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COMPOSTING OF SPENT PIG LITTER AT DIFFERENT SEASONAL TEMPERATURES IN SUBTROPICAL CLIMATE

S. M. Tiquia,[a,b] N. F. Y. Tam[a]* and I. J. Hodgkiss[b]

[a]*Department of Biology and Chemistry, City University of Hong Kong, Tat Chee Avenue, Kowloon, Hong Kong*
[b]*Department of Ecology and Biodiversity, The University of Hong Kong, Pokfulam Road, Hong Kong*

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Abstract
To investigate the effects of seasonal temperatures on the composting of spent pig-manure sawdust litter (spent litter), two sets of experiments were carried out: one during winter, the other during summer. Physicochemical and microbial parameters including temperature, pH, inorganic N, humification indicators (HA and FA), heavy metals (Cu and Zn), total aerobic heterotrophs, ATP content and dehydrogenase activity were measured to understand changes in the spent litter during composting. Results demonstrated that the composting was faster during summer than winter. The spent litter during the summer trial reached maturity at day 56 whereas that of the winter trial was still immature at the end of composting (days 91). Microbial activities during the thermophilic stage of composting were much lower in the winter trial. Values began to increase during the latter part of composting, indicating that the spent litter in this winter trial was biologically unstable and must be further composted to reach full maturity. The changes in the microbial activities of the spent litter during summer or winter reflected the changes in their temperatures and chemical properties. The maturation of the spent litter during summer was accompanied by stabilization of the microbial and chemical properties and a drop in temperature to ambient level. Results of correlation analysis showed that temperature correlated not only with the microbial parameters but also with most of the chemical parameters. These parameters also correlated with each other. Among all the parameters measured, the trend of temperature changes is the simplest and most rapid parameter that can be used to evaluate the maturity of spent litter. © 1998 Elsevier Science Ltd. All rights reserved

Keywords: Composting, pig manure, humification indicators, heavy metals, microbial activity.

INTRODUCTION

Like many other large cities, Hong Kong is facing a dilemma in terms of urban infringement on agricultural lands where production of crops and livestock is threatened. This problem is further aggravated by the fact that Hong Kong is a small territory with only approximately 100 km^2 of arable land. The competing economic forces and demand for land continue to put pressure on agriculture to be an efficient and non-polluting industry. Agricultural wastes, particularly pig manure, have been shown to be the major contributor to stream pollution in the New Territories and in parts of Urban Hong Kong (Hodgkiss and Griffiths, 1987). As a solution to the pig waste problem, the Agriculture and Fisheries Department of Hong Kong initiated in 1987 the pig-on-litter system of pig raising. Under this system, the pigs are raised in pens, the floor of which is covered with 30 cm of sawdust which is mixed with a commercial bacterial product that helps to decompose the waste. The waste is partially decomposed in the pen, and the pig-manure sawdust litter remains in the pen during the entire period of pig raising (about 10–13 weeks). The success of this approach has been shown in Japan, Taiwan, New Zealand, and The Netherlands (Fukuda, 1991). Under this system, the discharge of effluent is unnecessary, and the only waste that needs to be discharged is the spent litter (a mixture of partially decomposed pig manure and sawdust).

The spent litter disposed from the pig-on-litter system contains high concentrations of organic matter, N, P, K, and trace elements (Tam and Vrijmoed, 1990, 1993) and can be utilized as a soil fertilizer, conditioner, or for both purposes (Tam and Wong, 1995) but requires further composting to reach maturity (Tiquia, 1996; Tiquia *et al.*, 1996*a*). Compost maturity has been measured by a variety of methods including drop in compost temperature, O_2 consumption, C:N ratio, cation-exchange capacity and humification indices (Golueke, 1977; Barberis and Nappi, 1996).

In windrow composting, the temperature within the compost mass is affected by ambient temperature (Gray and Biddlestone, 1973). These authors reported that about 1 ton of waste is needed to ensure that a reasonable proportion of the heap reaches a satisfactory thermophilic temperature during summer, whereas in cold weather, 3 tons of waste are necessary to reach thermophilic temperatures. However, more heat may be

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*To whom correspondence should be addressed. Fax: (852) 27887406; e-mail: bhntam@cityu.edu.hk conserved within the pile during summer, and the compost temperatures reach a level higher than the optimum thermophilic temperature (> 60–65°C), which will then significantly reduce the rate of bio-oxidation in compost piles (Crowford, 1983). On the other hand, during winter, heat loss would occur especially when the pile is being turned too frequently and will prevent the pile from reaching optimum thermophilic temperatures. If thermophilic temperatures are not sufficiently high, the pathogenic organisms and parasites may not be destroyed, thereby producing hygienically unsafe compost. For these reasons, it is important to investigate the effect of seasonal temperatures on the composting of the spent litter.

MATERIALS AND METHODS

The windrow composting trials were carried out at the Ta Kwu Ling Pig Breeding Centre, New Territories, Hong Kong. Spent litter was collected from pig pens employing the pig-on-litter system and was piled up in an open shed in the farm for windrow composting. Duplicate piles were set up during winter (December–March) and also during summer (June–September). Each pile was triangular in shape, about 2 m in width at the base and 1.5 m in height. The piles were turned every four days using a truck and front-end loader until the end of the composting period (91 days). During the process of windrow composting, the ambient temperature and the temperature within each pile at a depth of 60 cm towards the central part of the pile were measured before turning. The moisture content of the piles was adjusted to 60% at the beginning of composting but no further moisture adjustment was carried out.

Spent litter samples were collected at day 0 and then weekly until day 91. At each sampling period, composite samples of the spent litter were taken at five symmetrical locations in each pile. Triplicate composite samples (about 1 kg each) were collected from each pile and were brought back to the laboratory for analysis. The spent litter in the two trials was analyzed for pH (1:10 w/v litter:water extract) using a pH meter; concentrations of NH_4^+-N and $(NO_3^- + NO_2^-)$-N (Keeney and Nelson, 1982); humic (HA) and fulvic (FA) acids (Schnitzer, 1982); total and water-extractable Cu and Zn concentrations using atomic absorption spectrophotometry; population size of total aerobic heterotrophs by the dilution agar-plate method (APHA, 1989); ATP content using an ATP detection kit (firefly luciferin–luciferase) (APHA, 1989) and a luminometer (Monolight 1500, manufactured by the Analytical Luminescence Laboratory, USA); and dehydrogenase activity (Tabatabai, 1982). Simple correlation coefficients were calculated to determine the relationships among all the parameters measured (Zar, 1984).

RESULTS

Physical properties of the spent litter

Temperature

During the winter season, the air temperature fluctuated between 5 and 25°C (Fig. 1). The temperature of the winter spent litter pile was 40°C immediately after piling (day 0) then rose to a peak of 56°C at day 14. After peaking, the temperature dropped quickly to about 38°C by day 21; fluctuated between 36 and 42°C from day 28 to day 49; decreased rapidly to 22°C by day 56, and was maintained at this level until day 74. By day 77, the temperature began to rise again and reached 39°C by day 91. The air temperature during the summer season was maintained between about 24 and 28°C. The initial temperature of the summer spent litter pile was 31°C; it peaked at 62°C by day 14; declined to 31°C by day 63 and this temperature was maintained until day 91 (Fig. 1).

Chemical properties of the spent litter

pH and inorganic N

The pH in the winter pile was sustained at about 6.9 to 7.3 during the first 28 days of composting, then decreased gradually to 5.8 by day 63 (Fig. 2(a)). After day 63, the pH in this pile increased slightly to 6.2 by day 91. The pH in the summer pile decreased from an initial 7.9 to 5.6 during the first 46 days of composting, and this value was maintained until day 91 (Fig. 2(a)).

The initial NH_4^+-N content of both piles was similar (Fig. 2(b)); decreased gradually from an initial 6.5 to 7.0 mg g^{-1} to about 4.0 mg g^{-1} by day 35 and, thereafter, decreased dramatically to essentially non-

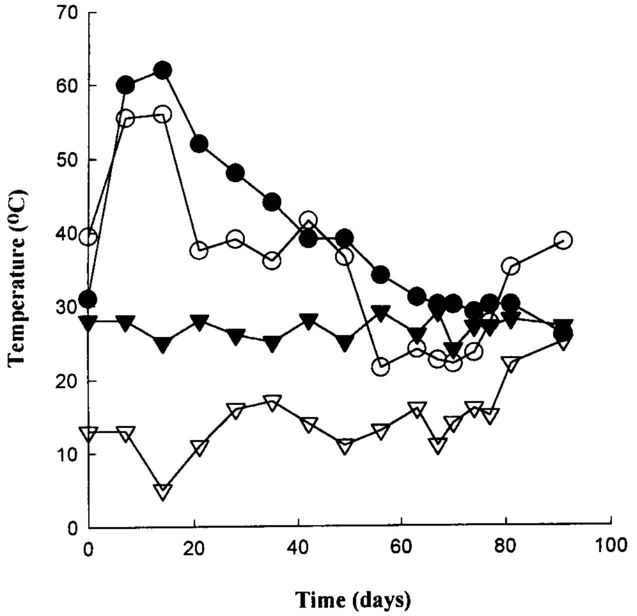


Fig. 1. Changes in air temperature and temperature within each pile of the spent litter during the composting process. (○ = winter pile; ● = summer pile; ▽ = air temperature, winter ▼ = air temperature, summer).

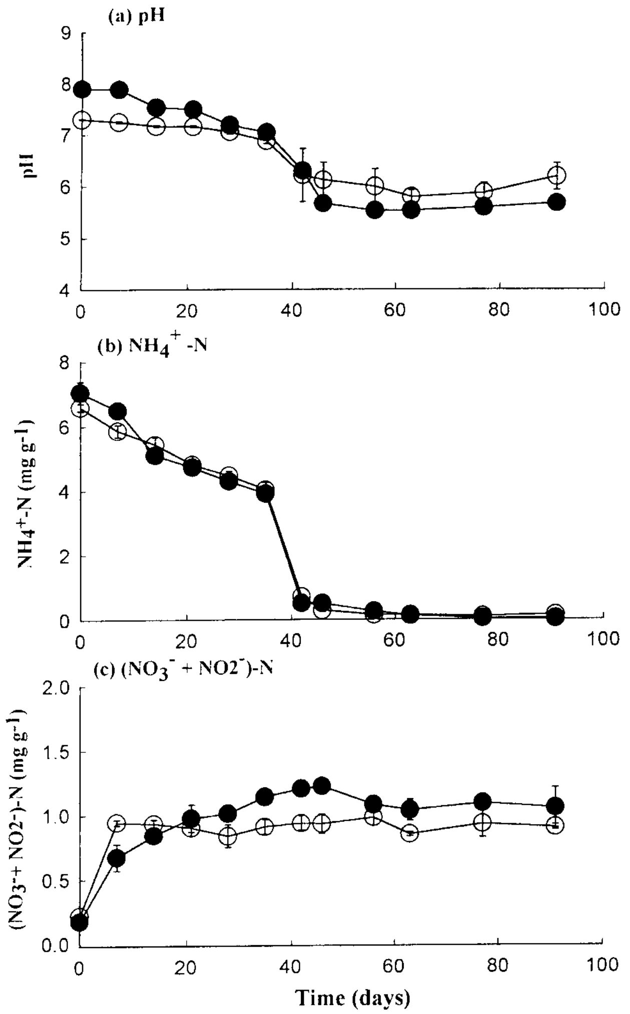


Fig. 2. Changes in (a) pH value and concentration of (b) NH_4^+-N and (c) $(NO_3^- + NO_2^-)$-N of the spent litter during the composting process. (○ = winter pile; ● = summer pile; mean and standard deviation of the three replicates are shown).

detectable levels. The NH_4^+-N content in the winter pile decreased to 0.71 mg g^{-1} and then to 0.14 mg g^{-1} by day 91. The NH_4^+-N content in the summer pile decreased to a level lower than the winter pile (0.5 mg g^{-1}) and further declined to 0.03 mg g^{-1} by the end of composting (Fig. 2(b)).

The $(NO_3^- + NO_2^-)$-N content in summer or winter piles was at low levels (0.18-0.22 mg g^{-1}) at the beginning of the composting process. The $(NO_3^- + NO_2^-)$-N content of the summer pile increased continuously during the first 46 days of composting to as high as 1.22 mg g^{-1}, but declined at day 63 to 1.03 mg g^{-1} and then remained at this level until day 91. The $(NO_3^- + NO_2^-)$-N content in the winter pile increased to 0.94 mg g^{-1} after seven days of composting and was maintained around this level until the end of the composting process (Fig. 2(c)).

Humic acid (HA), Fulvic acid (FA) and HA:FA ratio

Both winter and summer piles, had an HA content of about 20 to 35 g kg^{-1} (organic matter) O.M. during the first 21 days of composting (Fig. 3(a)). Thereafter, significant differences ($p = 0.0351$ according to the t-test) were observed between the two piles. The HA content in the summer pile rose dramatically to 80 g kg^{-1} O.M. at day 28 and was maintained at this level until day 91. That of the winter pile also increased at day 35, but the increase was lower (to about 55–58 g kg^{-1} O.M.) than the summer one, and it stabilized at this level until the end of composting (Fig. 3(a)).

The trend of changes in FA content of both piles was similar except during the last three weeks of composting. It increased slowly until day 63, and then declined in the summer pile, but it continued to increase in the winter pile (Fig. 3(b)).

The HA:FA ratios of both piles were similar during the first 21 days of composting but were different from day 35 onwards (Fig. 3(c)). The summer pile had a higher HA:FA ratio than the winter pile from day 35 until the end of composting.

Total and water-extractable Cu

At day 0, the total Cu concentration of both piles was similar (462–465 μg g^{-1}) (Fig. 4(a)). Thereafter, the total Cu in the summer pile increased rapidly to 560 μg g^{-1} by day 14 and remained at this level until day 91. Total Cu of the winter pile was maintained at about

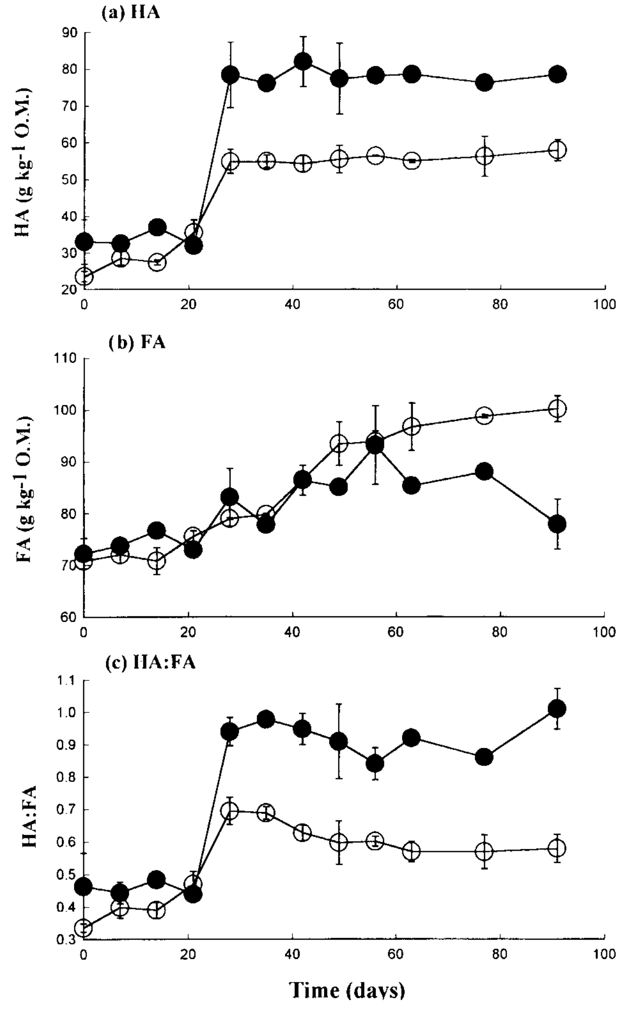


Fig. 3. Changes in contents of (a) humic acid (HA) and (b) fulvic acid (FA), and (c) HA:FA ratio of the spent litter during the composting process. (same legend as Fig. 2).

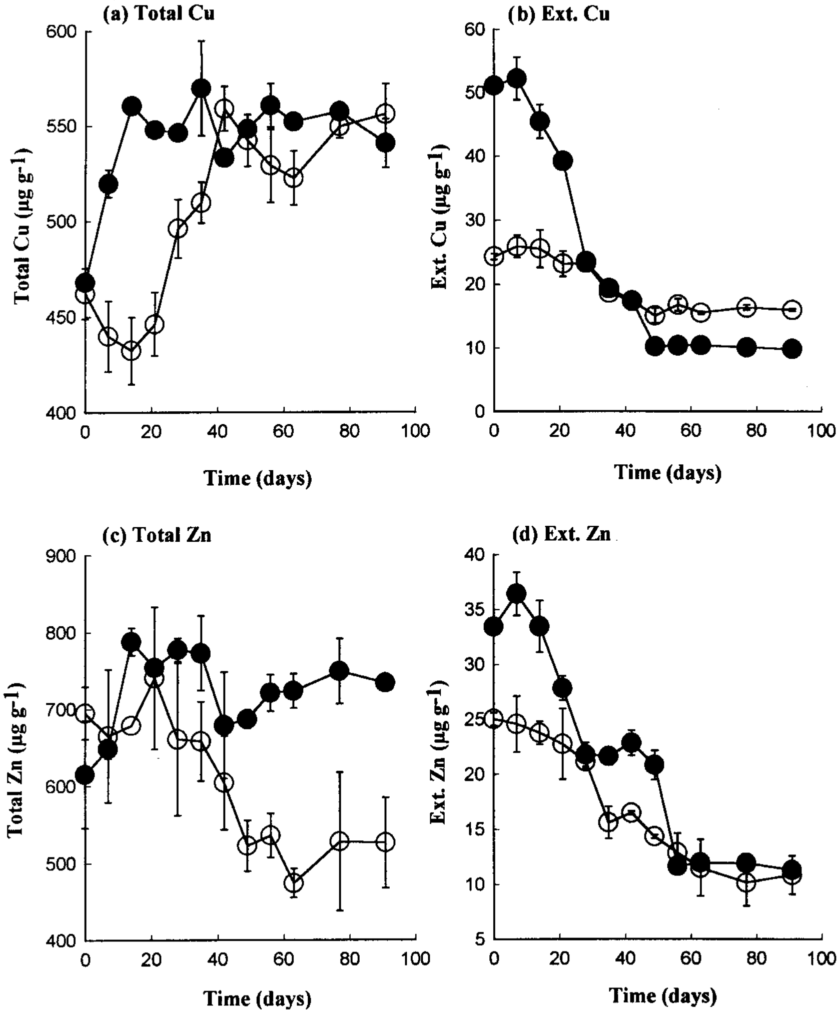


Fig. 4. Changes in (a) total Cu, (b) water-extractable Cu, (c) total and (d) extractable Zn content of the spent litter during the composting process. (same legend as Fig. 2).

450 $\mu g\,g^{-1}$ during the first 28 days of composting, increased to 558 $\mu g\,g^{-1}$ by day 42 and was maintained at this level until day 91.

Initial water-extractable Cu concentration in the summer pile (51 $\mu g\,g^{-1}$) was higher than in the winter pile (Fig. 4(b)) but dropped continuously to a very low level (10 $\mu g\,g^{-1}$) by day 49. This level remained constant until day 91. In the winter pile, the initial water-extractable Cu was only 25 $\mu g\,g^{-1}$. This level did not change during the first 28 days of composting. After day 28, the water-extractable Cu declined slowly to 15 $\mu g\,g^{-1}$ and was maintained at this level until the end of composting (Fig. 4(b)). The difference between initial and final readings was 41.33 $\mu g\,g^{-1}$ Cu in the summer pile, five times that in the winter pile (where the difference was 8.38 $\mu g\,g^{-1}$ Cu).

Total and water-extractable Zn

The total changes in Zn concentrations differed in piles composted during the winter and summer seasons (Fig. 4(c)). The total Zn content in the winter pile fluctuated at a level of 665 to 740 $\mu g\,g^{-1}$ during the first 21 days of composting, declined continuously to 522 $\mu g\,g^{-1}$ from day 49 onwards, and was maintained at this level until day 91. On the other hand, less fluctuation was observed in the summer pile. The total Zn content in this pile increased from an initial 615 to 787 $\mu g\,g^{-1}$ by day 14, was maintained at this level until day 35, and then decreased and was maintained at a level of about 730 $\mu g\,g^{-1}$ until the end of composting (Fig. 4(c)).

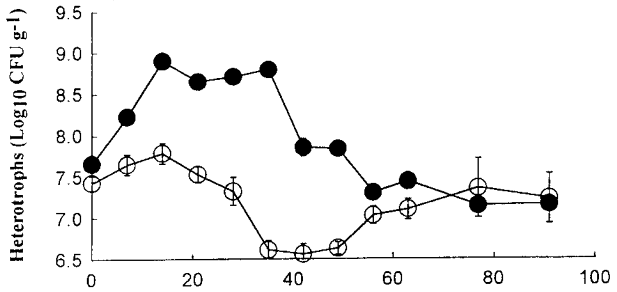
The water-extractable Zn in the summer pile was higher and decreased at a faster rate than in the winter one (Fig. 4(d)). Thus, it declined rapidly from an initial 33.44 to 11.65 $\mu g\,g^{-1}$ by day 56 and then leveled off. In the winter pile, it declined slowly from 25.02 to 21.15 $\mu g\,g^{-1}$ by day 21, and then further decreased about two-fold (10.84 $\mu g\,g^{-1}$) by day 91 (Fig. 4(d)). The difference between initial and final readings in the summer pile (22.44 $\mu g\,g^{-1}$ Zn) was almost twice that in the winter pile (14.10 $\mu g\,g^{-1}$ Zn).

Microbiological properties of the spent litter

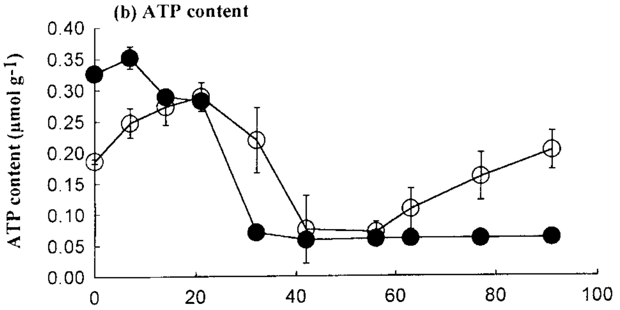
Total aerobic heterotrophs

From an initial value of 7.66 Log_{10} (colony forming unit) CFU g^{-1}, the total aerobic heterotrophs in the summer pile reached a peak of 8.89 Log_{10} CFU g^{-1} by day 14 (Fig. 5 (a)). This level was sustained for four

(a) Heterotrophs



(b) ATP content



(c) Dehydroganase activity

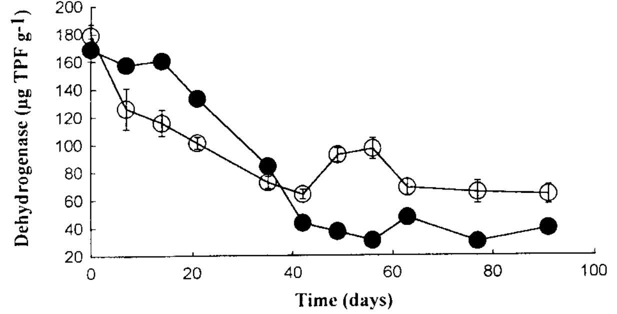


Fig. 5. Changes in the population of (a) total aerobic heterotrophs, (b) ATP content and (c) dehydrogenase activity of the spent litter during the composting process (same legend as Fig. 2).

weeks but then declined rapidly until day 56, reaching a level of 7.30 Log_{10} CFU g^{-1} by day 91. In winter, the total aerobic heterotrophs peaked at 7.78 Log_{10} CFU g^{-1} by day 14 and declined continuously to 6.61 Log_{10} CFU g^{-1} by day 35. Counts were maintained at this level for three weeks (until day 49) and then began to increase after this period of stability, reaching a second peak (7.35 Log_{10} CFU g^{-1}) by day 77. Numbers then declined slightly to 7.23 Log_{10} CFU g^{-1} by day 91 (Fig. 5(a)).

ATP content

The ATP content in the winter pile increased continuously from an initial 0.19 to 0.29 $\mu\text{mol}\,g^{-1}$ by day 21, declined to 0.07 $\mu\text{mol}\,g^{-1}$ by day 56, and then increased again to 0.20 $\mu\text{mol}\,g^{-1}$ by day 91 (Fig. 5(b)). The initial ATP content in the summer pile was higher (0.33 $\mu\text{mol}\,g^{-1}$) than in the winter one, but it dropped continuously to 0.06 $\mu\text{mol}\,g^{-1}$ by day 42 before leveling off (Fig. 5(b)).

Dehydrogenase activity

The dehydrogenase activity of both piles was highest at the beginning of composting and then declined as composting proceeded (Fig. 5(c)). Both piles had a similar trend of changes in dehydrogenase activity during composting except that the activity in summer leveled off three weeks earlier (at day 42) and the values were lower than those in winter.

DISCUSSION

Results of the present study demonstrated that seasonal ambient temperature affected the changes in physical, chemical and microbial properties of the spent litter during composting and that temperature was the simplest and most rapid parameter indicating the maturity of spent litter. The rate of composting in the winter pile was slower than in the summer pile, and it did not reach maturity even by the end of composting (91 days). The peak temperature achieved in the winter pile (56°C) was lower than that in summer (60°C) (Fig. 1). The temperature in the winter pile also dropped more quickly than the summer one, but then its temperature increased again during the latter stage of composting. Such an increase during the latter part of the composting process suggests that decomposition in the winter pile was incomplete within the 90-day composting period and that the spent litter might still be immature. The temperature recorded in the summer pile followed a pattern ideal to the composting process (Gray and Biddlestone, 1973; Crowford, 1983; Tiquia, 1996). That is, the temperature inside the composting mass increased rapidly to 45–50°C, remained at this level for 24–48 hours, continued to rise to a maximum temperature of 60–65°C, which persists until the active decomposition is over and, thereafter, slowly decreased. The material is considered to be mature if the declining temperature reaches ambient level.

Temperature within a composting mass determines the rate at which many biological processes take place (Stentiford, 1996*a*,*b*), and within a composting mass, the thermal properties and the breakdown rates are such that a wide temperature variation can exist. Stentiford (1996*a*) reported that the operating temperatures within a composting mass are selected in most cases to maximize sanitization (where high temperatures are most effective) and stabilization (where high temperatures inhibit the process). He suggested that temperatures greater than 55°C maximize sanitation, that 45 to 55°C maximizes the biodegradation rate, and that 35 to 40°C maximizes microbial diversity in the composting process. Temperatures greater than 55°C were reached in the winter pile in the present study; but such temperatures were not sustained, and they dropped to 38°C by day 21. Moreover, temperatures of 45 to 55°C occurred only for a few days during the winter composting. Less heat was generated during winter (probably due to lower microbial activities), and it is also more difficult to conserve heat within the pile during winter. Therefore, the sanitization in the winter pile was not maximized. Strauch (1996) listed the standards for judging the sanitization in a windrow operation in various countries. In Germany, it has been proposed that a temperature

> 55°C for at least two weeks, or 65°C for at least one week is required for hygienic control of composts. In the United States, a temperature > 55°C for at least 15 days with at least 5 turnings within that period are required. In Hong Kong, temperatures around 60 to 65°C for 2 to 3 weeks with 4 days turning frequency were needed for hygienic control of spent litter (Tiquia, 1996). In the summer pile, temperatures greater than 55°C were achieved during composting and were sustained for two weeks. A temperature of 45 to 55°C was also sustained for three weeks (from day 21 to day 35) suggesting that composting carried out in summer will achieve better and more satisfactory sanitization and biodegradation than in winter.

The compost microbiota determine the rate of composting, affect the quality of the product, and produce most of the physical and chemical changes in the compost (McKinley and Vestal, 1985; Tiquia *et al.*, 1996*b*). In the present study, three microbial parameters, namely total aerobic heterotrophs, ATP content, and dehydrogenase activity were used to examine the rate of composting during the winter and summer trials. These three parameters have been considered as good measures of microbial activity and good indicators of degradation of spent litter (Tiquia, 1996; Tiquia *et al.*, 1996*b*, 1997). The population of the total aerobic heterotrophs (Fig. 5(a)), ATP content (Fig. 5(b)) and dehydrogenase activity (Fig. 5(c)) in the winter pile were lower than those in the summer during the thermophilic stage of composting. Furthermore, the values of these three microbial parameters increased again in the winter pile during the latter part of composting, which further confirmed that the spent litter compost in the winter pile was biologically unstable and immature, and must be further composted to reach full maturity. On the other hand, the temperature and microbiological properties in the summer pile stabilized at low levels at day 56, indicating that the spent litter compost became mature on day 56. In the present study, all microbial parameters were not only correlated with temperature, but also with most of the chemical parameters (Table 1).

Ambient temperature also affected the changes in the chemical properties of the spent litter during composting. The summer pile had higher increases in HA content and HA:FA ratio than the winter one. The formation and properties of humic substances (HA and FA) during composting have been studied widely (Barberis and Nappi, 1996; Chefetz *et al.*, 1996). Barberis and Nappi (1996) reported that during composting, the HA evolves and becomes increasingly dominant over the FA, so that the ratio between the two acids is used as an important index of compost maturity. In the present study, the spent litter of both piles contained higher levels of FA and low levels of HA at the beginning of composting. During composting, the HA increased more than two-fold. The FA content of the spent litter also increased, but the increase was very small (only about $10\,g\,kg^{-1}$ O.M.). The formation of HA in the summer pile was much higher than in the winter pile and so the HA:FA ratio recorded during summer was higher than during winter. This result suggests that the decomposition during summer was faster.

The presence and mobility of heavy metals have been shown to be of paramount importance for a correct measurement of environmental hazards during the utilization of animal compost on land, since heavy metals can accumulate in agricultural soil and enter the food chain (Adriano, 1986). The contents of total Cu and Zn in the spent litter compost were high (Fig. 4(a) and 4(c)), 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 content (Petruzzelli *et al.*, 1989; Tam and Tiquia, 1994; Tiquia *et al.*, 1996*c*). In the present study, the water-extractable Cu and Zn content of both piles decreased during composting. This decrease coincided with increases in HA

Table 1. Correlation coefficients among chemical parameters of the spent litter[a]

	T°	pH	NH_4^+	No_x	HA	FA	HA:FA	Tot-Cu	Ext-Cu	Tot-Zn	Ext-Zn	Hetero	ATP
T°													
pH	0.74**												
NH_4	−0.99***	0.98***											
NO_x	−0.62*	−0.62*	−0.66*										
HA	−0.66**	−0.83***	−0.84***	0.66*									
FA	−0.77**	−0.98***	−0.94***	−0.60*	−0.95***								
HA:FA	−0.66**	−0.70*	−0.73***	0.63*	0.98***	−0.93***							
Tot-Cu	−0.62*	−0.90***	−0.92***	−0.74**	−0.95***	0.90***	0.90***						
Ext-Cu	0.76**	0.94***	0.95***	−0.67*	0.95***	−0.94***	−0.88***	−0.97***					
Tot-Zn	0.84***	0.94***	0.68*	−0.07	−0.47	−0.70*	−0.33	−0.91***	−0.58*				
Ext-Zn	0.84***	0.94***	0.92***	−0.57	0.88***	−0.95***	−0.78**	−0.91***	0.96***	0.58*			
Hetero	0.84***	0.82***	0.82***	−0.20	−0.69*	−0.82***	−0.57	−0.68*	0.78**	0.88***	0.77***		
ATP	0.77**	0.90***	0.91***	−0.53	−0.96***	−0.91***	−0.92***	−0.90***	0.94****	0.66*	0.85***	0.87***	
Dehydro	0.60*	0.86***	0.87***	−0.80**	−0.96***	−0.86***	−0.92***	−0.96***	0.98***	0.35	0.91***	0.61*	0.88**

[a] Correlations were based on 24 average data of the 4 piles during composting; *, ** and *** indicate correlation significant at 0.05, 0.01 and 0.001 probability levels, respectively.

T° = temperature; NH_4 = NH_4^+-N content; NO_x = $(NO_3^- + NO_2^-)$-N content; HA = humic acid; FA = fulvic acid; Tot-Cu = total Cu; Ext-Cu = water-extractable Cu; Tot-Zn = total Zn; Ext-Zn = water-extractable Zn; Hetero = total aerobic heterotrophs; ATP = ATP content; Dehydro = dehydrogenase activity.

and FA content of the spent litter indicating the ability of humic substances to form stable complexes with metal ions due to their high content of oxygen-containing functional groups, including COOH, phenolic-, alcoholic and enolic-OH, and C=O structures of various types (Chen and Stevenson, 1986). Despite the differences in the initial water-extractable Cu and Zn contents in the summer and winter piles, the final values did not show any significant difference between winter or summer as the rate of decrease in the summer pile was higher. This finding suggests that the windrow composting performed during summer was faster than in winter.

In summary, the composting carried out in winter was slow and the final product was biologically unstable and immature. The irregularities in temperature patterns and microbial changes in the winter pile showed how a composting process that is not well controlled resulted in an immature and poor quality final product. Although ambient temperature is an environmental factor that cannot be controlled, composting during winter in Hong Kong can be improved by controlling other environmental factors that could combat the effects caused by ambient temperature. The spent litter piles might have to be turned less frequently (e.g. every 7 days instead of every 4 days) to conserve more heat and to achieve a satisfactory thermophilic temperature (between 60–65°C). Flynn and Wood (1996) pointed out that larger compost heaps also may promote greater heat retention. The volume of the spent litter piles in the present study was about $2\,m^3$. Increasing the volume of the spent litter to 2.5 to $3.0\,m^3$ may also help in attaining a higher thermophilic temperature and consequently, promoting greater efficiency of composting during winter.

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