure management: an application of probabilistic risk assessment. Journal of Environmental Quality 27, 481–487.

Jongbloed, A.W., Lenis, N.P., 1998. Environmental concerns about animal manure. Journal of Animal Science 76, 2641–2648.

Keener, H.M., Elwell, D.L., Ekinci, K., Hoitink, H.A.J., 2001. Composting and value-added utilization of manure from a swine finishing facility. Compost Science and Utilization 9, 312–321.

Kowalchuk, G.A., Naoumenko, Z.S., Derikx, P.J.L., Felske, A., Stephen, J.R., Arkhipchenko, I.A., 1999. Molecular analysis of ammonia-oxidizing bacteria of the beta subdivision of the class Proteobacteria in compost and composted materials. Applied and Environmental Microbiology 65, 396–403.

Levanon, D., Pluda, D., 2002. Chemical, physical and biological criteria for maturity in composts for organic farming. Compost Science and Utilization 10, 339–346.

Mills, H.A., Jones, J.B. Jr., 1996. Plant Analysis Handbook II. Micro–Macro Publishing, Jefferson City.

Moller, H.B., Sommer, S.G., Andersen, B.H., 2000. Nitrogen mass balance in deep litter during the pig fattening cycle and during composting. Journal of Agricultural Science, Cambridge 135, 287–296.

Ouatmane, A., Provenzano, M.R., Hafidi, M., Senesi, M., 2000. Compost maturity assessment using calorimetry, spectroscopy and chemical analysis. Compost Science and Utilization 8, 124–134.

Pang, X.P., Letey, J., 2000. Organic farming: challenge of timing nitrogen availability to crop nitrogen requirements. Soil Science Society of America Journal 64, 247–253.

Rynk, R.M., 1992. On-Farm Composting Handbook. Northeast Regional Agricultural Engineering Service (NRAES) 54. Cornell University, Ithaca.

Scaglia, B., Tambone, F., Genevini, P.L., Adani, F., 2000. Respiration index determination: dynamic and static approaches. Compost Science and Utilization 8, 90–99.

Stone, A.G., Traina, S.J., Hoitink, H.A.J., 2001. Particulate organic matter composition and Pythium damping-off of cucumber. Soil Science Society of America Journal 65, 761–770.

Thompson, W., Leege, P., Millner, P., Watson, M.E., 2003. Test Methods for the Examination of Composts and Composting. The US Composting Council, US Government Printing Office http://tmecc.org/tmecc/index.html

Weppen, P., 2002. Determining compost maturity: evaluation of analytical properties. Compost Science and Utilization 10, 6–15.

Woods End Research Laboratory, 1999. Guide to Solvita® Testing For Compost Maturity Index. Woods End Research Laboratory Inc. P.O. Box 207, Mt. Vernon, ME 04352.

Zucconi, F., Pera, A., Forte, M., de Bertoldi, M., 1981. Evaluating toxicity in immature compost. Biocycle 22, 54–57.