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Characterization and composting of poultry litter in forced-aeration piles

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Abstract

The environmental problems associated with raw poultry manure application could be mitigated by stabilizing its nutrient and organic matter (OM) contents by composting before application to agricultural soils. In the present study, quantitative changes in physical, chemical, and microbial properties of poultry litter (a mixture of poultry manure, wood shavings, waste feed, and feathers) were studied in order to understand the composting process and evaluate the suitability of the composted product as a soil amendment. The poultry litter was composted in forced-aeration piles. Results of this study showed that the poultry litter went through physico-chemical and microbial changes similar to other composting systems, including changes like self-heating of the compost mass, relative increases in total Cu, Zn, P, K, and NO_x^--N and decreases in microbial population numbers, C, OM, and extractable C, Cu, Zn, and NH_4^+-N contents. Despite differences in thermophilic temperatures at different locations of the forced-aeration piles, temperatures in these locations reached ambient level almost at the same time by day 128, indicating that the poultry litter was becoming stable. Nitrogen loss was a major problem during composting of poultry litter, even when the piles were not turned under the forced-aeration system. About 18 kg of the initial N (58% of the initial N) was lost during composting, which indicates that composting reduced the value of the poultry litter as N fertilizer. However, the composted litter contained a more humified (stabilized) OM compared with the uncomposted litter, which could enhance its value as a soil conditioner. In conclusion, composting of poultry litter converted the soluble nutrients to more stable organic forms, thereby reducing their bioavailability and susceptibility to loss when applied to crop fields. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: Composts; Animal manure; Forced-aeration; Compost maturity; N loss

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1. Introduction

The magnitude of poultry waste generation in Hong Kong has led to improper disposal, including over application and improperly timed application for crop nutrient demands. Such practices could lead to serious environmental problems such as increased nutrient loss through leaching, erosion, and runoff from agricultural fields [1,2]. Characterization of soil-applied organic material is necessary to clarify the nature of organic matter and evaluate the availability of nutrients in it. The environmental problems associated with raw manure application could be mitigated by chemically and biologically stabilizing soluble nutrients to more stable organic forms by composting before application to agricultural soils. From an environmental perspective, Velthof et al. [3] observed that it is important to reliably determine the availability of nutrients so that organic wastes can be diverted from landfills and recycled for use as soil amendment. This should benefit farmers because their efficient use could reduce mineral fertilizer requirements especially for N, P, and K.

Composting manure has been recognized as an effective way to partially solve the growing concern of solid waste management [4] as the process improves the handling characteristics of the manure by reducing its volume and weight, kills pathogens, and stabilizes the nutrients and organic matter in it [5–7]. The use of manure as a soil amendment has increased over the years since the use contributes to the disposal of wastes

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and enhances the preservation of the environment [4]. The acceptance of composting, however, depends on how well the operating strategies being employed are developed for both product quality [7] and environmental protection [8]. Proper evaluation of the system is, therefore, required if an acceptable product is to be generated, and the system efficiency is to be maximized. In Hong Kong, composting is one of the alternative methods for treating animal manure generated from farms [10,11]. The manure is usually composted with manual turning in windrows (conventional composting method), which is often labour intensive and creates air pollution (e.g. dust and odour). Turning requires additional space for the pile as it involves tearing down the piles, spreading the manure into a one foot-layer, and stacking the layered manure into windrows. Moreover, a manoeuvering area for the turning equipment (front-end loader) also would be required. Therefore, other operating strategies that can reduce manpower and space such as forced-aeration composting would be worth exploring.

Composting using forced-aeration has been developed in the United States in the last 25 years [12]. This composting method uses a ventilation unit (centrifugal blower) to force air into a perforated system located underneath the compost pile, to induce air convection movement into the material and deliver oxygen to microorganisms [12–15]. The forced-aeration composting method would be more suitable in Hong Kong where space is a problem. Like many large cities in the world, Hong Kong is facing a problem in terms of urban infringement on agricultural lands. This problem is further aggravated by the fact that Hong Kong is a very small territory, with only approximately 100 km^2 of arable land [16]. Because of the lack of sufficient land, the Hong Kong Government continues to put pressure on agriculture to be an efficient and nonpolluting industry. To comply with environmental protection legislation, all livestock farms are required to be licensed and must install an appropriate livestock waste treatment system.

In the present study, the forced-aeration composting system has been used to reduce the labour cost and space requirement for the windrow composting (turning method). Since the forced-aeration composting system is not a turning method, the efficiency of composting at different locations may be different due to variations in aeration levels. This result might affect the efficiency of composting, and quality of the final product. Therefore, it is important to evaluate the composting process at different locations of the forced-aeration piles.

Most of the criteria used in the evaluation of the composting process, compost stability (maturity), and quality were based on physical and chemical parameters of the organic material, whose behaviour reflects the metabolic activity of microorganisms involved in the composting process [17–19]. These parameters include a drop in temperature, degree of self-heating capacity, oxygen consumption, phytotoxicity assays, cation exchange capacity (CEC), organic matter (OM) and nutrient contents, and C/N ratio. In the present study, 22 physical, chemical, and microbial parameters were examined to (1) evaluate the composting process under forced-aeration system; and (2) characterize the properties of the composted poultry litter.

2. Materials and methods

2.1. Composting in static piles

The poultry litter (a mixture of poultry manure, wood shavings, waste feed, and feathers) used in the present study was collected from the pullet growing facilities at the centre, and from the Poultry Breeding Center at Castle Peak, New Territories. The litter collected from these two sites was mixed homogeneously using a front-end loader before piling in the composting sheds. The poultry litter was composted with forced-aeration. Three piles were built on perforated pipes connected to an air pump. Polyvinyl chloride (PVC) pipes (20 mm diameter) were laid on the base of the pile, with perforations (25 mm diameter) facing upward. The distance between each perforation was 20 cm. The pipes were covered with wood chips to prevent blockage of the holes, and air was blown to the piles (from bottom to top of the pile) using a Cole Palmer air pump. The air pump with an average flow rate of 0.69 $l_{air}\ kg_{compost}^{-1}\ min^{-1}$ and a maximum output of 0.83 $l_{air}\ kg_{compost}^{-1}\ min^{-1}$, was switched continuously during the entire period of composting. The chicken litter piles were then topped off with 5 cm layer of mature compost to insulate the piles, and act as a biofilter to minimize odours. Each pile was pyramidal in shape, about 2 m in width at the base and 1.5 m in height. Before piling, the moisture content of the litter was adjusted to 65% (w/v). No further adjustment in moisture was made throughout the composting process.

2.2. Sampling and analysis of compost properties

Poultry litter samples were gathered from four different locations of the pile: top (130 cm from the base of the pile), middle (75 cm from the base of the pile), bottom (30 cm from the base of the pile), and surface (5 cm from the surface of the pile). One kilogram of poultry litter compost was collected in each location at day 0, and then weekly until the end of the composting process (day 168). Pile temperatures were monitored manually using analogue thermometers. Temperature readings were taken towards the central part of the top, middle, and bottom locations of the piles. For the surface temperature, the temperature probe was plunged into the compost at a depth of 5 cm from the surface of the piles. Samples and temperature readings were taken, twice a week until the termination of composting trial. The poultry litter compost samples were characterized for the following parameters: water content (105 °C for 24 h); pH (1:10 w/v litter–water extract) using a pH electrode; electrical conductivity (EC) (1:5 w/v sample–water extract) using an electrical conductivity probe; total C and organic matter (OM) contents (loss on ignition); water-extractable C (1:10 w/v litter–water extract) by TOC analyzer (Shimadzu TOC-500); total (acid digest) and water-extractable Cu and Zn (1:10 w/v litter–water extract) by atomic absorption spectrometry; total P (acid digest) by flow injector analyzer; total K (acid digest) by atomic absorption spectrometry; Kjeldahl N [20]; NH_4^+-Nand NO_x^--N [21]. The theoretical total N concentration of the chicken litter was calculated by adding the Kjeldahl N with the NO_x^--N, whereas the organic N concentration was derived by subtracting the NH_4^+-N from the Kjeldahl N. The C/N ratio was then computed based on the concentration of total C and N. The digest for total Cu and Zn determination was prepared using the hydrofluoric, nitric, perchloric, and sulphuric acid method described by Reed and Martens [22]. This method solubilizes Cu and Zn through destruction of inorganic and organic compost fractions by action of the HF, HNO_3, $HClO_4$, and H_2SO_4 acids in the presence of heat (80 °C). The bulk density of the poultry litter compost at different stages of composting was determined using the method described by Day et al. [23]. In order to improve the reproducibility of this determination, a standardized test was developed. This involved the determination of the weight of the compost material contained in a 500 ml wide-mouthed jar (8.0 cm in diameter) using a standard compaction procedure. The compaction was done by dropping a plastic bottle (with 7.5 cm diameter base) containing water and weighing 500 g, three times. Following compaction, more compost sample was added up to the rim of the jar. The jars were oven-dried at 105 °C for 24 h, and the bulk density was calculated as follows:

$$\text{Bulk density (kg m}^{-3}) = \frac{\text{dry weight of compost sample (kg)}}{\text{volume of the jar (m}^{-3})}$$

Quantitative estimation of ammonium- and nitrite-oxidizing bacteria was assayed on selective media [24] using the plate frequency technique. The plate frequency technique involves inoculating 0.1 ml of the serially diluted compost suspension on the eight sections of the agar plate. Observation of bacterial colonies in any of the eight sections was scored positive. The total number of positive growths was counted, and the population size of microorganisms in the sample was estimated using a most probable number (MPN) method [25]. The denitrifying bacterial population was quantified by inoculation of tubed liquid media [26] using the MPN method [25].

2.3. Statistical analyses

The mean and standard deviation of the three replicates from each location were reported for all parameters measured. A regression analysis was carried out to examine the cause and effect of temperature on different composting properties determined. One-way analysis of variance (ANOVA) statistical analysis was performed to compare variations in compost properties at different locations of the forced-aeration piles. Sigma Stat for Windows 1.0 computing package (Jandel Corporation, USA) was used to perform all statistical analyses.

3. Results and discussion

The results of this study have shown that the poultry litter went through physico-chemical and microbial changes similar to other composting systems [27–29]. The changes included self-heating of the compost mass, relative increases in total Cu, Zn, P, K, and NO_x^--N and decreases in microbial population numbers, and concentrations of C, OM, and extractable fractions (i.e. water-extractable C, NH_4^+-N, and heavy metal contents) of the poultry litter.

3.1. Temperature patterns

The peak temperatures that occurred in the middle (63 °C) and bottom (58 °C) parts were higher than those recorded in the top (54 °C) and surface (48 °C) locations of the forced-aeration piles (Fig. 1). The low top and surface temperature could be attributed to the excess loss of heat since these two locations were closer to the ambient air than the other two locations (middle and bottom). Temperatures at different locations of the forced-aeration piles reach ambient level almost at the same time (day 128) despite their differences in thermophilic temperatures (Fig. 1), indicating that the poultry litter is becoming stable.

Temperature has been widely recognized as one of the most important parameters in the composting process [30,31]. The rise and fall of temperature have been reported to correlate with the rise and fall of microbial activities [6]. Temperature has also been found to be correlated with most of the important compost properties such as C/N ratio, pH, total C, NH_4^+-N, NO_x^--N, ash, and CEC [11]. The result of the regression analysis in the present study showed a curvilinear relationship between temperature and some chemical parameters such as water content, bulk density, pH, P, NH_4^+-N, NO_x^--N, and water-extractable C, Cu, and Zn (Table 1).

3.2. Characterization of microbial properties

Differences in pile temperatures at different locations of the forced-aeration piles did not significantly affect the changes in numbers of total aerobic heterotrophs and ammonium- and nitrite-oxidizing bacteria and denitrifying bacteria (Table 2). The population of these four microbial groups was similar in all four locations of the forced-aeration piles during composting. The total aerobic heterotroph counts were highest (10.3–10.6 $\log_{10}$ MPN g^{-1}) at the beginning of composting. Their numbers dropped until the end of the composting trial.

The ammonium- and nitrite-oxidizers were maintained at high population sizes during the decomposition process (8.0–10.4 $\log_{10}$ MPN g^{-1}), suggesting a rapid oxidation of NH_4^+-N to NO_3^--N. These levels were higher than that reported in soil, which range from a few hundred to 10^5 g^{-1} soil [32]. The numbers of ammonium- and nitrite-oxidizing bacteria dropped by day 7 and were maintained at about 8–9 $\log_{10}$ MPN g^{-1} until the end of the trial (Table 2). Like the other three microbial groups, the population sizes of denitrifying bacteria are highest at the beginning of composting (Table 2). The establishment of a large population of denitrifying bacteria suggests that some anaerobic microhabitats had existed within the piles although the composting system was maintained under aerobic condition. These microhabitats could have developed within the piles partially due to the rich contents of OM and nitrogen present in the poultry litter compost (Tables 3 and 5), which could promote microbial activity to the extent of causing depletion in O_2 content in isolated pockets within the piles. The high initial moisture content (65%) also hinders aeration and could induce anaerobic condition during composting [15]. Under these conditions, the denitrifying bacteria use NO_3^- as an electron acceptor instead of O_2, leaving N and N_2O gases to be released from the compost piles to the atmosphere. Moreover, some species of denitrifying bacteria may be facultative and grow aerobically [33]. Some microbial genera capable of denitrification are *Bacillus*, *Flavobacterium*, and *Pseudomonas*. These microbial groups have been found not only in soils [33], but also during composting [34]. It seems that as the composting proceeded, the denitrifying bacteria became

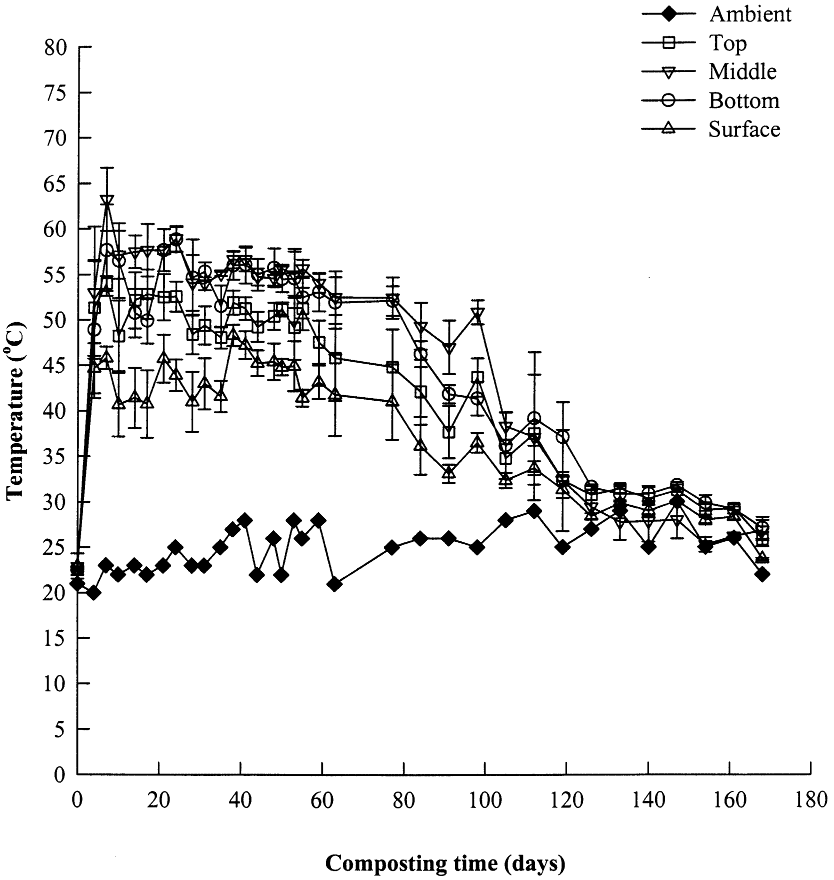

Fig. 1. Air and pile temperature changes during composting of poultry litter. $P = 0.004$; Top < Middle = Bottom < Surface.

Table 1
Regression analyses between compost properties and temperature of poultry litter during composting

Compost properties [a]	Regression equation	r^2	Significance [b]
Bulk density	$0.23+(2.0\times10^{-3}\times\text{temp.})-(3.1\times10^{-5}\times\text{temp.}^2)$	0.84	$P\leq0.001$
pH	$11.9-(0.24\times\text{temp.})\ (3.8\times10^{-3}\times\text{temp.}^2)$	0.67	$P\leq0.001$
Total N	$66.5-(2.6\times\text{temp.})+(0.03\times\text{temp.}^2)$	0.23	ns
Org. N	$50.3-(2.1\times\text{temp.})+(0.03\times\text{temp.}^2)$	0.31	ns
NH_4^+-N	$26.8-(1.15\times\text{temp.})+(0.01\times\text{temp.}^2)$	0.42	$P\leq0.01$
NO_x^--N	$-3.5+(0.32\times\text{temp.})-(5.0\times10^{-1}\times\text{temp.}^2)$	0.55	$P\leq0.01$
C/N ratio	$-9.06+(1.9\times\text{temp.})-(0.03\times\text{temp.}^2)$	0.15	ns
OM	$997-(11.5\times\text{temp.})+(0.15\times\text{temp.}^2)$	0.37	$P\leq0.05$
Total C	$578-(6.6\times\text{temp.})+(0.89\times\text{temp.}^2)$	0.36	$P\leq0.05$
Ext. C	$15.7-(0.4\times\text{temp.})+(5.0\times10^{-1}\times\text{temp.}^2)$	0.38	$P\leq0.05$
Total P	$23.5-(0.4\times\text{temp.})+(4.8\times10^{-3}\times\text{temp.}^2)$	0.42	$P\leq0.01$
Total K	$36.0-(1.0\times\text{temp.})+(1.0\times10^{-3}\times\text{temp.}^2)$	0.03	ns
Total Cu	$-2.1+(6.9\times\text{temp.})-(0.10\times\text{temp.}^2)$	0.57	$P\leq0.01$
Ext. Cu	$28.2-(1.1\times\text{temp.})+(0.02\times\text{temp.}^2)$	0.50	$P\leq0.01$
Total Zn	$-1570+(121.6\times\text{temp.})-(1.62\times\text{temp.}^2)$	0.58	$P\leq0.01$
Ext. Zn	$73.9-(2.7\times\text{temp.})+(0.39\times\text{temp.}^2)$	0.17	ns
EC	$3.6+(0.06\times\text{temp.})-(7.5\times10^{-4}\times\text{temp.}^2)$	0.001	ns
Heterotrophs	$15.7-(0.4\times\text{temp.})+(5.0\times10^{-3}\times\text{temp.}^2)$	0.38	$P\leq0.05$
Ammonifiers	$12.0-(0.1\times\text{temp.})+(1.0\times10^{-3}\times\text{temp.}^2)$	0.39	$P\leq0.05$
Nitrifiers	$12.0-(0.1\times\text{temp.})+(9.0\times10^{-3}\times\text{temp.}^2)$	0.46	$P\leq0.01$
Denitrifiers	$18.5-(0.7\times\text{temp.})+(5.0\times10^{-3}\times\text{temp.}^2)$	0.27	ns

[a] OM: organic matter; Org. N: organic N; NO_x^--N: $(NO_3^-+NO_2^-)$-N; Ext. C: water-extractable C; Ext. Cu: water-extractable Cu; Ext. Zn: water-extractable Zn; EC: electrical conductivity; Heterotrophs: total aerobic heterotrophs; Ammonifiers: ammonium-oxidizing bacteria; Nitrifiers: nitrite-oxidizing bacteria; Denitrifiers: denitrifying bacteria.

[b] ns: Not significant at $P\leq0.05$; temp. = temperature. Regression analysis was based on 40 (10 composting period × 4 locations) averaged data.

Table 2
Changes in microbial properties of the poultry litter at four locations (top, middle, bottom, and surface) of the forced-aeration piles during composting

Microbial properties	Pile locations [a]	Composting time (days)							P value
		0	7	14	35	91	133	168	
Total aerobic heterotrophs (MPN g^{-1})	T	10.4	8.3	8.8	8.5	7.4	7.6	7.7	0.608
	M	10.3	8.1	8.4	8.4	7.6	7.9	7.7	
	B	10.4	8.3	9.3	8.5	8.0	8.0	7.7	
	S	10.6	8.2	9.2	8.3	7.6	8.1	7.6	
Ammonifiers (MPN g^{-1}) [b]	T	10.4	8.4	8.4	8.7	8.4	9.0	8.5	0.724
	M	10.4	8.4	8.5	8.3	8.4	9.1	8.0	
	B	10.1	8.4	8.9	9.0	9.3	9.3	8.8	
	S	10.3	9.13	8.8	8.8	8.6	9.2	7.8	
Nitrifiers (MPN g^{-1})[c]	T	10.4	8.5	8.5	9.0	9.0	8.9	8.7	0.564
	M	10.4	8.5	8.5	8.2	8.7	9.0	8.7	
	B	10.2	9.3	9.3	9.2	8.5	8.9	8.8	
	S	10.3	9.0	9.0	9.0	9.0	9.1	8.6	
Denitrifiers (MPN g^{-1})[d]	T	8.9	8.8	7.8	6.4	6.1	5.9	5.7	0.904
	M	7.7	8.1	7.4	6.3	5.4	5.9	5.0	
	B	9.2	8.3	7.3	6.0	6.1	5.4	5.8	
	S	9.5	8.2	7.2	6.5	6.4	5.7	5.0	

Mean of three replicates from each location are shown. Data presented are based on 105 °C dry weight basis. *P* value shows the results of one-way ANOVA testing whether there are any significant differences among four locations of the poultry litter piles.

[a] T: top; M: middle; B: bottom; S: surface.

[b] Ammonifiers: ammonium-oxidizing bacteria.

[c] Nitrifiers: nitrite-oxidizing bacteria.

[d] Denitrifiers: denitrifying bacteria.

smaller in number (Table 2), indicating that very little denitrification took place once the air was blown in the pile. The NO_x^--N concentration also started to increase at a faster rate as composting progressed (Table 3).

3.3. Characterization of physico-chemical properties

The compost bulk density, which is inversely related to total compost volume and particle size, increased during composting (Table 4). Bulk densities reached a

Table 3
Changes in different forms of N of poultry litter at four locations (top, middle, bottom, and surface) of the forced-aeration piles during composting

Forms of N	Pile locations [a]	Composting time (days)					*P* value
		0	35	91	133	168	
Total N (g kg^{-1})	T	33.65	18.36	21.10	21.42	16.31	0.889
	M	32.19	22.14	19.07	18.96	9.91	
	B	35.55	20.88	18.68	19.01	13.43	
	S	34.04	16.84	22.99	19.11	14.94	
Org. N (g kg^{-1}) [b]	T	22.32	12.51	14.38	14.97	11.78	0.774
	M	21.10	15.54	10.88	12.22	5.93	
	B	24.28	15.82	13.32	12.99	11.20	
	S	22.80	9.99	16.20	13.56	10.35	
NH_4^+-*N* (g kg^{-1})	T	11.06	5.54	4.28	3.74	4.53	0.883
	M	10.86	5.83	5.35	4.03	3.98	
	B	10.84	3.98	3.38	2.87	2.23	
	S	11.00	5.56	4.08	2.95	4.59	
NO_x^--*N* (g kg^{-1}) [c]	T	0.20	0.46	1.43	2.44	2.71	0.994
	M	0.16	0.26	1.84	2.84	2.71	
	B	0.28	0.34	1.51	1.99	3.15	
	S	0.38	0.44	1.58	2.70	2.60	

Mean of three replicates are shown. Data presented are based on 105 °C dry weight basis. *P* value shows the results of one-way ANOVA testing whether there are any significant differences among four locations of the poultry litter piles.

[a] T: top; M: middle; B: bottom; S: surface.

[b] Org. N: organic N.

[c] NO_x^--N: (NO_3^- + NO_2^-)-N.

Table 4
Changes in water content, bulk density, pH, and electrical conductivity (EC) of the poultry litter at four locations (top, middle, bottom, and surface) of the forced-aeration piles during composting

Parameters	Pile locations [a]	Composting time (days)					*P* value
		0	35	91	133	168	
Bulk density (kg m^{-3})	T	251	330	419	544	540	0.065
	M	246	339	450	587	563	
	B	250	339	453	591	537	
	S	250	348	425	524	556	
pH	T	8.25	7.44	7.29	7.34	7.01	0.767
	M	8.18	7.65	6.97	7.76	7.10	
	B	8.33	7.86	6.86	7.34	7.08	
	S	8.27	7.75	7.25	7.56	7.08	
EC (dS m^{-1})	T	5.77	3.69	6.06	3.85	3.31	0.417
	M	5.65	4.17	5.59	3.61	4.10	
	B	5.32	5.36	5.48	3.74	4.34	
	S	5.39	3.80	5.08	3.71	4.11	

Mean of three replicates from each location are shown. Data presented are based on 105 °C dry weight basis. *P* value shows the results of one-way ANOVA testing whether there are any significant differences among four locations of the poultry litter piles.

[a] T: top; M: middle; B: bottom; S: surface.

Table 5
Changes in chemical properties of the poultry litter at four locations (top, middle, bottom, and surface) of the forced-aeration piles during composting

Chemical properties	Pile locations [a]	Composting time (days)					*P* value
		0	35	91	133	168	
OM (g kg^{-1}) [b]	T	851	826	810	772	783	0.730
	M	842	824	818	771	781	
	B	848	800	784	794	738	
	S	849	822	792	798	769	
Total C (g kg^{-1})	T	493	479	470	448	452	0.760
	M	488	478	474	447	453	
	B	492	464	455	460	428	
	S	492	471	464	464	446	
Ext. C (g kg^{-1}) [c]	T	24.01	55.90	39.50	11.73	16.48	0.737
	M	24.21	55.62	37.62	13.91	17.63	
	B	22.88	44.33	19.55	5.92	835	
	S	24.69	45.76	29.97	9.20	12.47	
C/N ratio	T	15:1	28:1	27:1	21:1	28:1	0.971
	M	15:1	24:1	27:1	24:1	38:1	
	B	14:1	24:1	25:1	25:1	32:1	
	S	14:1	29:1	21:1	24:1	31:1	
Total P (g kg^{-1})	T	13.86	14.22	12.52	15.73	15.57	0.199
	M	13.70	16.12	12.68	18.94	15.30	
	B	13.01	14.78	13.37	15.97	15.51	
	S	13.80	14.34	14.06	14.20	15.12	
Total K (g kg^{-1})	T	15.39	15.25	11.48	17.63	17.27	0.737
	M	15.49	15.56	13.94	16.72	15.96	
	B	15.33	17.18	15.12	16.74	19.78	
	S	14.91	14.13	20.52	15.58	17.18	

Mean of three replicates from each location are shown. Data presented are based on 105 °C dry weight basis. *P* value shows the results of one-way ANOVA testing whether there are any significant differences among four locations of the poultry litter piles.

[a] T: top; M: middle; B: bottom; S: surface.

[b] OM: organic matter.

[c] Ext. C: water-extractable C.

steady value of between 520 and 560 kg m^{-3} towards the end of composting. The initial pH of the poultry litter ranged between 8.18 and 8.33 in all four locations of the forced-aeration piles. By the end of the composting process, the pH fell to nearly neutral values (~ 7.0), which is an indication of stabilized organic matter [35]. During composting total P, K, Cu, and Zn increased (Tables 5 and 7). These increases were probably due to losses of organic C, H, N, and O from the forced-aeration piles as CO_2 and H_2O during composting, leaving Cu and Zn behind and consequently giving a relative increase in concentrations of these elements. Increases in these elements corresponded with decreases in OM, C, and N (Tables 3 and 5).

The changes in total N concentration of the poultry litter piles were very similar to that of the organic N (Table 3). This result relates to the facts that the inorganic fractions (NH_4^+-N and NO_x^--N) were low, and that organic N was the major nitrogenous constituent in both feedstocks. After the slight increase in organic N by day 21, the organic N gradually decreased (Table 3). The NH_4^+-N concentration decreased dramatically during composting. The decline in NH_4^+-N concentration was from 11 to 3.8 g kg^{-1} (a decrease of 7.2 g kg^{-1} NH_4^+-N). The dramatic decline in NH_4^+-N concentrations of the spent pig litter-sludge and poultry litter did not, however, correspond to a rapid increase in NO_x^--N, which indicated that some of the NH_4^+-N in these piles had been lost through NH_3 volatilization and/or microbial denitrification. The increase in NO_x^--N concentration in the poultry litter during composting was only 2.6 g kg^{-1}. Some of the NH_4^+ ions in the poultry litter were not converted to NO_3^-/NO_2^- but were lost through NH_3 volatilization as the pH in the poultry litter was > 7.0 (Table 4), giving conditions that favoured NH_3 volatilization. On the other hand, some of the NH_4^+ that was converted to NO_3^-/NO_2^- ions was also lost through microbial denitrification as the population of denitrifying bacteria was high during the early stage of composting (Table 2).

To determine the actual loss in the poultry litter piles, mass and balances of N, OM, and C were calcu-

Table 6
Mass and balances of N, OM, and total C during composting of poultry litter

Composting time	Mass and balance (kg)		
	N	OM	C
Day 0	31	779	452
Final	13	707	409
Balance	−18	−73	−42

The balances of N, OM, and C were calculated by subtracting the final from the initial mass. Data are based on 105 °C dry weight basis. OM: organic matter.

lated (Table 6). About 42 kg of C was converted to CO_2. The total N in the compost mass (N concentration × dry mass of the pile) dropped from 31 to 13 kg during the entire period of composting (Table 6). This loss was comparable to losses reported in animal manure (21–71%) [36,37]. In this experiment, losses of N could be attributed largely to NH_3 volatilization. It has been noted that the properties of the initial material, in particular the C/N ratio, and the composting conditions such as aeration, moisture content, and temperature are affected by the degree of N loss [2,38]. The initial C/N ratio in the present study was very low ($>20:1$) (Table 5). This narrow C/N ratio could have contributed to losses of N in the poultry litter via NH_3 volatilization. As composting progressed, the C/N ratio increased (Table 5). The increase in C/N values during composting could be due to vigorous NH_3 volatilization [39], which normally occurs during composting of animal manure [2,28].

Although total Cu and Zn increased during composting, most of their components are unavailable (Table 7). Only about 18.3 and 23.8% of the total Cu and Zn, respectively, are water-extractable at the beginning of composting. As composting progressed, the water-extractable Cu and Zn decreased continuously. At the termination of the composting trial, 5.1% of the total Cu and 2.7% of the total Zn are water-extractable (Table 7), which is three (for Cu) and nine (for Zn) times lower than the initial values. The decline in water-extractable Cu and Zn concentrations during composting could be attributed to the formation of complexes of these metals with chelating organic matter [40], thus making them not water-extractable and biologically unavailable.

3.4. Composting time and properties of the composted poultry litter

The evaluation of composts has focused on their maturity as an index to determine the completion of the composting process as well as the mineralization rate [17–19]. In the present investigation, the poultry litter began to stabilize by day 128 (4 months) as the pile temperature reached ambient level (Fig. 1) using the

Table 7
Changes in heavy metal contents of the poultry litter at four locations (top, middle, bottom, and surface) of the forced-aeration piles during composting

Heavy metal contents	Pile locations [a]	Composting time (days)					P value
		0	35	91	133	168	
Total Cu (mg kg^{-1})	T	92.59	117.42	118.75	119.79	138.96	0.194
	M	78.89	74.13	117.34	110.20	109.35	
	B	92.59	87.38	128.67	104.96	150.87	
	S	85.93	86.36	110.83	119.02	132.45	
Ext. Cu [b] (mg kg^{-1})	T	15.81	15.19	14.43	8.25	7.94	0.808
	M	16.14	12.11	10.28	5.06	6.92	
	B	15.49	15.63	12.91	6.14	5.98	
	S	16.58	11.72	8.08	4.09	6.20	
Total Zn (mg kg^{-1})	T	268.70	346.52	661.92	642.08	642.08	0.996
	M	233.33	303.54	638.57	611.19	611.19	
	B	151.75	341.27	683.04	678.57	678.57	
	S	198.48	431.82	697.08	651.96	651.96	
Ext. Zn [c] (mg kg^{-1})	T	51.68	53.91	35.07	22.24	22.24	0.368
	M	49.00	39.80	23.28	21.28	21.28	
	B	52.20	38.55	18.06	10.09	10.09	
	S	50.01	36.94	24.83	15.89	15.89	

Mean of three replicates from each location are shown. Data presented are based on 105 °C dry weight basis. *P* value shows the results of one-way ANOVA testing whether there are any significant differences among the four locations of the poultry litter piles.

[a] T: top; M: middle; B: bottom; S: surface.

[b] Ext. Cu: water extractable Cu.

[c] Ext. Zn: water-extractable Zn.

forced-aeration system. The available N released from the composted manure was considerably less than the fresh manure (day 0) (Table 3). The decline in water-extractable C, NH_4^+-N, Cu, and Zn to low levels provided an indication of relative compost maturity. Collectively, the physical, chemical, and microbial properties of the poultry litter provided substantial evidence that the poultry litter compost could be utilized as a soil amendment after 128 days of composting using the forced-aeration method.

The time to reach stability varies between 15 to 180 days depending on the nature of organic material being composted (i.e. organic and nutrient contents, C/N ratio, self-heating capability), pile size, frequency of aeration, moisture content, and composting method [5,9,41]. In-vessel composting usually takes shorter time (15–21 days) than windrow composting (45–150 days) [9,27,29]. In windrows with manual turning, it takes more than 60–80 days (well-turned windrows) to 120–150 days (infrequently turned windrows) to convert manure into stabilized compost [2,5]. Composting time is also affected by the rate of decomposition of C compounds from different organic materials [2,9]. For example, straw decomposes and releases its C to the microorganisms more easily than woody materials. This occurs because the C compounds in woody materials are largely bound by lignin (organic compounds which are highly resistant to biological breakdown) [37]. Conversely, the C in simple sugars such as that found in fruit wastes is more quickly consumed than the cellulose C in straw [9]. In the present study, the poultry litter contained considerable amount of wood shavings, which is difficult to decompose; thus, the rate of composting was slower compared to other manure composted using the forced-aeration system [42–44], which took 60–77 days to stabilize.

Nitrogen loss was a major problem during composting of poultry litter, even when the piles were not turned under the forced-aeration system. About 18 kg N was lost during composting. This loss was more than half (58%) of the initial N. Such a finding demonstrates that composting reduced the value of the poultry litter as N fertilizer. However, the composted poultry litter contained a more humified (stabilized) OM compared with the uncomposted (raw) poultry litter, which could enhance its value as a soil conditioner. One method that can be used to conserve nutrients (particularly N) during poultry litter composting is the addition of bulking agents such as peat moss, rice hull, or yard trimmings. Bulking agents have been used in the past to conserve N as they usually possess high water and cation absorption capabilities [45]. For instance, sphagnum peat moss can absorb NH_3 up to 2.5% of its dry weight [45]. Morisaki et al. [39] reported that NH_3 binds tightly with the components of the bulking agent, and therefore N loss is reduced during composting. The addition of bulking agents to the poultry litter may also help increase the low initial C/N ratio (14:1–15:1) of the poultry litter to an acceptable C/N ratio (25:1–30:1) [9], thus improving the efficiency of composting and the quality of the composted product.

Table 8 shows the characteristics of the composted poultry litter and other animal manure composts. The chemical constituents of the composted poultry litter were comparable to other animal manure. The pH in these manure composts ranged between 5.60 and 8.50 and EC between 2.40 and 3.97 dS m^{-1} (Table 8). For the improvement of agricultural soils, compost of $pH < 7.2$ is required [9], whereas for EC, the acceptable level for compost is > 4.0 dS m^{-1} [37]. The pH (7.07) and EC (3.93 dS m^{-1}) values in the poultry litter compost satisfied these criteria. For total Cu and Zn concentrations, the acceptable concentrations for composts were < 1500 and < 1800 mg kg^{-1}, respectively [37]. These levels were far too high compared to that found in the composted poultry litter and other animal manures (Table 8). Tiquia [40] used the seed germination technique to test the phytotoxicity of spent pig litter compost using different vegetable seeds in Hong Kong. In her study, the phytotoxicity in the litter disappeared (germination index = $> 80\%$), when the water-extractable metal concentrations were ≤ 15 mg kg^{-1} (for water-extractable Cu) and ≤ 20 mg kg^{-1} (for water-extractable Zn). These concentrations were much lower compared to the concentrations (water-extractable Cu = 6.8 mg kg^{-1}; water-extractable Zn = 17.5 mg kg^{-1}) found in the composted poultry litter (Table 7).

Composts made from different manures varied in nutrient contents (Table 8). For instance, horse manure had the lowest P concentration (3.88 g kg^{-1}), whereas the poultry litter in this study had the highest (15.38 g kg^{-1}). The spent pig litter co-composted with sludge had the highest N concentrations (34.4 g kg^{-1}), whereas the dairy manure compost had the lowest (8.7 g kg^{-1}) (Table 8). Interestingly, the poultry litter compost in this study had the highest concentration of $(NO_3^- + NO_2^-)$-N among all manure composts shown in Table 8. This could be attributed to the fact that the composting trial in the present study lasted much longer (168 days) than the other manures (21–120 days). It has been reported that manures that have been composted three to four months tend to have higher concentrations of $(NO_3^- + NO_2^-)$-N [9].

3.5. Applications

The addition of stabilized manure to soil can affect soil fertility by modifying the physical, chemical, and biological properties of the soil [46]. The physical changes include modifications of soil's bulk density, structure, strength, and water relations. The chemical changes include the store of organic plant nutrients, the soil's ion exchange capacity, chelating activity, and buffering ability. In addition, composted poultry ma-

Table 8
Properties of composted poultry litter and other animal manure composts

Compost properties	Poultry litter	Unamended poultry litter	Poultry litter + SPF	Dairy manure	Dairy manure + peat	Horse manure + yard trimmings	Horse manure + sludge	Spent pig litter	Spent pig litter + sludge	Hoop manure	Sheep manure + peat
pH	7.07	8.50	7.50	7.80	8.35	7.00	6.95	5.60	6.70	ND	7.40
EC (dS m^{-1})	3.97	ND	ND	3.60	ND	3.40	3.30	2.40	ND	ND	ND
Total C (g kg^{-1})	445	315	345	ND	400	ND	ND	500	476	316	313
Total N (g kg^{-1})	13.65	51.14	11.90	8.7	20.9	12.1	11.7	27.4	34.4	17.6	22.7
Org. N (g kg^{-1})	9.82	ND	ND	ND	ND	ND	ND	ND	32.7	ND	ND
NH_4^+-N (g kg^{-1})	3.83	ND	ND	0.09	0.74	ND	ND	0.20	0.46	4.19	2.70
NO_x^--N (g kg^{-1})	2.79	ND	ND	0.18	0.05	ND	ND	1.29	1.3	0.17	0.25
C/N ratio	32:1	6:1	31:1	10:1	19:1	ND	ND	19:1	15:1	18:1	14:1
Total P (g kg^{-1})	15.38	ND	ND	5.32	10.80	3.88	7.04	17.70	ND	10.84	5.90
Total K (g kg^{-1})	17.55	ND	ND	10.80	34.0	12.62	6.81	16.5	ND	21.96	22.80
Total Cu (mg kg^{-1})	133	ND	ND	ND	53	18	145	585	ND	ND	23.4
Ext. Cu (mg kg^{-1})	6.8	ND	ND	ND	ND	ND	ND	2.4	ND	ND	ND
Total Zn (mg kg^{-1})	645.95	ND	ND	ND	210	100	200	638	ND	ND	440
Ext. Zn (mg kg^{-1})	17.4	ND	ND	ND	ND	ND	ND	10.9	ND	ND	ND
Source of reference	Present study	Elwell et al. [29]	Ekinci [47]	Eghball et al. (1997)	Mathur et al. [14]	Warman and Termeer [48]	Warman and Termeer [48]	Tiquia and Tam [19]	Tam and Tiquia [43]	Tiquia et al. [2]	Mathur et al. [14]

ND: not determined; Ext. Cu: water-extractable Cu; Ext. Zn: water-extractable Zn; SPF: short paper fibre.

nure can increase the nutritional base for soil microorganisms. Incorporated manure composts also become part of the soil humus and thus exert their influence on a long-term basis. This type of input is particularly important in Hong Kong where the soils are very poor in terms of OM content (personal communication with the officers of Agriculture, Fisheries and Conservation Department, Hong Kong). Many countries in the Asian region, including Mainland China, also need this type of input as farmers have relied on inorganic fertilizers for many years, without paying attention to soil structure.

4. Conclusions

The maturation of poultry litter compost was accompanied by a decline of compost temperatures to ambient level, relative increases in total Cu, Zn, P, K, and NO_x^--N and decreases in C, OM, and extractable fractions (i.e. water-extractable C, NH_4^+-N, and heavy metal contents) of the poultry litter. It took 128 days to convert an immature poultry litter to mature compost. During composting, significant losses in N was observed which could decrease its value as N fertilizer. However, the composted poultry litter contained a more stabilized OM. The compost made from poultry litter contained nutrients essential for plant growth, including trace elements.

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