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Microbiological and Chemical Parameters for Evaluating the Maturity of Spent Pig-Litter Compost

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Abstract

Windrow composting of spent pig litter (partially decomposed pig manure and sawdust) of different initial litter materials was carried out under different composting strategies to determine potential microbiological and chemical parameters that indicate compost maturity. Spent litter was collected from pens where the pig-on-litter system was employed, and nine composting piles were managed under different operating strategies. During composting and at maturation, concentrations of NH_4^+-N, $[NO_3^- + NO_2^-]$-N, extractable P and K, total and water-extractable Cu and Zn, and pH were similar in all piles regardless of the initial material or operating strategy. The dehydrogenase activity, a microbiological parameter, was also unaffected by initial material or composting strategy. The concentrations of Kjeldahl N, total P and K, C:N ratio, total aerobic heterotroph numbers, ATP content, and microbial biomass C and N of the composted product, were dependent on the initial material, composting strategy, or both. Among all parameters measured, dehydrogenase activity, pH, and concentrations of NH_4^+-N and water-extractable Cu and Zn are the simplest, least expensive and most easily measured indicators of maturity of spent pig litter.

Key Words: decomposition, dehydrogenase, hog manure, mature compost, nitrogen forms

Introduction

The traditional method of waste disposal employed by hog producers in Hong Kong is washing the wastes down with plenty of water. While this method cools down the animals, it generates a lot of wastewaters, which pollute the waterways and cause social problems. As a solution to the pig manure problem, the pig-on-litter system of pig raising was initiated in Hong Kong in 1987. Also known as *in-situ* composting, pigs in this system are raised in pens, the floor of which is covered by a 30-cm-thick layer of sawdust (bedding material), mixed with a commercially available bacterial inoculum to aid decomposition (EPD, 1990; Tiquia and Tam, 1998a). The discharge of effluent is unnecessary, and the spent litter is the only material that needs to be removed.

The spent litter (a mixture of partially decomposed sawdust and pig manure) from the pig-on-litter system is a relatively new material compared with other animal manure. Previous studies have shown that the decomposition of the pig manure within the pig-on-litter system is incomplete. Therefore, the spent litter requires further composting in windrows to achieve full maturity (Tiquia and Tam, 1998a; Tiquia et al. 1996a and 1996b) before it can be recycled back onto agricultural land. Forster et al. (1993) stated that the decisive feature of mature compost is the completion of a thermophilic and a subsequent mesophilic phase of organic matter degradation, which involves a multitude of saprophytic bacteria, actinomycetes and fungi. Our previous studies revealed that the maturation of the spent litter is accompanied by changes in chemical and physical parameters (Tiquia and Tam, 1998a; Tiquia et al. 1998). These changes are directly related to microbial activity and bacterial population density (Tiquia et al. 1996b). However, due to variations in the number of pigs, types of commercial bacterial products, amounts of sawdust, and management practices in the pig-on-litter system, the properties of the spent litter from different pigpens are likely to be different. Such differences in the spent litter would affect the time required for maturation and the quality of the mature compost. On the other hand, the operating strategies being used during windrow composting of this spent litter would also influence maturation.

It has been reported that composting leads to a homogeneity in the composition of the composted product irrespective of the initial material and the composting process (Garcia et al. 1993; Serra-Wittling et al. 1996). Such homogeneity will be useful in establishing maturity indices, which can be quantified. On the other hand, previous studies have also shown that the chemical and microbiological properties of the mature compost vary depending on the properties of the initial material (Michel et al. 1996; Savage, 1996). The present paper is a review of our previous studies on composting of spent litter. In these studies, a distinct pattern of changes in chemical and microbiological properties of the spent litter has been observed during composting irrespective of the differences in moisture content (Tiquia et al. 1996a and 1996b), turning frequency (Tiquia et al. 1997a), moisture adjustment (Tiquia et al. 1997b) and seasonal temperature (Tiquia et al. 1997c). The review aims to (1) evaluate the effects of different initial spent litter material and composting strategies on the microbiological and chemical properties of the mature spent litter compost, (2) identify the most suitable microbiological and chemical parameters that can be used as an index of compost maturity and, (3) determine what constitutes a mature compost.

Materials and Methods

The composting trials were conducted between 1993 and 1996. Spent litter was collected from different pens where the pig-on-litter system was employed. The same feed type was fed to the pigs in the pig-on-litter system. The treatments in 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). Nine pyramidal piles, about 2 m in width at the base and 1.5 m in height were built from the spent litter collected from the five pens. The nine operating strategies (piles 1 to 9) used are listed in Table 2. All piles except pile 1 were turned every four days. The initial moisture content of all piles was adjusted to 60% with the exception of piles 1 and 3, whose moisture contents were adjusted to 50%, and pile 5, whose moisture content was adjusted to 70%. The moisture content of piles 7 and 9 were adjusted to their designed values (60%), while no further adjustment was carried out with the rest of the piles during composting. The ambient temperature and temperature within each pile were measured before turning to monitor the progress of the composting process. The spent litter was considered mature after the piles had gone through a thermophilic stage (pile temperature increase to about 55°C–65°C for two to three weeks) and a subsequent decline in pile temperature to ambient level.

Samples of initial (day 0) and mature (final product) spent litter were collected at five random locations in each of the nine piles. These five samples were combined and mixed to provide a composite sample. Triplicate composite samples were taken from each pile. The spent litter samples were analyzed for adenosine triphosphate (ATP) content by the luciferin-luciferase method using a luminometer (Monolight 1500); dehydrogenase activity (Page et al. 1982); population size of total aerobic heterotrophs by dilution agar-plate technique; and microbial biomass C and N using the fumigation-extraction technique (Vance et al. 1987; West et al. 1986).

The spent litter samples were also analyzed for chemical properties such as Kjeldahl N (Page et al. 1982); total and Olsen-extractable P using the ascorbic acid method (APHA, 1989); total and water-extractable K, Cu and Zn (atomic absorption spectrophotometry); NH_4^+-N and

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

Treatment	Pen A	Pen B	Pen C	Pen D	Pen E
Size of pig pen (m^2)	32	30	40	40	30
Number of pigs	32	30	40	40	30
Age of pigs at start (days)	99	82	113	72	78
Raising period (days)	92	115	91	123	117
Litter management	Mixing	Layering	Layering	Layering	Layering
Total feed consumption‡ (Kg)	6545	8308	8196	11910	9619
Total sawdust consumption (bags)	60	70	81.5	91	90
Bacterial product used	Elimexal	Vitacogen	Biogreen	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 was collected from Pen A; spent litter in piles 3, 4, and 5 was collected from Pen B; spent litter in pile 6 was collected from Pen C; spent litter in pile 7 was collected from Pen D; spent litter in piles 8 and 9 was collected from Pen E. ‡ 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. Operating strategies used, seasonal conditions, duration of composting, and time of maturation of spent pig litter.

Pile	Operating Strategy			Season	Duration of composting Trial (days)	Time required to reach maturity (days)
	Turning frequency (days)	Initial moisture adjustment (%)	Regular moisture correction			
1	2	50	No	Spring-summer	126	74
2	4	50	No	Spring-summer	126	74
3	4	50	No	Summer-autumn	91	60
4	4	60	No	Summer-autumn	91	60
5	4	70	No	Summer-autumn	91	91
6	4	60	No	Summer	91	56
7	4	60	Yes	Summer	91	56
8	4	60	No	Summer	91	56
9	4	60	Yes	Summer	91	56

$(NO_3^- + NO_2^-)$-N (Page et al. 1982); electrical conductivity (EC) (1:5 spent litter:slurry using a conductivity electrode; pH (1:10 spent litter:slurry) using a pH electrode; total C and ash content (loss on ignition); humic and fulvic acids (Page et al. 1982); and cation-exchange capacity (CEC) (Harada and Inoko, 1980).

One-way analysis of variance was performed to determine differences among the nine piles during the initial and mature stages. Significant differences among means were then compared using the Bonferroni Test. A *t*-test was carried out to compare the difference between the initial spent litter and mature compost product in each pile. All statistical analyses were based on the procedures described by Zar (1984).

Results

ATP content, dehydrogenase activity, total aerobic heterotrophs and microbial biomass C and N

The ATP content, dehydrogenase activity, total aerobic heterotrophs count and microbial biomass N of the spent litter piles varied significantly on day 0 (Tables 3 and 4). At maturity, dehydrogenase activity was similar in all piles, while ATP content, total aerobic heterotrophs count and microbial biomass C and N varied depending upon the composition of the initial spent litter material and the composting strategy.

Kjeldahl N, total P and K

The initial concentrations of N, P, and K of the spent litter piles were not significantly different from those of the mature product in all piles (Table 5). However, significant differences were found among nine piles at maturity in terms of the Kjeldahl N and total P content. The total

K content of all the nine piles was similar at the mature stage, with the exception of piles 7 and 8 whose values were higher.

Table 3. ATP content and dehydrogenase activity of the initial and mature spent litter.

Pile	Parameter†			
	ATP (μmol g^{-1})		Dehydrogenase (μg TPF g^{-1})	
	Initial material	Mature product	Initial material	Mature product
1	0.077a	0.015a	174.91ab	49.78a
2	0.056a	0.015a	192.50ab	47.28a
3	0.288c	0.043ab	183.06ab	42.76a
4	0.298c	0.037ab	199.76ab	34.56a
5	0.232b	0.040ab	163.43b	41.66a
6	0.330bc	0.060b	168.71ab	47.35a
7	0.405e	0.065b	268.00a	46.03a
8	0.365cd	0.060b	168.71ab	47.35a
9	0.360d	0.070b	246.21ab	40.19a
Grand mean±SD‡	0.264 ± 0.12	0.044 ± 0.02	196.20 ± 39.53	44.11 ± 4.76

† Column means (three replicates) with the same letter are not significantly different ($P<0.05$);
‡ Mean ± standard deviation (SD) of the nine piles.
TPF= tri-phenyl formazan

Table 4. Total aerobic heterotroph counts and contents of microbial biomass C and N of the initial and mature spent litter.

Pile	Parameter†					
	Heterotrophs (CFU g^{-1})		Biomass C (mg g^{-1})		Biomass N (µg g^{-1})	
	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
1	NA	NA	1.55a	5.88a	113.10bc	36.61ab
2	NA	NA	1.56a	5.58a	91.08c	35.64ab
3	9.74a	9.61a	1.53a	5.15a	84.54c	35.82a
4	9.66a	9.88a	1.38a	5.28a	66.46c	35.33ab
5	9.70a	9.44a	1.14a	3.72b	74.89c	32.24ab
6	7.58b	8.29b	1.44a	5.19a	134.03b	22.51b
7	7.76b	8.22b	1.02a	5.54a	251.10a	32.44a
8	7.65b	8.30b	1.47a	5.64a	172.11b	33.17ab
9	7.68b	8.32b	1.43a	5.75a	158.43b	33.80a
Grand mean±SD‡	8.54 ± 1.03‡	8.72 ± 0.89	1.39 ± 0.27	5.30 ± 0.64	122.30 ± 65.97	33.06 ± 4.26

† Column means (three replicates) with the same letter are not significantly different ($P<0.05$); ‡ Mean ± standard deviation (SD) of the nine piles; NA= no data available.

Table 5. Kjeldahl N, total P and K concentrations of the initial and mature spent litter.

Pile	Parameter†					
	N (%)		P (%)		K (%)	
	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
1	1.86a	1.98a	1.80a	2.04a	1.49a	1.60a
2	2.14ac	1.90a	1.76ab	1.99ab	1.50a	1.62a
3	1.95a	2.71bc	1.32c	1.51c	1.06c	1.42a
4	2.02ac	2.68bc	1.35c	1.51c	1.11c	1.50a
5	1.80a	2.48b	1.37c	1.48c	1.06c	1.53a
6	2.56acd	3.13cd	1.64ab	1.88ab	1.43a	1.36a
7	3.05bd	3.19cd	1.67ab	1.81b	2.11b	2.01b
8	2.56acd	3.13cd	1.64ab	1.82ab	1.90b	1.94b
9	2.74bc	3.45d	1.59b	1.82ab	1.70a	1.86ab
Grand mean±SD‡	2.29 ± 0.45	2.74 ± 0.54	1.57 ± 0.17	1.77 ± 0.23	1.48 ± 0.37	1.65 ± 0.23

† Column means (three replicates) with the same letter in the superscript position are not significantly different ($P<0.05$);

‡ Mean ± standard deviation (SD) of the nine piles are shown.

Inorganic N, and extractable P and K

The concentrations of NH_4^+-N and $(NO_3^- + NO_2^-)$-N of the initial spent litter varied significantly among piles (Table 6). The initial NH_4^+-N content of the spent litter piles ranged from 3.88 to 7.20 mg g^{-1}, and decreased to 0.12 to 0.46 mg g^{-1} at maturity. Conversely, the $(NO_3 + NO_2^-)$-N content increased from initial values of 0.08 to 0.27 mg g^{-1} to 1.16 to 1.44 mg g^{-1} at the mature stage. The concentrations of $(NO_3^- + NO_2^-)$-N did not differ among piles at maturity. The NH_4^+-N concentrations of all mature piles were also not significantly different, except for piles 3 and 4 (Table 6), which had higher concentrations.

During the initial stage of composting (day 0), the extractable P and K contents of the spent litter piles ranged from 3.64 to 5.45 mg g^{-1} and 6.65 to 10.37 mg g^{-1}, respectively. At mature stage, these levels both increased significantly ($P < 0.0001$) to between 6.41 and 7.44 mg g^{-1} for extractable P and 9.72 to 11.45 mg g^{-1} for extractable K (Table 6). No significant difference was found in the extractable P content among all nine piles at maturity. Although some differences in extractable K were found among the nine piles, the difference was only about 1.0 mg g^{-1}.

Electrical conductivity (EC), pH, total C and ash

The EC, pH, total C and ash content of the initial spent litter piles all varied significantly (Table 7). During composting, the EC and ash content increased, while the total C concentration and pH decreased. The total C concentrations of the spent litter piles at mature stage did not vary except for piles 3, 4 and 5, whose values were about 1% higher than the other piles. The ash contents of the nine piles were similar except for piles 3, 4 and 5 whose ash contents were lower. At maturity, pH did not differ among all piles. Piles 3 and 5 had lower EC than the rest.

Table 6. Concentrations of NH_4^+-N, (NO_3^- + NO_2^-)-N and, extractable P and K of the initial and mature spent litter.

Pile	Parameter†							
	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	Mature product	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
1	6.04a	0.12a	0.08a	1.38a	5.45a	7.44a	9.71a	11.45b
2	6.57a	0.13a	0.12a	1.42a	5.55a	7.30a	10.37a	10.14ab
3	4.40c	0.42b	0.19ac	1.26a	3.64b	6.41a	7.77ac	9.90a
4	3.99c	0.46b	0.26bc	1.20a	3.81b	6.49a	6.65bc	10.04a
5	3.88c	0.18a	0.27bc	1.44a	3.84b	6.59a	6.73bc	10.05a
6	7.01b	0.12a	0.18ac	1.16a	5.12a	6.70a	8.40ac	9.72a
7	7.20b	0.12a	0.05a	1.26a	5.18a	6.66a	9.00ac	10.16ab
8	5.76a	0.12a	0.18ac	1.16a	5.12a	6.70a	8.40ac	10.72ab
9	5.75a	0.12a	0.11a	1.31a	5.37a	7.17a	9.05ac	10.12a
Grand mean±SD‡	5.56 ± 1.24	0.20±0.14	0.16± 0.08	1.29 ± 0.15	4.78 ± 0.77	6.83 ± 0.42	8.45 ± 1.30	10.25 ± 0.55

† Column means (three replicates) with the same letter in the superscript position are not significantly different (*P*<0.05);
‡ Mean ± standard deviation (SD) of the nine piles are shown.

Table 7. Electrical conductivity (EC), pH, total C and ash content of the initial and mature spent litter.

Pile	Parameter†							
	EC (mS cm^{-1})		pH		Total C (%)		Ash (%)	
	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
1	2.03b	2.11a	8.47a	6.04a	50.5b	49.6b	12.91a	14.50a
2	1.91b	2.40a	7.92b	5.43a	50.6b	49.4b	12.71a	14.90a
3	1.52c	1.87a	8.50a	5.63a	52.5a	50.8a	9.85c	12.50b
4	1.47c	2.18a	8.28c	5.69a	52.3a	50.7a	9.73c	12.40b
5	1.48c	1.56b	8.12c	5.51a	52.3a	50.9a	10.39bc	11.90b
6	2.68a	3.14a	7.90b	5.67a	51.6ab	49.6b	10.96ac	14.50a
7	2.51a	2.69a	8.18c	5.66a	50.8b	49.7b	12.34a	14.30a
8	2.74a	3.19a	8.24c	5.53a	51.6ab	49.6b	11.00ac	14.50a
9	2.72a	2.60a	8.27c	5.59a	51.3ab	49.5b	11.53ac	14.70a
Grand mean±SD‡	2.12 ± 0.54	2.41 ± 0.56	8.21 ± 0.21	5.64 ± 0.27	51.5 ± 0.76	50.0 ± 0.65	11.3 ± 1.21	13.8 ± 1.17

† Column means (three replicates) with the same letter in the superscript position are not significantly different ($P<0.05$);
‡ Mean ± standard deviation (SD) of the nine piles are shown.

Humic acid, fulvic acid, cation exchange capacity and C:N ratio

The humic acid content of all nine piles were not significantly different at day 0 (initial stage) (Table 8). At maturity, the humic acid content of all piles increased but the increases in piles 6, 7, 8 and 9 were significantly higher than in the other six piles (Table 8). The fulvic acid content of all piles remained relatively stable during composting, whereas the CEC content and C:N ratio varied significantly among piles during the initial and mature stages of composting.

Total and water-extractable Cu and Zn

As composting progressed, the concentrations of total Cu and Zn increased, whereas the water-extractable Cu and Zn decreased significantly (*P* <0.0001). The initial water-extractable Cu and Zn concentrations of the spent litter piles differed significantly among piles as a result of the different treatments during the initial pig-on-litter system. When the spent litter piles reached maturity, total and water-extractable Cu and Zn concentrations were similar in all piles (Table 9).

Discussion

Variations in the treatments (i.e., number of pigs, amount of sawdust added, type of bacterial inoculum added and litter management) under the pig-on-litter system resulted in differences in chemical and microbiological properties of the initial spent litter material, which could affect the quality of the composted product. Among all the properties investigated, there are chemical (Kjeldahl N, total P, K and C, ash, humic acid, CEC, EC and C:N ratio) and microbiological (ATP content, population sizes of total aerobic heterotrophs and microbial biomass C and N) parameters of the mature compost whose values were influenced either by the initial material or composting strategy, or both. Therefore, these parameters cannot be used in establishing maturity indices that can be quantified.

Table 8. Concentrations of humic acid, fulvic acid and cation-exchange capacity (CEC), and C:N ratio of the initial and mature spent litter.

Pile	Parameter†							
	Humic acid (g Kg^{-1} O.M.)		Fulvic acid (g Kg^{-1} O.M.)		CEC (meq 100 g^{-1} ash-free)		C:N ratio	
	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
1	31.6a	41.1a	109.2a	109.9a	55.4a	68.4d	26.2a	25.6a
2	34.7a	42.8a	113.5a	103.9a	54.0a	70.5cd	26.4a	25.6a
3	27.0a	45.0a	105.1a	97.6ab	39.2ab	93.4b	26.5a	18.8c
4	27.4a	42.8a	114.0a	107.9a	38.9ab	93.5a	24.6a	18.9c
5	25.2a	37.3a	112.4a	114.6a	42.3ab	88.7a	27.4ab	20.6b
6	30.8a	77.5b	72.2b	71.8b	33.5b	102.7ab	20.2bc	15.9d
7	29.8a	89.7b	69.7b	80.3ab	27.9b	102.9ab	16.7c	11.9f
8	33.1a	83.5b	72.2b	70.9b	33.5b	102.7ab	20.1bc	15.9d
9	20.7a	85.7b	70.8b	70.9b	35.8b	115.5a	18.8c	14.4e
Grand mean±SD‡	28.9 ± 5.30	60.6 ± 22.12	93.2 ± 20.6	92.0 ± 18.5	40.0 ± 9.53	93.1 ± 15.31	23.0 ± 3.98	18.6 ± 4.61

† Column means (three replicates) with the same letter in the superscript position are not significantly different (*P*<0.05);
‡ Mean ± standard deviation (SD) of the nine piles are shown. O.M.= organic matter.

Table 9. Total and water-extractable Cu and Zn concentrations of the initial and mature spent litter.

Pile	Parameter†						
	Total Cu (μg g^{-1})		Ext. Cu (μg g^{-1})		Total Zn (μg g^{-1})		E
	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product	Initi mate
1	551a	633a	49.3a	14.5a	744a	780a	18.
2	503a	627a	46.6a	15.9a	675a	674a	21.
3	468a	590a	42.2ab	9.8a	616a	774a	23.
4	454a	611a	43.3ab	13.2a	604a	820a	23.
5	428a	592a	38.3b	10.2a	545a	804a	23.
6	468a	552a	51.1a	10.4a	615a	723a	33.
7	483a	545a	38.2b	13.9a	706a	730a	33.
8	468a	555a	52.2a	11.4a	615a	723a	33.
9	486a	558a	42.7ab	13.0a	623a	732a	35.
Grand mean±SD‡	479 ± 42	585 ± 38	44.9 ± 5.7	12.5 ± 2.4	751.4 ± 55	638 ± 72	27.5 ±

† Column means (three replicates) with the same letter in the superscript position are not significantly different ($P<0.05$);

‡ Mean ± standard deviation (SD) of the nine piles are shown.

The Kjeldahl N, total P and K concentrations of the mature compost varied depending on the concentrations of these elements in the initial material. Spent litter piles with higher initial concentrations of Kjeldahl N and total P and K also had higher concentrations at the mature stage (Table 5). The total nutrient content of the spent litter increased slightly during composting, indicating that this process did not reduce the agronomic quality of the end-product. It has been shown that composting is mainly decomposition and transformation (Golueke, 1977; Tam and Tiquia, 1999). The humic acid content was influenced mainly by the composting strategy, but the CEC content of the spent litter was influenced by the initial material and by the operating strategy used during windrow composting. Their values increased over the composting period, and at the end of maturation there was a wide variation in humic acid concentration (37.3 to 89.7 g kg^{-1}) and CEC (68.4-115.5 meq 100 g^{-1}). The total C and ash content were also influenced by the operating strategy.

The ATP content of the spent litter at maturity varied depending on the concentration in the initial material. Spent litter piles with higher initial ATP content also had higher ATP values at mature stage (Table 3). Like the ATP content, the total aerobic heterotroph population of the spent litter was also influenced by the initial material. During composting, the population of total aerobic heterotrophs increased, and then declined back to a level similar to the initial population. The microbial biomass C, on the other hand, was more influenced by the operating strategy (Table 4).

Garcia et al. (1992 and 1993) and Serra-Wittling et al. (1996) noted that for a parameter to be considered as a suitable indicator of compost maturity, it is not sufficient that it follow a similar pattern of change during composting as other parameters. Rather, it is important that the parameter reach a similar value in all compost at maturity, regardless of differences in the initial material and composting strategy used. Amongst all the chemical parameters studied, the concentrations of inorganic nutrients (NH_4^+-N, [NO_3^- + NO_2^-]-N, extractable P and K), and pH would be suitable as indicators of maturity of spent litter, because their numerical values were not influenced by the initial material or the operating strategy employed during windrow composting. When the spent litter reached maturity, compost from all piles shared the same quality in terms of these chemical parameters. Moreover, these chemicals have direct links to the fertility of the compost and thus contribute largely to the quality of the compost material. These parameters are also considered as useful indicators of maturity of sewage sludge (Riffaldi et al. 1986), green wastes (Forster et al. 1993), cattle manure (Inbar et al. 1993) and municipal solid waste (Avnimelech et al. 1996) composts. These authors report that the water-extractable chemical parameters, such as those reported in the present study, are useful for the determination of maturity.

Total and water-extractable Cu and Zn concentrations of the mature compost were also not affected by the starting spent litter material and composting strategy, as these parameters reached similar values in all piles at mature stage. Therefore, they can also be considered as a useful index for the maturity of spent litter in the present study. However, in the literature, these parameters have never been considered as indices of compost maturity. Rather, they are often used to assess the quality of compost in terms of potential environmental contamination (Massiani and Domeizel, 1996; Savage, 1996; Tiquia and Tam, 1998b) especially when composts are recycled back to agricultural land. The concentrations of total Cu and Zn in the spent litter compost were high, and this fact cannot be avoided since these two metals are added in the pig diet. However, as far as the application of compost on agricultural land is concerned, the content of the water-extractable form of the heavy metals is more important than the total metal concentration

(Petruzzelli et al. 1989; Tiquia et al. 1996c). The water-extractable Cu and Zn concentrations decreased during composting because they bind with the humic substances. The final concentrations are therefore not due to the moisture content of the windrow, turning frequency, or feed types. Leaching of Cu and Zn due to run-on and run-off was not observed. In the present study, decreases in water-extractable Cu and Zn concentrations coincided with increases in humic acid content of the spent litter, indicating the ability of humic substances to form stable complexes with metal ions. Therefore, the water-extractable Cu and Zn can be used as suitable parameters to indicate maturity of spent litter.

The dehydrogenase activity of the spent litter was not affected by either the initial material or the operation strategy used in the present study. At maturity, the values of this parameter did not differ significantly among the nine piles (Tables 3). The activity of this enzyme can therefore be used as a suitable indicator of maturity of spent litter. Moreover, this parameter also has a direct link to the microbial activity and degradation of the spent litter (Tiquia et al. 1996b; Tiquia et al. 1997c). The dehydrogenase enzyme is involved in the respiratory chains of all organisms and has been used to evaluate the microbial activity in soils (Serra-Wittling et. al. 1995). It has also been used to evaluate the maturity of animal and green-waste composts (Foster et. al. 1993; Vuorinen and Saharinen, 1997). These authors used dehydrogenase activity as an indicator of compost maturity because its numerical value in the oldest compost was lower than in the youngest compost, and it reached a constant level after two to three months of curing.

For practical composting operations, it would be desirable to use simple, inexpensive and easy indicators of compost maturity. The measurement of parameters such as pH, EC, ammonium, dehydrogenase activity and possibly water-extractable Cu and Zn concentrations of the composted product satisfied these criteria, and can be used as indices of maturity. The spent litter can be considered mature if it reached values summarized in Table 10.

Table 10. Changes during composting, and maturity values of the important microbiological and chemical parameters of the spent pig litter.

Maturity parameter	Change during composting	Maturity values
Dehydrogenase activity	Greatest at the beginning of composting and declines continuously as composting progresses	≤ 50 µg TPF g^{-1}
NH_4^+-N	Declines and stabilizes to low levels by the end of composting	≤ 0.50 mg g^{-1}
$(NO_3^- + NO_2^-)$-N	Increases and stabilizes by the end of composting	~ 1.50 mg g^{-1}
pH	Declines and stabilizes by the end of composting	5.5. to 6.0
EC	Increases and stabilizes by the end of composting	1.5 to 3.0 mS cm^{-1}
Water-extractable Cu	Decreases to low levels and stabilizes by the end of composting	≤ 15 µg g^{-1}
Water-extractable Zn	Decreases to low levels and stabilizes by the end of composting	≤ 15 µg g^{-1}

TPF= tri-phenyl formazan

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References

APHA (American Public Health Association), 1989. Standard Methods for the Examination of Water and Wastewater. 16th Edition. APHA, Washington, D.C., U.S.A.

Avnimelech, Y., Bruner, M., Ezrony, I., Sela, R., and Kochba, M. 1996. Stability indexes for municipal solid waste compost. Compost Sci. Util.,4 (2): 13-20.

EPD (Environmental Protection Department), 1990. Environment Hong Kong 1990. Hong Kong Government Press. Hong Kong.

Forster, J.C., Zech, W., and Wurdinger, E. 1993. Comparison of chemical and microbiological methods for the characterization of the maturity of composts from contrasting sources. Biol. Fertil. Soils, 16: 93-99.

Garcia, C., Hernandez, T., Costa, F., and Ayuso, M. 1992. Evaluation of the maturity of municipal waste compost using simple chemical parameters. Commun. Soil Sci. Plant Anal., 23 (13 and 14): 1501-1512.

Garcia, C., Hernandez, T., Costa, F. Ceccanti, B., Masciandaro, G., and Calcinai, M. 1993. Evaluation of the organic matter composition of raw and composted municipal wastes. Soil Sci. Plant Nutr., 39: 99-108.

Golueke, C.G. 1977. Biological Reclamation of Organic Wastes. Rodale Press. Emmaus, Pennsylvania, U.S.A.

Harada, Y. and Inoko, A., 1990. The measurement of cation-exchange capacity of composts for the estimation of degree of maturity. Soil Sci. Plant Nutr., 26(1): 123-134

Inbar, Y., Hadar,Y., and Chen, Y. 1993. Recycling of cattle manure: The composting process and characterization of maturity. J. Environ. Qual., 22 (4): 857-863.

Massiani, C. and Domeizel, M. 1996. Quality of composts: Organic matter stabilization and trace metal contamination. In: M. De Bertoldi, P. Sequi, P. Lemmes and T. Papi. (Editors), The Science of Composting. Chapman and Hall. London, U.K. pp. 185-194.

Michel, F.C., Huang, J.F., Forney, L.J., and Reddy, C.A. 1996. Field scale study of the effect of pile size, turning regime and leaf grass mix ratio on the composting of yard trimmings. In: M. De Bertoldi, P. Sequi, P. Lemmes and T. Papi. (Editors), The Science of Composting. Chapman and Hall. London, U.K. pp. 577-584.

Page, A.L., Miller, R.H., and Keeney, D.R., 1982. Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. No. 9 (Part 2), Series Agronomy, Wisconsin, USA.

Petruzzelli, L., Lubrano, L., and Guidi, G. 1989. Uptake by corn and chemical extractability of heavy metals from a four years compost treated soil. Plant Soil, 16: 23-27.

Riffaldi, R., Levi-Minzi, R., Pera, A., and de Bertoldi, M. 1986. Evaluation of compost maturity by means of chemical and microbial analyses. Waste Manage. Res., 4: 387-396.

Savage, G.M. 1996. The importance of waste characteristics and processing in the production of quality compost. In: M. De Bertoldi, P. Sequi, P. Lemmes and T. Papi. (Editors), The Science of Composting. Chapman and Hall. London, U.K. pp. 784-791.

Serra-Wittling, C. Houot, S., and Barriuso, E. 1995. Soil enzymatic response to addition of municipal solid-waste compost. Biol. Fertil. Soils, 20: 226-236.

Serra-Wittling, C., Barriuso, E., and Houot, S. 1996. Impact of composting type on composts organic matter characteristics. In: M. De Bertoldi, P. Sequi, P. Lemmes and T. Papi. (Editors), The Science of Composting. Chapman and Hall. London, U.K. pp. 262-273.

Tam, N.F.Y. and Tiquia, S.M. 1999. Nitrogen transformation during co-composting of spent pig manure, sawdust litter and sludge in forced-aerated system Environ. Technol., 20: 259-267.

Tiquia, S.M., and Tam, N.F.Y. 1998a. Composting of pig manure in Hong Kong. BioCycle, 39(2): 78-79.

Tiquia, S.M. and Tam, N.F.Y 1998b. Elimination of phytotoxicity during co-composting of spent pig-manure sawdust litter and pig sludge. Biores. Technol., 65: 43-49.

Tiquia, S.M., Tam, N.F.Y., and Hodgkiss, I.J. 1996a. Effect of moisture content on composting of pig-manure sawdust litter disposed from the pig-on-litter (POL) system. In: M. De Bertoldi, P. Sequi, P. Lemmes and T. Papi. (Editors), The Science of Composting. Chapman and Hall. London, U.K. pp. 1361-1364.

Tiquia, S.M., Tam, N.F.Y., and Hodgkiss, I.J. 1996b. Microbial activities during composting of spent pig-manure sawdust litter at different moisture contents. Biores. Technol., 55: 201-206.

Tiquia, S.M., Tam, N.F.Y., and Hodgkiss. I.J. 1996c. Effects of composting on phytotoxicity of pig-manure sawdust litter. Environ. Pollut., 93 (3): 249-256.

Tiquia, S.M., Tam, N.F.Y., and Hodgkiss, I.J. 1997a. Effects of turning frequency on composting of spent pig-manure sawdust litter. Biores. Technol., 67: 37-42.

Tiquia, S.M., Tam, N.F.Y., and Hodgkiss, I.J. 1997b. Effects of bacterial inoculum and moisture adjustment on composting of pig manure. Environ. Pollut., 96 (2): 161-171.

Tiquia, S.M., Tam, N.F.Y., and Hodgkiss, I.J. 1997c. Composting of spent pig litter at different seasonal temperatures in subtropical climate. Environ. Pollut., 98 (1): 97-104.

Tiquia, S.M., Tam, N.F.Y., and Hodgkiss, I.J. 1998. Changes in chemical properties during composting of spent pig litter at different moisture contents. Agric. Ecosys. Environ., 67: 79-89.

Vance, E.D., Brookes, P.C. and Jenkinson, D.S., 1987. An extraction method for measuring soil microbial biomass C. Soil Biol. Biochem., 18: 569-576.

Vuorinen, A.H., and Saharinen, M.H. 1997. Evolution of microbiological and chemical parameters during manure and straw co-composting in a drum composting system. Agric. Ecosys. Environ., 66: 19-29.

West, A.W., Sparling, G.P., and Grant, W.D., 1986. Correlation between four metods to estimate microbial biomass in stored, air-dried and glucose-amended soils. Soil Biol., Biochem., 18: 569-576.

Zar, J.H. 1984. Biostatistical Analysis. Prentice Hall, Englewood Cliffs, NJ, U.S.A.