ELSEVIER

Bioresource Technology 72 (2000) 1–7

BIORESOURCE TECHNOLOGY

Co-composting of spent pig litter and sludge with forced-aeration

S.M. Tiquia [a,*], N.F.Y. Tam [b]

[a] Department of Agricultural and Biosystems Engineering, Iowa State University, Ames, IA 50011, USA
[b] Department of Biology and Chemistry, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, People's Republic of China

Received 28 April 1999; received in revised form 23 June 1999; accepted 26 June 1999

Abstract

Co-composting spent pig (*Sus scrofa* L.) litter (a mixture of partially decomposed pig manure and sawdust) with pig sludge (the sludge that settled at the bottom of the primary sedimentation tank in treating slurries) was evaluated as a means to reduce the volume of wastes and to produce a stable organic soil amendment. Three piles with forced-aeration were established by mixing 2:1 wet (v/v) ratio of spent litter and pig sludge. Composting process parameters monitored over 91 days included some physical, chemical, and biological properties of the spent litter-sludge mixture. The efficiency of composting at the top location of the forced-aeration piles was slower than the middle, bottom and surface locations. The top location took 63 days to return to ambient level. It took 49 days for the middle and bottom locations, and only 28 days were needed for that in the surface location. The variations in temperature at different locations of the forced-aeration piles were also reflected in differences in some chemical and biological parameters. The top location had the lowest total aerobic heterotroph numbers, suggesting that the microbial activity was slower. Moreover, this zone also had the lowest germination index and highest concentrations of NH_4^+–N and water-extractable Cu and Zn during the first 49 days of composting, indicating that the elimination of phytotoxicity and the composting rate was slower than the middle, bottom and surface locations. However, these differences were evident only during the first 49 days of composting. By day 63, the spent litter-sludge at the top location had similar properties with that of the other three locations. © 1999 Elsevier Science Ltd. All rights reserved.

Keywords: Pig manure; Composting process; Compost; Compost maturity; Fecal coliforms; Phytotoxicity

1. Introduction

The pig industry has seen a steady growth in recent years in Hong Kong. Pigerries have been identified among agricultural livestock industries as the most significant point source contributors to stream pollution (Hodgkiss and Griffiths, 1987; Tiquia and Tam, 1998a). Pollution from piggeries accounts for 70% of all stream pollution in the New Territories and 50% of organic matter entering the sea (Hodgkiss and Griffiths, 1987). As a solution to the declining inland and marine water quality in Hong Kong, several methods have been developed to treat pig wastes to a discharge limit of 50 mg l^{-1} BOD (biological oxygen demand) and 50 mg l^{-1} SS (suspended solids). These treatment methods include the (1) wet and dry muck-out technique, (2) sequential batch reactor system, (3) batchwise activated sludge system, and (4) pig-on-litter system (EPD, 1990).

Composting is one of the most promising avenues to recycle the wastes generated from these four treatment methods, as the process reduces the volume, and stabilizes the wastes. The use of organic wastes in application to farmland has increased over the years since the use contributes to the disposal of wastes and enhances the preservation of the environment. The high organic matter content in the composted product also preserves soil fertility. Various studies have characterized composting of pig manure (Lau et al., 1993; Liao et al., 1993; Lo et al., 1993; Bhamidimarri and Pandey, 1996; Tiquia and Tam, 1998a; Tiquia et al., 1998a). These studies focused mostly on the evaluation of environmental factors (i.e., aeration, moisture content, and temperature) for efficient composting of pig manure. Bhamidimarri and Pandey (1996) have successfully co-composted piggery wastes with sawdust. They reported that sawdust appears to be an ideal bulking agent for composting pig manure because of its ability to absorb moisture, and its structure provides adequate porosity in

---

[*] Corresponding author. Present address: Department of Food, Agricultural and Biological Engineering, Agricultural Research and Development Center (OARDC), Ohio State University, Wooster, OH 44691, USA; e-mail: tiquia1@osu.edu

0960-8524/00/$ - see front matter
PII: S0960-8524(99)00092-9

the compost heap. However, the effects of co-composting two or more wastes on the decomposition process and on the quality of the mature product are not well understood. Co-composting could bring environmental benefits, but it could also create environmental risks, as there is a possibility that pathogens, heavy metals, and other phytotoxic contaminants may remain at high levels in the composted product. In the present study, the pig sludge that settled at the bottom of the sedimentation tank in the waste treatment plant was co-composted with that of the spent pig litter-waste disposed from the pig-on-litter system (Tiquia, 1996). Our previous studies on composting of spent pig litter revealed that the phytotoxicity (using seed germination and root elongation assay) of the spent pig litter is eliminated with increasing maturity (Tiquia et al., 1996a, 1997). Fecal coliform bacteria are also significantly reduced to low levels by the end of composting (Tiquia et al., 1998b). Therefore, the aim of the present study is to evaluate the changes in physical, chemical, and biological properties of co-composted mixture of spent litter and pig sludge.

To reduce the labor cost and space requirements, a forced-aeration composting system was developed and examined. Forced-aeration windrow composting uses a perforated pipe system located underneath the compost pile, to induce air movement into the material and deliver oxygen to the microorganisms (Epstein et al., 1976; Stentiford et al., 1985; Brouillette et al., 1996; Tiquia and Tam, 1998b). Since forced-aeration composting is a non-turning method, the efficiency of composting at different locations in the pile may be different due to variations in aeration level. Therefore, the efficiency of composting at different locations of the forced-aeration piles was evaluated.

2. Methods

The pig sludge was collected from the primary sedimentation tank of the waste treatment plant at Ta Kwu Ling Pig Breeding Centre, New Territories of Hong Kong. The chemical properties of the pig sludge used in this study are reported (Table 1). The spent pig litter disposed from the pig-on-litter system was mixed with the sludge at a ratio of 2:1 (spent litter:sludge; wet volume). The moisture content of the spent litter-sludge mixture was 65% (w/v) before piling, and no moisture adjustment was carried out thereafter. Three spent litter-sludge piles were built on perforated pipes connected to an air pump. Details of the forced-aeration windrow composting set-up were described by Tiquia and Tam (1998b,1998c). Each pile was pyramidal in shape, about 2 m in width at the base and 1.5 m in height. The air pump was on continuously during the entire period of composting. Spent litter-sludge samples were taken at four different locations of the forced-aeration pile: top (130 cm from the base of the pile); middle (75 cm from the base of the pile); bottom (30 cm from the base of the pile); and surface (5 cm from the outer surface of the pile). Samples were collected at day 0, and then weekly until day 77. The temperatures in the forced-aeration piles were recorded at the four different locations every four days.

The spent litter-sludge samples were analyzed for pH (1:10 w/v sample:water extract) using a pH probe; electrical conductivity (EC) (1:5 w/v sample:water extract) using an electrical conductivity probe; water-extractable C (by TOC analyzer, Shimadzu TOC-500); total P and K, and different forms of N (Sparks, 1996); total and water-extractable C, Cu, and Zn (by atomic absorption spectrophotometry); denitrifying bacteria (Weaver et al.,

Table 1
Physico-chemical properties of the initial spent litter, pig sludge and spent litter–sludge mixture

Parameters	Types of materials		
	Spent litter[a]	Pig sludge[b]	Spent litter–sludge[b]
Moisture content (%)	30–45	89 ± 3.50	65 ± 1.77
pH	7.90–8.50	7.44 ± 0.30	8.60 ± 0.32
EC (dS m^{-1})	1.47–2.74	3.50 ± 0.11	2.85 ± 0.17
Ash content (g kg^{-1})	97–129	239 ± 2.28	148 ± 2.27
Total C (g kg^{-1})	505–525	441 ± 1.15	494 ± 1.45
Total N (g kg^{-1})	18.0–30.5	65.6 ± 0.22	28.1 ± 5.82
Organic N (g kg^{-1})	14–23	59.2 ± 1.15	25.0 ± 2.28
NH_4^+–N (g kg^{-1})	3.9–7.2	6.3 ± 0.15	3.0 ± 1.13
$(NO_3^- + NO_2^-)$–N (g kg^{-1})	0.08–0.27	0.13 ± 0.01	0.06 ± 0.02
C:N ratio	16.7–27.4	6.73 ± 1.20	17.58 ± 1.15
Total P (g kg^{-1})	13.2–18.0	12.2 ± 0.08	16.0 ± 0.12
Total K (g kg^{-1})	10.6–21.1	8.9 ± 0.02	11.0 ± 0.18
Total Cu (mg kg^{-1})	428–551	120 ± 29.38	276 ± 9.12
Water-extractable Cu (mg kg^{-1})	38.2–52.2	3.68 ± 0.58	42.6 ± 0.85
Total Zn (mg kg^{-1})	615–744	428 ± 174.96	556 ± 68.71
Water-extractable Zn (mg kg^{-1})	18.8–35.7	8.09 ± 1.29	7.87 ± 0.98

[a] Data ranges were obtained from Tiquia and Tam (1998b), and Tiquia et al. (1996a, 1998a).

[b] Data (mean and standard deviation of three replicates) obtained from this study.

1994); fecal coliform count (Dudley et al., 1980); and the seed germination index (GI) of two local vegetables: Chinese cabbage (*Brassica parachinensis* Bailey) and Chinese spinach (*Amaranthus espinosus* L.) (Tiquia and Tam, 1998c; Tiquia et al., 1996a). The population sizes of total aerobic heterotrophs, and fecal coliforms were assayed using the plate frequency technique (Tiquia and Tam, 1998b; Tiquia et al., 1998a). This technique involves inoculating 0.1 ml of the serially diluted spent litter suspension on eight sections of the agar plate. Bacterial colonies observed in any of the eight sections were considered positive growth. The total numbers of positive growth were counted, and the population size of microorganisms in the sample was estimated using a most probable number (MPN) computing package (Tam, 1982).

The mean and standard deviation of the three replicates were reported for all parameters measured. To compare the variations in physical, chemical, and biological parameters at different locations (top, middle, bottom, and surface) in the forced-aeration piles, a one-way analysis of variance (ANOVA) statistical analyses followed by the Bonferroni test were performed using the procedure described by Zar (1984).

3. Results and discussion

3.1. Temperature and moisture content

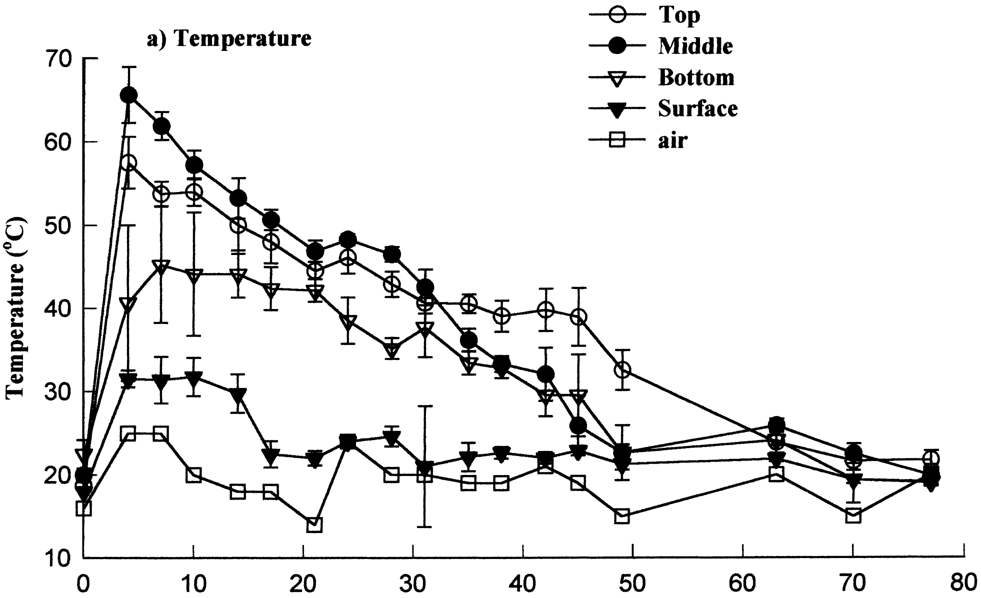
The temperature profiles at different location (top, middle, bottom and surface) of the spent litter-sludge piles are reported (Fig. 1(a)). The top (130 cm from the base of the pile) and middle (75 cm from the base of the pile) locations had smaller variations compared to the surface (5 cm from the outer surface of the pile) and bottom (30 cm from the base of the pile) locations. The surface location had the lowest temperature, as it was closest to the ambient air. The maximum temperature achieved in this location was only 31°C. On the other hand, the peak temperature recorded at the bottom location was also lower (45°C) compared to the top and middle (65°C and 58°C, respectively) locations. However, the temperature of the bottom zone was sustained for 21 days, whereas that of the top and middle locations dropped continuously after peaking at day 7.

During composting, the moisture content of the spent litter-sludge piles decreased from 65% to around 40–55% (Fig. 1(b)). The main mechanism of water removal in this composting process was the evaporation of water as a consequence of microbial heat generation. Water evaporation caused a continuous heat removal in the forced-aeration piles and dried the spent litter-sludge progressively. The continuous decrease in moisture content during composting is an indication of organic matter decomposition (Miller and Finstein, 1985). From day 49 onwards, very little drying occurred, indicating a low rate of decomposition and heat production, and the temperature of the spent litter-sludge piles began to drop to ambient levels (Figs. 1(a) and (b)).

3.2. Chemical characteristics and phytotoxicity assays

The initial pH of the spent litter-sludge ranged between 8.23 and 8.67 in all four locations of the forced-aeration piles. These values are within the optimum range for composting (Bertoldi et al., 1983; Miller, 1992). By the end of the process, the pH fell to nearly neutral values (6.5–7.0), which is an indication of stabilized material (Sesay et al., 1997). The levels of NH_4^+–N decreased, but the $(NO_3^- + NO_2^-)$–N increased during composting. These trends are typical of a good composting process (Riffaldi et al., 1986). In the present study, the decrease in NH_4^+–N concentration was more rapid at the bottom location of the spent litter-sludge piles, where it was closest to the aeration pipes. The increase in $(NO_3^- + NO_2^-)$–N concentration was higher in this location. Brouillette et al. (1996) reported that the respective decrease in NH_4^+–N and increase in $NO_3^- + NO_2^-$–N concentrations are higher as the aeration level increases. The decreasing NH_4^+–N concentration to low levels often has been looked upon with optimism in terms of determining the quality of the mature product and process performance (Sesay et al., 1997). In a well-managed process, much of the readily available N is converted into stable forms that resist further ammonification (Miller, 1992). The drop in NH_4^+–N concentration to low levels (0.18–0.61 g kg^{-1}) by day 77, therefore, indicate favorable composting conditions. The C:N ratio of the spent litter-sludge piles changed little with time (Table 2). Since C:N ratios of the spent litter-sludge piles never exceeded 20:1–25:1, it is unlikely that the available nitrogen ever limited microbial decomposition.

The seed germination index (GI, a factor of relative seed germination and relative root elongation) of Chinese cabbage and Chinese spinach was below 50, showing a retardation of growth at day 0 (Table 3). As composting proceeded, the GI of the two plant species increased to between 80% and 98% by the end of composting. Increases in GI values corresponded with decreases in concentrations of NH_4^+–N and water-extractable Cu and Zn (Tables 2 and 3). The decrease in water-extractable Cu and Zn could be attributed to the formation of metal–humus complex in the spent litter-sludge, thus making these two metals not water-extractable and biologically unavailable. The electrical conductivity (EC) values of the spent litter-sludge piles increased to as high as 3.67–4.26 dS m^{-1} during composting (Table 2). These high EC values did not have a negative effect on the GI of Chinese cabbage and Chinese spinach (Table 3). It has been reported that a GI



b) Moisture content

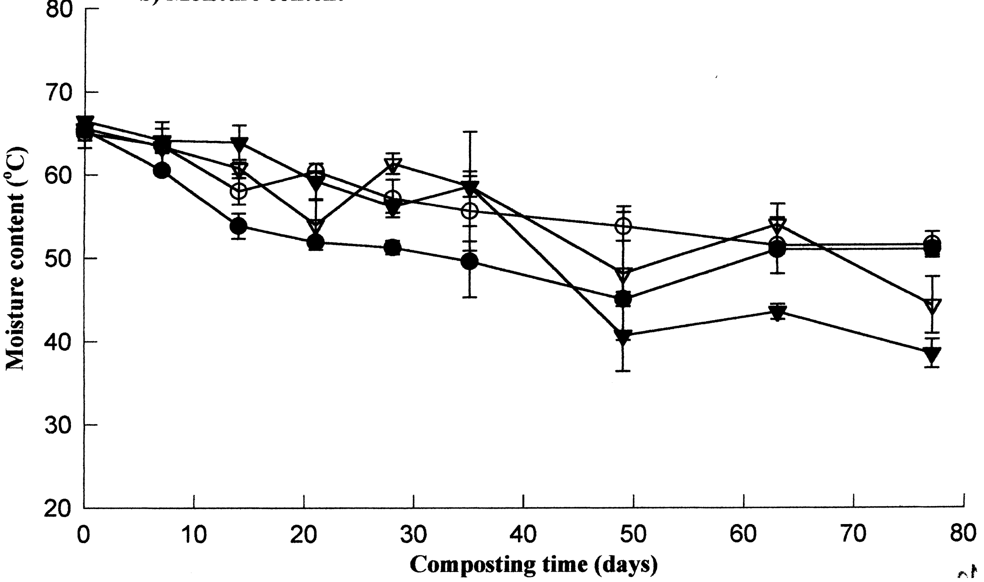


Fig. 1. Changes in (A) air and pile temperature, and (B) moisture content of the spent litter–sludge piles during a 77-day composting process (mean and standard deviation of the three replicates are shown).

value ⩾ 80% indicated the disappearance of phytotoxins in composts (Zucconi et al., 1981; Tiquia et al., 1996a). This value was reached from day 63 onwards in this composting process.

3.3. Microbial properties

The compost microbiota determine the rate of composting, affect the quality of the product, and produce most of the physical and chemical changes in compost (McKinley and Vestal, 1985). In the present study, the population of total aerobic heterotrophs was used to examine the rate of composting. This parameter also has been considered as a good measure of microbial activity (Jimenez and Garcia, 1989; Tiquia et al., 1996b). In the present study, the total aerobic heterotroph counts were highest at the beginning of composting (Table 3). Counts decreased sharply by day 14 and then leveled off towards the end of composting. The population of total aerobic heterotrophs at the top location of the forced-aeration piles was significantly lower than at the other three locations (Table 4), indicating a slower rate of decomposition in this location. However, by the end of composting, counts were similar in all four locations of the forced-aeration piles.

Table 2
Changes in chemical properties of the spent litter–sludge at four locations (top, middle, bottom, and surface) of the forced-aeration piles

Parameters[a]	Pile locations	Composting time (days)				
		0	14	35	63	77
C:N ratio	Top	19.3	10.9	11.5	14.5	11.0
	Middle	18.6	12.0	12.1	13.9	14.5
	Bottom	16.4	11.8	14.0	13.4	15.4
	Surface	16.5	11.5	12.5	12.7	15.0
NH_4^+–N (g kg^{-1})	Top	2.80	4.84	3.45	0.71	0.59
	Middle	2.96	1.08	0.23	0.76	0.46
	Bottom	3.04	0.12	0.57	0.35	0.18
	Surface	3.19	1.45	0.77	0.76	0.61
$(NO_3^- + NO_2^-)$–N (g kg^{-1})	Top	0.08	0.29	1.03	0.93	1.78
	Middle	0.06	0.19	0.84	1.58	1.88
	Bottom	0.06	0.30	1.37	1.29	1.99
	Surface	0.06	0.43	1.12	1.21	1.55
pH	Top	8.67	9.10	7.12	7.09	6.52
	Middle	8.64	7.84	7.23	7.08	6.92
	Bottom	8.89	7.11	7.02	6.87	6.92
	Surface	8.23	8.07	6.92	7.05	6.50
EC (dS m^{-1})	Top	2.83	3.03	4.21	4.19	4.04
	Middle	2.76	3.65	4.21	4.36	3.67
	Bottom	2.61	2.82	3.80	3.58	4.61
	Surface	3.07	2.72	3.83	3.83	4.26
Water-extractable Cu (mg kg^{-1})	Top	43	42	13	10	5
	Middle	43	11	12	8	4
	Bottom	45	7	5	6	5
	Surface	44	18	5	8	9
Water-extractable Zn (mg kg^{-1})	Top	7.0	24.0	14.1	9.6	5.7
	Middle	7.9	23.0	6.3	4.9	4.8
	Bottom	9.5	8.2	7.3	4.0	8.6
	Surface	7.1	10.2	7.1	7.7	6.0

[a] Mean of three replicates are shown. Data presented are based on 105°C dry weight basis.

Table 3
Changes in microbial and phytotoxicity of the spent litter–sludge at four locations (top, middle, bottom, and surface) of the forced-aeration piles

Parameters[a]	Pile locations	Composting time (days)				
		0	14	35	63	77
Heterotrophs ($\log_{10}$ MPN g^{-1})	Top	10.17	7.80	5.98	6.61	6.77
	Middle	10.25	8.85	7.79	7.77	7.16
	Bottom	10.18	9.25	7.47	7.61	7.49
	Surface	10.04	8.19	7.50	7.56	7.62
F. coliforms ($\log_{10}$ MPN g^{-1})	Top	6.34	3.31	ND	ND	ND
	Middle	6.52	3.89	ND	ND	ND
	Bottom	6.18	2.95	ND	ND	ND
	Surface	6.31	3.39	ND	ND	ND
Germination index (cabbage)	Top	28	21	78	81	98
	Middle	19	2	77	81	87
	Bottom	32	84	82	87	87
	Surface	47	73	88	87	82
Germination index (spinach)	Top	9	5	89	84	82
	Middle	5	8	92	96	92
	Bottom	12	69	98	100	91
	Surface	6	60	94	99	92

[a] Mean of three replicates are shown. Data presented are based on 105°C dry weight basis. F. coliforms – fecal coliforms. ND – not detected.

Table 4
Effects of composting on physical, chemical, microbial and biological properties of the spent litter–sludge at four locations (top, middle, bottom, and surface) of the forced-aeration piles

Parameters[a]	Top	Middle	Bottom	Surface
Physical parameters				
Temperature (°C)	39.67^{a}	39.50^{a}	33.49^{ab}	23.76^{b}
Moisture content (%)	57.41^{a}	53.31^{a}	56.70^{a}	54.61^{a}
Chemical parameters				
C:N ratio	12.94^{a}	14.46^{a}	13.56^{a}	13.14^{a}
NH_4^+–N (g kg^{-1})	3.13^{a}	1.20^{b}	0.60^{c}	1.34^{b}
$(NO_3^- + NO_2^-)$–N (g kg^{-1})	0.75^{a}	0.70^{a}	0.88^{a}	0.86^{a}
pH	8.04^{a}	7.76^{a}	7.37^{a}	7.48^{a}
EC (dS m^{-1})	3.54^{a}	3.56^{a}	3.23^{a}	2.34^{a}
Extractable Cu (mg kg^{-1})	31.3^{a}	17.4^{b}	11.7^{b}	17.9^{b}
Extractable Zn (mg kg^{-1})	16.71^{a}	9.02^{b}	6.90^{b}	9.93^{b}
Microbial parameters				
Hetero ($\log_{10}$ MPN g^{-1})	7.37^{a}	8.44^{b}	8.55^{b}	8.19^{b}
F.coli ($\log_{10}$ MPN g^{-1})	1.80^{a}	1.95^{a}	1.84^{a}	1.76^{a}
Biological parameters				
GI (cabbage)	46.23^{a}	60.66^{b}	76.93^{b}	70.40^{b}
GI (spinach)	40.48^{a}	63.50^{b}	75.79^{b}	66.13^{b}

[*] Row means followed by the same letter are not significantly different according to the ANOVA test. Significant differences among means were compared using the Bonferroni test at $P \leqslant 0.05$ probability level; Hetero – total aerobic heterotrophs; F. coli – fecal coliforms; GI – germination index.

In cases where the mature spent litter is to be applied to agricultural soils and where public health aspects are of concern, the levels of pathogens and their elimination during the composting process are important criteria that must be evaluated. In the present study, the spent litter-sludge was examined for fecal contamination during composting. The fecal coliform numbers were as high as 6.18–6.65 $\log_{10}$ MPN g^{-1} at the beginning of composting. By day 35, fecal coliforms were eliminated in the spent litter-sludge piles (Table 3). No fecal coliforms were detected thereafter although the temperatures in the forced-aeration piles were near ambient levels, indicating that high temperature killed the coliforms. There are also other mechanisms that influenced pathogen destruction or suppression occurred in the spent litter-sludge piles, in addition to thermal inactivation. Bertoldi et al. (1991) reported that bacteria and pathogenic organisms can generally metabolize readily assimilable organic matter such as alcohols, and sugars whereas they cannot multiply on complex compounds such as cellulose, lignin, and humic substances. During composting, the immature compost material is mineralized and humified to more complex organic matter (Garcia et al., 1991; Robertson and Morgan, 1995; Tiquia et al., 1998a). The resulting limitation in available organic matter during the later stage of composting might explain why fecal coliforms did not survive in the spent litter-sludge in the present study. Similar findings were observed also by Sesay et al. (1997) during composting of paper pulp sludge in aerated static piles.

3.4. Spatial variation in the degree of composting

Result of the ANOVA statistical testing showed that temperature had a significant effect on spatial variations in forced-aeration piles (Table 4). The time required for the temperature to reach ambient level varied between locations. For instance, the top location took 63 days to return to ambient level. It took 49 days for the middle and bottom locations, and only 28 days were needed for that in the surface location (Fig. 1(a)). These differences indicate that the aeration condition and the degree of decomposition varied at different locations in the pile. The variations in temperature at different locations of the forced-aeration piles parameters were also reflected in differences in some chemical and biological parameters, such as NH_4^+–N, water-extractable Cu and Zn, germination index (GI), and total aerobic heterotrophs. The top location (the zone that took the longest time to reach the ambient level) had the lowest total aerobic heterotroph numbers (Table 3), suggesting that the microbial activity in this zone was slower than the other three zones. Moreover, the top location had the lowest germination index (Table 3) and highest concentrations of NH_4^+–N and water-extractable Cu and Zn during the first 35 days of composting (Table 2). These results imply that the elimination of phytotoxicity and the composting rate was slower than the middle, bottom and surface locations of the forced-aeration piles. As the air was blown into the pile from bottom to the top, less air would be available at the top. This may be why composting at the top location was slower than the other three locations of the forced-aeration piles in the present study. However, this was only evident during the first 49 days of composting. By day 63, composting in all four locations was similar. At this stage, the physical, chemical and biological properties of the spent litter-sludge appeared to be stabilized, suggesting that no further decomposition was taking place in the spent litter-sludge. Results of the phytotoxicity assay and fecal coliform counts showed that the spent litter-sludge is suitable for use on agricultural land. Compost maturity was achieved within 63 days in the present study. Moreover, the efficiency of composting the spent litter-sludge was comparable to that of composting spent pig litter alone in turned or in forced-aeration composting systems (Tiquia and Tam, 1998b; Tiquia et al. 1996b, 1998a).

Acknowledgements

The authors thank Mr. Alex Chan of the Agriculture and Fisheries Department, Hong Kong Government, and all his staff for all the technical assistance offered. This project was financially supported by the Central Matching Fund (Post-doctoral Fellowship) of the City University of Hong Kong.

References

Bertoldi, M.de, Vallini, G., Pera, A., 1983. The biology of composting. Waste Manage. Res. 1, 157–176.

Bertoldi, M.de, Zucconi, F., Civilini, M., 1991. Temperature, pathogen control and product quality. In: The staff of BioCycle (Ed.), The BioCycle Guide to the Art and Science of Composting. The JG Press, Emmaus, PA, USA, pp. 195–199.

Bhamidimarri, S.M.R., Pandey, S.P., 1996. Aerobic thermophilic composting of piggery solid wastes. Wat. Sci. Technol. 33 (8), 89–94.

Brouillette, M., Trepanier, L., Gallichand, J., Beauchamp, C., 1996. Composting paper mill deinking sludge with forced-aeration. Can. Agric. Engr. 38 (2), 115–122.

Dudley, D.J., Guentzel, M.N., Ibarra, M.J., Moore, B.E., Sagik, B.P., 1980. Enumeration of potentially pathogenic bacteria from sewage sludge. Appl. Environ. Microbiol. 39 (1), 118–126.

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

Epstein, E., Willson, G.B., Burge, W.D., Mullen, D.C., Enkiri, N.K., 1976. A forced aeration system for composting of wastewater sludge. J. Wat. Contr. Fed. 48, 688–694.

Garcia, C., Hernandez, T., Costa, F., 1991. Changes in carbon fractions during composting and maturation of organic wastes. Environ. Manage. 15 (3), 433–439.

Hodgkiss, I.J., Griffiths, D.A., 1987. Need pig wastes pollute? Hong Kong Engr. 15 (5), 43–48.

Jimenez, I.E., Garcia, V.P., 1989. Evaluation of city refuse maturity: A review. Biol. Wastes 27, 115–149.

Lau, A.K., Liao, P.H., Lo, K.V., 1993. Evaluation of swine waste composting in vertical reactors. J. Environ. Sci. Health A 28 (4), 761–777.

Liao, P.H., Vizcarra, A.T., Chen, A., Lo, K.V., 1993. Composting separated solid swine manure. J. Environ. Sci. Health A 28 (9), 1889–1901.

Lo, K.V., Lau, A.K., Liao, P.H., 1993. Composting of separated solid swine wastes. J. Agric. Engr. Res. 54, 307–317.

McKinley, V.L., Vestal, J.R., 1985. Effects of different temperature regimes on microbial activity and biomass in composting municipal sewage sludge. Can. J. Microbiol. 31, 919–925.

Miller, F.M., 1992. Composting as a process based on the control of ecologically selective factors. In: Metting Jr., F.B. (Ed.), Soil Microbial Ecology. Marcel Dekker, New York, USA, pp. 515–544.

Miller, F.C., Finstein, M.S., 1985. Materials balance in the composting of wastewater sludge as affected by process control. J. Wat. Pollut. Contr. Fed. 57, 122–127.

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

Robertson, F.A., Morgan, W.C., 1995. Mineralization of C and N in organic materials as affected by duration of composting. Austral. J. Soil Res. 33, 511–524.

Sesay, A.A., Lasaridi, K., Stentiford, E., Budd, T., 1997. Controlled composting of paper pulp sludge using the aerated static pile method. Compost Sci. Util. 5 (1), 82–96.

Sparks, D.L., 1996. Methods of Soil Analysis. Part 3 – Chemical Methods. SSSA, Madison, WI, USA.

Stentiford, E.I., Mara, D.D., Taylor. P.L., 1985. Forced-aeration composting of domestic refuse and sewage sludge in static piles. In: Gasser, J.K.R. (Ed.), Composting of Agricultural and Other Wastes. Elsevier, New York, USA, pp. 42–55.

Tam, N.F.Y., 1982. The use of organic waste to reclaim colliery spoils. Ph.D. Thesis, University of York, UK.

Tiquia, S.M., 1996. Further composting of pig manure disposed from the pig-on-litter (POL) System in Hong Kong. Ph.D. Thesis, The University of Hong Kong, Hong Kong.

Tiquia, S.M., Tam, N.F.Y., Hodgkiss, I.J., 1997. Effects of turning frquency on composting of spent pig-manure sawdust litter. Biores. Technol. 62, 37–42.

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

Tiquia, S.M., Tam, N.F.Y., 1998b. Composting of spent pig litter in turned and forced-aerated piles. Environ. Pollut. 99, 329–337.

Tiquia, S.M., Tam, N.F.Y., 1998c. 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., Hodgkiss, I.J., 1996a. Effects of composting on phytotoxicity of spent pig-manure sawdust litter. Environ. Pollut. 93 (3), 249–256.

Tiquia, S.M., Tam, N.F.Y., 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., Hodgkiss, I.J., 1998a. 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., Hodgkiss, I.J., 1998b. *Salmonella* elimination during composting of spent pig litter. Biores. Technol. 63, 193–196.

Weaver, R.W., Angle, J.S., Bottomley, P.S., 1994. Methods of Soil Analysis. Part 2 – Microbiological and Biochemical Properties. SSSA, Inc., Madison, WI, USA, 1121 p.

Zar, J.H., 1984. Biostatistical Analysis, Prentice-Hall, New York, USA, 718 p.

Zucconi, F., Forte, M., Monaco, A., Bertoldi, M.de, 1981. Biological evaluation of compost maturity. BioCycle 22, 27–29.