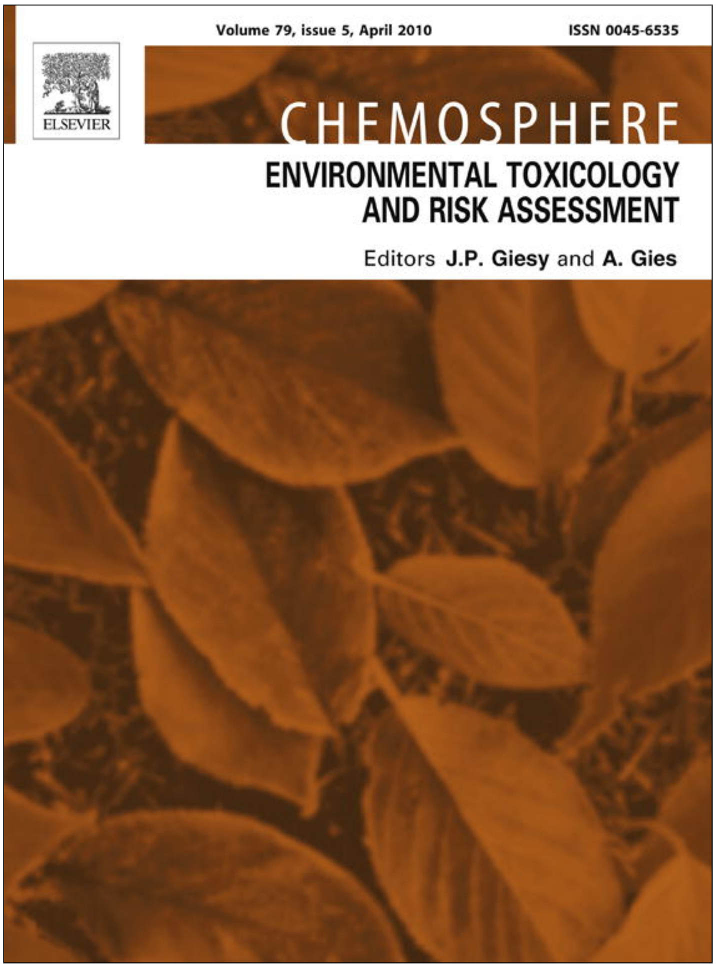
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Reduction of compost phytotoxicity during the process of decomposition

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ABSTRACT

Hog manure from windrows composted at different operating strategies was used in a bioassay to determine phytotoxicity. Twelve windows that differed in composting strategies (i.e. turning frequency and moisture content adjustment) were built. The effects of hog manure water extracts on seed germination and primary root growth of cress (*Lepidum sativum* L.) was measured. The germination index (GI, a product of relative seed germination and root elongation) was related to the chemical characteristics (electrical conductivity, nitrogen compounds, C:N ratio, heavy metals and humification parameters) of the hog manure. The water-extractable chemical properties of the hog manure that showed the highest negative correlation with GI were extractable Cu, extractable Zn and NH_4^+N, demonstrating that these chemical compounds gradually decrease during composting due to transformation to other compounds and immobilization effects. A GI > 80 (an indicator of the disappearance of phytotoxicity) was reached when the concentrations of NH_4^+–N, extractable Cu, and extractable Zn were $\leqslant 2$ g kg^{-1}, $\leqslant 15$ mg kg^{-1}, and $\leqslant 15$ mg kg^{-1}, respectively. Multiple regression analysis revealed that NH_4^+–N was the most important factors affecting the phytotoxicity of the hog manure. Composting strategies employed affected the speed of composting, time of maturation, and disappearance of phytotoxicity. The disappearance of phytotoxicity corresponded with the time of maturation of the hog manure. If optimum composting conditions (windrows turned every 4 d with weekly moisture adjustment to 60%) are met, phytotoxicity disappears within 56 d.

1. Introduction

Hog manure has properties comparable to the conventional manure compost, with high concentrations of organic matter and nutrients (Tiquia et al., 2000a, 2002; Tiquia, 2003). It can be re-utilized as a resource material such as soil fertilizer, conditioner, or both. However, care must be taken in its use, and it is necessary to understand the characteristics of the end product (composted product) in order to avoid any undesirable effects. One of the problems associated with the use of hog manure is that it often contains high concentrations of heavy metals (Cu and Zn, in particular) (Hsu and Lo, 2001; Cang et al., 2004), salts (Tiquia, 2003; Yao et al., 2007), and an excess of ammonium (Jongbloed and Lenis, 1998; Tiquia et al., 2000a). Other negative effects such as excess accumulation of organic acids, phenolic substances, ethylene, and ammonia are often present during decomposition of immature manure (Wong et al., 1983; Tiquia et al., 2000b, 2001; Tiquia, 2003; Gomez-Brandon et al., 2008). Thus, maturity is one of the most important aspects of compost quality, particularly if the hog manure were to be used in high-value horticultural applications. A process such as composting can contribute to the maturity and ultimate reduction of these phytotoxic compounds.

The operating strategies (i.e. turning frequency, moisture content adjustment) are likely to influence the composting process and the speed of maturation. Oxygen supply is of primary importance in any composting process and if composting is to proceed rapidly, an adequate oxygen supply must be maintained so that it does not become a limiting factor. In windrow composting, aeration is often provided by turning the windrow, and during turning, abrasion of particles can occur, exposing new surfaces for microbial attack and thereby speeding the composting process (Tiquia, 2005). Moisture content is also a critical factor since it affects gaseous exchange and bacterial growth and activities. The optimal turning frequency and moisture however vary significantly depending on the composition of the initial material (Epstein, 1997; Liang et al., 2003; Tiquia et al., 2000a, 2005).

In order to guarantee that the hog manure be re-cycled back to agricultural land, without causing any environmental risks, a quick method to evaluate its phytotoxicity is essential. In the present study, the toxicity of the hog manure at various stages of decomposition, and the impact of different composting strategies on phytotoxicity reduction were examined. Garden cress (*Lepidum sativum* L.) seeds were chosen as test species to determine the phytotoxicity of hog manure collected during in situ

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and windrow composting. Garden cress seeds were found to be most sensitive to toxicity of sewage sludge (Houdaji et al., 2003; Dubova and Zarin, 2004), refuse composts (Devleeschauwer et al., 1981), chicken litter-green manure (Yetilmezsoy and Sapci-Zengina, 2009), food wastes (Aslam et al., 2007), municipal solid wastes (Said-Pullicino et al., 2007), olive-mill wastes (Alburquerque et al., 2006), and soils contaminated with heavy metals (Dubova and Zarin, 2004). An attempt was also made to correlate the some chemical properties hog manure on seed germination and root elongation, and to establish chemical parameters that can be used as indicators of phytotoxicity.

2. Materials and methods

2.1. Composting process

To determine the effect of windrow composting on the elimination of phytotoxicity in the hog manure, a windrow composting experiment was carried out. A total of 12 heaps, about 2 m in diameter at the base and 1.5 m in height were built. The windrows were composted in a composting shed. The composting strategies used in these study were based on those used by several compost operators and livestock farmers, and on that reported in the literature (Rynk et al., 1992; Epstein, 1997). During composting, air temperature and windrow temperatures at a depth of 60 cm were monitored, after turning. Temperatures were taken twice a week during composting. Five temperature readings were taken from each windrow. The windrows were turned using a front-end truck loader. Windrow 1 was turned every 2 d and the rest were turned every 4 d during the process. At the beginning of composting, the moisture content of the windrows was adjusted to 50–70%. Moisture contents of windrows 4, 5, and 6 were adjusted to 50%, 60%, and 70%, respectively on days 15, 32, and 63, whereas those of windrows 9 and 11 were adjusted to 60% weekly until the end of composting. Water was added to these windrows to adjust the moisture to their designed values. The weight, density, and moisture content of each windrow were considered in calculating the amount of water needed to adjust the moisture content of the hog manure to the desired values. No further adjustment in moisture content was carried out in windrows 1, 2, 3, 7, 8, 9 and 11 after the initial moisture adjustment at day 0.

The composting trial was terminated between 74 and 126 d, when compost temperatures declined to ambient level. Samples were collected at five random locations in each windrow at day 0 and then weekly until the end of composting. These five samples were combined and mixed to generate a composite sample. Triplicate composite samples were taken from each windrow for chemical and microbial analyses.

2.2. Preparation of hog manure extracts and phytotoxicity assay

Aqueous hog manure extracts were prepared by shaking the samples with distilled water at 1:10 w/v ratio using a horizontal shaker for 1 h, and then filtered using a filter paper (Whatman # 42). The phytotoxicity bioassay was evaluated using the seed germination technique (Zucconi et al., 1981a,b). This method involves incubating the compost extract with seeds at 22 °C for 5 d in the dark, and then measuring the number of seeds germinated and root growth thereafter. After 5 d of incubation in the dark, the seed germination and root length of the five plants in the extracts were determined. The seed germination percentage and root elongation of the plants in deionized water were also measured and used as the control. A 5-mm primary root was used as the operational definition of seed germination (USEPA, 1982). This means that if the root was $\geqslant$5 mm, germination was positive. The relative seed germination, relative root elongation and germination index (GI, the product of relative seed germination and relative root elongation) were calculated as follows:

$$\text{Relative seed germination (\%)} = \frac{\#\text{ of seeds germinated in litter extract}}{\#\text{ of seeds germinated in control}} \times 100$$

$$\text{Relative root growth (\%)} = \frac{\text{Mean root length in litter extract}}{\text{Mean root length in control}} \times 100$$

$$\text{Germination index (GI)} = \frac{(\%\text{ Relative seed germination}) \times (\%\text{ Relative root growth})}{100}$$

2.3. Chemical analysis of hog manure samples

The hog manure samples were analyzed for concentrations of total (HNO_3^-) and water-extractable Cu and Zn (atomic absorption spectrophotometry); total C and N (CHN analyzer); NH_4^+–N, and (NO_3^- + NO_2^-)–N (KCl extract); and electrical conductivity (EC) (1:5 litter:water extract) using a conductivity electrode. The humic (HA) and fulvic (FA) acid fraction of the hog manure was analyzed using a precipitation method (Swift, 1996). Hog

Table 1
Temperature characteristics of the hog manure at different stages of composting.

Windrows	Temperature characteristics[a]					
	Initial temperature (°C)	Time to reach 55 °C (d)	Time to reach >55 °C (d)	Peak temperature (°C)	Time to reach peak temperature (d)	Duration of thermophilic phase (d)	Time to drop to ambient level (30–35 °C) (d)
1	48	4	5	63	15	22	60
2	51	2	4	65	21	28	64
3	48	2	4	64	21	28	126
4	50	2	4	69	4	45	91
5	44	2	4	69	7	45	91
6	48	2	4	59	7	17	64
7	40	4	4	57	14	14	91
8	31	4	4	63	4	14	64
9	31	4	5	62	17	20	91
10	31	4	9	64	10	20	56
11	32	4	9	58	14	24	56
12	31	4	9	63	10	20	56
Range	31–51	2–4	4–9	57–69	4–21	20–45	56–126

[a] Windrow temperatures were taken at a depth of 60 cm in each windrow twice a week. Five temperature readings were taken from each windrow.

manure samples were diluted with NaOH (0.1 M) in a conical flask and the air inside was displaced with N_2. The conical flask was stoppered and shaken at 200*g* at 23 °C for 24 h. After 24 h, the supernatant, which is the humic material fraction or humus extract, was separated by centrifugation at 2000*g* for 10 min. The precipitate was washed with distilled water and separated by centrifugation. The supernatant fraction, which is a combination of alkaline extracts and the washings, was collected and acidified to pH 2 using HCl. The sample was allowed to stand at room temperature for 24 h, and then acidified. The supernatant was the FA-like fraction and the precipitate was the HA-like. Both fractions were dried and weighed. The HA- and FA-like substances were calculated based on g HA or FA per kg OM. All chemical properties, with the exception of EC, were calculated on 105 °C dry weight basis.

2.4. Statistical analyses

Pearson Product Moment correlation coefficients were computed to show relationship between phytotoxicity assays and chemical properties of the hog manure during windrow composting. A stepwise multiple regression analysis was performed to determine the most important chemical factors inhibiting growth of *L. sativum* L. All statistical analyses were based on the procedures described by Zar (2009).

3. Results

3.1. The composting process

The temperature profile of each windrow was unique for each composting treatment (Table 1). Initial compost temperatures ranged from 31 to 51 °C. As composting proceeded, these temperatures increased rapidly. By days 2–4, compost windrows reached thermophilic temperature (55 °C). Highest peak temperature was observed in windrows 4 and 5, and this peak temperature was reached within a shorter period of time (4–7 d) compared with the rest of the windrows, which took 10–21 d. Temperatures in windrows 4 and 5 approached >65 °C and had the longest (45 d) duration of thermophilic phase (>55 °C) (Table 1). The time to reach ambient level varied significantly among different windrows. Windrow 3 (50% initial moisture, no moisture adjustment, turned once a week) took 126 d to reach ambient temperature. Windrows 10–12 (60% moisture, turned twice a week) took 56 d to reach ambient level (Table 1).

Table 2
Variation of the chemical constituents of the initial and composted hog manure.

Windrows	Chemical properties[a]													
	C:N ratio		EC (mS cm^{-1})		Total Cu (μg g^{-1})		Total Zn (μg g^{-1})		HA (g kg^{-1} OM)		FA (g kg^{-1} OM)		HA:FA ratio	
	Initial	Mature	Initial	Mature	Initial	Mature	Initial	Mature	Initial	Mature	Initial	Mature	Initial	Mature
1	26	26	3.00	2.00	550	636	790	730	31.6	41.1	109.2	109.9	0.29	0.37
2	26	26	1.95	2.40	550	630	600	650	34.7	42.8	113.5	103.9	0.31	0.41
3	21	22	1.90	3.25	500	660	695	930	37.2	37.9	118.0	105.0	0.32	0.36
4	27	19	1.80	2.30	460	530	610	790	27.0	45.0	105.1	97.6	0.26	0.46
5	24	19	1.50	2.60	450	585	590	850	27.4	42.8	114.0	107.9	0.24	0.40
6	27	21	1.20	1.30	420	580	580	850	25.2	37.3	112.4	114.6	0.22	0.33
7	20	24	2.60	3.25	460	560	700	550	34.0	60.0	75.0	79.0	0.45	0.76
8	27	25	2.85	3.20	470	540	610	750	24.0	60.0	73.0	100.0	0.33	0.60
9	20	16	2.80	3.40	495	590	710	770	30.8	77.5	72.2	71.8	0.43	1.08
10	17	12	2.60	2.40	490	550	705	740	29.8	89.7	69.7	80.3	0.43	1.12
11	20	16	2.70	2.80	485	550	625	720	33.1	83.5	72.2	70.9	0.46	1.18
12	18	14	2.70	2.30	460	550	620	700	20.7	85.7	70.8	70.9	0.29	1.21
Range	17–27	12–26	1.20–3.00	1.30–3.40	420–550	530–660	530–660	650–930	20.7–34.7	37.3–89.7	69.7–118.0	70.9–114.6	0.22–0.46	0.33–1.21

HA = humic acid; FA = fulvic acid; OM = organic matter.
[a] Samples were collected at five random locations of the windrows after turning. These five samples were combined and mixed to generate one composite sample. Means of three composite samples from each windrow are shown. Final data refer to that time point mentioned in Table 3. Data shown are based on 105 °C dry weight.

Table 3
Simple correlation coefficient values between GI and chemical properties of the hog manure.

Windrows	Germination index (GI)[a]									
	Total Cu	Ext. Cu	Total Zn	Ext. Zn	NH_4–$^+$N	NO_x^- N	EC	C:N ratio	HA	FA
1	0.78*	−0.86***	−0.78*	0.76*	−0.96***	0.76*	0.67	−0.87***	0.70*	0.12
2	0.85***	−0.87***	0.57	0.85***	−0.90***	0.84**	0.42	−0.70*	0.68	−0.31
3	0.78*	−0.86***	0.39	0.86***	−0.89***	0.86***	0.85**	−0.14	−0.47	−0.43
4	0.58	−0.75*	0.71*	0.51	−0.84**	0.87***	0.49	−0.82***	0.70*	−0.62
5	0.30	−0.64	0.43	0.48	−0.79*	0.75**	0.60	−0.33	0.45	−0.63
6	0.58	−0.91***	0.43	0.44	−0.87***	0.85***	−0.04	−0.72*	0.49	−0.07
7	0.80**	−0.79*	−0.81**	−0.83***	−0.89***	0.72**	0.19	−0.66	0.86***	0.96***
8	0.62	−0.74*	−0.29	−0.74***	−0.86***	0.71**	0.39	−0.78**	0.78*	0.17
9	0.89***	0.87***	0.23	0.90***	−0.92***	0.78*	0.93***	−0.83***	0.85***	0.64
10	0.57	0.75*	−0.31	0.76*	−0.77*	0.72*	−0.44	−0.88***	0.77*	0.40
11	0.59	0.80**	0.20	0.85**	−0.90***	0.77*	0.34	−0.78*	0.77*	0.70*
12	0.58	0.75*	0.26	0.75*	−0.81**	0.67	−0.65	−0.65	0.75*	0.23

*, **, and *** indicate correlation was significant at 0.05, 0.01 and 0.001 probability levels, respectively. Negative correlation means germination goes down as concentration of chemical parameter goes up. Ext. Cu = water-extractable Cu; Ext. Zn = water-extractable Zn; NO_x^- N = NO_3^- + NO_2^- N; HA = humic acid; FA = fulvic acid.
[a] Correlations were based on 24 observations (eight composting period × three replicates).

3.2. Chemical profiles

The C:N ratio, EC, total Cu, Zn, HA, FA and HA:FA ratio were influenced by differences in the components of the initial compost material and composting strategy (Tables 1 and 2). At the beginning of composting, there was a wide variation in the concentration of these parameters across the different windrows (Table 2). The C:N ratio varied between 17 and 27; the EC between 1.2 and 3.0 mS m^{-1}; the total Cu contents between 420 and 550 mg kg^{-1}; total Zn contents between 530 and 660 mg kg^{-1}; HA contents between 20.7 and 34.7 g kg^{-1} O.M; FA contents between 69.7 and 118.0 7 g kg^{-1} O.M; and HA:FA ratios between 0.22 and 0.46 (Table 3). At the end of composting, these parameters decreased with the exception of FA contents, which had very little change (Table 2). During composting, HA contents of the hog manure evolved and become predominant

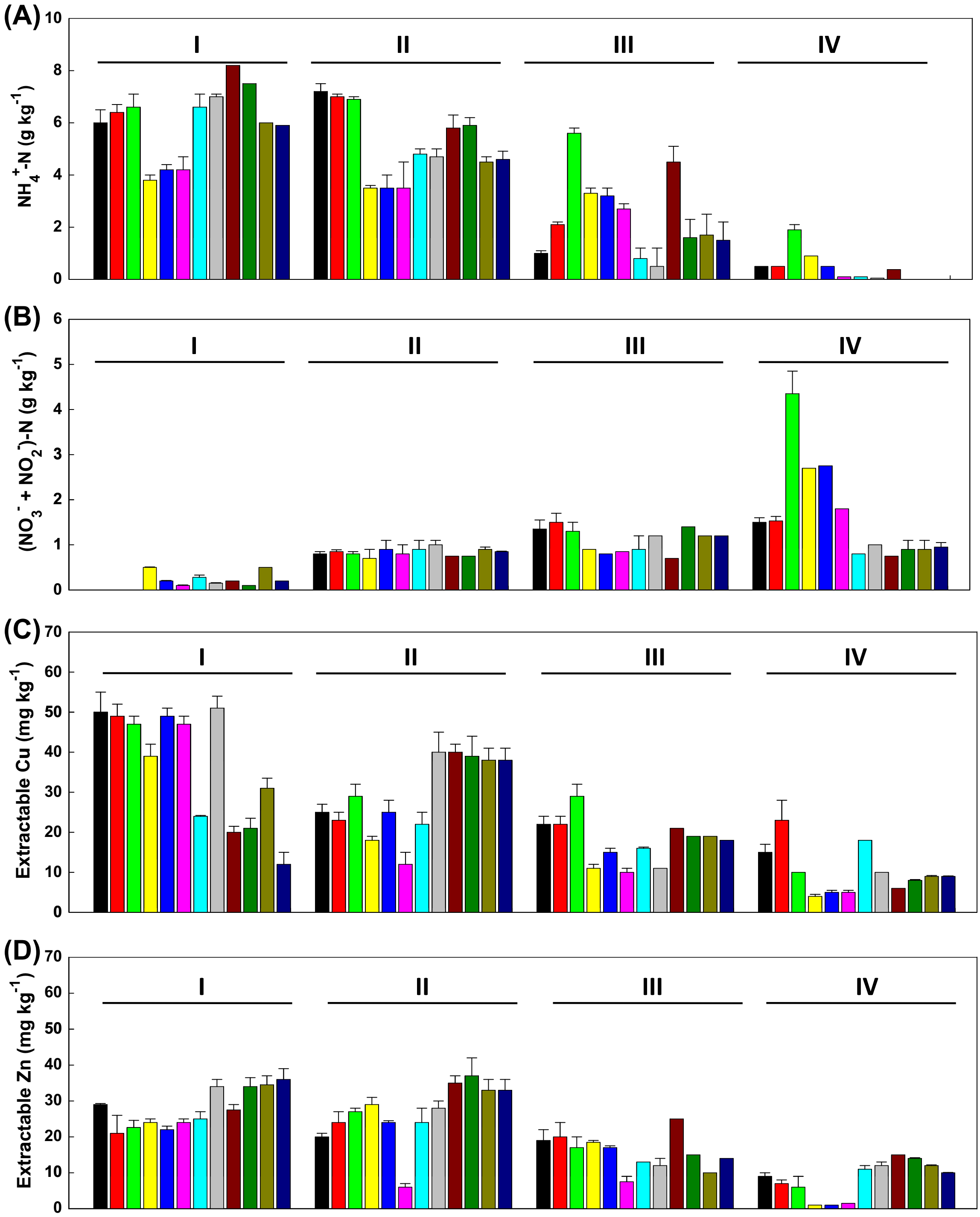

Fig. 1. Changes in concentrations of (A) NH_4^+–N, (B) (NO_3^- + NO_2^-)–N, (C) water-extractable Cu, and (D) water-extractable Zn of the 12 windrows at different phases of composting. Mean of three composite samples are shown. Initial phase (1) = day 0, windrow temperatures ranged from 31 to 51 °C; thermophilic phase (II) = days 20–45, windrow temperatures range from 55–69 °C; cooling phase (III) = days 21–120, windrow temperature ranging from 40 to 50 °C; mature phase (IV) = days 56–126, windrow temperatures ranged 28–35 °C. (■) Pile 1; (■) Pile 2; (■) Pile 3; (■) Pile 4; (■) Pile 5; (■) Pile 6; (■) Pile 7; (■) Pile 8; (■) Pile 9; (■) Pile 10; (■) Pile 11; (■) Pile 12.

over FA. Greatest increase in HA contents was observed in windrows 10–13 (Table 2). HA:FA ratios in windrows 9–12 increased over 80% at the end of composting, whereas windrows 1–5 increased only between 28% and 50%. These results suggest that the degree of humification in windrows 9–12 was higher than windrows 1–5 (Table 2). Decrease in NH_4^+–N content to low levels was associated with the accumulation of (NO_3^- + –NO_2^-)–N (Fig. 1A and B) via the nitrification process. On the other hand, the decline in water-extractable Cu and Zn coincided with increases (Fig. 1C and D) in humification parameters (HA and FA) (Table 2).

3.3. Phytotoxicity assays

The germination indices (GI) obtained for each windrow clearly demonstrated a trend of decreasing phytotoxicity with composting time. Both seed germination and root elongation of *L. sativum* L. were severely retarded (GI = 0 to 43), indicating that severe toxicity occurred in the hog manure at the beginning of composting. Extreme plant growth retardation was observed from manure extracts obtained from windrows 9–12. The extracts from these windrows damaged the seeds and thus showed no GI values on *L. sativum* L. As composting proceeded, GI increased and reached 80 to 100 at the termination of composting (Fig. 2). Interestingly, the manure extracts that caused the most severe plant growth retardation showed the greatest reduction of phytotoxicity (GI > 95). These manures were obtained from windrows (windrows 9 and 11) that received weekly moisture adjustment to 60%.

4. Discussion

Phytotoxicity or poor plant response can result from several factors from lack of oxygen due to high microbial activity, the accumulation of toxic compounds (i.e. organic acids), the immobilization of nitrogen with high C:N ratio, high ammonia concentration, and the presence of heavy metals and mineral salts (Epstein, 1997). Most of these factors influence seed germination simultaneously and it is difficult to assess which parameter determines the greatest influence. Hog manure often contained high concentrations of Cu and Zn compared with other animal manures, since they are normally added to hog diets and are voided in the feces (Hanharam and O'Grady, 1968). The maximum concentration of total Cu and Zn were 660 and 930 $\mu g\ g^{-1}$, respectively (Table 2). Because of the relatively high amount of organic compounds (Tiquia, 2003), most of these metals bind to the organic compounds and are not bioavailable (Walker et al., 2004). Hog manures also contained high concentrations of nitrogenous compounds, as excess dietary N is often excreted in the urine (Tiquia et al., 2000b, 2002). Some of these compounds are lost through ammonia volatilization, and some are transformed via a number of microbially mediated processes (ammonification, immobilization, nitrification, and denitrification) (Tiquia, 2002). The immobilization of nitrogen with high C:N ratio and high ammonia concentration contribute to compost phytotoxicity (Epstein, 1997).

Unlike the results of other phytotoxicity experiments, C:N ratio and EC appeared not to be inversely affecting seed germination and root growth. Composts with high C:N ratio can cause nitrogen immobilization upon amendment to soil (Hoitink and Boehm, 1999) and those with low C:N ratio can cause ammonium toxicity (Epstein, 1997). Researchers have suggested various ideal C:N ratios ranging from 12 to 25 (Jimenez and Garcia, 1992; Erhart and Burian, 1997; Tiquia and Tam, 2000; Brewer and Sullivan, 2003). In the present study, the C:N ratios of the hog manures are within acceptable levels (between 12 and 27) although decreases in C:N ratios during composting corresponded in increases in GI (Tables 2 and 3). EC, on the other hand, measures the concentration of soluble ions or the salinity of the compost. Excessive salinity in compost can cause phytotoxicity directly, depending on the salt tolerance of the plant species (Mengel et al., 2001). Salinity also can develop from nitrogen mineralization and production of organic acids (Epstein, 1997). In general, salinity effects are mostly negligible in extracts with EC readings of 2 $mS\ cm^{-1}$ or less (Mengel et al., 2001). Iannotti et al. (1994) reported that for L. *sativum* L. bioassays, salinity of the water extracts that had an EC values of >10 $mS\ cm^{-1}$ were responsible for compost phytotoxicity. The EC of the hog manure in the present study ranged from 1.2 to 3.4 $mS\ cm^{-1}$ (Table 2), which implies that the concentrations of soluble salts were in the range considered non-phytotoxic or marginally phytotoxic for the germination tests.

The inhibitory effects in plant growth may be attributed to some characteristics of the hog manure water extracts. Tiquia and Tam (1998) found a curvilinear relationship between GI and the water-extractable chemical properties of hog manure and sludge. They reported that the changes in the GI values are strongly dependent on the water-extractable chemical properties of the compost material. The water-extractable chemical parameters showing the highest negative correlation with GI were extractable Cu, extractable Zn, and NH_4^+N (Table 3). It has been known that metals cause a marked delay in germination, and that they can inhibit plant growth severely (Munzuroglu and Geckil, 2002). Ammonium also appears to inversely affect root growth (Wong

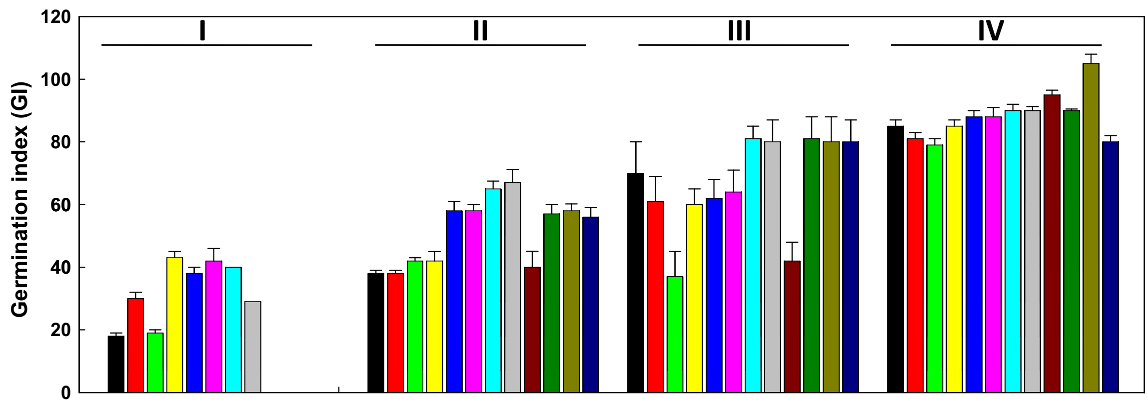

Fig. 2. Germination indices (GI) of *Lepidum sativum* in hog manure extracts from the 12 windrows at different phases of composting. Mean of three composite samples are shown. Initial phase (I) = day 0, windrow temperatures ranged from 31 to 51 °C; thermophilic phase (II) = days 20–45, windrow temperatures range from 55 to 69 °C; cooling phase (III) = days 21–120, windrow temperature ranging from 40 to 50 °C; mature phase (IV) = days 56–126, windrow temperatures ranged 28–35 °C. (■) Pile 1; (■) Pile 2; (■) Pile 3; (■) Pile 4; (■) Pile 5; (■) Pile 6; (■) Pile 7; (■) Pile 8; (■) Pile 9; (■) Pile 10; (■) Pile 11; (■) Pile 12.

Table 4
Multiple regression analysis of the phytotoxicity assays and water-extractable properties of the spent hog litter.

Windrows	Multiple regression equation[a]	Multiple R value	Adjusted R^2 value	F value	Significance of F
1	GI = 93.56 − (6.85 ∗ NH_4) − (0.49 ∗ Ext. Cu)	0.98	0.96	98.14	<0.0001
2	GI = 101.54 − (8.06 ∗ NH_4)	0.87	0.72	24.68	0.0011
3	GI = 98.84 − (6.06 ∗ NH_4) − (.92 ∗ Ext. Cu)	0.95	0.87	31.79	0.0005
4	GI = 66.2 − (7.25 ∗ NH_4) + (3.67 ∗ Ext. Cu)	0.99	0.97	104.70	0.0004
5	GI = 123.9 − (14.8 ∗ NH_4) + (0.59 ∗ Ext. Cu)	0.96	0.88	24.00	0.0059
6	GI = 127.1 − (7.30 ∗ NH_4) − (0.24 ∗ Ext. Cu)	0.99	0.97	83.70	0.0005
7	GI = 119.2 − (4.09 ∗ NH_4) − (1.86 ∗ Ext. Zn)	0.99	0.98	220.1	<0.0001
8	GI = 120.7 − (4.19 ∗ NH_4) − (1.97 ∗ Ext. Zn)	0.89	0.70	26.00	<0.0099
9	GI = 105.38 − (13.78 ∗ NH_4)	0.97	0.94	114.60	<0.0001
10	GI = 103.68 − (3.78 ∗ NH_4)	0.74	0.46	7.06	0.0377
11	GI = 94.43 − (12.02 ∗ NH_4)	0.91	0.79	27.75	0.0019
12	GI = 115.16 − (10–11 ∗ NH_4)	0.82	0.62	12.50	0.0123

GI = germination index; Ext. Cu = water-extractable Cu; Ext. Zn = water-extractable Zn; NH_4 = NH_4^+–N.
[a] Regression equation was based on five water-extractable chemical parameters with STEPWISE METHOD (probability to F-enter) = 0.050 limit; NS = not significant at PIN = 0.05 limit.

et al., 1983; Tiquia and Tam, 1998). As the concentrations of extractable Cu, extractable Zn and NH_4^+N decreases with composting, the GI increases. Zucconi et al., 1981a,b), and Tiquia and Tam, 1998 used a GI value of ⩾80 as an indicator of the disappearance of phytotoxicity in composts In this study, such value was reached when the chemical concentrations were: ⩽2 g kg^{-1} for NH_4^+–N, ⩽15 mg kg^{-1} water-extractable Cu, ⩽15 mg kg^{-1} for water-extractable Zn, and (Fig. 1A, C and D). Increases in $(NO_3^- + NO_2^-)$–N to ~1.0 g kg^{-1} exerted a positive influence on the GI (Fig. 1B). When these values were reached during composting, the phytotoxicity of the hog manure, in terms of these chemicals, was eliminated. Results of the multiple regression analysis demonstrated that NH_4^+–N was the most important chemical factor affecting phytotoxicity of L. *sativum* L. (Table 4). The large retarding effect of NH_3 found in this study, was due to excess of dietary N excreted via urine. This study however, demonstrated that the toxicity of the manure with respect to NH_4^+–N can reduced or eliminated by composting.

Despite the differences in composting strategies (i.e. turning frequency, moisture adjustment) applied to windrows, the composting process went through predictable changes in temperature and chemical components. Composting strategies employed in this study affected the speed of composting, time of maturation, and disappearance of phytotoxicity (Table 1). For instance, it took 126 d for pile 3 to drop to ambient level; 91 d for windrows 4, 5, 7 and 9; 67 d for windrows 2, 6, and 8; 60 d for pile 1; and 56 d for piles windrows (Table 1). For efficient composting, moisture content must be maintained weekly at 60% with a 4-d turning frequency. The disappearance of phytotoxicity corresponded with the time of maturation of the hog manure. When optimum composting conditions (windrows turned every 4 d and weekly moisture content adjusted to 60%) are met, phytotoxicity disappears within 56 d.

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