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EFFECTS OF BACTERIAL INOCULUM AND MOISTURE ADJUSTMENT ON COMPOSTING OF PIG MANURE

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Abstract

Spent litter (a mixture of partially composted pig manure and sawdust) was taken from pig pens employing the pig-on-litter system with and without the addition of a commercial bacterial product (Odor control (OC)-organic fertilizers (OF)). A duplicate series of windrows was set up with spent litter which contained the bacterial product and a further duplicate series was set up with spent litter which did not contain the bacterial product. All four sets had their initial moisture content adjusted to 60% but one of each duplicate pair had its moisture content adjusted to 60% during the entire period of further composting in windrows. The rate of further (windrow) composting was significantly different in the litter which contained no bacterial product and which only had its moisture content adjusted at the beginning of the experiment. Decomposition was incomplete in this set even after day 91. In the three other sets, the rate of decomposition was faster and the spent litter became stabilised by day 56. This result suggests that if the bacterial product has been added during the initial pig-on-litter composting process, moisture adjustment during further (windrow) composting is not important. Conversely, if moisture was adjusted during further composting, the addition of bacterial product during initial pig-on-litter composting would be of no value. Such a finding is of remarkable significance in the further composting of spent litter since this indicates that the process could be run on a much more economical basis. © *1997 Elsevier Science Ltd*

Keywords: Decomposition, physico-chemical parameters, bacterial product, spent litter, microbial activity.

INTRODUCTION

The pig-on-litter system has been developed as one of the most highly recommended methods to treat pig wastes in Hong Kong (EPD, 1988, 1990). The pig-on-litter system is a pig production method where pigs are raised on a litter bedding (sawdust) and the pig waste (both faeces and urine) is composted *in situ*. Tam and

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Vrijmoed (1990) found that during *in situ* composting in the pig-on-litter system, the excreta, once deposited, were quickly mixed with the bedding material, the nitrogenous compounds being partially decomposed leading to the eradication of the offensive odor of ammonia. In recent years, the method has been practised by pig farmers in many countries, such as Japan, Taiwan, New Zealand and The Netherlands (Fukuda, 1991). In Hong Kong, the system has been operating at the Ta Kwu Ling Pig Breeding Centre since 1987, and has since been adopted in some pig production farms (Chan *et al.*, 1994).

A commercial bacterial product is often added to the sawdust to ensure the establishment of initial microbial population and proper composting conditions, and so enhance the pig-on-litter composting process (Tam and Vrijmoed, 1990; Fukuda, 1991; Chan *et al.*, 1994). Some commercial bacterial products which have been used to enhance the composting process are Bactostim (Ecopor, The Netherlands), EnviStim (Finn Feeds International, United Kingdom) and SEF-C (Nissan, Japan). Chaw (1996), Tam (1995) and Tam *et al.* (1996) further studied the specific role of various commercial bacterial products during *in situ* composting of pig waste under the pig-on-litter system and they found that with proper management of the pig pens, the addition of the commercial bacterial product had little effect on the performance of the pig-on-litter system. Since then, the pig-on-litter system in Hong Kong has been operated without the addition of any commercial bacterial product.

The pig-on-litter system is also a zero discharge treatment method—neither waste water nor effluent needs to be discharged. The only waste discharged from this system is the spent litter (a mixture of partially composted sawdust and pig manure). The spent litter contains high concentrations of N, P, K, organic matter and trace elements and can be utilized as a soil conditioner and/or fertilizer (Tam and Vrijmoed, 1993), but requires further composting (in windrows) to reach full maturity (Tiquia, 1996; Tiquia *et al.*, 1996a,b).

The effects of the addition of a commercial bacterial inoculum during pig-on-litter composting on further (windrow) composting are not yet understood. Therefore, the present experiment was designed to compare

the efficiency of further composting of the spent litter with and without the addition of a commercial bacterial product during the operation of the pig-on-litter system.

Tiquia (1996) pointed out that the success of the further composting process of spent litter is governed by the control of various environmental conditions such as aeration, moisture content and temperature. Moisture content was one of the most important environmental factors affecting composting of spent litter. Tiquia et al. (1996a) pointed out that moisture content affects the changes in temperature and microbial properties during further composting of spent litter. High moisture content (about 70%) resulted in a lower microbial activity especially during the thermophilic stage of composting and a delay in reaching thermophilic temperature, which consequently slowed down the composting process. Hence a moisture content of between 50 and 60% was suggested, since the microbes adapted well at this moisture level. The importance of moisture adjustment and the interaction between bacterial application and moisture adjustment on further composting of spent litter also needs to be understood. Up to the present, no information has been published concerning whether moisture adjustment during further (windrow) composting of spent litter might aid in speeding up the composting process if a bacterial product was present rather than absent, or whether addition of the bacterial product without moisture adjustment would shorten the composting process. In order to understand the process, the interaction between moisture adjustment and further composting of spent litter with and without bacterial product will be evaluated.

MATERIALS AND METHODS

Two ordinary pig pens employing the pig-on-litter system with or without the addition of a commercial bacterial product (Odor control (OC)-organic fertilizers (OF)) were set up at Ta Kwu Ling Pig Breeding Centre, New Territories, Hong Kong (Table 1). Odor control (OC)-organic fertilizers (OF) is manufactured by C. J. Rockwell, Inc., USA. It is a powdered blend commercial bacterial product of selectively adapted organisms blended with crude enzymes and emulsifiers specifically

designed to liquefy, digest and deodorise agricultural wastes. An initial dosage of 5 lb per 6000 gallons was applied evenly over the litter bedding of one of the pig pens weekly for a month. Thereafter, the dosage was reduced to 1 lb per 3000 gallons and dosed on a monthly basis. After 13 weeks of pig raising, the two pig pens were left idle. The spent litter from these two pens was taken and stacked in windrows. Four piles were set up, piles A and B were collected from a pig pen without bacterial product whereas piles C and D were collected from a pig pen with bacterial product. Each pile was pyramidal, about 2 m square at the base and 1.5 m in height. The heaps were turned every four days using a truck and front loader tractor. All four piles had their initial moisture content adjusted to 60% (w/w). Thereafter, no more moisture adjustment was done in piles A and C until the end of the further composting (day 91) whereas the moisture contents of piles B and D were adjusted to 60% at days 20, 41, 55, 76 and 90 (Fig. 2).

During the process of further composting, which lasted for 91 days, the ambient temperature and temperature within each pile at a depth of 60 cm towards the central part of the pile were measured before turning. Composite samples of the spent litter (about 2 kg) were collected from five symmetrical locations in each pile immediately after turning and samples were collected weekly until the end of the composting period. The spent litter was analysed for: pH (1:10 w/v litter:water extract) using a pH meter; cation-exchange capacity (CEC) (Harada and Inoko, 1980); concentrations of NH_4^+-N and $(NO_3^- + NO_2^-)$-N (Keeney and Nelson, 1982); humic (HA) and fulvic (FA) acids (Schnitzer, 1982); population of total aerobic heterotrophs by the dilution agar-plate method (APHA, 1989); dehydrogenase activity (Tabatabai, 1982); ATP content using an ATP detection kit (firefly luciferin-luciferase) and a luminometer (Monolight 1500) manufactured by the Analytical Luminescence Laboratory (USA); and microbial biomass C and N (Vance et al., 1987; West et al., 1986).

Analysis of variance (ANOVA) statistical testing was carried out and the multiple comparison of means was analysed using the Student-Newman-Keuls test (Zar, 1984).

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

|	Type of pig pens	
	Without bacterial product	With bacterial product
Size of pig pen	40 m²	30 m²
Number of pigs	40	30
Age of pigs at start	72 days	78 days
Raising period within POL system	123 days	117 days
Litter management	Layering	Layering
Feed consumption	11910 Kg	9619.2 Kg
Sawdust consumption	91 bags	90 bags
Bacterial product used	none	Odor control (OC)-organic fertilizers (OF)
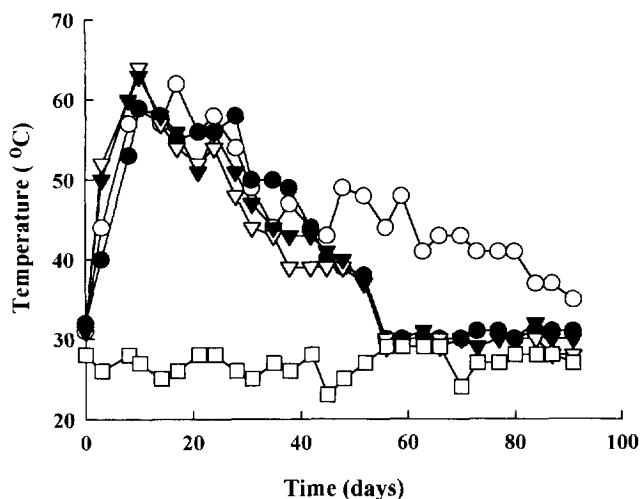
Fig. 1. Changes in air temperature and temperature within each pile during the composting process. (○ = Pile A; ● = Pile B; ▽ = Pile C; ▼ = Pile D; □ = Air temperature; mean and standard deviation values of three replicates are shown.)
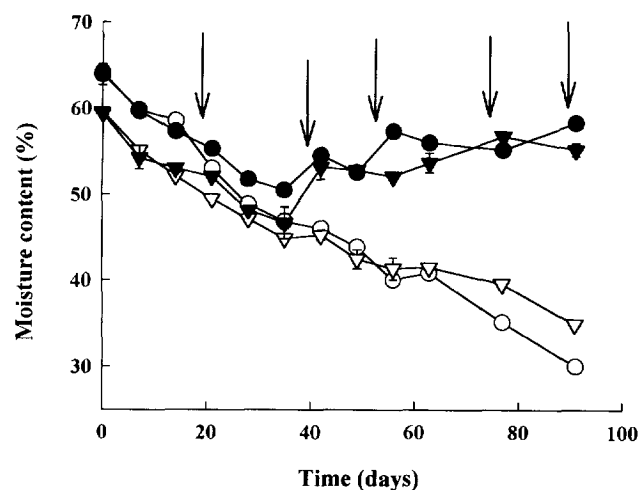

Fig. 2. Changes in moisture content of the spent litter during the composting process. (○ = Pile A; ● = Pile B; ▽ = Pile C; ▼ = Pile D; ↓ indicates the day water was added to piles B and D to adjust the moisture content; mean and standard deviation values of three replicates are shown.)

RESULTS

Temperature

Air temperature varied within a narrow range of 24–29°C during the composting period as the experiment was carried out during the summer (June–August). The initial temperature within the piles after moisture adjustment (day 0) was around 31–32°C (Fig. 1) but it increased very rapidly thereafter. Temperature readings in both piles of spent litter without bacterial product (A and B) rose to about 40–44°C by day 4. This temperature rose even more to a peak of 59°C by day 10 then dropped slowly to around 54–58°C by day 28. On the other hand, the temperature of piles from spent litter with bacterial product (C and D) rose to about 64°C by day 10 then dropped slowly to around 48–50°C by day 28. The temperatures of all piles further dropped to around 39–43°C by day 45. A similar trend of changes was observed in the first 45 days between the four piles, but the peak temperature obtained in piles with bacterial product (C and D) was slightly higher than piles without bacterial product (A and B). After day 45, the temperatures in the piles which had no bacterial product and further moisture adjustment (B), or which had bacterial product with (D) or without (C) further moisture adjustment were similar and dropped dramatically from 40°C to between 28 and 30°C from day 48 to day 56 and were maintained at that level until day 80. A different pattern of change was observed from day 48 onwards in pile A (spent litter without bacterial product and without adjustment in moisture after the initial adjustment (Fig. 1)). Its temperature rose slightly to 49°C at day 48, was maintained at that level for 10 days (day 59), and then decreased slowly to 35°C at day 91. The temperature drop in this pile was the slowest among all four piles, and its temperature had still not reached ambient level by day 91.

Moisture content

The moisture contents of all piles are depicted in Fig. 2. At the beginning of the composting period (day 0), the moisture contents of the piles were as follows: A (without bacterial product and without further adjustment of moisture content) 64%; B (without bacterial product but with moisture adjustment) 64%; C (with bacterial product but without moisture adjustment) 60%; and D (with bacterial product and with moisture adjustment) 59%. As the composting proceeded, the moisture content of all piles dropped gradually to about 45–51% in the first 35 days. The water loss of piles A, B, C and D by day 35 was 27, 21, 25 and 21%, respectively. Thereafter, the moisture content of piles A and C (spent litter without moisture adjustment) continuously decreased to between 30 and 35% at the end of the composting process (day 91). Even though water was added to piles B (103 liters) and D (224 liters) to adjust the moisture content to 60% at day 20, their moisture contents continued to decrease until day 41 when further adjustment of moisture was done. After this adjustment, the moisture content was between 53 and 55%. Adjustments in these two piles took place every two weeks thereafter and during this stage the moisture was maintained at around 55–59% (Fig. 2). The moisture contents of the piles without further moisture adjustment (A and C) were significantly lower than those with further moisture adjustment (B and D) (Table 2).

pH level

The pH values of all piles were high (8.2) at the beginning of the composting process (Fig. 3). This observation was reflected by high concentrations of NH_4^+-N (5.75–8.43 mg g^{-1}) at the beginning of the composting period (Fig. 4(a)). The pH values of piles B (spent litter without bacterial product and with moisture adjustment), C (spent litter with bacterial product but without

Table 2. Effect of bacterial product on the physical, chemical and microbiological properties of the spent litter during the 91-day study. Means of the three replicates are shown

Parameters	Pile A	Pile B	Pile C	Pile D
Physical properties				
Temperature (°C)	46^{a*}	43^b	41^b	42^b
Moisture content (%)	47^a	56^b	46^a	53^b
Chemical properties				
pH	7.47^a	6.69^b	6.64^b	6.71^b
NH_4^+-N (mg g^{-1})	5.07^a	3.15^b	2.68^b	2.76^b
NO_x^--N (mg g^{-1})	0.74^a	1.03^b	0.96^b	0.97^b
CEC (meq $100\,g^{-1}$)	61.3^a	72.1^b	72.5^b	75.6^b
HA (g kg^{-1} OM)	36.4^a	65.6^b	65.4^b	61.3^b
FA (g kg^{-1} OM)	77.4^a	75.7^a	78.5^a	74.7^a
HA:FA	0.47^a	0.86^b	0.82^b	0.82^b
Microbiological properties				
Heterotrophs (Log_{10} CFU g^{-1})	9.00^a	8.28^b	8.44^b	8.43^b
ATP content (μmol g^{-1})	0.28^a	0.20^b	0.16^b	0.19^b
Dehydrogenase (μg TPF g^{-1})	135^a	117^b	85^b	107^b
Microbial biomass C (mg g^{-1})	3.66^a	3.76^a	3.98^a	4.30^a
Microbial biomass N (μg g^{-1})	254^a	237^a	181^a	166^a

*Row means followed by same letter are not significantly different according to ANOVA test ($P > 0.05$).

moisture adjustment) and D (spent litter with bacterial product and with moisture adjustment) dropped to around 7 as composting proceeded during the first 35 days, further decreased dramatically to 5.7 by day 49, and were stabilized at this level subsequently. The trend of changes in pH in pile A (spent litter without bacterial product and without moisture adjustment) was different from those of piles B, C and D. Its pH value was maintained at about 8.2 for the first 14 days of the composting period. As the composting process continued, its pH value dropped to 7.3 at day 35, decreased slightly to 7.1 by day 49, and was maintained at this level until the end of the composting period. This steady and alkaline pH value ($\sim$7.0) from day 43 onwards coincided with the steadiness in the temperature readings (Fig. 1) and NH_4^+-N concentrations (Fig. 4(a)) of pile A. Piles B, C and D were very similar during the whole composting period and were significantly different from pile A (Table 2).

Inorganic N

The NH_4^+-N concentrations of all piles are depicted in Fig. 4(a). The initial NH_4^+-N contents in piles A and B (spent litter without bacterial product) were similar (about 7.20 and 8.43 mg g^{-1}) and were significantly higher than those of piles C and D (spent litter with bacterial product) (5.54 and 5.75 mg g^{-1}). As composting proceeded, the NH_4^+-N contents of all piles declined gradually to between 3.90 and 4.71 mg g^{-1} by day 35. Thereafter, significant differences were observed between pile A (spent litter without bacterial product and without moisture adjustment) and the other three piles (Table 2). The NH_4^+-N contents of piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment), and D (spent litter with

bacterial product and with moisture adjustment) decreased more dramatically to 0.09–0.25 mg g^{-1} by day 56 and were maintained at that level until day 91, whereas that of pile A decreased slowly to 3.37 mg g^{-1} by the end of the composting trial (Fig. 4(a)).

The initial $(NO_3^- + NO_2^-)$-N concentrations of all piles were around 0.05–0.18 mg g^{-1} at the beginning of the composting period (Fig. 4(b)). The $(NO_3^- + NO_2^-)$-N contents of piles B, C and D increased dramatically to around 0.82 to 0.85 mg g^{-1} by day 7, further increased to around 1.18–1.35 mg g^{-1} by day 42 and were maintained at that level until day 91. A similar trend of changes was observed in pile A, but the $(NO_3^- + NO_2^-)$-N content was slightly lower. Its $(NO_3^- + NO_2^-)$-N content rose continuously until day 42 (0.95 mg g^{-1}),

Fig. 3. Changes in pH values of the spent litter during the composting process. ($\bigcirc$ = Pile A; $\bullet$ = Pile B; $\triangledown$ = Pile C; $\blacktriangledown$ = Pile D; mean and standard deviation values of three replicates are shown.)

(a) NH4+-N

(b) (NO3-+ NO2-)-N

Time (days)

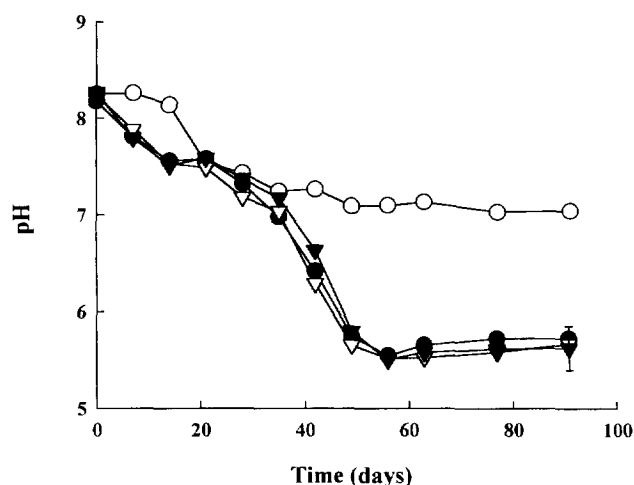Fig. 4. Changes in NH_4^+-N and $(NO_3^- + NO_2^-)$-N contents of the spent litter during the composting process. (○ = Pile A; ● = Pile B; ▽ = Pile C; ▼ = Pile D; mean and standard deviation values of three replicates are shown.)
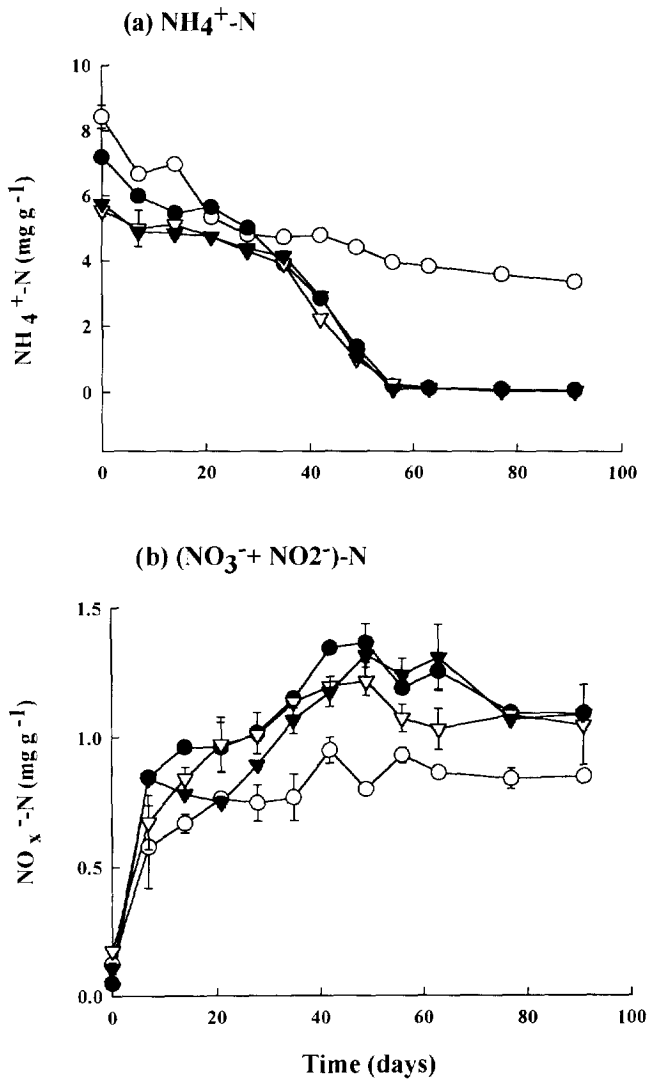
29 meq 100 g⁻¹ to only 90 meq 100 g⁻¹, and then was maintained at that level until day 91.

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

The HA contents of all piles were similar and did not change much during the first 21 days of composting (Fig. 5(b)). After day 21, changes were observed among the piles. The HA contents of piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment) and D (spent litter with bacterial product and with moisture adjustment) increased dramatically to around 64–78 g kg⁻¹ organic matter (OM) at day 28. Thereafter, the HA contents of these three piles increased gradually to between 86 and 90 g kg⁻¹ OM and remained at this level until day 91. Pile A (spent litter without bacterial product and without moisture adjustment) had a lower HA content than piles B, C or D, and its HA content increased slowly to 49 g kg⁻¹ OM by day 63 and was maintained at this level until day 91 (Fig. 5(b)). Piles B, C and D were not significantly different from each other but were significantly different from pile A (Table 2).

The initial FA contents of piles A, B, C or D were about 69–72 g kg⁻¹ OM (Fig. 5(c)). As composting proceeded, the FA contents of all piles increased gradually to between 80 and 83 g kg⁻¹ OM until day 42. After day 42, the FA contents in piles A and C (piles without moisture adjustment) were maintained at around 80–83 g kg⁻¹ OM, whereas that of piles B and D (piles with moisture adjustment) decreased slightly to around 70–74 g kg⁻¹ and remained at this level until day 91 (Fig. 5(c)). No significant difference was observed among piles (Table 2).

The changes in HA:FA ratio of the spent litter piles were similar to the changes in HA content (Figs 5(b) and (d)). Statistical analysis showed that piles B, C and D were not significantly different from each other but were significantly different from pile A (Table 2).

dropped slightly to 0.86 mg g⁻¹ by day 49 and was maintained at that level until the end of the composting process. Piles B, C and D were similar but were significantly different from pile A (Table 2).

Cation-Exchange Capacity (CEC)

The initial CEC values of piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment) and D (spent litter with bacterial product and with moisture adjustment) were similar during the whole composting period (Table 2) and increased from an initial value of between 28 and 38 meq 100 g⁻¹ to between 112 and 115 meq 100 g⁻¹ by day 63, then remained at that level until day 91. The CEC values of pile A (spent litter without bacterial product and without moisture adjustment) followed a similar pattern of changes to that in piles B, C, and D, but its increase in CEC during composting was slower (Fig. 5(a)). Its CEC value increased from an initial

Total aerobic heterotrophs

The population of total aerobic heterotrophs of all piles was around 7.5–7.7 Log₁₀ CFU (colony forming units) g⁻¹ at the beginning of the composting period (Fig. 6). The population rose rapidly to between 8.9 and 9.5 Log₁₀ CFU g⁻¹ by day 14 and was maintained at this level until day 21. After day 21, the population of total aerobic heterotrophs of piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment) and D (spent litter with bacterial product and with moisture adjustment) dropped very significantly to around 7.4–7.8 Log₁₀ CFU g⁻¹ by day 49, increased to around 8.2–8.4 Log₁₀ CFU g⁻¹ and were maintained at this level until day 91, whereas that of pile A (spent litter without bacterial product and without moisture adjustment) was maintained at a level of 9.0–9.6 Log₁₀ CFU g⁻¹ until the end of the composting process (Fig. 6). The changes of total aerobic heterotrophs in piles B, C, and D were very similar during
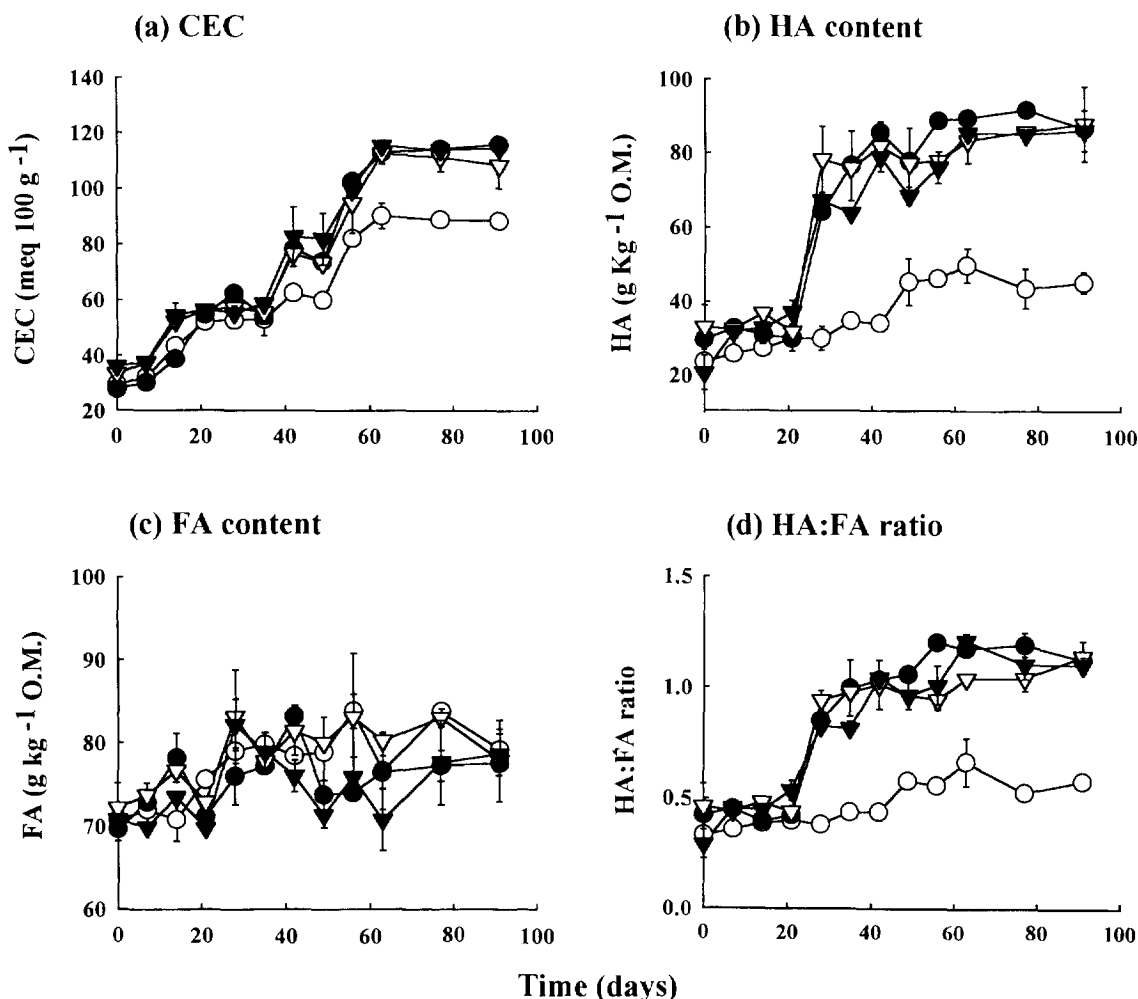
Fig. 5. Changes in contents of CEC, HA, FA and HA:FA ratio of the spent litter during the composting process. (○ = Pile A; ● = Pile B; ▽ = Pile C; ▼ = Pile D; mean and standard deviation values of three replicates are shown.)

the whole composting period but were significantly lower than that of pile A (Table 2). The increase in total aerobic heterotrophs during the first 35 days of composting marked the rise of temperature (Fig. 1).

Dehydrogenase activity

The dehydrogenase activity of all piles was highest at the beginning of composting (Fig. 7(a)). Thereafter, the dehydrogenase activity of all piles decreased until day 49. From day 56 onwards, the dehydrogenase activity in piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment) and D (spent litter with bacterial product and with moisture adjustment) was maintained at approximately 31–52 μg triphenyl formazan (TPF) g^{-1}. The dehydrogenase activity in pile A (spent litter without bacterial product and without moisture adjustment) decreased very slowly to a value (100 μg TPF g^{-1}) significantly higher than piles B, C and D by day 91 (Fig. 7(a) and Table 2).

ATP content

The initial ATP contents of all piles were high (around 0.33–0.41 μmol g^{-1}) (Fig. 7(b)). These high initial values

are probably due to a large microbial biomass in the spent litter (Figs 7(c) and (d)), which reflects the large quantity of nutrients, including high initial nitrogen content and high carbon content (Tiquia, 1996). This high level of ATP content was maintained until day 28. At day 35, the ATP content of piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment), and D (spent litter with bacterial product and with moisture adjustment) dropped dramatically to between 0.07 and 0.11 μmol g^{-1} and then was maintained at this level until day 91. On the other hand, the ATP content of pile A (spent litter without bacterial product and without moisture adjustment) dropped slowly from day 35 (0.26 μmol g^{-1}) to a level of 0.18 mol g^{-1} at day 91 (Fig. 7(b)). The decrease in ATP content coincided with the decline in microbial biomass N (Figs 7(c) and 7(d)), NH$_4^+$-N content (Fig. 4(a)), pH (Fig. 3) and temperature (Fig. 1). The ATP content of piles B, C and D remained practically stable from day 35 onwards while that of pile A continued to decrease. The three piles (piles B, C and D) were not significantly different from each other but were significantly lower than pile A (Table 2).
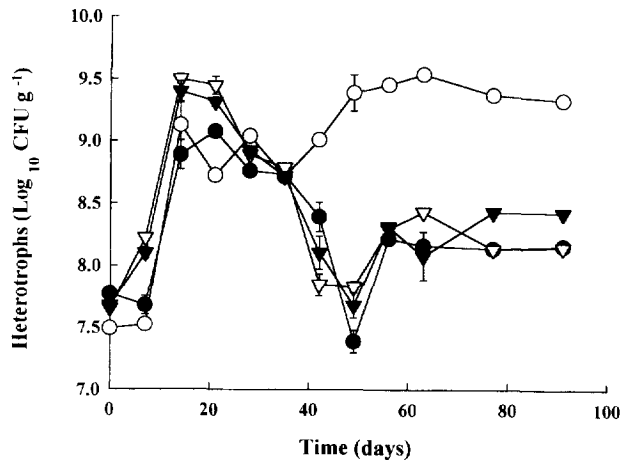
Fig. 6. Changes in the population of total aerobic heterotrophs of the spent litter during the composting process. (○ = Pile A; ● = Pile B; ▽ = Pile C; ▼ = Pile D; mean and standard deviation values of three replicates are shown.)

Microbial biomass C

The microbial biomass C contents of piles A and B (spent litter without bacterial product), and C and D (spent litter with bacterial product) were as high as $0.60\,mg\ g^{-1}$ and $1.40\,mg\ g^{-1}$, respectively, during the initial stage of the composting trial (Fig. 7(c)). As composting proceeded, the microbial biomass C contents of

all piles increased at a similar rate to a level between 5.05 and $5.60\,mg\ g^{-1}$ by day 56 and were maintained at this level until day 91 (Fig. 7(c)). No significant differences in microbial biomass C occurred during composting among the four piles (Table 2).

Microbial biomass N

The microbial biomass N contents of all piles varied between 158 and $251\,\mu g\ g^{-1}$ during the initial stage of the composting trial (Fig. 7(d)). Thereafter, the microbial biomass N contents of all piles rose very rapidly to a peak of between 430 and $575\,\mu g\ g^{-1}$ by day 14 and were maintained at this level for one week (until day 21). After day 21, the microbial biomass N contents of the piles declined. The microbial biomass N contents of piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment), and D (spent litter with bacterial product and with moisture adjustment) declined to between 33 and $55\,\mu g\ g^{-1}$ by day 56 and were maintained at this level until day 91, whereas that of pile A (spent litter without bacterial product and without moisture adjustment) declined to a level apparently slightly higher than piles B, C, or D ($107\,\mu g\ g^{-1}$) and was maintained at this level until day 91 (Fig. 7(d)). All piles were not significantly different from each other (Table 2).

(a) Dehydrogenase

(b) ATP content

(c) Biomass C

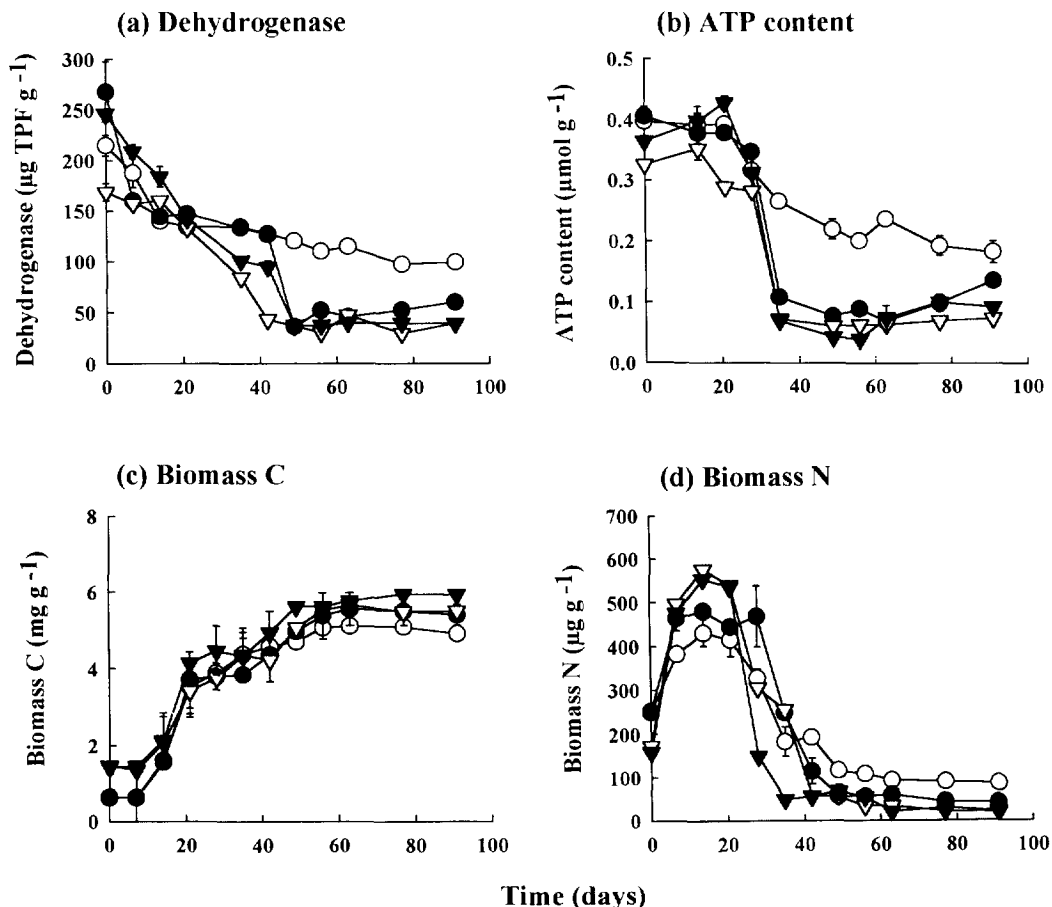**(d) Biomass N**

Time (days)

Fig. 7. Changes in dehydrogenase activity, contents of ATP and microbial biomass C and N of the spent litter during the composting process. (○ = Pile A; ● = Pile B; ▽ = Pile C; ▼ = Pile D; mean and standard deviation values of three replicates are shown.)

DISCUSSION

Measurement of the rate and extent of composting of spent litter

Studies of the rate and extent of decomposition of compost materials have focused on the measurement of the changes in total nitrogen, water soluble organic matter, hemicelluloses, cellulose, lignin, protein and ash (Bertoldi *et al.*, 1983; Garcia *et al.*, 1991; Schwab *et al.*, 1994). Although these parameters give an excellent indication of the rate and extent of decomposition, a simpler criterion for judging the rate and extent of decomposition for practical composting operations would be desirable.

The course of temperature changes in a compost pile was indicative of the progress of the process from beginning to completion (Golueke, 1977; Bertoldi *et al.*, 1983; Tiquia, 1996; Tiquia *et al.*, 1996a,b). Normally, the temperature inside the compost mass begins to rise immediately after piling, then the temperature increases rapidly to $55-65°C$ and remains at this level for about 2 to 3 weeks. Thereafter, the temperature slowly decreases and the material can be considered sufficiently stabilized when the declining temperature reaches the ambient level. This typical pattern of temperature change was observed in the present study (Fig. 1). The dehydrogenase activity (Fig. 7(a)), ATP content (Fig. 7(b)) and microbial biomass N (Fig. 7(d)) were reflected by the changes in temperature values and physico-chemical parameters (temperature, pH, various forms of N) of the spent litter. It was also observed that the maturation of the spent litter was accompanied by changes in HA, HA:FA and various forms of N. These changes were correlated to the microbial activities of the spent litter (Table 3).

The dehydrogenation process is basically a biological oxidation of organic compounds. The dehydrogenases fulfil a significant role in the oxidation of organic matter as they transfer hydrogen from substrates to acceptors. These enzymes are an integral part of the micro-organisms and, therefore, the result of the assay of dehydrogenase activity would show the activity of microbial populations (Tabatabai, 1982) and is believed to provide a good measure of microbial activity (Skujins, 1973; Tabatabai, 1982; Tiquia, 1996; Tiquia *et al.*, 1996a). In addition to dehydrogenase activity, the ATP content is another widely used parameter to estimate microbial activity and biomass (Jenkinson and Ladd, 1981). ATP content also represents the whole metabolic activity of the intact microbial cells during composting (Jenkinson, 1988).

The humification parameters (HA content and HA:FA ratio) have been widely used to assess the degree of decomposition of organic matter in the compost material and the stabilisation of the mature product (Senesi, 1989). During composting, the HA evolved and became increasingly predominant over FA: the ratio between the two being an important index of compost maturity (Barberis and Nappi, 1996).

Although dehydrogenase activity, content of ATP and HA, and HA:FA ratio give excellent information

on the complex processes involved during composting of spent litter, these parameters are not simple and easy to determine. In the present study, a simple correlation coefficient analysis was carried out to determine whether these parameters correlated with other simpler parameters such as temperature, pH and different forms of N. Results of the correlation coefficient analysis demonstrated that temperature was correlated with both physico-chemical (pH, NH_4^+-N, CEC, HA and HA:FA) or microbial (ATP content and microbial biomass N) parameters. These parameters also interacted and could, therefore, be used as indices of the rate and extent of decomposition of spent litter. Among all these parameters, temperature can be considered as the simplest and cheapest parameter that can be used for judging the rate and extent of composting of spent litter. Golueke *et al.* (1954) suggested temperature as a useful criterion in the studies of inoculation. They pointed out that although temperature can be affected by C:N ratio, moisture content, and insulating qualities of the material, this parameter proved to be a useful indicator of the rate and extent of decomposition.

Effect of the addition of commercial bacterial product on further composting of the spent litter

The popularity of the pig-on-litter system of pig farming has increased over the years and, hence, many bacterial products have been developed to enhance the fermentation process within the pig litter bedding (Lin, 1991; Van Schaijk, 1991; Chaw, 1996). However, the bacterial inocula and their role in composting have been controversial issues over the years. This investigation revealed that addition of bacterial product in the pig-on-litter system enhanced the rate of further composting of the spent litter in windrows. Likewise, moisture adjustment of the spent litter piles without bacterial product also enhanced the rate of further (windrow) composting. However, for spent litter collected from pig pens with bacterial inoculum, further moisture adjustment (after an initial adjustment to 60%) of the spent litter piles appeared to have no effect. Piles B (spent litter without bacterial product but with moisture adjustment), C (spent litter with bacterial product but without moisture adjustment) and D (spent litter with bacterial product and with moisture adjustment) had very similar trends of physical, chemical, and microbial changes during further composting but were significantly different from pile A (spent litter without bacterial product and without moisture adjustment). The rates of decomposition in these three piles were faster than pile A, and the spent litter became stabilized by day 56. The spent litter in pile A was still immature even at the end of windrow composting (day 91) and needed to be further composted to reach full maturation.

Results of this study demonstrated that the promoting effects of using bacterial inoculum during the operation of the pig-on-litter system on the further composting of spent litter could be compensated by moisture adjustment, so that if a bacterial product has been added in the initial pig-on-litter composting

Table 3. Correlation coefficients among physical, chemical and microbial parameters of the spent litter[a]

Parameters	Temperature	pH	NH₄⁺-N	NOₓ⁻-N	CEC	HA	FA	HA:FA	Hetero	ATP	Dehydro	Bio-C
Temperature												
pH	0.62**											
NH₄⁺-N	0.64**	0.64*										
NOₓ⁻-N	-0.05	-0.79**	0.75**									
CEC	-0.66*	-0.95***	-0.97***	0.67*								
HA	-0.60*	-0.93***	-0.92***	0.78***	0.89***							
FA	-0.29	-0.69*	-0.67*	0.72**	0.66*	0.85***						
HA:FA	-0.62*	-0.95***	-0.94***	0.78***	0.90***	0.99***	0.81**					
Hetero	0.39	-0.08	-0.06	0.39	0.16	0.07	0.31	0.05				
ATP	0.61*	0.92***	-0.90***	-0.72***	-0.80**	-0.93***	-0.65*	-0.94***	0.26			
Dehydro	0.46	0.98***	-0.97***	-0.88***	-0.91***	-0.93***	-0.82**	-0.94***	-0.25	0.75*		
Bio-C	-0.53	-0.94***	-0.92***	0.82***	0.90***	0.93***	0.76**	0.93***	0.26	-0.87***	-0.84***	
Bio-N	0.89***	-0.82***	0.81***	-0.43	-0.77***	-0.86***	-0.59*	0.87***	0.33	0.89***	0.44	-0.75**

[a]Correlations were based on 12 average data of the four piles during composting except for dehydrogenase activity and ATP content where 11 and 10 observations were taken, respectively.
*, ** and *** indicate significant correlation at 0.05, 0.01 and 0.001 probability levels, respectively.
CEC= cation-exchange capacity; HA = humic acid; FA = fulvic acid; hetero = total aerobic heterotrophs; dehydro= dehydrogenase activity; bio-C= microbial biomass C; bio-N= microbial biomass N.

process, moisture adjustment in the windrow compost-
ing is not important. Conversely, if the moisture content
of the spent litter is adjusted during windrow compost-
ing, addition of bacterial product during the pig-on-lit-
ter system is not necessary. Moreover, the addition of
bacterial product in the pig-on-litter system and moist-
ure adjustment of the spent litter during windrow com-
posting did not further increase the rate of composting,
indicating that there were no additive effects between
bacterial inoculum addition in the pig-on-litter system
and moisture adjustment later. Since moisture adjust-
ment alone would be good enough to enhance the com-
posting process in the spent litter in the windrows,
addition of bacterial product to the bedding material of
the pig pens in the pig-on-litter system was not necess-
ary. Such a finding is of remarkable importance since it
means that the whole process could be run on a more
economic basis.

Golueke et al. (1954) reported that the addition of bac-
terial inoculum is of value in composting only if the
bacterial population in the piles is unable to develop
rapidly enough to take full advantage of the compost
pile's capacity to support bacterial growth. They found
that inocula failed, in terms of temperature pattern and
chemical analyses, to benefit the composting, stemmed
from the adequacy of the microbial population already
existing on the material. The spent litter collected from
the pig-on-litter system already contains an adequate
microbial population (Tiquia, 1996). This investigation
proves that the control of the environmental conditions in
the spent litter piles (moisture content in particular) is the
most important factor governing the rate of composting
and the success of composting. Whenever the environ-
ment is appropriate, the indigenous mesophilic and
thermophilic organisms in the spent litter would be
expected to multiply with great rapidity, to the extent that
further composting in spent litter piles with bacterial
product and without bacterial product (but with moisture
adjustment) proceeded at equal rates in the present study.

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