Environmental Technology, Vol. 24. pp 97-107
© Selper Ltd, 2003

EVALUATION OF ORGANIC MATTER AND NUTRIENT COMPOSITION OF PARTIALLY DECOMPOSED AND COMPOSTED SPENT PIG LITTER

S. M. TIQUIA*

Environmental Sciences Division, Oak Ridge National Laboratory, Building 1505, Oak Ridge, Tennessee 37831, USA

(Received 6 May 2001; Accepted 10 June 2002)

ABSTRACT

Characterization of soil-applied organic material is necessary in order to clarify the nature of the organic matter and nutrients in it. In this study, the organic matter and nutrient contents of the spent pig litter (a mixture of partially decomposed pig manure and sawdust) was characterized before and after windrow composting to: (1) determine their changes during composting, and (2) assess the suitability of the composted spent litter as a soil amendment. Results demonstrated that the time required to reach maturity, and the composition of composted spent litter, depended on the chemical properties of the initial compost feedstock as well as the compost strategies used during composting. Total N, P, and K concentrations of the composted litter depended on chemical properties of the initial material. On the other hand, C:N ratio, humic and fulvic acid and cation-exchange capacity were influenced by differences in composition of the initial spent litter and composting strategy. If moisture content was maintained weekly at 60% with a four-day turning frequency, the litter reached maturity in 56 days. Maturation of spent litter was accompanied by a decline in total C, water-extractable metals, NH_4^+-N, increase in ash, $(NO_3^-+NO_2^-)$-N, humic acid, humic acid:fulvic acid ratio, and cation exchange capacity, and elimination of phytotoxicity. The stability of nutrient and organic matter, acceptable pH and electrical conductivity values, and low levels of undesirable components such as heavy metals and phytotoxic compounds of the spent litter provided substantial evidence that agronomically suitable compost can be obtained after composting in windrows.

Keywords: Cation-exchange capacity, compost maturity, decomposition, humic acid, deep litter system

INTRODUCTION

The standard method of raising pigs in Hong Kong is on concrete or slatted floors. The excreta are then hosed down to nearby water courses and streams. This practice is convenient but creates a serious pollution concern. In 1987, the Agriculture and Fisheries Department of Hong Kong initiated the pig-on-litter system, where pigs are raised on a litter bedding material (sawdust mixed with a commercial bacterial product) [1]. The pig excreta, once deposited, are quickly mixed with the litter bedding and are decomposed *in situ*. The bulking agent (sawdust) in the pen, and the rapid decomposition of nitrogenous compounds lead to the eradication of offensive odor of ammonia. The *in situ* composting process that takes place within the bedding material is similar to the mesophilic composting process described by Golueke [2]. The POL system is a zero discharge method of waste treatment as neither wastewater nor effluent needs to be handled. The only waste requiring disposal is the spent pig litter (a mixture of partially decomposed pig manure and sawdust) after 10–13 weeks. The spent pig litter disposed from the POL system contains high concentrations of organic matter and nutrients, and can be re-utilized as a soil amendment [1]. Previous investigations have shown that the spent pig litter also possesses a significant portion of active microbial biomass [3]. Moreover, when the litter was stacked in windrow, a rise and fall in temperature was also observed [1], suggesting that the decomposition in the spent pig litter is incomplete, and that the litter could be similar to an immature compost. Previous research work has demonstrated that application of immature compost onto the soil causes negative effects on plant growth and development [4]. These effects occur because immature compost induces high microbial activity, which reduces oxygen concentration in the soil, and blocks the existing soil-available N, which gives rise to serious N deficiencies in crops [5]. These problems could be mitigated by chemically and biologically stabilizing soluble nutrients in the spent pig litter to more stable organic forms by composting before application to agricultural soils. Compost maturity and stability have been measured by a variety of methods including a drop in temperature, degree of self-heating capacity, oxygen consumption, phytotoxicity assays, cation-exchange capacity (CEC), and C:N ratio [6–10]. In the present study, these parameters were measured to assess the stability and maturity of the spent pig litter.

Characterization of soil-applied organic material such as the spent pig litter is also necessary in order to clarify the nature of organic matter and evaluate the availability of nutrients in it. From an environmental perspective, it is important to reliably determine the availability of nutrients so that the wastes can be diverted from landfill and recycled for use as soil amendment. This should benefit farmers because their efficient use could reduce mineral fertilizer requirements especially for N, P, and K. In this paper, the organic matter and nutrient composition of the spent pig litter was characterized in order to determine its suitability as a soil amendment.

MATERIALS AND METHODS

Composting Set-up and Sampling

The composting trials were conducted at Ta Kwu Ling Pig Breeding Center, New Territories of Hong Kong. Spent litter was collected from different pens where the POL system was employed (Table 1). The pens differed in the number of pigs, amount of sawdust, type of bacterial inoculum (i.e. Elimexal, Vitacogen, Biogreen, Odor control-organic fertilizer) and litter management (i.e. layering, mixing) (Table 1). However, the same feed type was fed to the pigs in the pig-on-litter system. A total of 9 pyramidal piles, about 2 m in width at the base and 1.5 m in height were built from the spent litter collected from four different pens (pens A–D) (Table 1). During composting, air temperature and temperature at a depth of 60 cm of the piles were monitored before turning. Pile 1 was turned every 2 days and the rest were turned every 4 days during the process (Table 2). At the beginning of composting, the moisture content of all piles was adjusted to 50–70%. Moisture contents of piles 3, 4, and 5 were adjusted to 50, 60, and 70%, respectively on days 15, 32, and 63, whereas those of piles 7 and 9 were adjusted to 60% weekly until the end of composting. No further adjustment in moisture content was carried out in piles 1, 2, 7, and 9 after the initial moisture adjustment at day 0. Samples were collected at 5 random locations in each of the 9 piles. These five samples were combined and mixed to generate a composite sample. Triplicate composite samples were taken from each pile.

Analytical Determination

The spent pig litter samples were analyzed for: pH (1:10 w/v litter:water extract) using a pH electrode; EC (1:5 w/v litter:water extract) using an electrical conductivity probe; Kjeldahl N [11]; total and Olsen-extractable P using the ascorbic acid method [12]; total and water-extractable K, Cu, and Zn (atomic absorption spectrometry); NH_4^+-N and $(NO_3^- + NO_2^-)$-N using distillation method [13]; and organic matter (OM), ash contents, and total organic C contents by loss on ignition (550°C for 5 h) [14]. The (OM) concentration of the spent pig litter was computed from the ash content:

$$\text{Ash content (g kg}^{-1}\text{)} = \frac{\text{ash weight of spent pig litter (g)}}{\text{dry weight of spent pig litter (kg)}}$$

$$\text{OM content (g kg}^{-1}\text{)} = 1000 - \text{ash content of spent pig litter (g kg}^{-1}\text{)}$$

Table 1. Description of the pigpens during pig rearing under the pig-on-litter system.

	Pens			
Pens	A	B	C	D
Size of pig pen (m^2)	32	30	40	30
Number of pigs	32	30	40	30
Age of pigs at start (days)	99	82	72	78
Raising period (days)	92	115	123	117
Litter management	Mixing	Layering	Layering	Layering
Total feed consumption‡ (Kg)	6545	8308	11910	9619
Total sawdust consumption (bags)	60	70	91	90
Bacterial product used	Elimexal	Vitacogen	no bacterial product added	Odor control (OC)-organic fertilizers (OF)
Composting pile†	1, 2	3, 4, 5	6,7	8,9

†Spent litter in piles 1 and 2 were collected from Pen A; spent litter in piles 3, 4, and 5 were collected from Pen B; spent litter in piles 6 and 8 was collected from Pen C; spent litter in piles 7 and 9 was collected from Pen D; ‡The feed contained a mixture of corn yellow, soya bean meal, fish meal, fat, and small amount of dicalcium phosphate, lysine, Tasmix 77 (with pre-mixed Cu and Zn), Tylan and Hygromix.

Table 2. Composting treatments and temperature characteristics of spent pig litter piles.

Composting treatments/ Temperature characteristics	Composting piles								
	Pile 1	Pile 2	Pile 3	Pile 4	Pile 5	Pile 6	Pile 7	Pile 8	Pile 9
Composting treatments									
Initial moisture (%)	50	50	50	60	70	60	60	60	60
Moisture adjustment	no	no	yes	yes	yes	no	yes	no	yes
Moisture adjustment frequency	-	-	days 15, 32, and 63	days 15, 32, and 63	days 15, 32, and 63	-	Week 1 y	-	Week 1 y
Turning frequency	Every 2 days	Every 4 days	Every 4 days	Every 4 days	Every 4 days	Every 4 days	Every 4 days	Every 4 days	Every 4 days
Temperature characteristics									
Initial temperature (°C)	48	51	50	44	48	31	31	32	31
Time to reach 55°C (days)	4	2	2	2	2	4	4	4	4
Time to reach > 55°C (days)	5	4	4	4s	4	5	9	9	9
Peak temperature (°C)	63	65	69	69	59	62	64	58	63
Time to reach peak temperature (days)	15	21	4	7	7	17	10	14	10
Duration of thermophilic phase (> 55°C) (days)	22	28	45	45	17	20	20	24	20
Time to drop to ambient level (30-35°C) (days)	60	64	84	91	67	91	56	56	56

The total organic C was estimated from the OM value using the conventional "Van Bemmelem factor" of 1.724. This factor is based on the assumption that soil OM contains 58% C [15]. The theoretical N concentration of the spent pig litter was calculated by adding Kjeldahl N concentrations with $(NO_3^-+NO_2^-)$-N concentrations. The C:N ratio was then based on the concentration of total organic C and total N.

The humic (HA) and fulvic (FA) acid fraction of the spent pig litter was analyzed using a precipitation method [16]. Spent pig litter 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 100 rpm 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 1000 rpm 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 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 fraction and the precipitate was the HA. Both fractions were dried and weighed. The HA and FA substances were calculated based on g HA or FA per kg OM.

The CEC of the spent pig litter was analyzed using the acid-washing method [17]. The spent pig litter was placed in sintered glass filter (3G3) fitted with a rubber tube and a pinchcock. Hydrochloric acid solution (0.05 M) was added to the litter and then stirred intermittently for 20 min. The sample was re-filtered using suction. Hydrochloric acid solution (0.05 M) was added once more and then filtered. The sample was washed with distilled water until the sample was free of chloride. A $Ba(OAc)_2$ solution adjusted to pH 7.0 was added and the sample was allowed to stand for 1 h. After 1 h, the sample was filtered and then washed with distilled water thoroughly. The $Ba(OAc)_2$ filtrate was combined with the washings and the mixture was titrated up to an inflection point with standard 0.05 M NaOH solution, using thymol blue as an indicator. A blank titration was carried out with the same quantity of $Ba(OAc)_2$ solution. The difference between the two titration values was equated with the proton released from the sample, which gave the CEC. The CEC was expressed in terms of meq 100 g^{-1}.

The phytotoxicity of the spent pig litter extracts (1:10 w/v compost:water extract) on four plant species namely, Chinese cabbage (*Brassica parachinensis*), Chinese spinach (*Amaranthus espinosus*), cucumber (*Cucumis sativus*), and tomato (*Lycopersicon esculentum*) was monitored using seed germination technique [18]. After 5 days of incubation in the dark, the seed germination percentage and root length of *B. parachinensis* in the extracts and deionized water (control) were determined. Finally, the germination index (GI) of the spent pig litter was calculated based on relative seed germination percentage and relative root elongation.

Statistical Analyses

One-way analysis of variance was performed to determined differences among 9 piles during the initial and final stages of composting. Significant differences among means were then compared using the Bonferroni test. A t-test was carried out to compare the difference between the initial and the final product. All statistical analyses were computed using the SYSTAT statistical computing package (SYSTAT version 9.0).

RESULTS AND DISCUSSION

Temperature Characteristics of the Compost Piles

The course of temperature changes in the compost pile was indicative of the progress of the decomposition process from the beginning to completion [19]. During composting, the degradable organic matter and nitrogenous compounds in the starting material are broken down by microorganisms. This process results in the release of heat, and so the temperature increases. By the end of composting, no more further decomposition is taking place, so the chemical properties of the compost material become stabilized. Consequently, no more heat would be released and therefore, the temperature drops to ambient level. Normally, the temperature inside the compost mass begins to rise immediately after piling, then the temperature increases rapidly to 55 to 65° C and remains at this level for about 2 to 3 weeks. Thereafter, the temperature slowly decreases and the material can be considered sufficiently stabilized when the declining temperature reaches the ambient level [20]. In the present study, the temperature characteristics for each pile were unique for each composting treatment (Table 2). Highest peak temperature (69° C) was observed in piles 3 and 4, and this peak temperature was reached within a shorter period of time (4 to 7 days) compared to the rest of the piles, which took 10 to 21 days. Golueke [19] noted that temperatures above 70° C can kill organisms most active in successful composting, and that the ideal temperatures should not exceed 60 to 65° C. Temperatures in piles 3 and 4 approached > 65° C and had the longest (45 days) duration of thermophilic phase (>55° C) (Table 2). The longer thermophilic phase could be attributed to the drying and wetting conditions that took place within the piles and subsequent turning, which stimulated the activities of microorganisms and thereby caused an increase in temperature and prolonged the thermophilic phase. Repeated wetting and drying conditions and subsequent turning of the piles break up aggregates in the piles and exposes new material for microbial attack [21]. In composting, microorganisms require a certain amount of water (50–70%) for their metabolic activities since water provides a medium for the transport of dissolved nutrients and waste products [20]. Therefore, when adequate moisture (50–70%) is added to the compost material, microbial activities are then stimulated. The subsequent turning of the piles causes particles to rub together, leading to the exposure of unattacked material [20], hence, the increase in temperature and prolonged thermophilic phase in the present study.

Organic Matter and Nutrient Contents

Differences in treatments in the POL system and composting strategies also affected the organic matter and nutrient composition of the composted product. The total N, P, and K concentrations of the composted spent pig litter piles varied significantly depending on the initial concentration of the initial material (partially composted spent pig litter) (Table 3). Spent pig litter piles with higher concentrations of N, P, and K also had higher concentration by the end of composting. Increases in total N, P, and K during composting were due to loss of C during composting [22]. The C:N ratio, HA, FA, and CEC were influenced by differences in the composition of the initial spent pig litter material and composting strategy. At the end of composting, there was a wide variation in the concentration of these parameters among different piles. The C:N ratio of all 9 piles varied between 10.7 and 27.4, HA content between 37.3 and 89.7 g kg^{-1} OM, FA content between 69.7 and 114.0 g kg^{-1} OM, and CEC between 68.4 and 115.5 meq 100 g^{-1} (Table 4).

Despite the differences in the OM and nutrient composition of the final product, the maturation of spent pig litter in all piles was accompanied by changes in C, ash, humification parameters (HA, and HA:FA ratio), nutrients, heavy metals, and elimination of phytotoxicity. Significant decreases in total C and NH_4^+-N (P <0.0001) during composting coincided with significant increases in ash and (NO_3^-+NO_2^-)-N contents (P <0.0001) of the spent pig litter (Tables 3 and 5). The decreasing trend in total C and NH_4^+-N and the increasing trend in ash and (NO_3^-+NO_2^-)-N content were the result of the nitrification process and oxidation of C to CO_2 by microorganisms during composting [23–24].

It has been suggested that a C:N ratio of 20:1 would reflect a satisfactory degree of compost maturity [25]. However, based on the results presented, this C:N ratio could not be used as an index of maturity of spent pig litter. The initial C:N ratio depended on the initial N contents of the spent pig litter (Tables 3 and 4). Spent pig litter with higher initial N content had a lower C:N ratio. The C:N ratio of the initial spent pig litter in piles 7 and 9 was lower than 20 (16.7 and 18.8, respectively) and that of piles 6 and 8 was around 20 (Table 4). At this stage, the spent pig litter in these piles was far from stabilization. Therefore a C:N ratio of 20 cannot be used as an index of compost maturity.

Humification parameters (HA and HA:FA ratio) have been widely used to assess the degree of decomposition in organic matter in the compost material and the stabilization of the mature product [26]. During composting the HA content of the spent pig litter evolved and became predominant over FA. The HA content increased from 20.7–34.7 g kg^{-1} OM to 37.3–89.7 g kg^{-1} OM while the FA had very little change (Table 4). The ratio of these two parameters has been used as an index of compost maturity [27]. However, the HA:FA ratio differs in various wastes but it generally increases to more than 80% during composting. Chen et al. [27] pointed out that an increase in HA:FA ratio to more than 80 indicates a high

Table 3. Mean concentrations of total organic C, ash, N, P, and K of the initial and composted spent litter.

Pen/Pile	C (g kg^{-1})		Ash (g kg^{-1})		N (g kg^{-1})		P (g kg^{-1})		K (g kg^{-1})	
	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted litter
A, 1	505	496^{ns}	129	145*	18.6	19.8^{ns}	18.0	20.4^{ns}	14.9	16.0^{ns}
	(0.6)†	(2.6)	(1.0)	(4.5)	(4.8)	(0.2)	(0.4)	(0.7)	(0.2)	(0.2)
A, 2	506	494^{ns}	127	149*	21.4	19.0^{ns}	17.6	19.9^{ns}	15.0	16.2^{ns}
	(5.8)	(0.3)	(10.0)	(0.3)	(0.6)	(0.1)	(0.2)	(1.9)	(0.6)	(1.1)
B, 3	525	508^{ns}	99	125*	19.5	27.1*	13.2	15.1^{ns}	10.6	14.2^{ns}
	(3.0)	(0.5)	(8.1)	(0.4)	(0.6)	(1.3)	(0.1)	(0.8)	(0.2)	(0.6)
B, 4	523	507*	97	124*	20.2	26.8*	13.5	15.1^{ns}	11.1	15.0^{ns}
	(0.9)	(1.2)	(2.7)	(1.1)	(0.8)	(0.0)	(0.7)	(0.1)	(0.4)	(7.8)
B, 5	523	509*	104	119^{ns}	18.0	24.8*	13.7	14.8^{ns}	10.6	15.3^{ns}
	(4.6)	(2.1)	(7.6)	(1.1)	(1.5)	(0.2)	(0.8)	(0.1)	(0.1)	(0.6)
C, 6	516	496*	110	145*	25.6	31.3*	16.4	18.8^{ns}	14.3	13.6^{ns}
	(0.4)	(4.2)	(0.6)	(7.3)	(0.1)	(0.3)	(0.3)	(0.8)	(0.4)	(0.6)
D, 7	508	497^{ns}	123	143*	30.5	31.9*	16.7	18.1^{ns}	21.1	20.1^{ns}
	(2.2)	(0.3)	(3.7)	(0.6)	(1.8)	(0.4)	(0.4)	(0.3)	(0.1)	(0.3)
C, 8	516	496*	110	145*	25.6	31.3*	16.4	18.2^{ns}	19.0	19.4^{ns}
	(0.4)	(4.2)	(0.8)	(7.3)	(0.1)	(0.3)	(0.3)	(0.8)	(0.2)	(0.7)
D, 9	513	495^{ns}	115	147*	27.4	34.5*	15.9	18.2^{ns}	17.0	18.6^{ns}
	(0.6)	(0.6)	(0.4)	(1.1)	(1.1)	(0.6)	(0.4)	(2.7)	(0.2)	(0.6)

†Values in parentheses are standard deviation of three composite samples from each pile. Column means followed by asterisks are values that changed significantly ($P \leq 0.05$) during composting. ns= not significant. Data shown are based on 105°C dry weight.

Table 4. Mean C:N ratio and concentrations of HA, FA, and CEC of the initial and composted spent litter.

	C:N ratio		HA (g kg^{-1} OM)		FA (g kg^{-1} OM)		HA:FA ratio		CEC (meq 100 g^{-1})	
Pen/Pile	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted litter
A, 1	26.2	25.6^{ns}	31.6	41.1*	109.2	109.9^{ns}	0.29	0.37^{ns}	55.4	68.4^{ns}
	(0.03)[†]	(0.20)	(0.37)	(1.17)	(0.34)	(3.95)	(0.08)	(0.03)	(1.22)	(1.08)
A, 2	26.4	25.6^{ns}	34.7	42.8*	113.5	103.9^{ns}	0.31	0.41^{ns}	54.0	70.5*
	(0.12)	(0.16)	(2.83)	(3.80)	(7.82)	(5.03)	(0.05)	(0.02)	(0.00)	(2.02)
B, 3	26.5	18.8*	27.0	45.0*	105.1	97.6^{ns}	0.26	0.46^{ns}	39.2	93.4*
	(0.47)	(0.07)	(0.46)	(0.87)	(0.13)	(0.10)	(0.06)	(0.03)	(0.95)	(5.35)
B, 4	24.6	18.9*	27.4	42.8*	114.0	107.9^{ns}	0.24	0.40^{ns}	38.9	93.5*
	(1.93)	(0.11)	(4.12)	(6.54)	(1.59)	(0.36)	(0.00)	(0.03)	(1.92)	(3.15)
B, 5	27.4	20.6*	25.2	37.3*	112.4	114.6^{ns}	0.22	0.33^{ns}	42.3	88.7*
	(2.18)	(0.07)	(0.27)	(0.31)	(1.50)	(2.72)	(0.02)	(0.09)	(3.14)	(5.13)
C, 6	20.2	15.9*	30.8	77.5*	72.2	71.8^{ns}	0.43	1.08*	33.5	102.7*
	(0.10)	(0.35)	(5.25)	(0.11)	(4.21)	(19.44)	(0.05)	(0.03)	(2.58)	(5.34)
D, 7	16.7	11.9*	29.8	89.7*	69.7	80.3^{ns}	0.43	1.12*	27.9	102.9*
	(1.07)	(0.16)	(3.10)	(1.05)	(2.00)	(6.72)	(0.05)	(0.02)	(2.09)	(3.34)
C, 8	20.1	15.9*	33.1	83.5*	72.2	70.9^{ns}	0.46	1.18*	33.5	102.7*
	(0.00)	(0.35)	(8.52)	(83.5)	(4.21)	(0.40)	(0.05)	(0.03)	(2.58)	(5.34)
D, 9	18.8	14.4^{ns}	20.7	85.7*	70.8	70.9^{ns}	0.29	1.21*	35.8	115.5*
	(0.64)	(0.37)	(6.69)	(2.99)	(0.52)	(0.40)	(0.03)	(0.04)	(2.09)	(2.95)

[†] Values in parentheses are standard deviation of three composite samples from each pile. Column means followed by asterisks are values that changed significantly ($P \leq 0.05$) during composting. ns= not significant. Data shown are based on 105°C dry weight. HA= humic acid; FA= fulvic acid; OM= organic matter; CEC= cation-exchange capacity.

Table 5. Mean concentration of NH^{+}_{4}-N, $(NO^{-}_{3}+NO^{-}_{2})$–N and, extractable P and K of the initial and composted spent litter.

Pen/Pile	NH_4^+-N (mg g^{-1})		$(NO_3^- + NO_2^-)$-N (mg g^{-1})		Extractable P (mg g^{-1})		Extractable K (mg g^{-1})	
	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted Litter
A, 1	6.04	0.12*	0.08	1.38*	5.45	7.44^{ns}	9.71	11.45^{ns}
	(0.5)[+]	(0.2)	(0.0)	(1.7)	(0.7)	(2.0)	(4.5)	(6.7)
A, 2	6.57	0.13*	0.12	1.42*	5.55	7.30^{ns}	10.37	10.14^{ns}
	(0.9)	(0.1)	(0.1)	(0.1)	(0.9)	(1.1)	(3.4)	(0.2)
B, 3	4.40	0.42*	0.19	1.26*	3.64	6.41*	7.77	9.90^{ns}
	(0.9)	(0.1)	(0.4)	(0.6)	(0.7)	(1.2)	(10.7)	(3.5)
B, 4	3.99	0.46*	0.26	1.20*	3.81	6.49*	6.65	10.04^{ns}
	(1.1)	(0.5)	(0.7)	(0.6)	(0.8)	(2.8)	(0.4)	(0.1)
B, 5	3.88	0.18*	0.27	1.44*	3.84	6.59*	6.73	10.05^{ns}
	(1.6)	(0.4)	(0.3)	(3.6)	(0.4)	(1.6)	(2.0)	(0.1)
C, 6	7.01	0.12*	0.18	1.16*	5.12	6.70^{ns}	8.40	9.72^{ns}
	(3.3)	(0.4)	(0.2)	(0.6)	(2.9)	(4.8)	(5.6)	(2.0)
D, 7	7.20	0.12*	0.05	1.26*	5.18	6.66^{ns}	9.00	10.16^{ns}
	(0.1)	(0.4)	(0.0)	(1.0)	(1.5)	(3.2)	(1.1)	(1.6)
C, 8	5.76	0.12*	0.18	1.16*	5.12	6.70^{ns}	8.40	10.72^{ns}
	(1.7)	(0.4)	(0.2)	(0.6)	(2.9)	(4.8)	(0.6)	(2.0)
D, 9	5.75	0.12*	0.11	1.31*	5.37	7.17^{ns}	9.05	10.12^{ns}
	(0.7)	(0.4)	(0.3)	(1.8)	(0.1)	(0.3)	(8.5)	(2.8)

[+] Values in parentheses are standard deviation of three composite samples from each pile. Column means followed by asterisks are values that changed significantly ($P \leq 0.05$) during composting. ns= not significant. Data shown are based on 105°C dry weight.

degree of polymerization since more polymerized components are found in the mature compost. In the present study, the HA:FA ratio in piles 6–9 increased to over 80% at the end of composting, whereas piles 1–5 increased only between 28 to 50%. These results suggest that piles 6–9 had a higher degree of maturity than piles 1–5.

A CEC value greater than 60 meq 100 g^{-1} was suggested as the minimum value needed to ensure an acceptable degree of maturity [17]. At the end of composting, all piles reached a CEC value greater than 60 meq 100 g^{-1} (Table 4), indicating that the spent pig litter in all 9 piles reached as acceptable degree of maturity.

Heavy Metals and Phytotoxicity

The concentrations of total Cu and Zn in the spent pig litter (partially composted) disposed from the POL system were high (Table 6). This fact cannot be avoided since these two metals are usually added in the pig diet. During composting, the total Cu and Zn increased. The increase in total heavy metal concentration was probably due to losses of organic matter C, H, and O from the piles through CO_2 and H_2O during composting, leaving Cu and Zn behind and consequently giving a relative increase in concentrations of these metals. On the other hand, the water-extractable Cu and Zn concentration decreased by the end of composting (Table 6) probably due to the formation of complexes of these metals with chelating organic compound formed, thus making them water-extractable and biologically unavailable. The initial water extractable Cu and Zn concentrations of the spent pig litter differed significantly among piles as a result of the different management strategies used during the initial pig-on-litter system. However, when the spent pig litter reached maturity, the water-extractable Cu and Zn were similar in all 9 piles (Table 6).

It has been noted that a GI ≥ 80% indicated the disappearance of phytotoxins in composts [5]. The GI value of the spent pig litter was between 0–45%, indicating the presence of phytotoxins. However, after composting in windrows, the GI value in the spent pig litter piles increases to greater than 80% (80–98%) (Table 7), revealing that the phytotoxicity in these piles was eliminated after windrow composting. The elimination of phytotoxicity has also been widely used as a measure of compost maturity [4, 8, 18]. However, these tests have not always supported the suggestion that low phytotoxicity indicates compost maturity. Zucconi et al. [5] pointed out that in properly controlled composting systems, the stage characterized by strong toxicity

Table 6. Mean concentration of total and water-extractable Cu and Zn concentrations of the initial and composted spent litter.

	Total Cu ($\mu g\ g^{-1}$)		Ext. Cu ($\mu g\ g^{-1}$)		Total Zn ($\mu g\ g^{-1}$)		Ext. Zn ($\mu g\ g^{-1}$)	
	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted product	Initial material	Composted product
A, 1	551	633*	49.3	14.5*	744	780*	18.8	10.4*
	(71)[†]	(26)	(5.4)	(2.35)	(17)	(15)	(0.2)	(1.4)
A, 2	503	627*	46.6	15.9*	675	674^{ns}	21.8	12.2*
	(17)	(67)	(5.3)	(0.18)	(9)	(9)	(3.7)	(0.4)
B, 3	468	590*	42.2	9.8*	616	774*	23.3	9.3*
	(55)	(31)	(1.7)	(1.39)	(72)	(37)	(2.2)	(0.4)
B, 4	454	611*	43.3	13.2*	604^{a}	820*	23.6	10.1*
	(5)	(21)	(2.5)	(3.70)	(37)	(32)	(5.8)	(1.8)
B, 5	428	592*	38.3	10.2*	545	804*	23.6	9.8*
	(41)	(10)	(6.1)	(0.17)	(22)	(2)	(0.1)	(0.1)
C, 6	468	552*	51.1	10.4*	615	723*	33.4	12.0*
	(4)	(2)	(1.3)	(0.28)	(98)	(32)	(0.5)	(0.1)
D, 7	483	545*	38.2	13.9*	706	730^{ns}	33.5	12.2*
	(24)	(7)	(0.4)	(0.82)	(69)	(64)	(1.2)	(0.9)
C, 8	468	555*	52.2	11.4*	615	723*	33.4	12.0*
	(4)	(5)	(4.7)	(0.28)	(97)	(32)	(0.5)	(0.8)
D, 9	486	558*	42.7	13.0*	623	732*	35.7	11.8*
	(10)	(6)	(0.1)	(1.22)	(18)	(15)	(1.8)	(0.9)

[†] Values in parentheses are standard deviation of three composite samples from each pile. Column means followed by asterisks are values that changed significantly ($P \leq 0.05$) during composting. ns= not significant. Data shown are based on 105°C dry weight.

Table 7. Germination indices (GI) % of Chinese cabbage, Chinese spinach, cucumber, and tomato in spent pig litter extracts at the beginning and end of composting.

Pen/Pile	Chinese cabbage		Chinese spinach		Cucumber		Tomato	
	Initial material	Composted litter	Initial material	Composted litter	Initial material	Composted product	Initial material	Composted product
A, 1	20	82*	NA	NA	NA	NA	50	82*
	(3.0)[†]	(1.0)					(3.5)	(2.0)
A, 2	26	93*	NA	NA	NA	NA	40	83*
	(4.0)	(5.0)					(4.5)	(1.0)
B, 3	44	80*	40	100*	50	83*	80	100*
	(6.3)	(1.0)	(5.0)	(4.0)	(5.0)	(2.0)	(1.0)	(5.0)
B, 4	45	81*	40	100*	80	85^{ns}	80	100*
	(5.0)	(1.0)	(5.0)	(5.0)	(5.0)	(5.0)	(1.0)	(5.0)
B, 5	36	81*	45	100*	75	105*	80	110*
	(6.5)	(1.0)	(5.5)	(2.0)	(8.0)	(4.0)	(1.5)	(5.0)
C, 6	0	80*	0	80*	35	86*	10	80*
	(0.0)	(1.0)	(0.0)	(1.0)	(4.0)	(5.0)	(3.0)	(0.0)
D, 7	0	98*	0	85*	45	95*	20	110*
	(0.0)	(4.0)	(0.0)	(0.0)	(5.0)	(5.0)	(4.0)	(5.0)
C, 8	0	98*	0	85*	45	95*	20	105*
	(0.0)	(4.0)	(0.0)	(0.0)	(5.0)	(5.0)	(4.0)	(5.0)
D, 9	0	96*	0	85*	65	95*	20	100*
	(0.0)	(5.0)	(0.0)	(0.0)	(5.0)	(5.0)	(4.0)	(5.0)

[†] Values in parentheses are standard deviation of three composite samples from each pile. Column means followed by asterisks are values that changed significantly ($P \leq 0.05$) during composting. ns= not significant. NA= no data available.

$$\text{GI (\%)} = \frac{\text{(\% relative seed germination) x (\% relative root growth)}}{100\%}$$

(GI lower than 50%) could be well completed before the end of the thermophilic phase. At this stage, the compost is far from stabilization. Therefore, the elimination of phytotoxicity in the spent pig litter could not be used as a sole indicator of compost maturity.

Evaluation of Compost Maturity

The evaluation of compost maturity is one of the most important criteria in the composting process and the subsequent application of the final product to land. This study showed that the composting process was reflected in the changes in temperature and physico-chemical properties of the compost piles. Maturation of the spent pig litter was accompanied by: (1) decline and stability of total C, water-extractable metals, NH_4^+-N to low levels; (2) increase and stability of ash, $(NO_3^-+NO_2^-)$-N, HA, HA:FA, and CEC values; and (3) elimination of phytotoxicity at the end of composting. For practical composting, it would be desirable to use simple, inexpensive, and easy indicators of compost maturity. The measurement of parameters such as temperature, ammonium, water-extractable Cu and Zn, and phytotoxicity assay satisfies these criteria, and can be used as indices of compost maturity. However, compost maturity is difficult to define by only employing physico-chemical and phytotoxicity parameters. The understanding of compost maturity has to be improved by employing microbiological parameters such as microbial counts, oxygen uptake rate, ATP content and dehydrogenase activity. These parameters together with the physico-chemical and phytotoxicity parameters suggested in this study will be useful in the estimation of compost maturity and the development of maturity index of spent litter compost.

Characteristics of the Composted Spent Pig Litter

Table 8 shows the composition ranges of major substances in composted spent pig litter and mature composts from several organic manures [28]. The nutrient content (N, P, and K) of the composted spent pig litter was comparable to other mature composts. Interestingly, the organic matter content of spent pig litter (851–876 g k^{-1}) was higher than other mature composts (250–800 g kg^{-1}). This means that the spent pig litter can provide more organic matter to agricultural soils, especially in Hong Kong, where the soils are very poor in terms of OM content (personal communication with officers of Agriculture, Fisheries and Conservation Department). Many countries in the Asian region, including Mainland China, also need this input as farmers have relied on inorganic matter for many years, without paying attention to soil structure.

Producing a consistently high-quality compost is especially important when the compost will be marketed and not just used on-farm. The importance of quality increases further if the compost will be used for high-value crops such as potted plants; used on food crops; applied to sensitive plants, such as young seedlings; used soon after composting; or used alone with other additives [29]. On the other hand, if one plans to use the compost only for farm use as a soil amendment for field crops and apply it well before planting, the quality of the compost produced is less of a concern. For instance, some quality criteria such as particle size, may not

Table 8. Composition ranges of major substances in composted spent pig litter and other mature composts.

Substance	Composted spent pig litter	Other mature composts†
pH	5.43–6.04	-
EC (dS m^{-1})	1.56–3.19	-
OM (g gk^{-1})	851–876	250–800
C (g gk^{-1})	494–509	80–350
N (g gk^{-1})	19.0–34.5	4–35
P (g gk^{-1})	15.1–20.4	1–16
K (g gk^{-1})	14.2–20.1	4–16
Ash (g gk^{-1})	124–149	200–750
GI (%)	80–110	-
Total Cu (mg kg^{-1})	545–633	-
Extractable Cu (mg kg^{-1})	9.8–14.5	-
Total Zn (mg kg^{-1})	674–804	-
Extractable Zn (mg kg^{-1})	9.3–12.2	-

† Data obtained from Dalzell et al. [28]
EC= electrical conductivity; OM=organic matter; GI= germination index

be important. The soil also buffers many potentially adverse effects of low quality [29]. Compost quality is generally based on particle size, pH, electrical conductivity (EC), stability and the presence of undesirable components such as heavy metals and phytotoxic compounds. In this study, the pH of the composted spent pig litter ranged between 5.93–6.04 and EC between 1.56–3.04 dS m^{-1} (Table 8). A compost with a pH between 6.0 and 7.8 [29], and EC <4.0 dS m^{-1} [30] would be acceptable. The pH and EC values of the composted spent pig litter satisfied these criteria. For total Cu and Zn, the acceptable concentrations for composts were > 1500 and > 1800 mg kg^{-1}, respectively [20]. These levels were far too high compared to those found in the composted spent pig litter. Tiquia and Tam[18] used seed germination technique to test the phytotoxicity of pig manure+sludge in Hong Kong. In her study, the phytotoxicity of manure disappeared when water-extractable Cu and Zn concentrations dropped to ≤ 15 mg kg^{-1} and ≤ and 20 mg kg^{-1}, respectively, during composting. The extractable Cu and Zn concentrations found in the composted spent pig litter in this study were lower than those values (Table 8), indicating that the spent pig litter can be used as a soil amendment without causing any heavy metal toxicity to plants.

Composting Strategy

Composting strategies employed affected the speed of composting and time of maturation (Table 2). For instance, it took 91 days for piles 4 and 6 to drop to ambient level; 84 days for pile 3; 67 days for pile 5; 60 days for pile 1; and 56 days for piles 7–9 (Table 2). Temperature, turning frequency, and moisture content are the most important factors relating to composting efficiency [1]. Results of this study showed that if moisture content was maintained weekly at 60%, and it was turned every 4 days, spent litter reached maturity in 56 days (Table 2). Composting in piles 7–9 was more efficient than piles 1– 6. Piles 7–9 also had higher HA, FA, HA:FA, and CEC values compared to the other five piles (Table 4), suggesting that the quality of the litter in these piles was better than the other piles in terms of the OM.

Composting in pile 7 (spent pig litter without bacterial inoculum but with moisture adjustment) proceeded at the same rate as piles 8 (spent pig litter with bacterial inoculum but without moisture adjustment) and 9 (spent pig litter with bacterial inoculum and with moisture adjustment), revealing that the addition of bacterial inoculum in the initial pig-on-litter *in situ* composting process was of no value if the moisture content was adjusted to 60% during further composting of spent pig litter (Tables 1 and 2). Such a finding is significant as it indicated that the process could be run on a much more economical basis.

Summary

This investigation revealed that control of the composting process of spent pig litter demands an understanding of the interaction of environmental factors such as temperature, aeration (by turning), and moisture content. For efficient composting, moisture content must be maintained weekly at 60% with a four-day turning frequency. Addition of bacterial inoculum onto the litter in the initial pig-on-litter system had no value on the rate of composting if moisture content was adjusted to 60% during windrow composting. The present study also demonstrated that if the above conditions are met, the spent pig litter reached maturity in 56 days. The maturation of the spent pig litter was accompanied by: (1) decline and stability of total C, water-extractable metals, NH_4^+-N to low levels; (2) increase and stability of ash, $(NO_3^-+NO_2^-)$-N, HA, HA:FA, and CEC values; and (3) elimination of phytotoxicity at the end of composting. Collectively, the physico-chemical properties of the composted spent pig litter (i.e. stability of nutrient and OM, pH, EC, low levels of undesirable components such as heavy metals and phytotoxic compounds) provided substantial evidence that agronomically suitable compost can be obtained after windrow composting of spent pig litter.

ACKNOWLEDGMENTS

The author is grateful to N.F.Y. Tam (City University of Hong Kong) and I.J. Hodgkiss (The University of Hong Kong) for the many invaluable comments. The author also acknowledges the financial support from the RGC Competitive Earmarked Research Grant (CERG) and the City University Research Grant.

REFERENCES

1. Tiquia S.M., Further Composting of Pig-manure from the Pig-on-litter (POL) System in Hong Kong. Ph.D. Thesis, The University of Hong Kong. 475 pp. (1996).
2. Golueke C.G., *Composting: A Study of the Process and Its Principles*. Rodale Press. Emmaus, Pennsylvania. 110 p. (1972)
3. Tam N.F.Y. and Vrijmoed L.L.P., Effects of the inoculum size of a commercial bacterial product and the age of sawdust bedding on pig waste decomposition in a pig-on-litter system. *Waste Manage. Res.*, **11**, 107–115 (1993).
4. Morel J.L., Colin F., Germon J.C., Godin P. and Juste, C., Methods for the evaluation of maturity of municipal refuse compost. In: *Composting of Agricultural and Other Wastes*. Gasser, J.K.R. (ed.), Elsevier Applied Science, New York. pp. 56–72

(1985).

5. Zucconi F., Forte M., Monaco A. and De Bertoldi M., Biological evaluation of compost maturity. *BioCycle*, **22**, 27–29 (1981).
6. Avnimelech Y., Bruner, M. Ezrony, I., Sela R. and Kochba M., Stability indexes for municipal solid waste compost. *Compost Sci. Util.*, **4**, 13–20 (1996).
7. Forster J.C., Zech W. and Wurdinger E., Comparison of chemical and microbiological methods for the characterization of the maturity of composts from contrasting sources. *Biol. Fertil. Soils*, **16**, 93–99 (1993).
8. Grebus M.E., Watson M.E. and Hoitink H.A.J., Biological, chemical, and physical properties of composted yard trimmings as indicators of maturity and plant disease suppression. *Compost Sci. Util.*, **2**, 57–71 (1994).
9. Iannotti D.A., Grebus M.E., Toth B.L., Madden L.V. and Hoitink H.A.J., Oxygen respirometry to assess stability and maturity of composted municipal solid wastes. *J. Environ. Qual.*, **23**, 1177–1183 (1994).
10. Inbar Y., Hadar Y. and Chen Y., Recycling of cattle manure: The composting process and characterization of maturity. *J. Environ. Qual.*, **22**, 857–863 (1993).
11. Bremmer J.M., Nitrogen-Total. In: *Methods of Soil Analysis Part 3- Chemical Methods.* Soil Science Society of America (SSSA), Madison, Wisconsin, USA. pp. 1085–1121 (1996).
12. APHA (American Public Health Association), *Standard Methods for the Examination of Water and Wastewater*, 19th Edition, APHA, Washington D.C. USA. (1995).
13. Mulvaney. R.L., Nitrogen-inorganic forms. In: *Methods of Soil Analysis Part 3- Chemical Methods.* Soil Science Society of America (SSSA), Madison, Wisconsin, pp. 1123–1184 (1996).
14. Nelson D.W. and Sommers L.E., Total carbon, organic carbon, and organic matter. In: *Methods of Soil Analysis Part 3- Chemical Methods.* Soil Science Society of America (SSSA), Madison, Wisconsin, pp. 961–1011 (1996).
15. Allison L.E., Organic carbon. In: *Methods of Soil Analysis Part 2- Chemical and Microbiological Properties.* C.A. Black, D. Evans, J.L. White L.E. Ensiminger F.E. Clark and R.C. Dinauer (eds.), Soil Science Society of America (SSSA), Madison Wisconsin, pp. 367–378.
16. Swift R.S. Organic matter characterization. In: *Methods of Soil Analysis Part 3- Chemical Methods.* Soil Science Society of America (SSSA), Madison, Wisconsin, USA. pp. 1011–1069. (1996).
17. Harada Y. and Inoko A., The measurement of cation-exchange capacity of composts for the estimation of degree of maturity. *Soil Sci. Plant Nutr.*, **26**, 123–134 (1980)
18. Tiquia S.M. and Tam N.F.Y., Elimination of phytotoxicity during co-composting of spent pig-manure sawdust litter and pig sludge. *Biores. Technol.*, **65**, 43–49 (1998).
19. Golueke C.G., *Biological Reclamation of Organic Wastes.* Rodale Press, Emmaus, Pennsylvania, 249 pp. (1977)
20. Epstein E., *The Science of Composting.* Technomic Publishing Company, Lancaster, Pennsylvania, USA. 487 pp. (1997).
21. Wild A., *Russel's Soil Conditions and Plant Growth*, 11th Edition, Longman Group UK Ltd., Essex, 991 pp. (1988)
22. Garcia C., Hernandez T. and Costa F., Changes in carbon fractions during composting and maturation of organic wastes. *Environ. Manage.*, **15**, 433–439 (1991).
23. Tiquia S.M., Richard, T.L. and Honeyman, M.S., Carbon, nutrient, and mass loss during composting. *Nutr. Cycl. Agroecosys.*, **62**, 15-24 (2002).
24. Tiquia S.M. and Tam N.F.Y., Fate of nitrogen during composting of chicken litter. *Environ. Pollut.*, **110**, 535–541 (2000).
25. Bernal, M.P., Paredes, C., Sanchez-Monedero, M.A. and Cegarra, J., Maturity and stability parameters of composts prepared with a wide range of organic wastes. *Biores. Technol.*, **63**, 91–99 (1998).
26. Senesi, N., Composted materials as organic fertilizers. *Sci. Total Environ.*, **81**, 521–542 (1989).
27. Chen Y., Chefetz B. and Hadar Y., Formation and properties of humic substance originating from composts. In: *The Science of Composting. Part I.* M. De Bertoldi P. Sequi P. Lemme, and T. Papi (eds.), Chapman and Hall, London, pp. 383–393 (1996).
28. Dalzell H.W., Biddlestone A.A., Gray K.R. and Thurairajan K., Soil management: Compost production and use in tropical and subtropical environments. FAO Soils Bulletin 56, Food and Agriculture Organization of the United Nations (FAO), Rome, pp. 1–8 (1973).
29. Rynk R., van de Kamp M., Willson G.B., Singley M.E., Richard T.L., Kolega J.L., Gouin F.R., Laliberty L., Jr., Day K., Murphy D.W., Hoitink H.A.J. and Brinton W.F., *On Farm Composting Handbook.* Natural Resource, Agriculture, and Engineering Service (NRAES), Cornell University, New York, USA. pp.186 (1992).
30. Allison F.E., *Soil Organic Matter and Its Role in Crop Production.* Elsevier, Amsterdam, 639 p[. (1973).