ELSEVIER

Environmental Pollution 99 (1998) 329–337

ENVIRONMENTAL POLLUTION

Composting of spent pig litter in turned and forced-aerated piles

S.M. Tiquia, N.F.Y. Tam *

Department of Biology and Chemistry, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong, PR China

Received 5 September 1997; accepted 21 December 1997

Abstract

A study was carried out to compare the composting efficiency of spent litter (a mixture of partially decomposed pig manure and sawdust) in turned and forced-aerated piles. Duplicate piles were built with manual turning (every 4 days) during composting, and duplicate piles were set up with forced aeration using an air pump. The present study demonstrated that the efficiency of composting in the turned and forced-aerated piles was similar. Spent litter in these piles reached maturity at the same time (60 days). The forced-aerated piles went through similar physical, chemical, and microbial changes with the turned piles during composting. The forced-aerated composting system was also as effective as the turned system in eliminating *Salmonella* sp. in the spent litter. These results suggest that a forced-aerated composting system could be used as an alternative method in composting spent litter. The similarities in temporal changes in temperature, chemical, and microbiological properties of the forced-aerated piles, compared with the turned piles, indicate that addition of a bulking agent under forced aerated composting of spent litter is not necessary. The partially decomposed sawdust in the spent litter provided enough free air space, allowing the delivery of oxygen for the microorganisms in the spent litter piles.

Keywords: Decomposition; Pig manure; Composting strategy; Enzyme activities; *Salmonella* elimination

1. Introduction

Composting is one of the alternative methods for treating pig waste in Hong Kong as it leads to minimization and waste utilization. The utilization of animal waste composts is particularly important in Hong Kong where the soils are very poor in terms of organic matter content (personal communication with officers of the Agriculture and Fisheries Department, Hong Kong Government). Many countries in the Asian region also need this type of input, as farmers have been using inorganic fertilizers for many years without paying particular attention for the long-term implication for soil structure. However, the acceptance of composting depends on how well the operating strategies being employed are developed and the success of the composting process. Proper evaluation of composting systems is, therefore, required if an acceptable product is to be generated, and the system efficiency is to be maximized (Tiquia, 1996; Sesay et al., 1997).

Pig-on-litter, also known as *in situ* composting, has been developed as one of the most highly recommended methods for treating pig wastes in Hong Kong (EPD, 1988). This environmentally friendly method involves raising pigs on a litter bedding (sawdust), and allowing the pig manure and urine deposits to decompose *in situ*. The *in situ* composting process that takes place within the bedding material is similar to the mesophilic composting process described by Golueke (1972). Under this system, no effluent is discharged. The only waste discharged from this system is the spent litter (a mixture of partially decomposed sawdust and pig manure), which contains organic matter and nutrients and which can be utilized as a soil conditioner or fertilizer. However, the spent litter still has active microbial populations and, therefore, requires further composting in windrows to reach full maturity (Tiquia, 1996; Tiquia et al., 1996a,b).

Our previous work on furthering composting of spent litter with manual turning in windrows (conventional composting method) revealed that it takes 60 days to convert spent litter to a mature compost if the proper operating conditions are met (Tiquia et al., 1996a,b, 1997a–c). Manual turning is often labor intensive and creates air pollution (e.g. dust). Moreover, turning requires additional space for the pile. Therefore, other operating strategies that can reduce the manpower and

* Corresponding author. Tel.: 852-27887793; fax: 852-27887406; e-mail: bhntam@cityu.edu.hk.

0269-7491/98/$19.00
PII: S0269-7491(98)00024-4

space would be worth exploring. Furthermore, composting time may be further shortened by other composting strategies. Epstein et al. (1976) reported that forced-aerated composting is a more efficient composting method, which ensures temperatures in the upper thermophilic range and provides an effective inactivation of pathogens. Forced-aerated windrow composting uses a ventilation unit (centrifugal blower) to force air into the perforated pipe system located underneath the compost pile, to induce air convection movement into the material and to deliver oxygen to the microorganisms (Epstein et al., 1976; Stentiford et al., 1985; Brouillette et al., 1996; Stentiford, 1996). Bulking agents such as wood chips, straw, peat, or sawdust are often mixed with the compost material to give the required open structure and to ensure adequate aeration (Willson, 1983; Stentiford et al., 1985; Mathur et al., 1990). This composting system is also a non-turning method and, therefore, saves space compared to the conventional windrow composting method. Such a system would be of outstanding value in Hong Kong, where space and labor are in short supply. However, this system has not yet been tried for composting spent litter. The present study, therefore, compares the composting efficiency of conventional and forced-aerated composting systems.

One of the major objectives of composting is to produce a hygienically safe and agriculturally useful product. In this study, the levels of *Salmonella* sp. were evaluated to determine whether the pathogens were eliminated during windrow composting. In cases where the mature spent litter is to be applied to agricultural soils, the evaluation of compost maturity is also necessary. Most of the criteria used in the evaluation of compost maturity were based on physical and chemical parameters of the spent litter, whose behavior reflects the metabolic activity of microorganisms involved in the process (Barberis and Nappi, 1996; Tiquia et al., 1996a,b, 1997a,c; Epstein, 1997). In this study, 16 physical, chemical, and microbiological parameters were examined to assess the maturity of spent litter.

2. Material and methods

The spent litter was collected from pig pens employing the pig-on-litter system for 12 weeks with 30 piglets raised in a $30\,m^2$ pen. The spent litter was mixed homogeneously, and the moisture content was adjusted to 60% (w/v) before piling. A duplicate series of windrows was set up with manual turning, and a duplicate series was set up with forced aeration. Each pile was triangular in shape, about 2 m in base-width and 1.5 m in height (Tiquia et al., 1996a). For the turned piles, aeration was provided by turning the piles every 4 days using a truck and front-end loader tractor. During the composting process, ambient temperature and temperature at a depth of 60 cm in these piles were monitored every 4 days (before turning). Composite samples were taken at five symmetrical locations of each pile at day 0 and then weekly until the end of the composting process (day 91). For the forced-aerated piles, 20-mm diameter polyvinyl chloride (PVC) pipes were laid at the base, with perforations (25 mm diameter) facing upward. The distance between each perforation was 20 cm. The pipes were covered by wood chips to prevent blockage of the holes, and air from the piles was supplied by an air pump, with an average flow rate of 19 liter min^{-1}, and a maximum output of 24 liter min^{-1}. The air pump was on continuously during the entire period of composting. The pipes were then topped off with a 5-cm layer of mature spent litter compost to insulate the piles and act as a biofilter to minimize odors. The temperatures in these two piles were taken from four different locations in the 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 surface of the pile) every 4 days. Samples were taken from these four locations of each pile at day 0 and then weekly until day 91.

The spent litter was analyzed for the following parameters: moisture content (105°C for 24 h); pH (1:10 w/v litter:water extract) using a pH probe; electrical conductivity (EC) (1:5 w/v litter:water extract) (Rhoades, 1996); total C (loss on ignition); total N (Bremner, 1996); NH_4^+–N and $(NO_3^- + NO_2^-)$–N (Mulvaney, 1996); particle size distribution by mechanical sieve method (Sheldrick and Wang, 1993); and actinomycete counts (Wellington and Toth, 1994). The population sizes of aerobic (mesophiles and thermophiles) and anaerobic (mesophiles and thermophiles) heterotrophs were assayed by dilution agar-plate method (APHA, 1989). For the anaerobic heterotrophs, plates were kept in an anaerobic jar (Oxoid HP11, Unipath, UK), then incubated at 25 and 50°C to allow enumeration of mesophiles and thermophiles, respectively. The population of faecal coliform and streptococci (Dudley et al., 1980), and the presence or absence of the bacterium *Salmonella* sp. using an Oxoid *Salmonella* Rapid Test kit (Oxoid FT-201, Unipath, UK) were also assayed. The enzyme activity was evaluated using APYZYM Kit (API Analytab Products, Plainview, NY, USA). APYZYM is a semi-quantitative micro-method designed for the systematic and rapid study of 19 enzymatic reactions. It consists of a series of microcupules containing dehydrated chromogenic substrates of 19 different enzymes and one control (a microcupule containing no enzyme substrate). A numerical value of 1–5 was assigned to each microcupule according to the color chart provided by the manufacturer. For the purposes of this study, the results were reported as reactions of low intensity (value of 1), moderate intensity (values of 2–4), and high intensity (value of 5). The drop technique

(Tiquia et al., 1997d) was used for all microbial counts carried out in this study. This technique involves inoculating 0.1 ml of the serially diluted spent litter suspension on the eight sections of the agar plate. Bacterial colonies observed in any of the eight sections was considered positive growth. The total number of positive growths was counted and the population of indicator organisms in the sample was estimated using a Most Probable Number (MPN) computing package (Tam, 1982). The physical, chemical, and microbial parameters of the spent litter during the turned and forced-aerated composting process were compared using Student's *t*-test (Zar, 1984).

3. Results

The physical, chemical, and microbiological properties of the spent litter from the four locations (top, middle, bottom, surface) of the forced-aerated piles were compared. No significant difference was found; therefore, the mean values in these four locations were reported in this investigation.

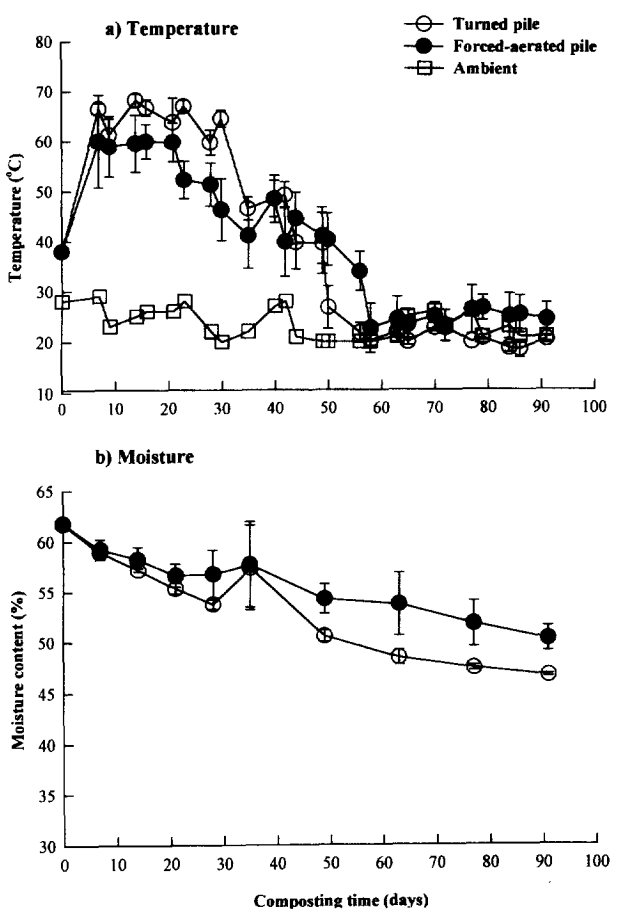

Fig. 1. Changes in air and pile temperatures, and moisture content of the spent litter during composting.

3.1. Temperature and moisture content

The initial mean temperature of the turned piles was 38°C and, at day 7, the temperature in this pile rose rapidly to 67°C. This high thermophilic temperature was maintained until day 30, and, thereafter, the temperature dropped continuously to 19°C by day 56. After day 56, the temperature varied within a narrow range (18–22°C) until day 91 (Fig. 1(a)). The forced-aerated pile followed a similar pattern of changes to the turned pile except that the maximum peak temperature achieved in this pile during the thermophilic stage of composting was lower (60°C) than the turned piles (Fig. 1(a)). No significant difference in temperatures occurred throughout the composting period between the two piles ($p = 0.74$ according to the *t*-test). The moisture content of the spent litter piles decreased gradually during composting (Fig. 1(b)). The moisture loss in the turned pile was higher (15%) than the forced-aerated pile (11%). However, the result of the *t*-test showed no significant difference ($p = 0.26$) between the two piles in moisture content throughout composting.

3.2. pH and electrical conductivity

The trends of pH and electrical conductivity (EC) of the turned and forced-aerated piles were similar during composting (pH, $p = 0.93$; EC, $p = 0.79$). The pH of both piles decreased from an initial 8.41 and 8.53 to 6.73 and 6.81 by day 63. This pH level remained relatively unchanged until day 91 (Fig. 2(a)). At day 0, the EC of the turned and forced-aerated piles ranged between 3.14 and 3.17 $\mu S\,cm^{-1}$. As composting proceeded, the EC of the two piles increased and leveled off at 4.04 to 4.58 $\mu S\,cm^{-1}$ by day 63 (Fig. 2(b)).

3.3. Total C, Kjeldahl N and inorganic N

During the process of composting, the total C concentration of the two piles decreased (from around 500 to 483 $g\,kg^{-1}$), and the total Kjeldahl N concentration fluctuated at a narrow range (around 18–27 $g\,kg^{-1}$) (Fig. 3(a, b)). The NH_4^+–N concentration dropped as composting progressed (Fig. 3(c)), followed by a continuous gradual accumulation of $(NO_3^- + NO_2^-)$–N from an initial low concentration ($< 1\,g\,kg^{-1}$) to 2.2 $g\,kg^{-1}$ by the end of composting (day 91; Fig. 3(d)). No significant difference was found between the turned and forced-aerated piles in terms of total C ($p = 0.20$), Kjeldahl N ($p = 0.50$), NH_4^+–N ($p = 0.18$) and $(NO_3^- + NO_2^-)$–N ($p = 0.42$) concentrations.

3.4. Particle size distribution

The coarse sand-sized fraction (> 2.0-mm mesh size) of the spent litter dominated at day 0 (Fig. 4). As

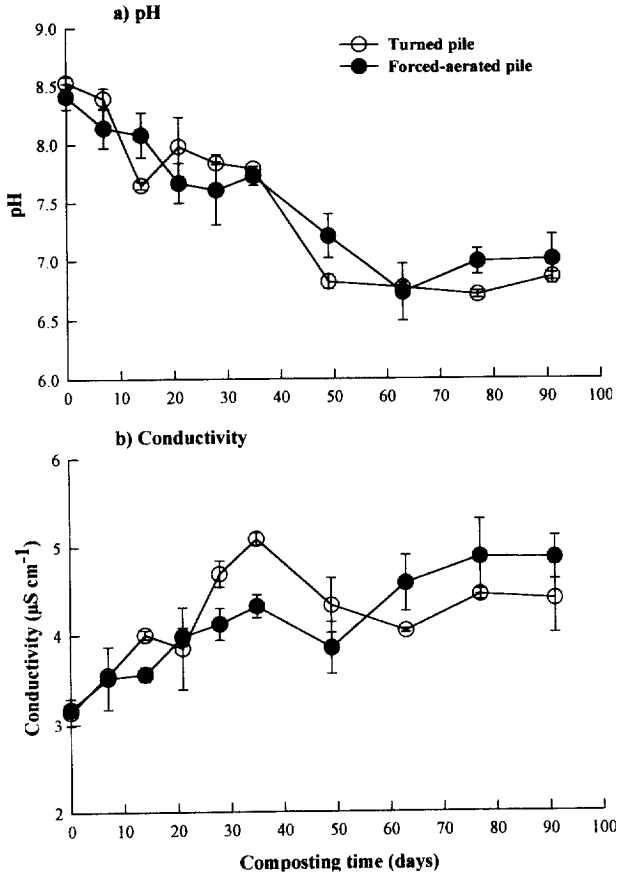

Fig. 2. Changes in pH and electrical conductivity (EC) of the spent litter during composting.

composting progressed, this fraction decreased, and the sand-sized (6.3-μm to 2.0-mm mesh size) and silt + clay-sized (< 63-μm mesh size) fractions increased. By the end of composting, the particle size distribution increased in the following order: sand-sized > coarse sand-sized > silt + clay-sized fractions (Fig. 4). The particle size distribution in turned and forced-aerated piles during composting was comparable (coarse sand-sized fraction, $p = 0.48$; sand-sized fraction, $p = 0.45$; silt + clay-sized fraction, $p = 0.21$).

3.5. Actinomycetes

Actinomycete numbers in the turned and forced-aerated piles were high (8.7–9.0 Log_{10} MPN g^{-1}) at the beginning of composting (Fig. 5). At day 7, the numbers declined, then increased continuously at a very slow rate from day 21 onwards. The turned pile had higher actinomycete counts than the forced-aerated pile during the thermophilic stage of composting, but both piles were very similar and almost overlapped from day 21 until day 91. The t-test showed no significant difference ($p = 0.24$) between the two piles during the entire period of composting.

3.6. Total aerobic and anaerobic heterotrophs

The aerobic mesophiles in the turned and forced-aerated piles decreased in the first 14 days, but then increased by day 21 and maintained at a level between 7.4 and 8.5 Log_{10} MPN g^{-1} until day 91. Populations of the aerobic thermophiles were as high as 6.5–7.0 Log_{10} MPN g^{-1}

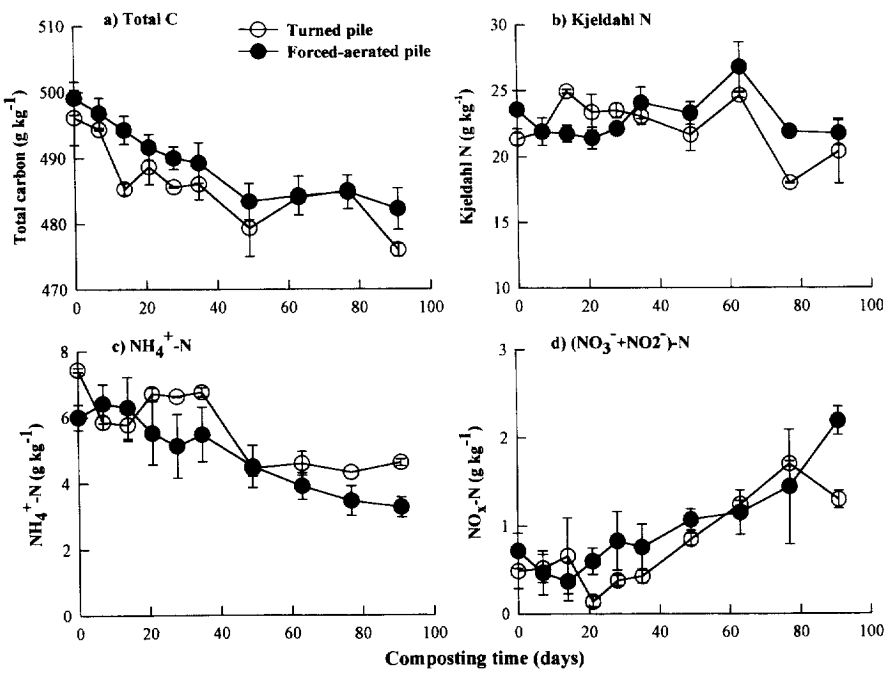

Fig. 3. Changes in contents of total C, Kjeldahl N, NH_4^+–N and (NO_3^- + NO_2^-)–N of the spent litter during composting.

during the first 21 days of composting, and declined as the piles started to cool (Fig. 1(a) and 6). Numbers of anaerobic mesophiles in both piles were highest at the onset of composting and decreased constantly to around 3.8 Log_{10} MPN g^{-1} by the end of composting. On the other hand, the numbers of anaerobic thermophiles were sustained at around 5.0–5.5 Log_{10} MPN g^{-1} during the first 35 days of composting and then declined slowly to 3.5 Log_{10} MPN g^{-1} by day 91 (Figs 6 and 7). No significant difference occurred between piles in terms of the aerobic mesophiles ($p=0.47$), aerobic thermophiles ($p=0.79$), anaerobic mesophiles ($p=0.25$), or anaerobic thermophiles ($p=0.26$).

3.7. Salmonella, *faecal coliform and faecal streptococci*

All references to *Salmonella* sp. in the following sections refer to the results from the test kit, which indicated the presence of organisms of the genus *Salmonella*. *Salmonella* sp. was found at the beginning of composting but was not detected from day 21 onwards in both turned and forced-aerated piles. The elimination of *Salmonella* sp. from the spent litter piles was observed to correspond with the progressive decrease in the numbers of faecal coliforms and faecal streptococci (Table 1). At the beginning of composting, the faecal coliform and streptococcal numbers ranged

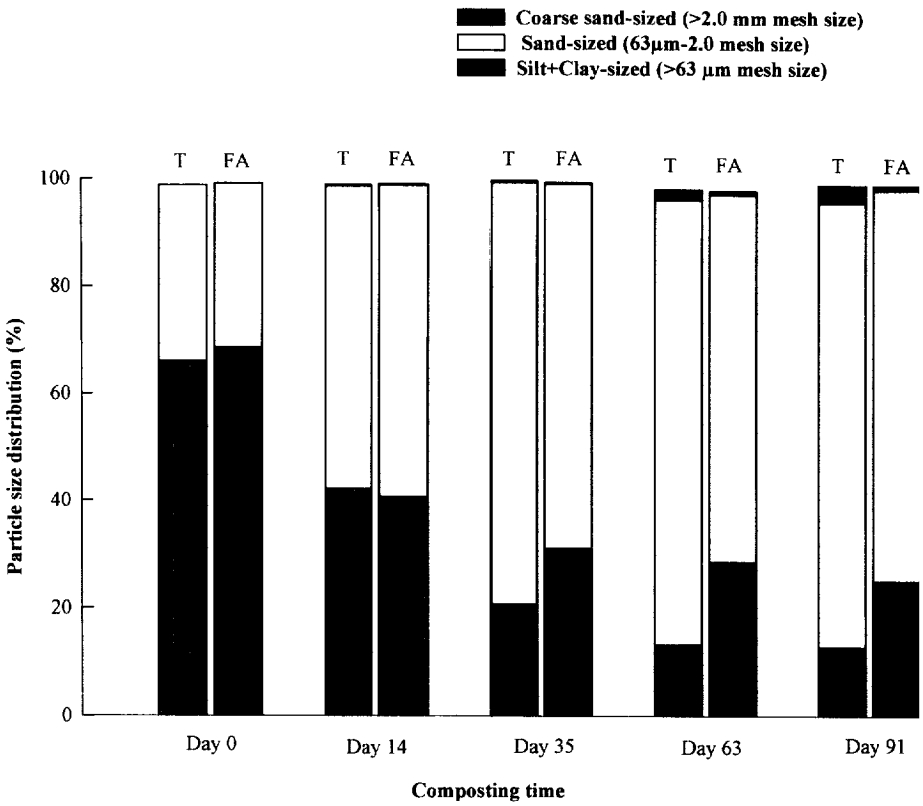

Fig. 4. Particle size distribution of the spent litter at different stages of composting (T, turned pile; FA, forced-aerated pile).

Table 1
Presence of *Salmonella* sp. and faecal coliform and streptococcal numbers in the turned and forced-aerated spent litter piles

Time (day)	*Salmonella* sp. (present/absent)		Faecal coliforms (Log_{10} MPN g^{-1})		Faecal streptococci (Log_{10} MPN g^{-1})	
	Turned pile	FA pile	Turned pile	FA pile	Turned pile	FA pile
0	present	present	5.00	5.38	2.49	2.49
7	present	present	4.55	5.38	2.33	2.10
4	present	present	4.78	4.98	2.30	2.08
21	absent	absent	4.30	4.05	2.29	2.05
35	absent	absent	3.73	3.33	2.22	2.02
63	absent	absent	2.74	1.39	2.14	1.96
91	absent	absent	2.27	1.18	2.12	1.94

FA, forced-aerated.

between 5.00 and 5.38 Log_{10} MPN g^{-1} and between 2.39 and 2.49 Log_{10} MPN g^{-1}, respectively. By the time the faecal coliform and streptococcal numbers reached a level of less than 4.30 Log_{10} MPN g^{-1} and less than 2.29 Log_{10} MPN g^{-1}, respectively, the pathogenic organism, *Salmonella* sp., was no longer detected (Table 1). At the end of composting (day 91), the numbers were further reduced to around 1.18–2.27 Log_{10} MPN g^{-1} (for faecal coliforms) and 1.94–2.12 Log_{10} MPN g^{-1} (for faecal streptococci). No statistical difference was found between the turned and forced-aerated piles in terms of the faecal coliform ($p=0.59$) and streptococcal ($p=0.16$) numbers.

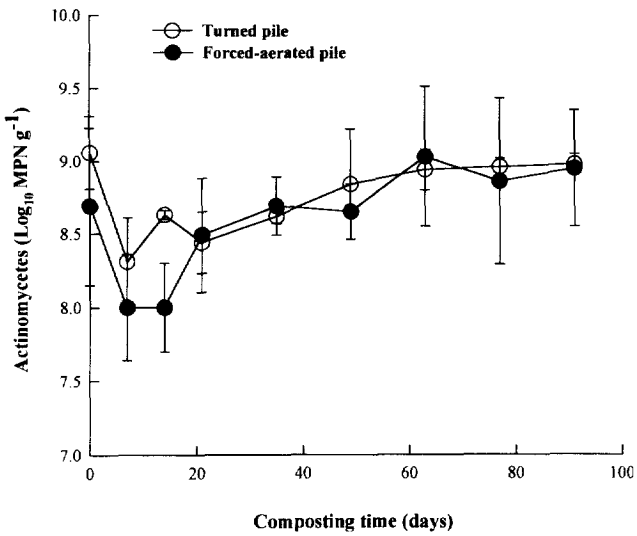

Fig. 5. Changes in actinomycete counts during composting of spent litter.

3.8. Enzyme activity

At different stages of composting, APYZYM assays were used to detect the presence of enzyme activity from 19 different enzymes, including three phosphatases, three esterases, three amino-peptidases, and eight glycosyl-hydrolases (Table 2). Alkaline and acid phosphatase activities in the turned or forced-aerated piles were high at the beginning of composting, reaching maximum activity at day 14 and maintaining at this level throughout the period of composting. Phosphohydrolase activity was low at the onset of composting, but reached moderate activity by day 63. This level of activity was sustained until day 91 (Table 2). Overall, a moderate level of lipase and esterase activity was found in turned or forced-aerated piles, whereas a high level of esterase–lipase activity was observed throughout the entire period of composting (91 days; Table 2). Leucine

Table 2
Relative activity of extracellular enzymes extracted from the spent litter at different stages of composting

Enzymes	Length of composting (days)							
	0		14		63		91	
	Turned pile	FA pile	Turned pile	FA pile	Turned pile	FA pile	Turned pile	FA pile
Phosphatases								
Alkaline phosphatase	4	4	5	5	5	5	5	5
Acid phosphatase	4	3	4	5	5	5	5	5
Phosphohydrolase	1	1	1	1	2	2	2	2
Esterases								
Esterase	4	4	4	4	4	4	4	4
Esterase lipase	5	5	5	5	5	5	5	5
Lipase	3	3	4	2	2	2	2	2
Amino-peptidases								
Leucine amino-peptidase	4	4	4	4	5	5	5	5
Valine amino-peptidase	2	2	2	1	1	1	1	1
Cystine amino-peptidase	2	2	1	1	1	1	1	1
Proteases								
Trypsin	0	0	0	0	1	1	1	1
Chymotrypsin	0	0	1	1	1	1	1	1
Glycosyl-hydrolases								
α-Galactonidase	0	0	0	1	0	2	0	2
β-Galactonidase	0	0	0	0	2	2	2	2
β-Gluconidase	0	0	0	0	3	4	3	4
α-Glucosidase	1	1	2	4	4	4	4	4
β-Glucosidase	1	1	1	1	5	5	5	5
n-Acetyl-β glucosaminidase	0	0	2	4	5	4	5	5
α-Mannosidase	0	0	0	0	0	0	0	0
α-Fucosidase	0	0	0	0	0	0	0	0

Low intensity (value of 1); moderate intensity (values of 2–4); high intensity (value of 5); FA, forced-aerated.

amino-peptidase was at moderate intensity in both piles in the first 2 months, and this increased to high intensity from day 63 until day 91. In contrast, valine amino-peptidase and cystine amino-peptidase decreased from moderate to low (for valine amino-peptidase) and non-detectable (for cystine amino-peptidase) levels during composting (Table 2). Trypsin and chymotrypsin showed no evidence of activity at day 0, but activity began at days 14 (for trypsin) and 63 (for chymotrypsin), and then continued at low intensity for the rest of the composting period (Table 2). Of the eight glycosyl-hydrolases, α-mannosidase and α-fucosidase showed no evidence of activity throughout the duration of the composting trial in both piles. Activities of α-galactonidase, β-galactonidase, β-gluconidase, and *n*-acetyl-β-glucosaminidase activity were not detected during the initial stage of composting, their values fluctuating from low to moderate activity as composting progressed. Low activity of α-glucosidase and β-glucosidase were detected at day 0, and as composting proceeded, their activity increased continuously to a high intensity level (Table 2). No significant difference was found between the turned and forced-aerated piles in terms of all 19 enzymes assayed.

4. Discussion

Composting efficiency of spent litter in turned piles was similar to that of the forced-aerated piles. Results of this investigation revealed that the forced-aerated piles went through physical, chemical, and microbiological changes similar to the turned composting piles. These changes included self-heating of the compost mass, evolution of microbial and enzyme activities, elimination of pathogen (*Salmonella* sp.), and decreases in contents of total C, NH_4^+–N, and pH. Both piles became stable and reached maturity at the same time (60 days). The composting process is, essentially, an aerobic decomposition of complex organic substances by microorganisms (de Bertolidi et al., 1983). It is believed to involve the action of enzymes accumulating outside the microbial cells as well as intracellularly catalyzed biochemical transformations (Godden et al., 1983). Analysis of APYZYM testing of the spent litter in turned and forced-aerated piles showed an overall increase in diversity and relative abundance of enzymes present. Phosphatases, esterases, proteases, amino-peptidases, and glycosyl-hydrolases increased in incidence with time. Although this enzyme test is rather preliminary, the results of this study seem to indicate the potential usefulness of enzyme activity measurements as indices of the course of the actual composting.

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, which must be evaluated. In the present study, *Salmonella* sp. was used as a representative pathogen. As it is present in most animal wastes, its presence in the final compost product indicates poor sanitization (de Bertoldi et al., 1991; Tiquia et al., 1997d). *Salmonella* sp. was eliminated in turned or forced-aerated spent litter piles by day 21. A temperature ranging from 60 to 67°C for 2–3 weeks is enough to kill *Salmonella* sp. during composting (Fig. 1(a) and Table 1). This elimination corresponded with the progressive decrease in numbers of indicator organisms, such as faecal coliforms and faecal streptococci. Since *Salmonella* sp. did not survive in the spent litter after day 21, the spent

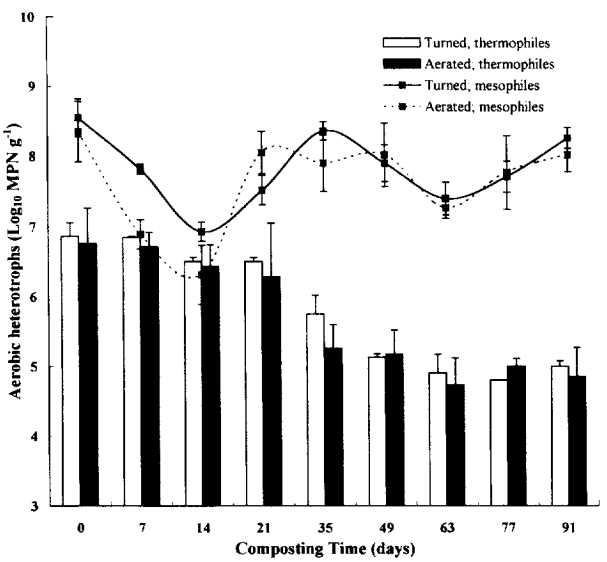

Fig. 6. Changes in total aerobic heterotroph counts (mesophiles and thermophiles) of the spent litter during composting.

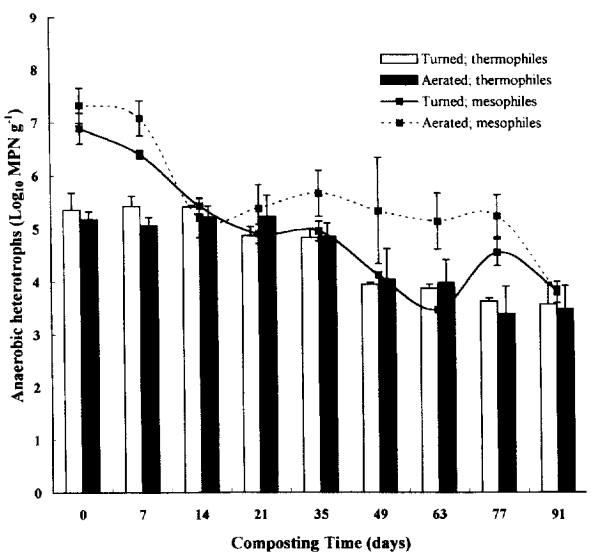

Fig. 7. Changes in total anaerobic heterotroph counts (mesophiles and thermophiles) of the spent litter during composting.

litter was considered as being sanitized and could be used on land without danger. These results suggest that any of these two systems (turned and forced-aerated) could be used in composting of spent litter. However, in deciding which method to use, economics is a major determinant of the level of technology that a community can employ. The literature is fairly sparse with respect to the economics of windrow (turned and forced-aerated) composting, probably because most of the attention has been directed towards in-vessel composting. In turned windrow composting, a large space is required. Turning involves tearing down the piles, spreading the spent litter material into a one-foot layer, and stacking the layered spent litter material into windrows. Moreover, a maneuvering area for the turning equipment (front-end loader) also would be required, plus an additional cost of labor for the operation of the turning equipment. The forced-aerated composting method seems to be more suitable in Hong Kong in the sense that it requires less space than the turned method. Under the forced-aerated composting method, the release of offensive odors, which normally occurs in turned windrows, is significantly minimized.

Composting using forced-aeration has been developed in the United States in the last 20 years (Epstein et al., 1976). In the majority of full-scale operations, wood chips have been used as bulking agent to give the required open structure, to ensure adequate aeration (Higgins, 1982; de Bertoldi et al., 1985; Stentiford et al., 1985; Stentiford, 1996), and adjust the moisture content of the compost material (Aasheim and Newbry, 1985). If a bulking agent is degraded slowly in the piles, the time required to complete the composting process may be extended due to composting of the bulking agent. Wood chips are relatively inert and are not changed greatly during composting (Stentiford et al., 1985), so at the completion of the process, they have to be screened and recovered from the compost pile and reused for the succeeding composting operation. The screening process involves a large amount of capital. In the present study, no bulking agent was used and yet the composting efficiency was still comparable to the turned system. The similarities in temporal changes in temperature, chemical, and microbiological properties of the forced-aerated piles, as compared with the turned piles indicate that addition of a bulking agent under forced-aerated composting of spent litter is not necessary. The partially decomposed sawdust in the spent litter provided enough free air space, allowing the delivery of oxygen for the microorganisms in the spent litter piles. The energy requirement for the forced-aerated composting operation is at most a modest amount as compared with the cost of energy and the manpower requirements in the turned composting method. In this study, the air pump was on during the entire period of composting (91 days). Intermittent aeration can be employed to reduce the energy consumption under this system. Further work will be carried out on this aspect.

Acknowledgements

The authors thank the Research Grant Council and the City University Research Grant Committee for their financial support. The authors would also like to thank Mr Alex Chan and all the technical staff of the Ta Kwu Ling Pig Breeding Centre, Agriculture and Fisheries Department, Hong Kong Government, for all the assistance offered during the compost trials.

References

Aasheim, S.E., Newbry, B.W., 1985. Composting. In: Sludge Stabilization. Manual Practice No. FD-9, Water Pollution Control Federation. Washington, DC, USA, pp. 55–80.

APHA (American Public Health Association), 1989. Standard Methods for the Examination of Water and Wastewater, 16th Edition. APHA, Washington DC, USA.

Barberis, R., Nappi, P., 1996. Evaluation of compost maturity. In: de Bertoldi, M. Sequi, P., Lemmes, B., Papi, T. (Eds.). The Science of Composting. Part I. Chapman and Hall, London, pp. 175–184.

de Bertoldi, M., Vallini, G., Pera, A., 1983. The biology of composting. Waste Management and Research 1, 157–176.

de Bertoldi, M., Vallini, G., Pera, A., 1985. Technological aspects of composting including modeling and microbiology. In: Gasser, J.K.R. (Ed.). Composting of Agricultural and Other Wastes. Elsevier Applied Science Publishers, New York, pp. 27–41.

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

Bremner, J.M., 1996. Nitrogen-Total. In: D.L. Sparks (Ed.). Methods of Soil Analysis. Part 3—Chemical Methods. SSSA, Madison, Wisconsin, pp. 1085–1121.

Brouillette, M., Trepanier, L., Gallichand, J., Beauchamp, C., 1996. Composting paper mill deinking sludge with forced aeration. Canadian Agriculture and Enginering 38, 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. Applied and Environmental Microbiology 39, 118–126.

Epstein, E., 1997. The Science of Composting. Technomic Publishing Company, Basel.

Epstein, E., Willson, G.B., Burge, W.D., Mullen, D.C., Enkiri, N.K., 1976. A forced aeration system for composting of wastewater sludge. Journal of the Water Control Federation 48, 688–694.

EPD (Environmental Protection Department), 1988. Environment Hong Kong 1988. Hong Kong Government Printer, Hong Kong.

Godden, B., Penninckx, M., Pierard, A., Lannoye, R., 1983. Evolution of enzyme activities and microbial populations during composting of cattle manure. European Journal of Applied Microbiology and Biotechnology 17, 306–310.

Golueke, C.G., 1972. Composting: a Study of the Process and Its Principles. Rodale Press, Emmaus, Pennsylvania.

Higgins, A.J., 1982. Ventilation for static pile composting. BioCycle 23, 36–41.

Mathur, S.P., Patni, N.K., Levesque, M.D., 1990. Static pile, passive aeration composting of manure using peat as a bulking agent. Biological Wastes 34, 323–333.

Mulvaney, R.L., 1996. Nitrogen—inorganic forms. In: Sparks, D.L. (Ed.). Methods of Soil Analysis. Part 3—Chemical Methods. SSSA, Madison, Wisconsin, pp. 1123–1184.

Rhoades, J.D., 1996. Salinity: electrical conductivity and total dissolved solids. In: Sparks, D.L. (Ed.). Methods of Soil Analysis. Part 3—Chemical Methods. SSSA, Madison, Wisconsin, pp. 417–435.

Sesay, A.A., Lasaradi, K., Stentiford, E., Budd, T., 1997. Controlled composting of paper pulp sludge using the aerated static pile method. Compost Science and Utilization 5, 82–96.

Sheldrick, B.H., Wang, C., 1993. Particle size distribution. In: Carter, M.R. (Ed.). Soil Sampling and Methods of Analysis. Lewis Publishers, Boca Raton, Florida, pp. 499–511.

Stentiford, E.I., 1996. Composting control: principles and practice. In: de Bertoldi, M. Sequi, P. Lemmes B., Papi, T. (Eds.). The Science of Composting. Part I. Chapman and Hall, London, pp. 49–59.

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 Applied Science Publishers, New York, 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., 1996a. Effect of moisture content on composting of pig-manure sawdust litter disposed from the pig-on-litter (POL) system. In: de Bertoldi, M., Sequi, P., Lemmes, P., Papi, T. (Eds.). The Science of Composting. Part II. Chapman and Hall, London, pp. 1361–1364.

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. Bioresource Technology 55, 201–206

Tiquia, S.M., Tam, N.F.Y., Hodgkiss, I.J., 1997. Effects of bacterial inoculum and moisture adjustment on composting of pig manure. Environmental Pollution 96, 161–171.

Tiquia, S.M., Tam, N.F.Y., Hodgkiss, I.J., 1997b. Effects of turning frequency on composting of spent pig-manure sawdust litter. Bioresource Technology **62**, 37–42.

Tiquia, S.M., Tam, N.F.Y., Hodgkiss, I.J., 1997c. Composting of spent pig litter at different seasonal temperature in subtropical climate. Environmental Pollution **98**, 97–104.

Tiquia, S.M., Tam, N.F.Y., Hodgkiss, I.J., 1997d. *Salmonella* elimination during composting of spent pig litter. Bioresource Technology (in press).

Wellington, E.M.H., Toth, I.K., 1994. Actinomycetes. In: Weaver, R.W., Angle, J.S., Bottomley, P.S. (Eds.). Methods of Soil Analysis. Part 2—Microbiological and Biochemical Properties. SSSA, Madison, Wisconsin, pp. 269–290.

Willson, G.B., 1983. Forced aeration composting. Water and Science Technology 15, 169–180.

Zar, J.H., 1984. Biostatistical Analysis. Prentice-Hall, USA.