In: Manure Management '99. Extension Division- University of Saskatchewan (Ed.). Saskatoon, Saskatchewan, Canada. pp 449-463.

Chemical Parameters For Maturity Determination of Pig Manure Disposed From the Pig-on-litter (POL) System in Hong Kong

S.M. Tiquia & N.F.Y. Tam

Abstract

The pig-on-litter system, also known as in-situ composting is one of the most highly recommended methods to treat pig wastes in Hong Kong. Pigs in this system are raised in pens, the floor of which is covered with a 30 cm thick layer of sawdust (bedding material), mixed with a commercially available bacterial product to aid decomposition. After 10-13 weeks, the spent litter is removed from the pigpens. The spent litter contains high concentrations of nutrients, organic matter and trace elements which can be utilized as a soil conditioner and/or fertilizer, but requires further composting in windrows to reach full maturity. In the present study, windrow composting of spent pig litter was carried out to investigate the effects of different composting strategies on the chemical properties of the mature compost, and to determine potential chemical parameters that indicate maturity. Nine composting piles were managed under different operating strategies (turning frequency, moisture content, and moisture adjustment). During composting and at maturation, concentrations of NH4+-N, [NO3- + NO2-]-N, extractable P and K, total and water-extractable Cu and Zn, and pH values were similar in all piles, regardless of the initial material or composting strategy. Among all chemical parameters measured, pH, concentrations of NH4+-N and water-extractable Cu and Zn are the simplest, least expensive and easiest parameters indicating the maturity of spent litter.

Keywords: composting, compost maturity, pig manure, decomposition, pig-on-litter system

Introduction

The standard method of raising pigs in Hong Kong is on concrete or slatted floors. The excreta is then hosed down to nearby water courses and streams. This practice is convenient but creates a serious pollution concern. In 1987, the Agriculture and Fisheries Department of Hong Kong initiated the pig-on-litter system, where pigs are raised on a litter bedding (sawdust mixed with a commercial bacterial product). The pig excreta, once deposited, are quickly mixed with the litter bedding and are decomposed in-situ. The bulking agent (sawdust) in the pig pen and the rapid decomposition of nitrogenous compounds lead to the eradication of offensive odor of ammonia. The success of this approach of raising pigs has also been demonstrated in Japan, New Zealand, and The Netherlands (Fukuda, 1991). The pig-on-litter system is a zero discharge method of waste treatment as neither waste water nor effluent needs to be handled. The only waste requiring disposal is the spent pig litter (a mixture of partially decomposed pig manure and sawdust) after 10-13 weeks. Previous studies have shown that the decomposition of the pig manure within the pig-on-litter system is incomplete, therefore, the spent pig litter (spent litter) requires further composting in windrows to achieve full maturity (Tiquia and Tam 1998a) before it can be recycled back onto agricultural land.

Due to variations in the number of pigs, types of commercial bacterial products, amounts of sawdust, and management practices in the pig-on-litter system, the properties of the spent litter from different pig pens are likely to be different. Such differences in the spent litter would affect the time of maturation and quality of the mature compost. On the other hand, the operating strategies being used during windrow composting of this spent litter would also influence the maturation. Tiquia and Tam (1998a) and Tiquia et al. (1997a) concluded that if the moisture content of the spent litter was maintained at 60% and turned every 4 days, the spent litter would reach maturity in 56 days. Spent litter piles with less frequent turning (every 7 days) took 126 days to reach maturity (Tiquia et al., 1997b), while spent litter piles with their moisture contents adjusted to 70% took 91 days to reach maturity (Tiquia et al., 1996a and 1996b). The decomposition of the spent litter during winter, without bacterial inoculum or moisture adjustment, was slow and the spent litter did not reach maturity at the end of the composting period (91 days) (Tiquia, 1996; Tiquia et al., 1997a and 1997c).

The acceptance of the spent pig litter compost as fertilizer and/or conditioner depends on the consistent composition of the mature compost. It has been reported that composting leads to a homogeneity in the composition of the product irrespective of the initial material and the composting process (Garcia et al., 1993; Serra-Wittling et al., 1996). Such homogeneity will be useful in establishing maturity indices which can be quantified numerically. On the other hand, previous studies have shown that chemical properties of the mature compost vary depending on the properties of the initial material (Michel et al., 1996; Savage, 1996). The present study therefore aims (1) to investigate the effects of different initial material and composting strategies on the chemical properties of the mature spent litter compost and, (2) to identify the most suitable chemical parameters that can be used as an index of compost maturity.

Materials and methods

The spent litter was collected from five different pens (pens A to E) where the pig-on-litter system was employed (Table 1). The same feed type was fed to the pigs in the pig-on-litter system and the composition of the feed is shown in Table 1. Nine triangular piles, about 2 m in width at the base and 1.5 m in height were built from the spent litter collected from the five pens. The nine operating strategies (piles 1 to 9) used are listed in Table 2. All piles except pile 1 were turned every 4 days. The initial moisture content of all piles were adjusted to 60% with the exception of piles 1 to 3, whose moisture contents were adjusted to 50% and pile 5, whose moisture content was adjusted to 70%. The moisture content of piles 7 and 9 were adjusted to their designed values, while no further adjustment in moisture content was carried out with the rest of the piles during composting. During the process of composting, the ambient temperature and temperature within each pile were measured before turning. The spent litter was considered mature when the temperature of the pile reached the ambient level.

Initial and mature compost samples were collected at 5 random locations in each of the piles. These samples were combined and mixed to provide a composite sample. Triplicate composite samples were taken from each pile. The samples were analyzed for Kjeldahl N (Page et al., 1982); total and Olsen-extractable P using ascorbic acid method (APHA, 1989); total and water-extractable (1:10 spent litter:water extract) K, Cu and Zn (atomic absorption spectrophotometry); NH_4^+-N and (NO_3^- + NO_2^-)-N (Page et al. 1982); electrical conductivity (EC) (1:10 spent litter:water extract) using a conductivity probe; pH (1:10 spent litter:water extract) using a pH probe; total C and ash content (loss on ignition); humic (HA) and fulvic (FA) acids (Page et al., 1982); and cation-exchange capacity (CEC) (Harada and Inoko, 1980)

Mean and standard deviation (SD) of the three replicates of each pile were calculated. One-way analysis of variance was performed to determine differences among the 9 piles during the initial and mature stage. Significant differences among means were then compared using the Bonferroni Test. A t-test was carried out to compare the difference between the initial spent litter and mature compost product in each pile. All statistical analyses were based on the procedures described by Zar (1984). The Sigma Stat for Windows 1.0 computing package (Jandel Corporation, USA) was used to perform all statistical analyses.

Results

Kjeldahl N, total P and K

At day 0 (initial stage), the Kjeldahl N, and total P and K concentrations of all piles ranged from 1.80 to 3.05%, 1.32 to 1.80% and 1.03 to 1.80%, respectively (Table 3). At maturity, these values slightly increased to 1.90 to 3.45 % for Kjeldahl N, 1.51 to 2.04 % for total P and 1.42 to 2.01% for total K (Table 3). The initial concentrations of N, P, and K of the spent litter piles were not significantly different from those of the mature product in all piles. However, significant differences were found among 9 piles at maturity in terms of the Kjeldahl N and total P content. The total K content of all 9 piles were similar at mature stage with the exception of piles 7 and 8 whose values were higher.

Inorganic N, and extractable P and K

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

During the initial stage of composting (day 0), the extractable P and K contents of the spent litter piles ranged from 3.64 to 5.45 mg g^{-1} and 6.65 to 10.37 mg g^{-1}, respectively. At mature stage, these levels increased significantly ($P < 0.0001$) between 6.41 to 7.44 mg g^{-1} for extractable P and 9.72 to 11.45 mg g^{-1} for extractable K. No significant difference was found in terms of the extractable P content among all 9 piles at maturity. Although some differences in extractable K were found between 9 piles, the difference was only about 1.0 mg g^{-1}.

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

The EC, pH, total C and ash content of the initial spent litter piles varied significantly from each other (Table 5). During composting, the EC value and ash content increased, while the total C and pH value decreased. The total C concentrations of the spent litter piles at mature stage did not vary from each other except for piles 3, 4 and 5 whose values were about 1% higher than the other piles. The ash contents of the 9 piles were similar except for piles 3, 4 and 5 whose ash values were lower. At maturity, pH and EC values did not differ among all piles except piles 3 and 5, whose EC values were lower than the rest.

Humic acid (HA), fulvic acid (FA), cation exchange capacity (CEC) and C:N ratio

The HA content of all 9 piles were not significantly different at day 0 (initial stage) (Table 6). At maturity, the HA content of all piles increased but the increases in piles 6, 7, 8 and 9 were significantly higher than the other 6 piles (Table 6). The FA content of all piles remained relatively stable during composting, while the CEC content and C:N ratio varied significantly from each other in all piles during the initial and mature stages of composting.

Total and water-extractable Cu and Zn

As composting progressed, the concentrations of total Cu and Zn increased, while the water- extractable Cu and Zn decreased significantly ($P < 0.0001$). The initial water-extractable Cu and Zn concentrations of the spent litter piles differed significantly from each other as a result of the different treatments during the initial pig-on-litter system (Table 1). When the spent litter piles reached maturity, the total and water-extractable Cu and Zn concentrations were similar among all piles (Table 7).

Discussion

Variations in the treatments (i.e. number of pigs, amount of sawdust added, type of bacterial inoculum added and litter management) under the pig-on-litter system (Table 1) resulted in the differences in chemical properties of the initial spent litter material which would affect the quality of the composted product. Among all the chemical properties investigated, there are chemical parameters (Kjeldahl N, total P, K and C, ash, HA, CEC, EC and C:N ratio) whose values were influenced by the initial material and therefore cannot be used in establishing the degree of maturity of spent litter. Similar results were observed on composting of horse manure (Warman and Termeer, 1996), broiler litter (Flynn and Wood, 1996) and municipal wastes (Garcia et al., 1992). These authors found that the chemical properties of the composted product such as N, P, K and C:N ratio are very much influenced by the initial feedstocks.

The Kjeldahl N, total P and K of the mature compost varied depending on the concentrations of the initial material. Spent litter piles with higher initial Kjeldahl N and total P and K also had higher nutrient values at mature stage (Table 5). The total nutrient content of the spent litter increased slightly during composting, indicating that this process did not reduce the agronomic quality of the end-product. It has been known that composting is mainly decomposition and transformation (Golueke, 1977). For nitrogenous compounds, the conversion is from protein to organic N, then to NH4+ and finally to NO3-/NO2- (with very little denitrification). This is why a decrease in NH4+-N concentration followed by an increase in (NO3-+NO2-)-N are common for composting process (Riffaldi et al., 1986; Forster et al., 1993).

The HA content was influenced mainly by the composting strategies, while the CEC content of the spent litter was influenced by both the initial material and the operating strategies used during windrow composting. Their values increased over the composting period, and at the end of maturation showed a wide variation in HA (37.3 to 89.7 g Kg-1) and CEC (68.4-115.5 meq 100 g-1) content, depending on the starting material and the operating strategies used. The total C and ash content were also influenced by the operating strategies.

One ratio which is frequently used as an index of compost maturity is the C:N ratio. The decline to between 20:1 at maturity has been recommended as an index of compost maturity (Jimenez and Garcia, 1991). If such criterion for maturity is to be used, the spent litter from piles 6, 7, 8 and 9 would be considered mature even at day 0 as their initial C:N ratios were less than 20:1 (Table 6). The C:N ratio was influenced by the initial spent litter material. The numerical values of the mature piles varied widely between 11.9 and 25.6 (Table 6), suggesting that C:N ratio cannot be used as a suitable index of maturity. Such problem was also encountered during composting of domestic sewage sludge (Jimenez and Garcia, 1991) and municipal solid wastes (Garcia et al., 1992). These authors suggested that C:N ratio of the water extract rather than that of the compost material could be more useful indicators of compost maturity.

To be considered as a suitable indicator of compost maturity, it is not sufficient that a parameter has a similar pattern of change during the course of composting. Rather it is important that the parameter reached similar values when the compost became mature, regardless of the differences in the initial material and composting strategies (Garcia et al., 1992; Garcia et al., 1993; Serra-Wittling et al., 1996). Amongst all the chemical parameters studied, the concentrations of inorganic nutrients (NH4+-N, [NO3- + NO2-]-N, extractable P and K), and pH can be used as suitable indicators of maturity of spent litter as their numerical values were not influenced by the differences in the initial material and the operating strategies employed during windrow composting. When the spent litter reached maturity, compost from all piles shared the same quality in terms of these chemical parameters. Moreover, these chemicals have direct link to the fertility value of the compost material and thus, contribute largely to the quality of the compost material.

Total and water-extractable Cu and Zn concentrations of the mature compost were also not affected by the starting spent litter material and composting strategy as these parameters reached similar values in all piles at mature stage. Therefore, they can be considered as a useful index for the maturity of spent litter in the present study. The concentrations of total Cu and Zn in the spent litter compost were high, and this fact cannot be avoided since these two metals are added in the pig diet. However, as far as the application of compost on agricultural land is concerned, the content of the water-extractable form of the heavy metals is more important than the total metal concentration (Petruzzelli et al., 1989; Tiquia et al., 1996c). The water-extractable Cu and Zn concentrations decreased during composting because they bind with the humic substances. It is therefore not due to the moisture content of the windrow, turning frequency, and feed types. Leaching of Cu and Zn due to run-on and run-off was not observed. In the present study, decreases in water-extractable Cu and Zn concentrations coincided with increases in HA content of the spent litter, indicating the ability of humic substances to form stable complexes with metal ions.

Therefore, the water-extractable Cu and Zn can be used as suitable parameters to indicate maturity of spent litter.

The present study revealed that a good operating strategy enhanced the quality of the mature spent litter compost. Spent litter piles with more frequent turnings (every 4 days) and moisture adjustment to 60% during composting had higher CEC and HA values compared with spent litter with less frequent turnings and without adjustments in moisture content. The addition of bacterial inoculum during the pig-on-litter in-situ composting had no effect on the chemical properties of the spent litter and the efficiency of the process if the operating strategies mentioned above are met. Such a finding is of remarkable importance since it means that the whole process could be run on a more economic basis.

For practical composting operations, it would be desirable to use simple, inexpensive and easy indicators of compost maturity. The measurement of chemical parameters such as pH, EC, ammonium and possibly water-extractable Cu and Zn concentrations of the composted product satisfied this criteria, and can be used as indices of maturity. However, compost maturity is difficult to define by only employing the chemical parameters. The understanding of compost maturity has to be improved by employing biological parameters such as microbial counts, oxygen uptake rate, germination index (Inbar et al., 1990; Brinton et al., 1995), and physical parameters such as bulk density and particle size distribution (Tiquia and Tam, 1998b). These parameters, together with the chemical parameters suggested in this study will be useful in the estimation of compost maturity and the development of maturity index of spent litter compost.

Acknowledgment

The authors would like to thank Ms. Christina Lo and all the technical staff of the Ta Kwu Ling Pig Breeding Centre, Agriculture and Fisheries Department, Hong Kong Government, for allowing this compost trials to be carried out at the Centre, and for all the assistance offered during these trials. This project was financially supported by the RGC Competitive Earmarked Research Grant (CERG) and the City University Research Grant.

References

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

Flynn, R. and Wood, C.W. (1996) Temperature and chemical changes during composting of broiler litter. Compost Science and Utilization 4 (3), 62-70.

Fukuda, T. (1991) Utilization of Fermentation Products in the 'Pig-on-litter' System of Pig

Farming. Japanese Council for the Propagation and Promotion of Fermentation Products. Tokyo, Japan.

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

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

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

Harada, Y. and Inoko, A. (1980) Relationship between cation-exchange capacity of composts for the estimation of degree of maturity. Soil Science and Plant Nutrition 26 (3), 353-362.

Inbar, Y., Chen, Y., Hadar, Y. and Hoitink, H.A.J. (1990) New approaches to compost maturity. BioCycle 31, 64-69.

Jimenez, I.E. and Garcia, V.P. (1991) Composting of domestic sewage sludge. I. Evolution of temperature, pH, C/N ratio cation-exchange capacity. Resources, Conservation and Recycling 6, 45-60.

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

Page, A.L., Miller, R.H. and Keeney, D.H. (1982) Methods of Soil Analysis. Part 2. Chemical and Microbiological Properties. 2nd edition. American Society of Agronomy. Madison, Wisconsin, U.S.A.

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

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

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

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

Tiquia, S.M. and Tam, N.F.Y. (1998b) Composting of spent pig litter in turned and forced-aerated piles. Environmental Pollution 99, 329-337.

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

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

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

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

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

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

Warman, P.P. and Termeer, W.C. (1996) Composting and evaluation of racetrack manure, grass clippings and sewage sludge. Bioresource Technology 55, 95-101.

Zar, J.H. (1984) Biostatistical Analysis. Prentice Hall, Inc. U.S.A. 718 pp.

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

Treatment	Pen A	Pen B	Pen C	Pen D	Pen E
Size of pig pen	32 m^2	30 m^2	40 m^2	40 m^2	30 m^2
Number of pigs	32	30	40	40	30
Age of pigs at start	99 days	82 days	113 days	72 days	78 days
Raising period	92 days	115 days	91 days	123 days	117 days
Litter management	Mixing	Layering	Layering	Layering	Layering
Total feed consumption‡	6544.5 Kg	8307.7 Kg	8196.1 Kg	11910 Kg	9619.2 Kg
Total sawdust consumption	60 bags	70 bags	81.5 bags	91 bags	90 bags
Bacterial product used	Elimexal	Vitacogen	Biogreen	no bacterial product added	Odor control (OC)-organic fertilizers (OF)

†Spent litter in piles 1 and 2 were collected from Pen A; spent litter in piles 3, 4, and 5 were collected from Pen B; spent litter in pile 6 was collected from Pen C; spent litter in piles 7 was collected from Pen D; spent litter in piles 8 and 9 were collected from Pen E. ‡ The same type of feed was fed to the pigs in pens A to E. The feed contained a mixture of corn yellow, soya bean meal, fish meal, fat, and small amount of dicalcium phosphate, lysine, Tasmix 77 (with pre-mix Cu and Zn), Tylan and Hygromix.

Table 2. Operating strategies and seasonal conditions during composting, duration of composting and time of maturation.

Pen	Pile	Operating Strategies			Season	Duration of composting trial	Time when temperature reached ambient level
		Turning frequency	Initial moisture adjustment	Regular moisture correction			
A	1	2 days	50 %	No	Spring-summer	126 days	74 days
A	2	4 days	50 %	No	Spring-summer	126 days	74 days
B	3	4 days	50 %	No	Summer-autumn	91 days	60 days
B	4	4 days	60 %	No	Summer-autumn	91 days	60 days
B	5	4 days	70 %	No	Summer-autumn	91 days	91 days
C	6	4 days	60 %	No	Summer	91 days	56 days
D	7	4 days	60 %	Yes	Summer	91 days	56 days
E	8	4 days	60 %	No	Summer	91 days	56 days
E	9	4 days	60 %	Yes	Summer	91 days	56 days

Table 3. Kjeldahl N, total P and K concentrations of the initial and mature spent litter.

Pen	Pile	N (%)		P (%)		K (%)	
		Initial material	Mature compost	Initial material	Mature compost	Initial material	Mature compost
A	1	1.86 ± 0.48^{a}†	1.98 ± 0.02^{a}	1.80 ± 0.04^{a}	2.04 ± 0.07^{a}	1.49 ± 0.02^{a}	1.60 ± 0.02^{a}
A	2	2.14 ± 0.06^{ac}	1.90 ± 0.01^{a}	1.76 ± 0.02^{ab}	1.99 ± 0.19^{ab}	1.50 ± 0.06^{a}	1.62 ± 0.11^{a}
B	3	1.95 ± 0.06^{a}	2.71 ± 0.13^{bc}	1.32 ± 0.01^{c}	1.51 ± 0.08^{c}	1.06 ± 0.02^{c}	1.42 ± 0.06^{a}
B	4	2.02 ± 0.08^{ac}	2.68 ± 0.00^{bc}	1.35 ± 0.07^{c}	1.51 ± 0.01^{c}	1.11 ± 0.04^{c}	1.50 ± 0.78^{a}
B	5	1.80 ± 0.15^{a}	2.48 ± 0.02^{b}	1.37 ± 0.08^{c}	1.48 ± 0.01^{c}	1.06 ± 0.01^{c}	1.53 ± 0.06^{a}
C	6	2.56 ± 0.01^{acd}	3.13 ± 0.03^{cd}	1.64 ± 0.03^{ab}	1.88 ± 0.08^{ab}	1.43 ± 0.04^{a}	1.36 ± 0.06^{a}
D	7	3.05 ± 0.18^{bd}	3.19 ± 0.04^{cd}	1.67 ± 0.04^{ab}	1.81 ± 0.03^{b}	2.11 ± 0.01^{b}	2.01 ± 0.03^{b}
E	8	2.56 ± 0.01^{acd}	3.13 ± 0.03^{cd}	1.64 ± 0.03^{ab}	1.82 ± 0.08^{ab}	1.90 ± 0.02^{b}	1.94 ± 0.07^{b}
E	9	2.74 ± 0.09^{bc}	3.45 ± 0.06^{d}	1.59 ± 0.04^{b}	1.82 ± 0.27^{ab}	1.70 ± 0.02^{a}	1.86 ± [illegible]^{b}
Range		1.80 - 3.05	1.90 - 3.45	1.32 - 1.80	1.51 - 2.04	1.06 - 2.11	1.42 - 2.01
Mean±SD‡		2.29 ± 0.45	2.74 ± 0.54	1.57 ± 0.17	1.77 ± 0.23	1.48 ± 0.37	1.65 ± 0.23

† Column Means ± standard deviation (three replicates) of the same letter in the superscript position are not significantly different from each other at $P<0.05$; ‡ Mean ± standard deviation of the 9 piles are shown.

Table 4. Concentrations of NH_4^+-N, (NO_3^- + NO_2^-)-N and, extractable P and K of the initial and mature spent litter.

Pen	Pile	NH_4^+-N (mg g^{-1})		(NO_3^- + NO_2^-)-N (mg g^{-1})		Extractable P (mg g^{-1})		Extractable K (mg g^{-1})	
		Initial material	Mature product	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
A	1	6.04 ± 0.05^{a}†	0.12 ± 0.02^{a}	0.08 ± 0.00^{a}	1.38 ± 0.17^{a}	5.45 ± 0.07^{a}†	7.44 ± 0.20^{a}	9.71 ± 0.45^{a}	11.45 ± 0.67^{b}
A	2	6.57± 0.09^{a}	0.13 ± 0.01^{a}	0.12 ± 0.01^{a}	1.42 ± 0.01^{a}	5.55 ± 0.09^{a}	7.30 ± 0.11^{a}	10.37 ± 0.34^{a}	10.14 ± 0.02^{ab}
B	3	4.40 ± 0.09^{c}	0.42 ± 0.01^{b}	0.19 ± 0.04^{ac}	1.26 ± 0.06^{a}	3.64 ± 0.07^{b}	6.41 ± 0.12^{a}	7.77 ± 1.07^{ac}	9.90 ± 0.35^{a}
B	4	3.99 ± 0.11^{c}	0.46 ± 0.05^{b}	0.26 ± 0.07^{bc}	1.20 ± 0.06^{a}	3.81 ± 0.08^{b}	6.49 ± 0.28^{a}	6.65 ± 0.04^{bc}	10.04 ± 0.01^{a}
B	5	3.88 ± 0.16^{c}	0.18 ± 0.04^{a}	0.27 ± 0.03^{bc}	1.44 ± 0.36^{a}	3.84 ± 0.04^{b}	6.59 ± 0.16^{a}	6.73 ± 0.20^{bc}	10.05 ± 0.01^{a}
C	6	7.01± 0.33^{b}	0.12 ± 0.04^{a}	0.18 ± 0.02^{ac}	1.16 ± 0.06^{a}	5.12 ± 0.29^{a}	6.70 ± 0.48^{a}	8.40 ± 0.56^{ac}	9.72 ± 0.20^{a}
D	7	7.20 ± 0.01^{b}	0.12 ± 0.04^{a}	0.05 ± 0.00^{a}	1.26 ± 0.10^{a}	5.18 ± 0.15^{a}	6.66 ± 0.32^{a}	9.00 ± 1.10^{ac}	10.16 ± 0.16^{ab}
E	8	5.76± 0.17^{a}	0.12 ± 0.04^{a}	0.18 ± 0.02^{ac}	1.16 ± 0.06^{a}	5.12 ± 0.29^{a}	6.70 ± 0.48^{a}	8.40 ± 0.56^{ac}	10.72 ± 0.20^{ab}
E	9	5.75 ± 0.07^{a}	0.12 ±0.04^{a}	0.11 ± 0.03^{a}	1.31 ± 0.18^{a}	5.37 ± 0.01^{a}	7.17 ± 0.03^{a}	9.05 ± 0.85^{ac}	10.12 ±0.28^{a}
Range		3.88 - 7.20	0.12 - 0.46	0.08 - 0.27	1.16 - 1.44	3.64 - 5.45	6.41 - 7.44	6.65 - 10.37	9.72 - 11.45
Mean±SD‡		5.56 ± 1.24	0.20±0.14	0.16± 0.08	1.29 ± 0.15	4.78 ± 0.77	6.83 ± 0.42	8.45 ± 1.30	10.25 ± 0.55

† Column Means ± standard deviation (three replicates) of the same letter in the superscript position are not significantly different from each other at $P<0.05$; ‡ Mean ± standard deviation of the 9 piles are shown.

Table 5. Electrical conductivity (EC), pH, total C and ash content of the initial and mature spent litter.

Pen	Pile	EC (mmhos cm^{-1})		pH		Total C (%)		Ash (%)	
		Initial material	Mature product	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
A	1	2.03 ± 0.04^{b}†	2.11 ± 0.07^{a}	8.47 ± 0.07^{a}†	6.04 ± 0.02^{a}	50.5 ± 0.06^{b}	49.6 ± 0.26^{b}	12.91 ± 0.10^{a}	14.50 ± 0.45^{a}
A	2	1.91 ± 0.04^{b}	2.40 ± 0.01^{a}	7.92 ± 0.05^{b}	5.43 ± 0.01^{a}	50.6 ± 0.58^{b}	49.4 ± 0.03^{b}	12.71 ± 1.00^{a}	14.90 ± 0.03^{a}
B	3	1.52 ± 0.07^{c}	1.87 ± 0.05^{a}	8.50 ± 0.03^{a}	5.63 ± 0.08^{a}	52.5 ± 0.30^{a}	50.8 ± 0.05^{a}	9.85 ± 0.81^{c}	12.50 ± 0.04^{b}
B	4	1.47 ± 0.01^{c}	2.18 ± 0.71^{a}	8.28 ± 0.04^{c}	5.69 ± 0.05^{a}	52.3 ± 0.09^{a}	50.7 ± 0.12^{a}	9.73 ± 0.27^{c}	12.40 ± 0.11^{b}
B	5	1.48 ± 0.06^{c}	1.56 ± 0.17^{b}	8.12 ± 0.01^{c}	5.51 ± 0.19^{a}	52.3 ± 0.46^{a}	50.9 ± 0.21^{a}	10.39 ± 0.76^{bc}	11.90 ± 0.11^{b}
C	6	2.68 ± 0.08^{a}	3.14 ± 0.08^{a}	7.90 ± 0.01^{b}	5.67 ± 0.01^{a}	51.6 ± 0.04^{ab}	49.6 ± 0.42^{b}	10.96 ± 0.06^{ac}	14.50 ± 0.73^{a}
D	7	2.51 ± 0.15^{a}	2.69 ± 0.14^{a}	8.18 ± 0.01^{c}	5.66 ± 0.02^{a}	50.8 ± 0.22^{b}	49.7 ± 0.03^{b}	12.34 ± 0.37^{a}	14.30 ± 0.06^{a}
E	8	2.74 ± 0.00^{a}	3.19 ± 0.08^{a}	8.24 ± 0.01^{c}	5.53 ± 0.01^{a}	51.6 ± 0.04^{ab}	49.6 ± 0.42^{b}	11.00 ± 0.08^{ac}	14.50 ± 0.73^{a}
E	9	2.72 ± 0.00^{a}	2.60 ± 0.02^{a}	8.27 ± 0.01^{c}	5.59 ± 0.01^{a}	51.3 ± 0.06^{ab}	49.5 ± 0.06^{b}	11.53 ± 0.04^{ac}	14.70 ± 0.11^{a}
Range		1.47 - 2.74	1.56 - 3.19	7.90 - 8.50	5.43 - 6.04	50.5 - 52.5	49.4 - 50.9	9.73 - 12.91	12.4 - 14.9
Mean±SD‡		2.12 ± 0.54	2.41 ± 0.56	8.21 ± 0.21‡	5.64 ± 0.27	51.5 ± 0.76	50.0 ± 0.65	11.3 ± 1.21	13.8 ± 1.17

† Column Means ± standard deviation (three replicates) of the same letter in the superscript position are not significantly different from each other at $P<0.05$; ‡ Mean ± standard deviation of the 9 piles are shown.

Table 6. Concentrations of humic acid (HA), fulvic acid (FA) and cation-exchange capacity (CEC), and C:N ratio the initial and mature spent litter.

Pen	Pile	HA (g Kg^{-1} O.M.)		FA (g Kg^{-1} O.M.)		CEC (meq 100 g-1 ash-free)		C:N ratio	
		Initial material	Mature product	Initial material	Mature product	Initial material	Mature Product	Initial material	Mature product
A	1	31.6 ± 0.37^{a}†	41.1 ± 1.17^{a}	109.2 ± 0.34^{a}	109.9 ± 3.95^{a}	55 ± 1.22^{a}	68 ± 1.08^{d}	26 ± 0.03^{a}	26 ± 0.2^{a}
A	2	34.7 ± 2.83^{a}	42.8 ± 3.80^{a}	113.5 ± 7.82^{a}	103.9 ± 5.03^{a}	54 ± 0.00^{a}	71 ± 2.02^{cd}	26 ± 0.12^{a}	26 ± 0.16^{a}
B	3	27.0 ± 0.46^{a}	45.0 ± 0.87^{a}	105.1 ± 0.13^{a}	97.6 ± .10^{ab}	39 ± 0.95^{ab}	93 ± 5.35^{b}	27 ± 0.47^{a}	19 ± 0.07^{c}
B	4	27.4 ± 4.12^{a}	42.8 ± 6.54^{a}	114.0 ± 1.59^{a}	107.9 ± 0.36^{a}	39 ± 1.92^{ab}	94 ± 3.15^{a}	25 ± 1.93^{a}	19 ± 0.11^{c}
B	5	25.2 ± 0.27^{a}	37.3 ± 0.31^{a}	112.4 ± 1.50^{a}	114.6 ± 2.72^{a}	42 ± 3.14^{ab}	89 ± 5.13^{a}	27 ± 2.18^{ab}	21 ± 0.07^{b}
C	6	30.8 ± 5.25^{a}	77.5 ± 0.11^{b}	72.2 ± 4.21^{b}	71.8 ± 19.44^{b}	34 ± 2.58^{b}	103 ± 5.34^{ab}	20 ± 0.10^{bc}	16 ± 0.35^{d}
D	7	29.8 ± 3.10^{a}	89.7 ± 1.00^{b}	69.7 ± 2.00^{b}	80.3 ± 6.72^{ab}	28 ± 11.46^{b}	103 ± 3.34^{ab}	17 ± 1.07^{c}	12 ± 0.16^{f}
E	8	33.1 ± 8.52^{a}	83.5 ± 8.59^{b}	72.2 ± 4.21^{b}	70.9 ± 0.40^{b}	34 ± 2.58^{b}	103 ± 5.34^{ab}	20 ± 0.00^{bc}	16 ± 0.35^{d}
E	9	20.7 ± 6.69^{a}	85.7 ± 2.99^{b}	70.8 ± 0.52^{b}	70.9 ± 0.40^{b}	36 ± 2.09^{b}	116 ± 2.95^{a}	19 ± 0.64^{c}	14 ± 0.37^{e}
Range		20.7 - 33.1	37.3 - 89.7	70.9 - 114.6	69.7 - 114.0	34 - 55.4	68 - 115.5	17 - 27	12 - 26
Mean±SD‡		28.9 ± 5.30	60.6 ± 22.12	93.2 ± 20.6	92.0 ± 18.5	40 ± 9.53	93 ± 15.31	23 ± 3.98	19 ± 4.61

† Column Means ± standard deviation (three replicates) of the same letter in the superscript position are not significantly different from each other at $P<0.05$; ‡ Mean ± standard deviation of the 9 piles are shown.

Table 7. Total and water-extractable Cu and Zn concentrations of the initial and mature spent litter.

Pen	Pile	Total Cu (μg g^{-1})		Ext. Cu (μg g^{-1})		Total Zn (μg g^{-1})		Ext. Cu (μg g^{-1})	
		Initial Material	Mature product	Initial material	Mature product	Initial material	Mature product	Initial material	Mature product
A	1	551 ± 71[a]†	633 ± 26[a]	49.3 ± 5.4[a]	14.5± 2.35[a]	744 ± 17[a]	780 ± 15[a]	18.8 ± 0.2[b]	10.4 ± 1.4[a]
A	2	503 ± 17[a]	627 ± 67[a]	46.6 ± 5.3[a]	15.9 ± 0.18[a]	675 ± 9[a]	674 ± 9[a]	21.8 ± 3.7[b]	12.2 ± 0.4[a]
B	3	468 ± 55[a]	590 ± 31[a]	42.2 ± 1.7[ab]	9.8± 1.39[a]	616 ± 72[a]	774 ± 37[a]	23.3 ± 2.2[b]	9.3 ± 0.4[a]
B	4	454 ± 5[a]	611 ± 21[a]	43.3 ± 2.5[ab]	13.2± 3.70[a]	604 ± 37[a]	820 ± 32[a]	23.6 ± 5.8[b]	10.1 ± 1.8[a]
B	5	428 ± 41[a]	592 ± 10[a]	38.3 ± 6.1[b]	10.2 ± 0.17[a]	545 ± 22[a]	804 ± 2[a]	23.6 ± 0.03[b]	9.8 ± 0.1[a]
C	6	468 ± 4[a]	552 ± 0.2[a]	51.1 ± 1.3[a]	10.4 ± 0.28[a]	615 ± 98[a]	723 ± 32[a]	33.4 ± 0.5[a]	12.0 ± 0.1[a]
D	7	483 ± 24[a]	545 ± 7[a]	38.2 ± 0.4[b]	13.9 ± 0.82[a]	706 ± 69[a]	730 ± 64[a]	33.5 ± 12[a]	12.2 ± 0.9[a]
E	8	468 ± 4[a]	555 ± 5[a]	52.2 ± 4.7[a]	11.4 ± 0.28[a]	615 ± 97[a]	723 ± 32[a]	33.4 ± 0.5[a]	12.0 ± 0.8[a]
E	9	486 ± 10[a]	558 ± 6[a]	42.7 ± 0.1[ab]	13.0 ± 1.22[a]	623 ± 18[a]	732 ± 95[a]	35.7 ± 1.8[a]	11.8 ± 0.9[a]
Range		428 - 551	545 - 633	38.2 - 52.2	9.8 - 14.5	615 - 744	674 - 804	18.8 - 35.7	9.3 - 12.2
Mean±SD‡		479 ± 42	585 ± 38	44.9 ± 5.7	12.5 ± 2.4	751.4 ± 55	638 ± 72	27.5 ± 7.1	10.9 ± 1.6

† Column Means ± standard deviation (three replicates) of the same letter in the superscript position are not significantly different from each other at *P*<0.05; ‡ Mean ± standard deviation of the 9 piles are shown.