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Carbon, nutrient, and mass loss during composting

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Abstract

Hoop manure (a mixture of partially decomposed pig manure and cornstalks from swine fed in hoop structures) was the subject of a nitrogen mass balance during the feeding period. The manure was then composted in windrows to investigate C, nutrient, and mass loss during the composting process. Feeding cycle mass balance results indicated that N losses from the bedded pack ranged from 24 to 36%. Composting treatments included construction with and without a manure spreader and subsequent management with and without turning. Significantly greater losses of mass, C, K, and Na were found in the turned windrow treatment. However, composting in turned windrows proceeded at a much faster rate, with temperatures dropping out of the thermophilic range within 21 days. Composting without turning was less rapid, with temperatures remaining in the thermophilic range to the end of the 42-day trial. Mass reduction and C loss was significantly higher in the turned windrows than in the unturned windrows. Nitrogen loss was between 37 and 60% of the initial N, with no significant effect from turning. It appears that the low initial C:N ratio (between 9:1 and 12:1) was the most critical factor affecting the N loss in this composting process. Phosphorus, K, and Na losses were also high during composting, which could be due to runoff and leaching from the hoop manure. These elements may be significant contributors to surface and groundwater pollution through runoff and leaching. Additional research is planned to understand the extent of losses through volatilization, runoff, and leaching during composting.

Introduction

Composting is increasingly recognized as a viable treatment method for animal manure. One advantage is the possible recycling of its end-product (composts) in agriculture or horticulture (Lopez-Real and Baptista, 1996). Because of their high concentration in organic matter, composts have been used for years as soil amendments. While composting has some advantages such as killing pathogens and weed seeds, and improves the handling characteristics of manure by reducing its volume and weight (Epstein, 1997), composting also can have some disadvantages. The disadvantages include nutrient during composting (Martins and Dewes, 1992; Rao Bhamidimarri and Pandey, 1996; Eghball et al., 1997; Tam and Tiquia, 1999; Tiquia and Tam, 2000a), the cost of land (Epstein, 1997), equipment and labor requirements (Lynch and Cherry, 1996), and possible odors associated with composting (Walker, 1993). About 20–77% of the initial N of the manure could be lost during composting (Martins and Dewes, 1992; Rao Bhamidimarri and Pandey, 1996; Tiquia and Tam 2000a). Volatilization losses of N vary depending on the balance with available carbon (Martins and Dewes, 1992; Rynk et al., 1992) and with oxygenation level (Michel and Reddy, 1998). These gaseous losses can include NH_3, N_2O, N_2, and possibly other NOx compounds (Martins and Dewes, 1992; Czepiel et al., 1996; Körner et al., 1999). Leaching can also be an important factor in N and other nutrient losses from compost, depending on rainfall conditions (Eghball et al., 1997). Eghball et al.

(1997) found 20 to 40% loss of N and 42 to 62% loss of C during composting of beef cattle manure, as well as significant losses of K and Na (>6.5% of total K and Na) in runoff from composting windrows during rainfall.

In Iowa, swine producers have recently shown a great deal of interest in the so-called hoop structures as swine production facilities (Brumm et al., 1997; Honeyman et al., 1999). The pigs in these structures are raised on a bedding material (often cornstalks), and the manure and urine deposits are allowed to decompose *in situ* (Tiquia et al., 2000). The *in situ* composting process that takes place within the bedded pack is similar to the mesophilic composting process described by Golueke (1972). The hoop manure (a mixture of partially decomposed pig manure and cornstalks) is generated over time and then removed from the system after each five-month production cycle (Brumm et al., 1997; Honeyman et al., 1999). Like other animal manure, hoop manure in its fresh or composted form can be re-utilized as a soil fertilizer and/or soil conditioner, to substitute for the often more costly commercial fertilizers used in crop production (Fleming et al., 1998). Since hoop structures are a relatively new livestock housing technology, little is known about the properties of the manure generated from this system, and how its properties change during *in situ* and further composting in windrows. These changes will ultimately affect the quality of the end product and subsequent application of the manure as a soil amendment.

Previous investigations have shown that the decomposition of the manure from deep litter systems is incomplete, and may require further composting in windrows to reach adequate maturity for use in certain applications (Tiquia, 1996). The success of the composting process, however, depends on how well the operating strategies being employed are implemented for both product quality (Tiquia et al., 1998a) and environmental protection (Rynk and Richard, 2000). In this investigation, the hoop manure was composted in windrows under field conditions. Because the windrows are exposed to the external environment, significant mass losses are likely to occur due to losses in water (from evaporation), carbon (through CO_2 evolution) and nutrients (through volatilization, leaching and run-off). These later factors would reduce the potential of the manure as a plant nutrient source, and could create an environmental threat (Richard and Choi, 1999). Quantification of the amount of nutrient loss and mass loss during composting in field conditions is also important in understanding the composting process, and for developing methods of conserving nutrients to reduce potential adverse environmental impacts. In this context, the objectives of this study were to determine the extent of N loss from hoop structures, and to quantify the amount of C, nutrient, and mass loss during composting of pig manure under field conditions.

Materials and methods

Three hoop structures were used for this trial at the Iowa State University Rhodes Research Farm, Rhodes, Iowa. Feeder pigs, at approximately 23 kg each were placed in each hoop structure at a stocking density of 1 m^2 (12 ft^2) per animal. The pigs were placed inside the hoop for a period of five months until they reached market weight (approximately 117 kg live weight) (Table 1). After the pig growing and finishing period, hoop manure samples were collected from a grid of 24 different locations in the hoop manure bedding and were characterized in the laboratory (Table 2). Each of these 24 samples was a composite of five subsamples taken from the full vertical profile of the bedded pack as the manure was being removed from the hoop structure. To estimate the extent of N losses in the hoop structure, the N input (mass N of the initial and added bedding material [cornstalks], feed consumed by pigs, and pigfeeder pigs initially placed in the hoops) and N output (mass N of final bedding material [cornstalk and pig manure] pig mortalities, and marketed pigs) were calculated (Table 1). The N content in pigs was calculated based on the formula described by Ewan (1998), NRC (1998), and NPPC (1999).

The hoop manure was then weighed on portable axle scales and stacked in windrows for further composting and maturation. The composting trial included two methods of windrow construction: piling using a manure spreader (John Deere 450 Hydro-Push) or tractor loader (John Deere 6400 Tractor), and two compost turning treatments: turning once a week or no turning were used. A total of twelve windrows were constructed. Windrows 1, 3, 5, 7, and 9 were turned weekly, whereas the other 6 windrows (windrows 2, 4, 6, 8, and 10) were left unturned during the entire period of composting (Table 3). Each windrow had the following dimensions: 6-m length, 2.5-m width, and 1.5-m height. Samples were collected from the left, middle, and right side of the windrows at 30, 60, and 90-cm depths. These 9 samples (3 sides × 3 depths)

Table 1. Treatments and N input and output in the structures

Treatments/N input and output	Hoop A	Hoop B	Hoop C
	———-Treatments———-		
Number of pigs raised	150	152	149
Bedding usage (kg)	15506	14395	15143
Raising period (months)	5	5	5
Windrows[a]	1–4	5–8	9–12
	———-N input and output———-		
N input (kg)			
Mass N of initial bedding material (cornstalk)	92	85	90
Mass N of feeds consumed by pigs	1334	1306	1313
Mass N of pigs at start	58	51	54
Total N input	1484	1442	1457
N output (kg)			
Mass N of final bedding material (hoop manure)	591	574	440
Mass N of pigs at finish	374	367	364
Total N output	965	941	804
N balance (kg)	319	305	456
N loss (% of initial)	35	35	45

[a]Hoop manure from windrows 1–4, 5–8, and 9–12 was collected from Hoops A, B, and C, respectively.

Table 2. Properties of the hoop manure (cornstalk+pig manure) before clean out

Properties[a]	Hoop A	Hoop B	Hoop C
Moisture content (%)	72	71	76
pH	7.5	7.9	7.5
Total N (g kg^{-1})	36.0	36.8	36.9
Total P (g kg^{-1})	11.5	12.3	11.4
Total K (g kg^{-1})	25.3	27.2	20.1
Total C (g kg^{-1})	409	423	398
C:N ratio	11:1	11:1	11:1
Total organic matter (g kg^{-1})	434	434	386
Ash content (g kg^{-1})	566	565	614
Available P (g kg^{-1})	23.8	26.0	20.4
Mg (g kg^{-1})	6.6	7.2	22.2
Ca (g kg^{-1})	21.5	26.2	32.9
Na (g kg^{-1})	6.2	7.0	6.2
Fe (mg kg^{-1})	1687	1779	1903
Al (mg kg^{-1})	742	706	801
Mn (mg kg^{-1})	219	226	216
Cu (mg kg^{-1})	62.6	67.1	55.9
Zn (mg kg^{-1})	432	460	364

[a]Mean of 24 composite samples are shown.

Table 3. Chemical properties of the hoop manure at the beginning of composting

Hoop #	Windrow #	Turning treatments	Windrow[a] construction	C:N ratio	Tot-C	Tot-N	NH_4^+	NO_3^-	Tot-P	Tot-K	Tot-Ca	Tot-Mg	Tot-Na
									$(g\ kg^{-1})^b$				
A	1	Turned	MS	11:1	374	35.6	18.3	0.36	10.8	25.7	18.4	6.12	7.19
A	2	Unturned	MS	12:1	426	37.0	17.8	0.36	11.3	26.0	18.9	6.18	6.18
A	3	Turned	TL	12:1	429	38.0	15.3	0.37	10.4	24.0	24.5	6.69	5.20
A	4	Unturned	TL	12:1	411	33.8	11.3	0.33	13.7	24.8	24.3	7.57	6.25
B	5	Turned	MS	12:1	431	34.5	12.3	0.34	12.5	29.7	23.2	7.51	7.51
B	6	Unturned	MS	12:1	442	35.5	10.5	0.35	12.3	25.7	33.1	7.32	6.62
B	7	Turned	TL	13:1	418	33.4	12.9	0.33	11.7	22.5	23.5	6.62	6.29
B	8	Unturned	TL	9:1	401	43.8	11.8	0.34	12.8	30.7	24.9	7.41	7.74
C	9	Turned	MS	9:1	334	36.9	20.2	0.37	10.8	24.8	27.6	6.72	5.60
C	10	Unturned	MS	11:1	396	36.0	18.4	0.37	10.5	25.5	27.7	6.37	6.37
C	11	Turned	TL	11:1	425	37.3	12.9	0.38	14.0	30.0	32.7	7.22	6.84
C	12	Unturned	TL	12:1	438	37.6	12.3	0.36	10.4	25.2	43.7	7.22	5.78

[a]MS=manure spreader; TL=tractor loader.
[b]Mean of three composite samples are shown. Data based on 75 °C dry weight. Tot-C=total carbon; Tot-N=Total nitrogen; NH_4^+=ammonium nitrogen; NO_3^-=nitrate nitrogen; tot-P=total phosphorus; tot-K=total potassium; tot-Ca=total calcium; tot-Mg=total magnesium; tot-Na=total sodium.

depths were combined and mixed to generate a single composite. The resulting three composite samples for each windrow (approximately 1 kg each) were collected on day 0 and then weekly until the termination of the composting trial (day 42). Air and windrow temperatures were monitored using a temperature probe during the entire composting process. The average windrow temperature was determined by taking three measurements at the south, center, and north side of the windrows at 30, 60, and 90 cm depths. All in all, 9 temperature readings were recorded for each windrow. For the turned windrows, temperatures and samples were taken after turning. Windrows were not wetted during composting.

The hoop manure samples collected were characterized for water content (75 °C for 48 h); pH (1:5 hoop manure:water extract) using a pH electrode; ash and total organic matter contents (loss on ignition; 550 °C for 5 h) (Allison, 1965); and concentrations of total P, K, S, Mg, Ca, Na, Fe, Al, Mn, Cu, Zn, available P, and NO_3^--N (AOAC, 1990). Total C and N were measured on samples that were acidified to pH 1.5 to minimize NH_3 volatilization, then air dried and ground, and finally combusted using a Carlo Erba CN analyzer. The weight of the hoop manure from each windrow was measured at the beginning (day 0) and end (day 42) of composting to determine the percentage reduction in mass. Masses of nutrients (N, P, K, Mg, Ca, and Na) and C in the windrows were determined (nutrient or C concentration × dry weight of the windrow), and the losses were computed as follows:

$$\text{Mass loss}_{\text{nutrient or C}}(\%\text{of initial}) = \frac{\text{initial mass}_{\text{nutrient or C}} - \text{final mass}_{\text{nutrient or C}}}{\text{initial mass}_{\text{nutrient or C}}} \times 100$$

A t-test (Zar, 1999) was used to compare differences between windrow turning (turned versus unturned) and windrow construction (manure spreader versus tractor loader) treatments. Statistical analysis was computed using SigmaStat 1.0 for Windows statistical package.

Results and discussion

N losses and characteristics of the manure from hoop structures

An issue of considerable importance in manure utilization is the extent of nutrient losses during storage and treatment. Pigs can excrete up to 70% of the N fed to them (Halstead, 1983), so that for every 1.0 kg of N consumed, 0.7 kg of N is lost as manure. Moreover, part of this 0.7 kg of manure N is usually lost before the manure can even be collected. In hoop structures, manure is stored within the bedded-pack in the hoop throughout the pig raising period, and as with other unsealed manure storage, there is potential for leaching and volatilization losses (USDA, 1992). The results of N input and output calculations in the hoop structure revealed that as much as 35 to 45% of the initial N in the hoop structures was lost during the 5-month feeding period (Table 1). Because the roof excludes most precipitation and bedding is used to soak up free moisture, N losses in the deep-bedded hoop structures could be attributed mainly to emission of gases such as NH_3, NO_x, and N_2 (Thelosen et al., 1993; Groenestein and Van Faassen, 1996). Dewes (1996) reported that N loss starts immediately after the animal waste is excreted. The most important factors that influence the emission of NH_3 from the hoop structures are pH value and C:N ratio. In this study, the pH value in the hoop bedding material was > 7.5, and the C:N ratio was 11:1 (Table 2). The N losses reported in this study were higher than those reported by Dewes (1996). In his study, cumulative ammonia emissions over 14 days were between 0.8 to 23% of the initial N. Some of the N loss could also be attributed to microbial denitrification to NO, N_2O, and N_2 (Thelosen et al., 1993; Groenestein and Van Faassen, 1996). Tam et al. (1996) pointed out that in deep litter systems, a large number of denitrifying bacteria developed due to high water content of the manure. The presence of these bacteria in the manure-bedding material favored in situ denitrification, which reduces nitrates to gaseous NO, N_2O, and N_2, thus creating another pathway for N loss.

Despite of the N loss, the hoop manure had abundant organic matter and nutrient contents after five months of *in situ* composting in the hoop structure (Table 2). These initial values were comparable with the ranges reported on other animal manures (Elwell et al., 1996; Pare et al., 1998; Tiquia et al., 1998b; Vuorinen and Saharinen, 1999). However, the C:N ratios were low (between 11:1 and 21:1) (Table 2). In other deep litter systems like the 'pig-on-litter' sawdust bedded system in Hong Kong, the manure is decomposed rapidly within the bedding material. This rapid biodegradation results in the disappearance of organic C, and accumulation of nutrients and microbial biomass (Tiquia and Tam 2000b), and thus a decrease in the C:N ratio was observed by the end of the pig raising period in the present study. The accumulation of nutrients was related to the continuous deposition of fresh pig manure in the cornstalk bedding throughout the pig raising period. Because of this continuous accumulation of fresh pig manure in the cornstalk bedding, the decomposition of pig manure is incomplete, and the freshly removed hoop manure bedded-pack could be considered an immature compost. Tiquia (2000) reported that the continuous deposition of fresh pig manure in the pig-on-litter system led to severe retardation of plant growth and development if the litter was used without composting. For hoop structure swine producers, composting can also provide convenient low-cost storage during periods when cropland is not available for land application, while decreasing the mass and volume of manure to reduce transportation and application costs. To examine the impact of composting on carbon and nutrient losses, the hoop manure was removed from the hoop structures and stacked in windrows for further composting and maturation. The chemical properties of the hoop manure immediately after piling (day 0) are reported in Table 3.

Temperature profile and chemical changes during windrow composting

The pattern of temperature change during composting was significantly affected (P=<0.0001) by windrow turning and not by the method of windrow construction (P=0.93) (Figure 1 and Table 4). The unturned windrows maintained thermophilic temperatures (> 60 °C) during the first 35 days of the composting trial (Figure 1). Temperatures in these windows did not approach ambient level during the 42 day trial, indicating the manure needs additional time to complete the composting process. The turned windrows peaked at 67 °C by day 7 and then dropped gradually to ambient levels at the termination of the composting trial (day 42). These results suggest that composting with turning proceeded at a much faster rate than composting without turning. The turned windrows also had lower NH_4^+-N (P=<0.0001) and NO_3^--N (P=0.0015) concentrations than the unturned windrows by the end of composting, indicating a much more dynamic N transformation during composting. The lower NO_3^--N concentration in the turned windrows at the end of the trial (Table 5) may be due to higher NH_3 loss in these piles, leaving a smaller amount of NH_4^+-N to nitrify compared to the unturned windrows.

Nutrient, C, and mass loss during windrow composting

To examine actual losses in C and nutrient quantities, mass balances of these chemical components of the hoop manure were calculated as previously described, and are reported in Table 6. Mass loss in the hoop manure windrows was between 27 and 57%. In the

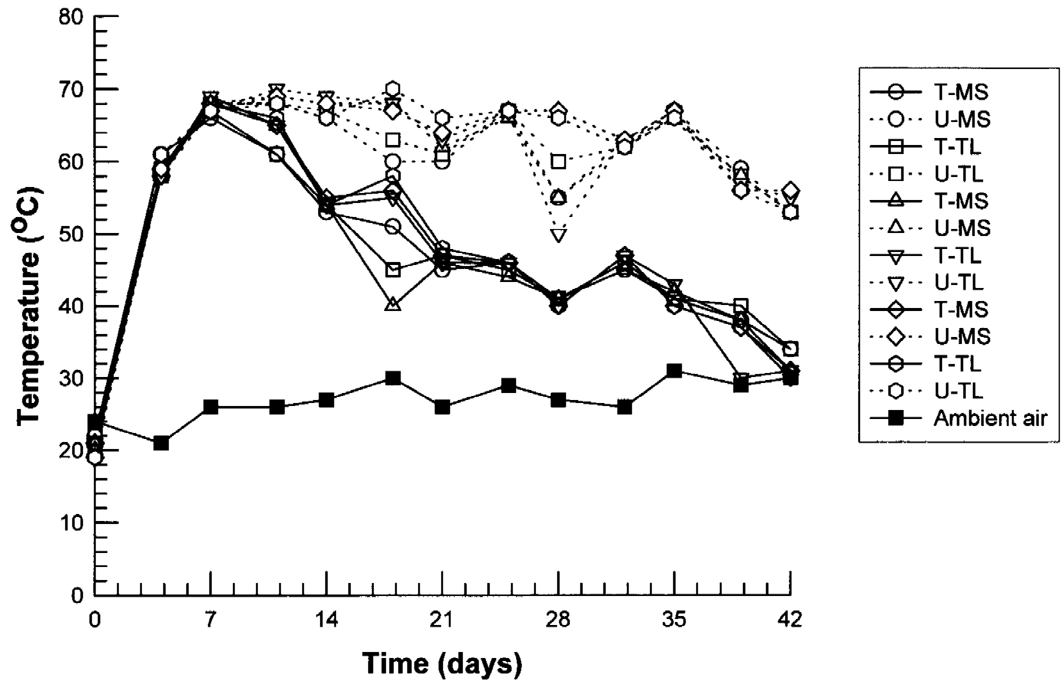

Figure 1. Changes in air and windrow temperatures during composting. (T-MS = turned-manure spreader; U-MS = unturned-manure spreader; T-TL = turned-tractor loader; U-TL = unturned-tractor loader).

Table 4. Results of *t*-test showing the effect of windrow turning (turned versus unturned) and windrow construction (manure spreader versus tractor loader) on chemical properties and some important composting parameters of the hoop manure

Parameters[a]	Effect of windrow turning				Effect of windrow construction[b]			
	Turned (Mean ±SEM)	Unturned (Mean ±SEM)	P value	Significance	MS (Mean ±SEM)	TL (Mean ±SEM)	P value	Significance
Temperature (°C)	46.5±1.43	57.7±1.52	<0.0001	***	53.1±1.60	53.2±1.63	0.930	NS
C:N ratio	17.8±0.87	18.3±0.72	0.670	NS	17.2±0.87	19.0±0.45	0.090	NS
C (g kg^{-1})	302.8±19.25	329.5±3.40	0.200	NS	310±15.5	318±18.00	0.750	NS
N (g kg^{-1})	16.8±0.58	18.3±0.74	0.140	NS	18.3±0.63	16.8±0.72	0.160	NS
NH_4^+-N (g kg^{-1})	1.42±0.43	6.95±0.71	<0.0001	***	4.15±1.70	4.22±0.92	0.970	NS
NO_3^--N (g kg^{-1})	0.17±0.007	0.23±0.011	0.0015	**	0.21±0.02	0.20±0.02	0.620	NS
P (g kg^{-1})	11.2±0.85	10.5±0.60	0.510	NS	11.1±0.63	10.6±0.85	0.700	NS
K (g kg^{-1})	20.7±1.04	23.3±1.06	0.110	NS	22.9±0.94	21.1±1.29	0.280	NS
Ca (g kg^{-1})	47.5±2.60	45.8±6.62	0.820	NS	43.3±3.93	50.0±5.57	0.350	NS
Mg (g kg^{-1})	8.61±0.46	8.10±0.40	0.420	NS	8.02±0.41	8.69±0.44	0.290	NS
Na (g kg^{-1})	4.55±0.23	5.22±0.24	0.070	NS	5.16±0.21	4.61±0.28	0.150	NS
Mass loss (%)	52.0±1.53	37.0±2.38	0.0003	***	45.2±3.66	43.8±4.12	0.810	NS
C loss (%)	64.0±1.21	50.2±1.90	0.0001	***	57.2±3.19	57.0±3.75	0.970	NS
N loss (%)	49.8±2.96	53.8±3.00	0.370	NS	52.0±2.99	51.7±3.23	0.940	NS
P loss (%)	32.0±2.96	29.7±2.78	0.580	NS	33.5±1.73	28.2±3.34	0.190	NS
K loss (%)	41.0±2.54	29.7±2.91	0.014	**	37.7±1.78	33.0±4.73	0.380	NS
Ca loss (%)	0.00±0.00	0.33±0.33	0.340	NS	0.33±0.33	0.00±0.00	0.340	NS
Mg loss (%)	9.50±3.60	19.00±4.35	0.120	NS	16.0±3.79	12.5±5.04	0.590	NS
Na loss (%)	46.8±2.81	36.5±1.81	0.012	*	43.7±2.22	39.7±3.93	0.400	NS

[a]Mean and standard error of mean (SEM) are shown.
[b]NS= not significant at $P \leq 0.05$; MS= manure spreader; TL= tractor loader.

Table 5. Chemical properties of the hoop manure after six weeks of composting

Hoop #	Windrow #	Turning treatments	Windrow[a] construction	C:N ratio	Tot-C	Tot-N	NH_4^+	NO_3^-	Tot-P	Tot-K	Tot-Ca	Tot-Mg	Tot-Na
					(g kg^{-1})[b]								
A	1	Turned	MS	14:1	243	17.2	0.85	0.21	13.4	21.9	37.0	9.34	5.10
A	2	Unturned	MS	16:1	326	20.8	5.80	0.22	11.9	27.2	28.0	8.48	6.03
A	3	Turned	TL	18:1	263	14.6	2.16	0.17	10.3	15.6	46.0	10.13	3.49
A	4	Unturned	TL	18:1	336	18.4	6.30	0.25	11.6	24.3	41.1	8.31	5.29
B	5	Turned	MS	20:1	347	17.7	0.31	0.16	11.1	22.2	45.0	7.81	4.69
B	6	Unturned	MS	17:1	321	19.3	10.27	0.25	11.0	23.5	54.0	8.02	5.51
B	7	Turned	TL	19:1	364	18.7	1.48	0.16	13.9	22.0	50.0	9.18	4.59
B	8	Unturned	TL	21:1	320	15.3	5.46	0.18	8.3	20.0	34.0	8.20	4.28
C	9	Turned	MS	17:1	289	16.6	0.64	0.16	9.9	21.6	51.7	8.16	4.80
C	10	Unturned	MS	19:1	334	18.0	7.04	0.24	9.0	20.8	44.2	6.31	4.85
C	11	Turned	TL	19:1	311	16.0	3.10	0.17	8.6	20.6	55.3	7.06	4.65
C	12	Unturned	TL	19:1	340	18.0	6.81	0.24	11.1	23.8	73.5	9.25	5.35

[a]MS= manure spreader; TL= tractor loader.
[b]Mean of three composite are shown. Data based on 75 °C dry weight. Tot-C= total carbon; Tot-N= Total nitrogen; NH_4^+= ammonium nitrogen; NO_3^-= nitrate nitrogen; tot-P= total phosphorus; tot-K= total potassium; tot-Ca= total calcium; tot-Mg= total magnesium; tot-Na= total sodium.

turned windrows, mass loss was between 47 and 57%, while in the unturned windrows it was between 27 and 43%. The C loss in the turned windrows was significantly higher (50 to 63%) (P=0.0001) than in the unturned windrows (30–54%) (Table 6), indicating a much higher biodegradation rate. This C loss occurred through bio-oxidation of C to CO_2 during composting. The C loss in this investigation (where cornstalks were the carbon amendment) was higher that losses reported from other manure composting studies with a wood-based carbon amendment (Flynn and Wood, 1996; Tiquia et al., 1998b). N loss was high, ranging between 37 and 60% of the initial N. It appears that the low initial C:N ratio (between 9:1 and 12:1) (Table 3) was the most critical factor affecting the N loss in this composting process. The C:N ratio of the initial material has been noted to affect the degree of N loss through ammonia volatilization (Bishop and Godfrey, 1983). Phosphorus and K losses were 23 to 39% and 20 to 52% of the initial P and K, respectively, while Na loss was between 32–53% of the initial Na (Table 6). Substantial losses of P, K, and Na could be attributed to run-off and leaching from the hoop manure since, unlike N, the available forms of these elements are not volatile. Loss in terms of mg was between 8 and 24%. Interestingly enough, no Ca loss was recorded during composting with the exception of windrow 2, with a minimal loss of 2% of the initial Ca (Table 6). A gain in Ca ranging from 4 to 50% was found in the 11 windrows (Table 6). This result could not be explained at the moment. Calcium loss will monitored closely in our future experimental runs.

T-test results showed no significant difference between two windrow construction methods (manure spreader and tractor loader) used in this study (Table 4). Irrespective of the differences in pile construction method, the chemical properties of the hoop manure yielded similar values by the end of six weeks of composting (Table 5). Losses in terms of the compost mass, C, and nutrients were also similar in both treatments (Tables 4 and 6). Compost turning is the operating strategy that had the greatest effect on a number of composting variables such as temperature, NH_4^+-N and NO_3^--N, and also on mass, C, and nutrient losses (Table 4). The turned windrows had higher mass, C, K, and Na loss (Table 6) than the unturned windrows. Although the unturned windrows appeared to conserve more nutrients (particularly K and Na) than the turned windrows, some important criteria for a successful composting are not as readily achieved without turning. Our recent work on windrow composting of hoop manure revealed that the turned windrows had higher oxygen levels than the unturned windrows (Tiquia et al., 2000), which has a positive impact on biodegradation kinetics (Suler and Finstein, 1977; Michel and Reddy, 1998; Richard and Walker, 1999). Turning also reduces particle size (Michel et al., 1996), which would also have the effect

Table 6. Mass, C and nutrient losses during windrow composting of hoop manure

Hoop #	Windrow #	Treatments	Mass loss	C loss	N loss	P loss	K loss	Ca loss	Mg loss	Na loss
			(% of initial)[a]							
A	1	T-MS	51	68	59	28	27	(50)	(14)	47
A	2	U-MS	34	48	40	31	31	2	10	36
A	3	T-TL	47	67	52	28	52	(37)	(11)	51
A	4	U-TL	43	54	60	33	22	(34)	13	33
B	5	T-MS	55	63	48	32	43	(49)	20	52
B	6	U-MS	37	54	59	38	37	(13)	24	43
B	7	T-TL	57	63	37	23	37	(37)	11	53
B	8	U-TL	27	42	52	20	20	(67)	(36)	32
C	9	T-MS	53	60	51	39	42	(25)	19	43
C	10	U-MS	41	50	55	33	36	(24)	23	41
C	11	T-TL	49	63	52	42	35	(61)	7	35
C	12	U-TL	40	53	57	23	32	(4)	8	34

[a]T-MS= turned-manure spreader; U-MS= unturned-manure spreader; T-TL= turned-tractor loader; U-TL= unturned-tractor loader. NA= no data available; values in parentheses are gained values

of increasing biodegradation rates (Hammelers, 1993; Tiquia et al., 1997). Compost turning has also been found to be effective in the sanitization process of the manure (Fischer et al., 1998; Tiquia et al., 1998c; Bahman and Lesoing, 2000). During turning, the manure in the outer layer of the windrow, which is usually close to ambient, is transported into the inner part of the pile where temperatures are high (55–70 °C) enough to quickly kill seeds and pathogens in the windrow. While both pathogens and weed seeds can be destroyed under sub-optimal composting conditions (Eghball and Lesoing, 2000), effective sanitation is likely to take many months rather than a few weeks. Where more rapid sanitization or biodegradation is required, turning may be necessary despite the potential for greater K and Na loss.

Nutrient conservation strategies

The addition of bulking agents to the hoop manure such as peat moss, rice hull, or sawdust is one method that can be used to conserve nutrients (particularly N) in the manure during composting. Bulking agents have been used in the past to conserve N as they usually posses high water and cation absorption capabilities (Barrington and Moreno, 1995; Morisaki et al., 1989). For example, sphagnum peat moss can absorb NH3 up to 2.5% of its dry weight (Barrington and Moreno, 1995). Morisaki et al. (1989) reported that NH3 binds tightly with the components bulking agent, and so N losses is reduced during composting. Addition of cornstalks to the hoop manure during windrow may also help increase the low initial C:N ratio (9:1–12:1) of the manure to an acceptable C:N ratio (25:1–30:1) (Golueke, 1972). This addition will then lead to reduce N losses during composting.

An alternative approach to reducing nutrient losses is to reduce the nutrient content of the swine excreta. In a review of balance data for pigs fed common commercially-available feed ingredients, Kornegay and Harper (1997) determined nutrient utilization rates of 30 to 55% for nitrogen and 20 to 50 percent for phosphorus. Thus, the nutrient excretion rate is 45 to 60% of the nitrogen consumed and 50 to 80% of the phosphorus consumed. There are several strategies that can be used to reduce the amount of nitrogen and phosphorus excreted. These strategies include (1) reducing excessive feeding levels of the nutrients (NRC, 1998), (2) using feedstuffs that are more highly digestible and available, formulating to the ideal protein level for the diet (Chung and Baker, 1991), (3) using crystalline amino acid supplementation to reduce overall dietary protein level (Kerr and Easter, 1995), (4) adding phytase to the diet to improve the availability of the dietary phosphorus from grain and oil seed feedstuffs (Jongbloed et al., 1992; Cromwell et al., 1993), and (5) phase and split sex feeding (Honeyman, 1993).

Conclusions

Field trials demonstrated that composting regardless of composting strategies used (composting turning and windrow construction) significantly reduced the nutrient content of hoop manure. Nutrient loss, specifically N, can be a major problem in composting hoop manure, with more than half of the total N content of the hoop manure being lost during composting. The lower initial C:N ratio had a major effect on N loss. The C:N ratio increased from an initial value of 9:1–12:1 to 14:1–21:1 during composting (Tables 3 and 5). Increases in C:N ratio have been reported during composting of sewage sludge (Morisaki et al., 1989) and chicken litter (Tiquia and Tam, 2000a) in which increasing C:N values occurred during composting due to vigorous NH_3 volatilization. Apart from N loss, P, K, and Na loss can also be significant. These elements may be significant contributors to surface and groundwater pollution through runoff and leaching. In order to understand the extent of losses through runoff and leaching, additional studies on nutrient fate and transport will be required.

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References

Allison LE (1965) Organic carbon. In: Black CA, Evans DD, White JL, Ensiminger LE, Clark FE and Dinauer RC (eds) Methods of Soil Analysis, Part 2. Chemical and Microbiological Properties. pp. 1367–1378 Madison, Wisconsin, USA: SSSA

Association of Official Analytical Chemists (AOAC) (1990) Official Methods of Analysis. Volume I. Agricultural Chemicals and Contaminants, Drugs. 15th edition. AOAC Inc., Arlington, Virginia, USA, 684 pp

Barrington SF and Moreno RG (1995) Swine manure nitrogen conservation in storage using sphagnum moss. J Environ Qual 24: 603–607

Bishop PL and Godfrey C (1983) Nitrogen transformations during sludge composting. BioCycle 24: 34–39

Bosi P, Macchioni P and Russo V (1997) Dietary means to reduce phosphorus pollution from finishing heavy pigs. Pigs News Info 18(4): 117N–121N

Brumm MC, Harmon JC, Honeyman MC and Kliebenstein JB (1997) Hoop Structures for Grow-finish Swine. Agricultural Digest. Number 4. Midwest Plan Service. Ames, Iowa, USA, 15 pp

Chung TK and Baker DH (1991) A chemically defined diet for maximal growth of pigs. J Nutr 121: 979–984

Cromwell GL, Stahly TS, Coffey RD, Monegue HJ and Randolph JH (1993) Efficacy of phytase in improving the bioavailability of phosphorus in soybean meal and corn-soybean meal diets for pigs. J Anim Sci 71: 1831–1840

Czepiel P, Douglas E, Harriss R and Call P (1996) Measurements of N_2O from Composted Organic Wastes. Environ Sci Technol 30: 2519–2525

Dewes T (1996) Effect of pH, temperature, amount of litter, and storage diversity on ammonia emission from stable manure. Agric Sci Cambridge 127: 501–509

Eghball B, Power JF, Gilley JE and Doran JW (1997) Nutrient, carbon and mass loss during composting of beef cattle feedlot manure. J Environ Qual 26: 189–193

Eghball B and Lesoing GW (2000) Viability of weed seeds following manure windrow composting. Compost Sci Util 8: 46–53

Elwell DL, Keener HM and Hansen RC (1996) Controlled, high rate composting of mixture of food residuals, yard trimmings and chicken manure. Compost Sci Util 4: 6–15

Epstein E (1997) The Science of Composting. Lancaster, Pennsylvania, USA: Technomic Publishing Company. 487 pp

Ewan RC (1998) Personal communication. Department of Animal Science, Iowa State University, Ames, Iowa, USA

Farrell JB (1993) Fecal pathogen control during composting. In: Hoitink HAJ and Keener HM (eds) Science and Engineering of composting: Design, Environmental, Microbiological and Utilization Aspects, pp 282–300. Worthington, Ohio, USA: Renaissance Publications

Fleming RA, Babcock BA and Wang E (1998) Resource or waste? The economics of swine manure storage and management. Rev Agric Econ 20: 96–113

Fischer JL, Beffa T, Lyon PF and Aragno M (1998) *Aspergillus fumigatus* in windrow composting: effect of turning frequency. Waste Manage Res 16: 320–390

Flynn RP and Wood CW (1996) Temperature and chemical changes during composting of broiler litter. Compost Sci Util 4: 62–70

Golueke CG (1972) Composting: A Study of the Process and Its Principles. Rodale Press, Emmaus, Pennsylvania, USA, 110 pp

Groenestein CM and Van Faassen HG (1996) Volatilization of ammonia, nitrous oxide and nitric oxide in deep-litter systems for fattening pigs. J Agric Eng Res 65: 269–274

Halstead RL (1983) Farm Animal Manures in the Canadian Environment. Publication No. NRCC 18976. National Research Council of Canada. Ottawa, Canada

Hamelers HVM (1993) A theoretical model of composting kinetics. In: Hoitink HAJ and Keener H (eds). Science and Engineering of composting: Design, Environmental, Microbiological and Utilization Aspects, pp. 36–58. Worthington, Ohio, USA: Renaissance Publications

Honeyman MS (1993) Environment-friendly feed formulation for swine. Am J Alter Agric 8(3): 128–132

Honeyman MS, Koenig FW, Harmon JD, Lay DC Jr, Kliebenstein JB, Richard TL and Brumm MC (1999) Managing market pigs in hoop structures. PIH-138. Pork Industry Handbook. Purdue University, West Layfayette, Indiana, USA, 8 pp

Jongbloed AW, Mroz Z and Kemme PA (1992) The effect of supplementary *Aspergillus niger* phytase in diets for pigs on concentration and apparent digestibility of dry matter, total phosphorus, and phytic acid in different sections of the alimentary tract. J Anim Sci 70: 1159–1168

Kerr BJ and Easter RA (1995) Effect of feeding reduced protein, amino acid-supplemented diets on nitrogen and energy balance in grower pigs. J Anim Sci 73: 3000–3008

Kornegay ET and Harper AF (1997) Environmental nutrition: Nutrient management strategies to reduce nutrient excretion of swine. The Professional Animal Scientist 13: 99–111

Körner I, Schlegelmilch M and Rainer S (1999) Regulation of nitrogen contents of composts during composting – first experimental results. In: Bidlingmaier W, de Bertoldi M, Diaz LF and Papadimitriou EK (eds). Proceedings of the International Conference on Biological Treatment of Waste and the Environment (ORBIT 99), pp 123–129. Berlin. Germany: Rhombos-Verl.

Lopez-Real J and Baptista M (1996) A preliminary comparative study of three manure composting systems and their influence on process parameters and methane emissions. Compost Sci Util 4(3): 71–82

Lynch NJ and Cherry RS (1996) Winter composting using the passively aerated windrow system. Compost Sci Util 4: 44–52

Martins O and Dewes T (1992) Loss of nitrogenous compounds during composting animal wastes. Biores Technol 42: 103–111

Michel Jr FC, Forney LJ, Huang AJF, Drew S, Czuprenski M, Lindeberg JD and Reddy CA (1996) Effects of turning frequency, leaves to grass mix ratio, and windrows vs. pile configurations on the composting of yard trimmings. Compost Sci Util 4: 26–43

Michel Jr FC and Reddy CA (1998) Effect of oxygenation level on yard trimmings composting rate, odor production, and compost quality in bench-scale reactors. Compost Sci Util 6: 6–14

Morisaki N, Phae CG, Nakasaki K, Shoda M and Kubota H (1989) Nitrogen transformation during thermophilic composting. J Ferment Bioeng 67: 57–61

National Pork Producers Council (NPPC) (1999) Fat-free lean prediction equations. Des Moines, Iowa, USA, 26 p

National Research Council (NRC) (1998) Nutrient Requirements of Swine. 10th edition. National Academy Press, Washington, DC. USA, 189 pp

Pare T, Dinel H, Schnitzer M and Dumontet S (1998) Transformations of carbon and nitrogen during composting of animal manure and shredded paper. Biol Fertil Soils 26: 173–178

Rao Bhamidimarri SM and Pandey SP (1996) Aerobic thermophilic composting of pigerry solid wastes. Water Sci Technol 33(8): 89–94

Richard TL and Choi HL (1999) Eliminating Waste: Strategies for Sustainable Manure Management. Asian-Aus J Anim Sci 12: 1162–1169

Richard TL and Walker LP (1999) Oxygen and temperature kinetics of aerobic solid-state biodegradation. In: Bidlingmaier W, de Bertoldi M, Diaz LF and Papadimitriou EK (eds) Proceedings of the International Conference on Biological Treatment of Waste and the Environment (ORBIT 99), Berlin. Germany: Rhombos-Verl pp 85–91

Rynk R, van de Kamp M, Willson GB, Singley ME, Richard TL, Kolega JJ, Gouin FR, Laliberty Jr L, Day K, Murphy DW, Hoitink HAJ and Brinton WF (1992) On-Farm Composting Handbook. NRAES, Cornell University, Ithaca, New York, USA, 186 pp

Rynk R and Richard TL (2000) Commercial composting production systems. In: Stoffella PJ and Kahn BA (eds) Compost Utilization in Horticultural Cropping Systems. Boca Raton, Florida, USA: CRC Press, (in press)

Suler DJ and Finstein MS (1977) Effect of temperature, aeration, and moisture on CO_2 formation in bench-scale, continuously thermophilic composting of solid waste. Appl Environ Microbiol 33: 345–350

Tam NFY and Tiquia SM (1999) Nitrogen transformation during co-composting of spent pig manure, sawdust litter, and sludge in forced-aerated system. Environ Technol 20: 259–267

Tam NFY, Tiquia SM and Vrijmoed LLP (1996) Nutrient transformation of pig manure under pig-on-litter system. In: De Bertoldi M, Sequi P, Lemmes B, Papi T (eds). pp 96–105. London, UK: Chapman and Hall

Thelosen JGM, Heitlager BP and Voermans JAM (1993) Nitrogen balances of two deep litter systems for finishing pigs. In: Verstegen MWA, den Hartog LA, van Kempen GJM and Metz JHM (eds) Nitrogen Flow in Pig Production and Environmental Consequences, pp 318–323. Wageningen, The Netherlands: EAAP Publication No. 69

Tiquia SM (1996) Further Composting of Pig-Manure Disposed from the Pig-on-litter (POL) System in Hong Kong. Ph.D. Thesis. The University of Hong Kong, Pokfulam Road, Hong Kong. 475 pp

Tiquia SM (2000) Evaluating toxicity of pig manure from the pig-on-litter system. In: Warman PR and Taylor BR (eds) Proceedings of the International Composting Symposium (ICS 1999), Volume II, pp 625–647. Nova Scotia, Canada: CBA Press, Inc.

Tiquia SM and Tam NFY (2000a) Fate of nitrogen during composting of chicken litter. Environ Pollut (in press)

Tiquia SM and Tam NFY (2000b) Microbiological and chemical parameters for compost maturity evaluation of spent pig litter disposed from the pig-on-litter system. In: Warman PR and Taylor BR (eds) Proceedings of the International Composting Symposium (ICS 1999). Volume II, pp 648–669. Nova Scotia, Canada: CBA Press, Inc.

Tiquia SM, Tam NFY and Hodgkiss IJ (1997) Effects of turning frequency on composting of spent pig-manure sawdust litter. Biores Technol 62: 37–42

Tiquia SM, Tam NFY and Hodgkiss IJ (1998a) Composting spent pig litter in turned and forced-aerated piles. Environ Pollut 99: 329–337

Tiquia SM, Tam NFY and Hodgkiss IJ (1998b) Changes in chemical properties during composting of spent litter at different moisture contents. Agric Ecosys Environ 67: 79–89

Tiquia SM, Tam NFY and Hodgkiss IJ (1998c) Salmonella elimination during composting of spent pig litter. Biores Technol 63: 193–196

Tiquia SM, Richard TL and Honeyman MS (2000) Effect of windrow turning and seasonal temperatures on composting of pig manure from hoop structures. Environ Technol (in press)

United States Department of Agriculture (USDA) (1992) Agricultural Waste Management Field Handbook. Natural Resources Conservation Service, USDA, Washington, D.C., USA. Internet URL: http://www.ncg.nrcs.usda.gov/tech_ref. html

Vuorinen AH and Saharinen MH (1999) Cattle and pig manure and peat cocomposting in a drum composting system: Microbiological and chemical parameters. Compost Sci Util 7: 54–65

Walker JM (1993) Control of composting odors. In: Hoitink HAJ and Keener HM (eds) Science and Engineering of Composting: Design, Environmental, Microbiological and Utilization Aspects, Worthington, Ohio, USA: Renaissance Publications pp 185–218.

Zar JH (1999) Biostatistical Analysis. Fourth edition. New Jersey, USA: Prentice Hall, 929 pp