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Full Length Research Paper

Effectiveness of combined thermophilic composting and vermicomposting on biodegradation and sanitization of mixtures of dairy manure and waste paper

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Thermophilic composting is commonly used for the treatment of organic wastes or for production of organic/natural fertilizers. Vermicomposting (V) is also increasingly becoming popular. These two techniques have their inherent advantages and disadvantages. In this study, vermicomposting and a combination of thermophilic composting and vermicomposting were compared as ways of sanitizing and biodegrading dairy manure and waste paper mixtures with C:N ratios of 30 and 45. Wastes with a C:N ratio of 30 proved more suitable for both vermicomposting and combined thermophilic composting and vermicomposting as their composts were more stabilized and with higher nutrient contents than composts made from wastes with a C:N ratio of 45. Both vermicomposting and combined composting and vermicomposting were effective methods for the biodegradation of dairy manure and paper waste mixtures with C:N ratio of 30 but the latter was more effective in the biodegradation of waste mixtures with a C:N ratio of 45. Combining therrmophilic composting and vermicomposting eliminated the indicator pathogen *Escherichia coli* 0157 from the final composts whereas vermicomposting only managed to reduce the pathogen population.

Key words: Biodegradation, C:N ratio, dairy manure, *Eisenia fetida*, *Escherichia coli* 0157, humification index, composting, vermicomposting, waste paper.

INTRODUCTION

The increasing rate at which organic wastes are being generated has created major waste disposal problems in both developed and developing countries. Different institutions produce large volumes of waste paper which is often incinerated, contributing to greenhouse gases, like CO_2, in the atmosphere. Intensive livestock farming, such as dairy farms, generate equally large amounts of wastes in the form of animal excreta. James et al. (2004) estimated that dairy cows in free stall barns produce approximately 1986 kg of manure/animal unit (AU)/yr on a dry weight basis (1 animal unit = 370 kg). A common disposal avenue for animal manures is their use in agriculture as soil amendments. Cattle manure is however, reported to contain pathogenic faecal bacteria and recent studies have established a link between application of raw manure and water contamination by faecal coliforms such as *Escherichia coli* 0157, which causes intestinal diseases and deaths (O'Connor, 2002). In fact, outbreaks of *E. coli* 0157:H7 infections associated with consumption of spinach, lettuce and other produce crops have linked animal manures as potential sources of pathogens in fruits and vegetables (Ackers et al., 1998;

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Abbreviations: HR, Humification ratio; **HI,** humification index; **MC,** moisture content; **CV,** combined vermicomposting; $\mathbf{C_{HA}}$**,** extractable humic acid carbon; $\mathbf{C_{FA}}$**,** extractable fulvic acid carbon; **EC,** electrical conductivity; **VS,** volatile solids; $\mathbf{C_{EX}}$**,** extractable carbon fraction.

CDCP, 2006; Rangel et al., 2005). Therefore, the management of animal manures for recycling in agriculture must, of necessity, incorporate sanitization to minimize potential disease transmission.

Thermophilic composting and vermicomposting are two of the best-known processes for the biological stabilization of solid organic wastes. Thermophilic composting involves the accelerated degradation of organic matter by micro-organisms under controlled conditions, in which a characteristic thermophilic stage allows sanitization of the waste by the elimination of pathogenic microorganisms (Lung et al., 2001). However, thermophilic composting requires long duration and frequent turning of the material which results in loss of nutrients during the prolonged process. The high temperatures (> 60℃) associated with the process are also known to inhibit decomposition (Bardos and Lopez-Real, 1991), while the heterogeneous nature of the final product makes it less desirable (Ndegwa and Thompson, 2001). Vermicomposting, which involves the bio-oxidation and stabilization of organic material by the joint action of earthworms and micro-organisms, results in a more homogenous product. Although microorganisms biochemically degrade the organic matter, earthworms are said to be the crucial drivers of the process, as they aerate, condition and fragment the substrate, thereby drastically altering the microbial activity (Lazcano et al., 2008). Earthworms modify the physical and chemical status of organic matter by reducing the ratio of C/N and increasing the surface area thus making it more favourable for microbial activity and further decomposition (Domínguez et al., 1997). However, pathogen removal is not ensured since the temperature is always in the mesophilic range, although some studies have provided evidence of suppression of pathogens (Monroy et al., 2008).

The combination of thermophilic composting and vermi-composting is increasingly receiving attention as a way of achieving stabilized substrates (Ndegwa and Thompson, 2001; Alidadi et al., 2004; Nair et al., 2006; Tognetti et al., 2007). Thermophilic composting enables sanitization of wastes and elimination of toxic compounds while the subsequent vermicomposting reduces particle size and increases nutrient availability. In addition, inoculation of the material resulting from the thermophilic phase of composting with earthworms reduces the expense and duration of the treatment process (Ndegwa and Thompson, 2001). Combined thermophilic and vermicomposting has been studied with biosolids (Ndegwa and Thompson, 2001; Alidadi et al., 2004), kitchen wastes mixed with green wastes (Nair et al., 2006) as well as cattle manure (Lazcano et al., 2008).

There is little or no information available on the effectiveness of combined thermophilic composting and vermicomposting on biological stabilization and sanitization of mixtures of dairy manure and waste papers. Therefore, this study was undertaken to: (i) Determine the comparative effectiveness of combined thermophilic composting and vermicomposting on the biodegradation of mixtures of dairy manure and paper waste with different C: N ratios and (ii) determine the effectiveness of combined thermophilic composting and vermicomposting on the sanitization of biodegraded dairy manure and paper wastes using the pathogen *E. coli* 0157 as the indicator organism.

MATERIALS AND METHODS

Experimental site, wastes and earthworms utilized

Composting was carried out at the University of Fort Hare (32°46′ S and 26°50′ E) in the Eastern Cape Province of South Africa in an open but shaded yard. Dairy manure was obtained from the Keiskammerhoek Dairy Project located about 60 km North East of the University of Fort Hare, while shredded waste paper was obtained from the Duplicating Center at the University of Fort Hare. Representative samples were taken from each of the feedstock materials (dairy manure and shredded paper), air dried and ground to pass through a 2 mm sieve and then analyzed for pH, electrical conductivity (EC), total N, C and P, available N and P, volatile solids (organic matter) and ash. The earthworm species *Eisenia fetida* (commonly known as red wigglers) (Edwards and Bohlen, 1996) was used in the experiments. The earthworms were obtained from East London, Eastern Cape Province, South Africa and had been fed on grass cuttings and vegetable wastes for three months.

Composting treatments

Composting was done using mixtures of dairy manure and waste paper with a C:N ratio of 30 and 45. The composting methods were (i) Control (C), (ii) vermicomposting (V) and (iii) combined thermo-phillic composting and vermicomposting (CV).

Control

In the control system, mixtures of dairy manure and shredded paper waste of C:N ratios of 30 and 45 were put into boxes (similar size as those for vermicomposting) and watered to the same moisture level of 80% recommended for vermicomposting but no worms were introduced. The waste mixtures were allowed to incubate for 56 days without further treatment except moisture adjustment. Moisture levels were adjusted to 80% moisture content (MC) by spraying/sprinkling the surface with water after a weekly analysis for moisture content.

Vermicomposting

Vermicomposting was performed in boxes measuring 0.50 x 0.40 x 0.30 m^3 (length x width x depth) which provided a 0.2 m^2 of exposed surface area. Mature earthworms were introduced at the recom-mended stocking rate of 1.6 kg-worms/m^{-2} into each of the worm boxes and fed at the recommended feeding rate of 0.75 kg-feed/kg-worm/day (Ndegwa et al., 2000). Enough feedstock consisting of mixtures of dairy manure and shredded waste paper of C:N ratios of 30 or 45 depending on treatment, was provided to meet the needs of the earthworms for the entire eight weeks in which the experiment was conducted. The experimental duration was chosen to coincide with the approximate generation time of *E. fetida* (Hartenstein and Hartenstein, 1981; Edwards, 1988). Moisture levels were maintained at about 80% MC level. At the end of the eighth week the worms were separated from the vermicompost.

Combined thermophilic composting and vermicomposting

Dairy manure was mixed with shredded waste paper to give feedstock materials with C:N ratios of 30 and 45. Thermophilic composting of the wastes was then done in boxes measuring 1 x 1 x 1 m (length x width x height) for 28 days. The wastes were weighed and mixed manually on a polythene sheet using shovels. Mixing was done repeatedly from one end to the other adding water to 60% moisture content, before the materials were loaded into the composting boxes. Compost and ambient temperatures were taken daily for 28 days while MC was determined weekly and used as a basis for its adjustment to 60%. Turning was done biweekly. At the end of 28 days, composting of the waste mixtures was continued using earthworms as described under vermicomposting. Adequate composted feedstock was provided to meet the needs of the earthworms for the entire four weeks (28 days) of this phase of the experiment. The vermicomposting process was terminated at the end of the fourth week at which time, worms were separated from the vermicompost.

Samples were taken for analysis at the beginning of the experiment (feedstock), four weeks (intermediate composting phase) and at eight weeks (final composts) for all the treatments.

Analyses

The parameters determined were MC, volatile solids (VS), ash content, total carbon (C), total nitrogen (N), inorganic N (nitrate- N and ammonium – N), total and available phosphorus (P), humic substances and *E. coli* 0157 population.

Methods of analyses

MC was determined gravimetrically by oven drying samples at 70°C to constant mass and expressed on a wet-weight basis. For other determinations, representative samples were dried in an oven at 60°C until constant weight and then ground to provide a homogenous sample. Volatile solids were obtained by ashing dried samples at 550°C for 4 h (Atiyeh et al., 2000). EC and pH were determined potentiometrically in a 1:10 (compost: water) suspension in de-ionised water as described by Ndegwa and Thompson (2001). This suspension was shaken on a mechanical shaker at 230 rpm for 30 min prior to pH or EC measurements.

Total nitrogen (N) and carbon (C) were determined using a Truspec CN carbon/nitrogen determinator (Anonymous, 2003). Total phosphorus (P) was extracted by wet digestion using the concentrated sulphuric acid, selenium, lithium sulphate and hydrogen peroxide mixture as described by Anderson and Ingram (1996). The concentration of P in the digest was then determined by the molybdenum blue colorimetric method.

Mineral nitrogen (NH_4^+-N and NO_3^--N) was extracted from fresh compost samples with a 0.5 M K_2SO_4 solution (Okalebo et al., 2002). The nitrate concentration was determined using a spectrophotometer after development of a yellow colour using 5% salicylic acid in concentrated sulphuric acid while ammonium concentration was also determined using a spectrophotometer after development of a blue colour using salicylate-nitroprusside colorimetric method (Okalebo et al., 2002). Available P of organic wastes was estimated using the Bray 1 extractant (Okalebo et al., 2002). The amount of phosphorus extracted was determined by the molybdenum blue colorimetric method.

Humic substances were extracted by treating samples with 0.1 M NaOH (1:20 w/v ratio) and constantly shaken for 4 h (Garcia et al., 1993). After centrifugation for 15 min, at 8000 x *g*, the supernatants were divided into two fractions, one of which was stored for later analysis of total extractable carbon fraction (C_{EX}) and the other adjusted to pH 2 with concentrated H_2SO_4 and allowed to coagulate for 24 h at 4°C. The precipitates that formed constituted the humic acid fraction (HA) while fraction that remained in solution constituted the fulvic acids (FA).

The two fractions were separated by centrifugation as described earlier and stored for C analyses by the Walkely Black method as described by Anderson and Ingram (1996). The carbon concentration of the humic acid fractions (C_{HA}) was calculated by subtracting the fulvic acid fraction C (C_{FA}) from the total extractable C fraction (C_{EX}). Humification ratio (HR) and humification index (HI) were calculated using Equations 1 and 2, respectively as follows:

$$HR = (C_{EX}/C) \times 100 \quad (1)$$

$$HI = (C_{HA}/C) \times 100 \quad (2)$$

Presence of *E. coli* in the initial and final composts was determined as outlined by Berry and Wells (2008). A sample (5 g) of either waste mixture or compost was added to 45 ml of peptone buffer and then mixed using a blender. Serial dilutions of 10^{-2}, 10^{-3}, 10^{-4}, 10^{-5} and 10^{-6}, were prepared from the 1: 10 dilution and the 10^{-5} and 10^{-6} dilutions were used for *E. coli* enumeration. A 50 µl portion was plated onto CHROMagar O157 (DRG International) containing 5 mg/l novobiocin and 2.5 mg/l potassium tellurite (ntCHROMagar O157). The CHROMagar O157 plates were incubated at 42°C for 24 h and enumerated. *E. coli* O157 colonies are flat, mauve-colored colonies without distinct centers. Plates with less than 20 or more than 300 colonies were discarded. The presumptive *E. coli* O157 colonies were identified via an agglutination test using *E. coli* O157:H7 latex. Presence of agglutination confirms the presence of *E. coli* O157 bacteria. Colonies subjected to agglutination test were then identified as *E. coli* with API 20E kits.

Statistical analysis

The various data sets obtained were statistically analyzed using GENSTAT (III) discovery statistical package while mean separations were done using least significant differences (LSD) at 0.05 level of significance.

RESULTS

Chemical characteristics of the wastes

Dairy manure had higher nitrogen and lower carbon content than waste paper resulting in a lower C/N ratio (Table 1). The pH of both dairy manure and waste paper was alkaline but EC was higher in dairy manure than in paper. The ash content of paper was also much lower than that of dairy manure. The P content of manure, at 2.9 g/kg, was much higher than that of waste paper which was only 0.39 g/kg resulting in a much lower C/P ratio for manure.

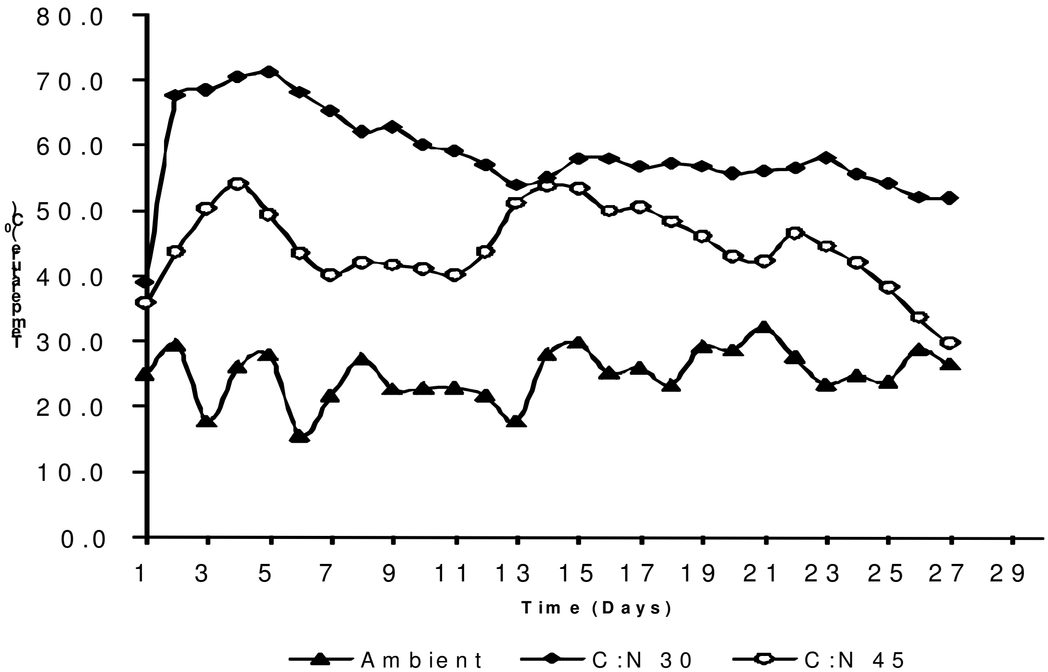

Figure 1. Temperature profiles of dairy manure–paper waste mixtures during the thermophillic composting phase prior to vermicomposting.

Table 1. Selected chemical properties of wastes used in the study.

Chemical property	Waste material	
	Dairy manure	Waste paper
pH	7.8	8.2
EC (mS/m)	440	0.18
Total N (g/kg)	24	3
Total C (g/kg)	321	370
C: N	13.2	205
Total P (g/kg)	2.9	0.5
C: P	110	740
Ash (g/kg)	379	178

Temperature profiles during the thermophilic composting phase

Composts with a C:N ratio of 30 maintained thermophilic temperatures from the second day up to the end of the composting period, reaching a maximum temperature of 72°C on the 5th day after establishment (Figure 1). By contrast, composts with C:N ratio of 45 attained a maximum temperature of only 54°C after 4 days of composting which dropped to 40°C by day 7. After, the first turning temperature increased to thermophilic ranges briefly but decreased thereafter until termination of this phase of the experiment after 28 days.

Degradation and humification of composted wastes

Feed-stocks with a C:N ratio of 30 had higher ash and lower volatile solid contents than feed-stocks with a C:N ratio of 45 (Table 2). Volatile solids decreased by 4 and 27% as a result of composting and the decreases were influenced by both composting method and C:N ratio of waste mixtures. The greatest reductions in volatile solid were observed in waste mixtures with a C:N ratio of 30 where volatile solid in final composts was reduced by 27 and 23% by vermin-composting and combined composting and vermin-composting, respectively. The reductions in volatile solid followed the order V30 > CV30 > VC45 > V45 > C30 > C45. By contrast, ash content of the composted mixtures increased by between 21 and 79%. The increase in ash was similarly affected by both composting method and C:N ratio. The increase in ash followed the order V30 > CV30 > CV45 > C30 = C45, which was similar to reductions in VS (Table 2).

Total C decreased with composting time while total N increased for all three composting methods (Tables 3 and 4). These changes were greater for feedstock materials with a C:N ratio of 30 than those of C:N ratio of 45 and translated to final composts with corresponding narrower C:N ratio at the end of week eight. For dairy manure-paper waste mixtures of C:N ratio 30, the C:N ratio decreased to 29, 22 and 23 after four weeks and further decreased to 25, 14 and 15 in the final (week 8) composts in the control, vermicompost and combined thermophilic

Table 2. Effect of composting method and C:N ratio of dairy manure and paper waste mixtures on ash, volatile solids (VS) contents and mean percentage change in these parameters in the final composts in response to treatments.

Feedstock C:N ratio	Composting method	Composting stage (weeks)	Ash	VS	% Change (feedstock vs final product) ash VS	
30	C	0	24	76		
		4	26	74		
		8	27	73	21[a]	-7[b]
	V	0	25	75		
		4	32	68		
		8	46	54	79[d]	-27[d]
	CV	0	25	75		
		4	34	66		
		8	42	58	72[d]	-23[d]
45	C	0	19	81		
		4	20	80		
		8	21	79	21[a]	-4[a]
	V	0	18	82		
		4	22	78		
		8	26	74	41[b]	-9[b]
	CV	0	18	82		
		4	26	74		
		8	28	72	53[c]	-12[c]

C = Control (dairy manure-paper waste mixtures allowed to decompose on their own); V = vermicomposting; CV = combined composting and vermicomposting.

Table 3. Effect of composting method and C: N ratio of dairy manure and paper waste mixtures on selected compost maturity parameters.

Composting method	Composting stage	Selected maturity parameters					
		Total C (%)	C: N	C_{HA}:C_{FA}	HI (%)	HR (%)	NH_4^+: NO_3^- ratio
Feed stock C:N ratio = 30							
C	0	36	31	0.2	1.4	13	2.5
	4	35	29	0.4	9.4	13	5.8
	8	34	25	1.0	10	19	0.2
V	0	36	30	0.1	1.5	14	2.5
	4	33	22	1.0	11.2	22	4.5
	8	28	14	2.8	39	53	0.1
CV	0	36	30	0.1	1.4	13	2.5
	4	33	23	1.4	9.7	24	4.1
	8	28	15	3.6	40	52	0.1
Feed stock C:N ratio = 45							
C	0	37	46	0.1	0.6	6	1.3
	4	36	43	0.4	5.3	7	6.5
	8	35	38	0.8	4.4	9	0.3
V	0	36	46	0.1	0.4	6	1.2
	4	35	41	0.5	5.4	8	3.5
	8	34	36	1.3	6.6	12	0.1
CV	0	36	45	0.1	0.5	6	1.3
	4	34	37	0.7	5.1	9	3.4
	8	33	33	1.6	8.1	13	0.1

C = Control (dairy manure-paper waste mixtures allowed to decompose on their own); V = vermicomposting; CV = combined composting and vermicomposting; C_{HA} = extractable humic acid carbon; C_{FA} = extractable fulvic acid carbon HI = humification index; HR = humification ratio.

Table 4. Effect of composting method and C:N ratio of dairy manure and paper waste mixtures total and extractable N and P contents.

Composting method	Composting stage	Total and extractable nutrients contents				
		Total N (%)	NH_4^+ (mg N/kg)	NO_3^- (mg N/kg)	Total P (%)	Bray 1 P (mg/kg)
Feed stock C: N ratio= 30						
C	0	1.16	6.5	2.6	0.18	59
	4	1.20	50.6	8.6	0.22	72
	8	1.34	5.1	28.4	0.31	83
V	0	1.15	6.3	2.5	0.17	59
	4	1.46	89.7	19.8	0.24	92
	8	2.06	10.5	139	0.71	141
CV	0	1.17	6.5	2.6	0.18	58
	4	1.43	197	48	0.38	97
	8	1.93	9.9	134	0.65	130
Feed stock C: N ratio= 45						
C	0	0.80	2.0	1.6	0.07	29
	4	0.83	18	2.8	0.15	32
	8	0.92	2.5	6.7	0.18	37
V	0	0.80	2.0	1.7	0.08	31
	4	0.86	18.4	5.3	0.18	40
	8	0.93	2.7	17.3	0.22	56
CV	0	0.81	2.1	1.6	0.07	32
	4	0.92	38.8	11.5	0.22	51
LSD ($p \leq 5$)	8	0.98	3.1	29.7	0.29	61
C:N*CM*time		0.10	2.2	4.8	0.03	5.0

C = Control (dairy manure-paper waste mixtures allowed to decompose on their own); V = vermicomposting; CV = combined composting and vermicomposting; CM = composting method.

and vermicomposting treatments, respectively (Table 3). The C:N ratios of dairy manure-paper waste mixtures with an initial C:N ratio of 45 also decreased with time reaching values of 38, 36 and 33 in the final (week 8) composts of the control, vermicompost and combine compost vermicompost treatments, respectively (Table 3). The ammonium:nitrate ratios increased and peaked in week four but decreased thereafter and reached very low values of less than 1 in all final composts regardless of composting method or feedstock C: N ratio (Table 3).

Dairy manure and waste paper mixtures with C:N ratio of 30 had higher C_{FA} and C_{HA} contents than mixtures with C:N ratio of 45 at the beginning of the experiment and this relative difference was maintained even in the final composts (Figure 3). The C_{HA} of waste mixtures of both C:N ratios increased with composting time while the C_{FA} content decreased (Figure 3). The increase in C_{HA} and decrease in C_{FA} translated to increases in the C_{HA}:C_{FA} ratio with composting time (Table 3). The HI and HR values in the final composts of vermicomposted and combined composted and vermicomposted wastes were comparable and far greater than those of the control compost for dairy manure –waste paper mixtures with a C:N ratio of 30. However, combined composting and vermicomposting resulted in greater humification parameters than vermicomposting alone for dairy manure-waste paper mixtures with a C:N ratio of 45. Humification ratios of 53 and 52% were realized with vermicomposting and combined composting and vermicomposting, respectively for feed stock materials with a C:N ratio of 30 after 8 weeks of composting. Corresponding HR values for feed stock waste mixture with a C:N ratio of 45 was 12 and 13%, respectively (Table 3). Therefore, dairy manure-waste paper mixtures with a C:N of 30 underwent greater humification than those with a C:N ratio of 45.

Effect of composting on total and extractable N and P contents

Total N increased with composting time for each of the different composting methods (Table 4). The largest increases occurred in vermicomposted wastes followed by those that were pre-composted before vermin-

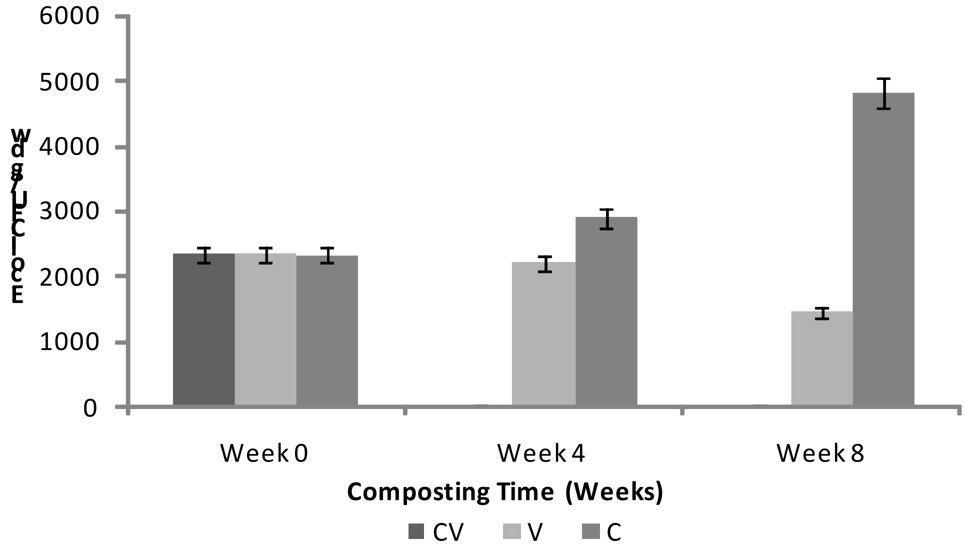

Figure 2. Changes in *E. coli* 0157 numbers in dairy manure paper waste mixtures with composting time (Error bars represent standard deviations).

composting. Ammonium N increased and reached maximum levels in week 4 and decreased thereafter for all composting methods and waste mixtures of both feed stock C:N ratios. By contrast, nitrate N levels increased steadily with time reaching maximum levels in the final composts (Table 4). The largest increases in nitrate N were, however, observed in feedstock materials of C:N ratio 30 which were vermicomposted or composted followed by vermicomposting. Total and extractable P also increased with composting time and followed patterns similar to those observed for total N and ammonium-N, respectively (Table 4).

For feedstock materials with C:N ratio of 30, both vermicomposting and combined compost and vermin-composting (CV) resulted in total N, ammonium N, nitrate N, total P and extractable P levels in the final composts that far exceeded levels observed in the control composts (Table 4). However, vermicomposting resulted in relatively higher nutrient levels than CV. By contrast, for feedstock materials with C:N ratio of 45, an opposite trend was observed whereby combined compost and vermicomposting resulted in generally higher total N, ammonium N, nitrate N, total P and extractable P levels than vermicomposting.

Effect of composting on *E. coli* 0157

All composting treatments had comparable populations of *E. coli* 0157 at the beginning of composting but those in the control treatment increased steadily with composting time (Figure 2). The *E. coli* 0157 population in the vermin-composting treatment, on the other hand, decreased steadily with time until week 8 of composting but it was not eliminated. By contrast, the thermophilic composting phase of the combined system completely eliminated *E. coli* 0157 within 4 weeks of composting and none was detected at the end of the vermicomposting phase (Figure 2).

DISCUSSION

Effectiveness of composting methods on the degradation of dairy manure- waste paper mixtures

The decrease in volatile solids and corresponding increases in the ash content in the final composts relative to the feedstock materials indicated degradation of organic matter (OM) in the dairy manure- waste paper mixtures during composting as reported by other workers (Bernal et al., 1998; Levanon and Pluda, 2002). The decrease with composting time of the C content of the waste mixtures composted by the different methods confirmed the loss in OM reflected by reduction in volatile solids contents. The greater effectiveness of vermin-composting in the degradation of OM in waste mixtures with C:N ratio of 30 than combine compost and vermicomposting and *vice versa* for waste mixtures with C: N ratio of 45 indicated that the effectiveness of the two composting methods in degrading organic matter was dependent on the C:N ratio of the mixtures being composted.

Increases in total N with composting time was probably due to a concentration effect caused by weight reduction of the composting mixtures as a result of degradation. It also suggests that limited nitrogen loss occurred during composting. Taking C:N ratio as an indicator of

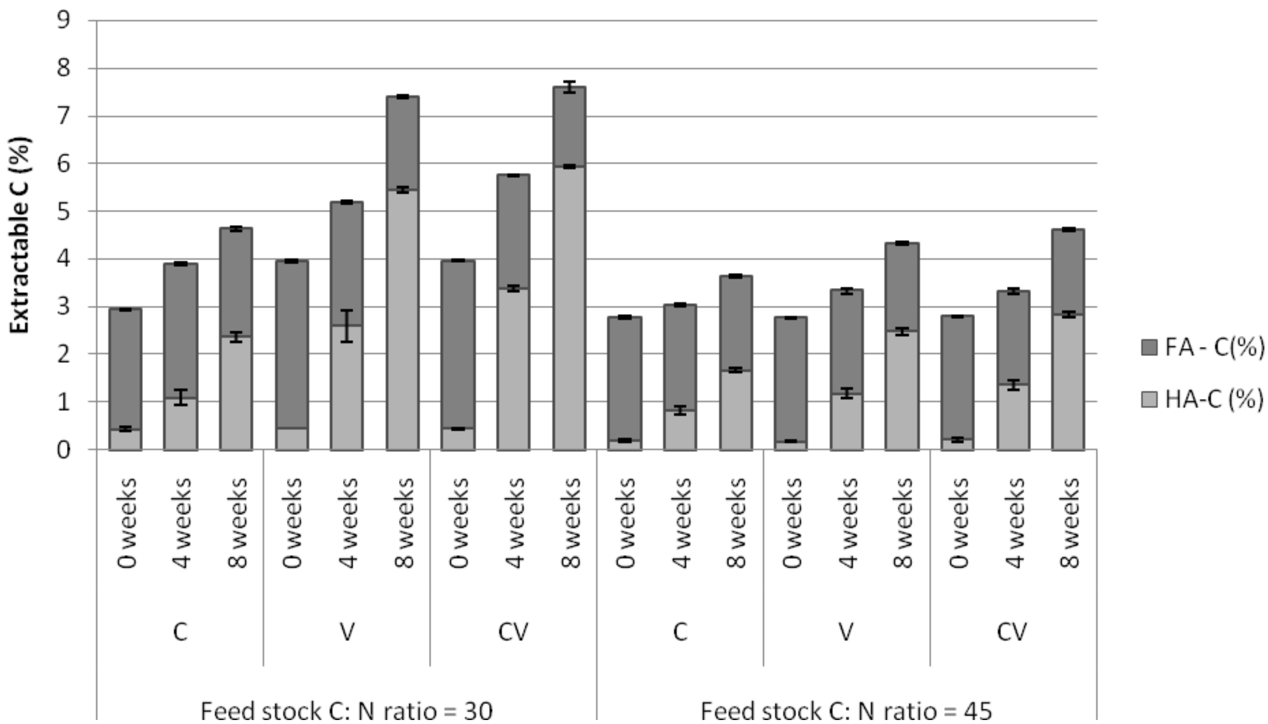

Figure 3. Effect of feed stock C:N ratio of dairy manure-paper waste mixtures and composting method on extractable fulvic acid (FA) and humic acid (HA) carbon contents. (Error bars indicate standard deviations). C= Control (dairy manure-paper waste mixtures allowed to decompose on their own); V= vermicomposting; CV = combined thermophillic composting and vermicomposting.

decomposition, the results indicated that vermicomposting was a more effective method of composting than combined composting and vermin-composting for waste mixtures with an initial C:N ratio of 30 as it resulted in final composts with a narrower C:N ratio. The opposite was the case for wastes with an initial C:N ratio of 45. According to Iglesias-Jiminez and Perez-Garcia (1992) a C:N ratio lower than 12 indicated a good degree of maturity for municipal waste compost, so none of our final composts could be considered sufficiently matured as all of them had C:N ratios greater than 12. However, according to Allison (1973) the vermin-composted and combine compost and vermicomposted waste mixtures which had final C:N ratios of 14 and 15 could be added to soil without altering the microbiological equilibrium of the soil.

Increases in the amount of C_{EX} with time (Figure 3) indicated conversion of organic matter into humus. The decline in the fulvic acid fraction with time and increase of the humic acid fraction indicated transformation of the easily degradable molecules that make the fulvic acid fraction to the more recalcitrant molecules of higher molecular weight which make up the humic acid fraction. This translated to increases in the C_{HA}/C_{FA} ratio with time with values in the final (week 8) compost samples which ranged from 0.8 to 3.6 (Table 3). Only vermicomposted and combined compost vermicomposted wastes with an initial C:N ratio of 30 resulted in C_{HA}/C_{FA} ratio values that exceeded the critical level of 1.9 which Iglesias-Jiminez and Perez-Garcia (1992) proposed as a maturity index for city-refuse and sewage sludge compost. Increases in HR and HI values throughout the process indicated humification of organic matter in the composted mixtures. Comparable HI and HR values in final composts of vermicomposted and combined composted and vermicomposted dairy manure –waste paper mixtures with a C:N ratio of 30 indicated that the two methods were equally effective for wastes of this C:N ratio. However, observed greater HI and HR values in combine compost vermicomposted wastes compared to vermicomposted dairy manure–waste paper mixtures with a C:N ratio of 45 indicated that the former is more effective in the humification of waste mixtures with a C:N ratio of 45.

The feed stock waste mixtures had NH_4^+: $N0_3^-$ ratios of 2.5 and 1.3 for feedstock materials of C:N ratio 30 and 45, respectively (Table 3). This ratio increased to peak values in week 4 reflecting the high values of NH_4-N observed during this period (Table 4). The NH_4^+: $N0_3^-$ ratio subsequently declined to values of about 0.1 in all final (week 8) composts which was less than the critical level of 0.16 suggested by Bernal et al. (1998) for mature composts. Therefore, in terms of this parameter, all final composts had desirable levels of NH_4^+ and $N0_3^-$.

Observed increases in extractable nutrients as a result of composting and vermicomposting, is consistent with results of previous studies (Tognetti et al., 2007; Zhang et al., 2000). The greater effectiveness of vermicomposting than CV in releasing larger quantities of nutrients from wastes with C:N ratio of 30 than those of C:N ratio of 45 indicated that the former was more suitable for vermin-composting. It is likely that a lower C:N ratio encouraged higher earthworm and microbial activity leading to greater degradation, higher nutrient content and stabilization of wastes with C:N ratio of 30 than 45.

Combining composting and vermicomposting was more effective than vermicomposting alone in degrading wastes with C:N ratio of 45 reflected by the higher ash, less VS and higher, C_{HA}: C_{FA} ratio, HI and HR; as well as greater quantities of total and extractable N and P in final composts. It would seem that composting of these waste prior to vermicomposting resulted in wastes that were more suitable for breakdown by earthworms. This was probably due to the reduction in C:N ratio and a probable increase in water soluble carbon in wastes due to the liberation of simple, soluble organic compounds at rates exceeding their degradation (Castaldi et al., 2005). This was in agreement with the result of Ndegwa and Thompson (2001) and Alidadi et al. (2004), which showed that combined composting and vermicomposting of biosolids produced composts with more nutrients than vermin-composting alone though this was not the case for wastes with C:N ratio of 30 where CV did not produce composts with more nutrients than vermicomposting alone.

Effectiveness of composting methods on sanitization of composts

The control waste mixtures of either C:N ratio showed progressive increases in *E. coli* 0157 with composting time. This increase could be attributed to creation of a good environment for multiplication of this pathogen through rehydration and subsequent availability of easily degradable substrates by dissolution following rehydration. These results indicate that dairy manure-waste paper mixtures allowed to simply compost in place could pose a health hazard to users and that alternative ways of handling the wastes that will result in a safer product are necessary.

Vermicomposting alone failed to eliminate *E. coli* 0157 but it significantly reduced its numbers by the 8th (final) week of vermicomposting. Similar observations were made by Brown and Mitchell (1981) who reported that *E. fetida* feeding on a growing medium inoculated with S*almonella eneritidus,* reduced the populations of this enteric pathogen after 28 days by 42 times compared to controls. The greatest reduction occurred in the first 4 days. The reduction in pathogen numbers by earthworms is ascribed to the digestion of some of the microbial constituents as they pass through the earthworm gut (Edwards et al., 1984). Complete elimination of pathogens through vermicomposting is reportedly achievable only with high earthworm populations (earthworm biomass: biosolids = 1:7 weekly) (Eastman et al., 2001). This earthworm stocking rate is about six times higher than the stocking rate of 1.6 kg-worms/m^{-2} and feeding rate of 0.75 kg-feed/kg-worm/day used in our study as recommended by Ndegwa et al. (2000) and may not be practically feasible in most cases.

The combined compost-vermicompost system, on the other hand, eliminated *E. coli* 0157 within the first 4 weeks of pre-composting. The elimination of *E. coli* 0157 in this system could be attributed to thermophilic temperatures attained by these composts during the thermophilic composting phase (Figure 1). According to Wu and Smith (1999), a temperature of 55°C must be maintained for 15 consecutive days for efficient composting and pathogen reduction. In this study, mixtures with a C:N ratio of 30 maintained such high temperatures for over 3 weeks. Mixtures with a C:N of 45 did not maintain temperatures of 55°C or higher for a long time, but *E. coli* 0157 was still eliminated in the final composts. A similar observation was made by Larney et al. (2003) who observed that 99.9% of *E. coli* 0157 was eliminated within 7 days when average windrow tempe-ratures observed were only 33.5 - 41.5°C, which were within the mesophilic temperature range but lower than the thermal kill limit of 55°C (USEPA, 1992). No measurements were taken earlier than the 4 weeks of composting in this study but it is likely that the elimination of *E. coli* from the composts could have occurred much earlier. Future studies will explore shorter composting periods before vermicomposting. Nevertheless, the results of this study indicated that combining composting and vermicomposting is the more practical option for elimination of pathogens in dairy manure-paper waste vermicomposts.

Conclusion

Mixtures of dairy manure and paper waste with C:N ratio of 30 proved more suitable for composting as these produced more mature and humified compost with higher ash, more total extractable N and P contents than wastes with a C:N ratio of 45. Both vermicomposting and combined composting and vermicomposting were effective methods for the biodegradation of mixtures of dairy manure and paper waste with C:N ratio of 30 but the latter was more effective in the biodegradation of waste mixtures with a C:N ratio of 45. Combined composting and vermicomposting eliminated the indicator pathogen *E. coli* 0157:H7 from dairy manure and waste paper mixtures whereas vermicomposting alone could only reduce pathogens level. Therefore, pre-composting the waste mixtures prior to vermicomposting is recommended where elimination of pathogens from composts is a critical consideration.

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