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Effects of stocking density and feeding rate on vermicomposting of biosolids

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Abstract

The double-pronged problem of quantity, and disposal of waste streams from a myriad of industries, is becoming increasingly acute, the world over. The use of earthworms as a waste treatment technique for such wastes is gaining popularity. This method is commonly known as vermicomposting. Compared to conventional microbial composting, vermicomposting produces a product that is more or less homogenous, with desirable aesthetics, with reduced levels of contaminants and tends to hold more nutrients over a longer period, without impacting the environment. Like in other related waste treatment techniques, certain parameters need to be established for the design of efficient and economical vermicomposting systems. Specifically, the focus of this study was to investigate and establish an optimal stocking density and an optimal feeding rate for the vermicomposting of biosolids, with paper mulch provided as bedding. A stocking density of 1.60 kg-worms/m^2 (0.33 lb-worms/ft^2) and a feeding rate of 1.25 kg-feed/kg-worm/day resulted in the highest bioconversion of the substrate into earthworm biomass. The best vermicompost was obtained at the same stocking density and a feeding rate of 0.75 kg-feed/kg-worm/day.

Keywords: Waste streams; Bioconversion; Environment; Vermicomposting; Stocking density; Feeding rate; Biosolids

1. Introduction

Scientific investigations have established the viability of using earthworms as a treatment technique for numerous waste streams (Hand et al., 1988; Raymond and Neuhauser, 1988; Edwards, 1988; Logsdon, 1994; Harris et al., 1990; Edwards and Bohlen, 1996). The action of earthworms in this process is both physical/mechanical and biochemical. The physical or the mechanical processes include: substrate aeration, mixing, as well as actual grinding. The biochemical process is effected by microbial decomposition of the substrate in the intestines of the earthworms. These physical/mechanical unit processes usually represent the largest cost associated with traditional microbial composting process. Vermicomposting saves on all these unit operations. Hand et al. (1988) thus define vermicomposting as a low cost technology system for the processing or treatment of organic wastes.

Also, as opposed to traditional microbial waste treatment, vermicomposting results in bioconversion of the waste streams into two useful products: the earthworm biomass and the vermicompost. The former product can further be processed into proteins (earthworm meal) or high-grade horticultural compost (Phillips, 1988; Sabine, 1988; Fisher, 1988; Edwards and Niederer, 1988). The latter product (vermicompost) is also considered an excellent product since it is homogenous, has desirable aesthetics, has reduced levels of contaminants and tends to hold more nutrients over a longer period, without impacting the environment.

Elvira et al. (1996) conducted small-lab-scale (in petri dishes) vermicomposting experiments of solid paper-pulp mill sludge with the primary focus of studying the growth and reproduction of *Eisenia andrei*. They later scaled-up their experiments into a pilot study (Elvira et al., 1998). The authors reported a significant difference in the growth rates and cocoon production by *E. andrei*, between the laboratory and the pilot experiments. Hartenstein and Hartenstein (1981) in their lab-scale (10 cm-diameter petri-dishes) experiments on vermicomposting of activated sludge observed that approximately 1 g worm could convert 4 g of activated sludge in 5 days. This converts to a feeding rate of 0.8 kg-feed/kg-worm/day. Riggle and Holmes (1994) noted that worms can consume their own weight in 24 h, while

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earlier studies conducted by Wright (1972) on *Lubricus terrestris* on feeding rates of worms showed that the feeding rate was dependent on the feed as well as the feed preparation or feed pretreatment. Reviewing the work of numerous researchers, Edwards and Bohlen (1996) also demonstrated that the feed rates varied greatly not only with earthworm species but also with the feed type. Further, Edwards and Bohlen (1996) observed that the amount of litter that the earthworms ingest seems to depend more on the total amount of suitable organic matter than on other factors, an observation which is corroborated by the earlier work of Neuhauser et al. (1980), in their studies on vermicomposting of activated sludge.

Studies on earthworm-stocking density have also focused more on its influence on the growth and production of earthworms than on vermicomposting of the respective substrates. Neuhauser et al. (1980) indirectly studied the effect of population density on growth and production of *E. foetida* and using linear regressions showed that growth declined with increase in population density, while production increased with population density. Using this same approach, the potential stocking density of *E. foetida* was estimated to be approximately 0.8 kg-worms/m^2 on horse manure and 2.9 kg-worms/m^2 on activated sludge. Similar studies by Dominguez and Edwards (1997) on the effect of stocking rate on growth and maturation of *Eisenia andrei* concluded that, whereas individual worms grew more and faster at the lowest population density, the total biomass production was maximum at the highest population density in their test. At higher rates, they noted, the worms sexually matured faster than in the lower stocking rates.

In general, studies on vermiculture and vermicomposting can be pegged on earthworm breeding, earthworm growth (for fishing bait), earthworm meal, production of earthworm castings (vermicompost) or for the treatment of material in question. Most of the pioneering work seems to have been more geared towards optimizing vermiculture (breeding and growth of worms) than in the treatment of waste (vermicomposting). In addition, these studies showed that, the effects of both the feeding rates and the stocking rates on breeding, and growth of worms, were dependent on species, feed type, and feed preparation and/or feed pretreatment. Although the viability of vermicomposting is not contestable, based on the preceding literature, pilot studies need to be conducted for the specific feed substrate or substrates-combination, and specific earthworm species, to provide accurate design criteria of efficient and economical vermicomposting facilities/systems. The pilot studies presented herein were primarily focused on treatment of fresh biosolids amended with paper mulch, using *Eisenia fetida* and investigated two important system-design parameters: the stocking density and the feeding rate.

2. Experimental design and analysis

Four stocking densities and three feeding levels were investigated. The stocking densities were investigated at 0.80, 1.20, 1.60 and 2.00 kg-worms/m^2 (0.17, 0.25, 0.33 and 0.42 lbs-worms/ft^2), while the feeding rates were investigated at 0.75, 1.0 and 1.25 kg-feed/kg-worm/day. Effects or responses to be investigated were: product stability, worm biomass, pH and nutrients; N, and P. The treatments or factors of interest were the stocking density and the feeding rate, at the four levels and the three levels given above, respectively. This design fits the classical two-way factorial design. This design saves on resources by efficiently using one worm-bin (a single treatment) to simultaneously provide a replicate for a stocking density and a feeding level. A two-way analysis of variance was therefore conducted for each response being studied.

3. Methods

Experiments were performed in worm-bins measuring 0.56 m $\times$ 0.38 m $\times$ 0.25 m (length $\times$ breadth $\times$ depth). This provided 0.21 m^2 of exposed top surface. Known weights of earthworms (*Eisenia foetida*), commonly known as red wigglers, were introduced into each of the similar worm-bins, to provide the desired stocking densities. To effect the four desired stocking densities mentioned above, earthworm live-biomass loadings were 0.17, 0.26, 0.34 and 0.42 kg, respectively. Three replicates for each of the four stocking densities were made. Each of the three replicates for every stocking density were, in turn, respectively, fed at 0.75, 1.0 and 1.25 kg-feed/kg-worm/day.

Initially, all the systems were fed for two weeks and thereafter fed continuously on a weekly basis until the seventh week. During the first two weeks, feed consisted of four parts biosolids to three parts paper mulch, by dry weight. The paper mulch was used to provide a bedding for the earthworms as well as a carbon supplement. The remainder of the weekly feed consisted entirely of biosolids. The experiments were conducted in an environment whose temperature was 25 ± 6°C. The substrate material was maintained moist by spraying/sprinkling the surface with water every two days using a spray can. In all the worm bins, moisture was maintained at 76.3% ± 1.6% (w.b).

At every feeding, the following feed parameters were determined: moisture content of the feed material, pH, the volatile solids and the ash contents. These analyses were either carried out immediately after the samples were obtained, or the samples were refrigerated at 4°C to minimize microbiological decomposition until analyzed.

Table 1
Feedstock components' parameters

Component	% N	% P	% VS	pH
Biosolids	6.02	2.51	70	7.38
Paper mulch	0.07	0.01	86	7.61
Biosolids water extract	1.69	0.21		
Paper mulch water extract	0.04	0.00		

Table 2
Change (%) in earthworm live-weight after eight weeks of vermicomposting

Initial earthworm density (kg-worms/m^2)	Feed levels (kg-feed/kg-earthworm/day)		
	0.75	1.0	1.25
0.80	−21.18	−19.24	138.47
1.20	8.63	47.80, 41.06	83.02, 174.24
1.60	79.12	50.41	109.24
2.00	−66.80	13.86	9.04

Solid matter was determined as residue by drying at 80°C for 23 h (APHA et al., 1989). Volatile solids were obtained by ashing the dried sample at 550°C for 8.5 h (APHA et al., 1989). Determination of pH was made potentiometrically in a 1:10 suspension of the sample in de-ionized water, a modification of the procedure adopted from Erhart and Burian (1997). This suspension was placed on a mechanical shaker at 230 rpm for 30 min prior to pH measurement. In the Erhart and Brian procedure, a 0.01M calcium chloride solution was used instead of de-ionized water. Determinations of nutrients (N and P) were made in an independent laboratory, using a Perkin–Elmer total C, N, S-analyzer. For these determinations, representative samples were dried at 80°C for 23 h (APHA et al., 1989) and then ground to provide a homogeneous sample. To obtain water extracts, 4 g of this homogenous sample was placed in 60 cm^3 de-ionized water and the mixture placed on a mechanical shaker for 30 min. The mixture was then centrifuged at 4000 rpm for 10 min and the supernatant filtered through a number 40 Whatman filter paper to obtain the water extracts.

The experiments were terminated at the end of the eighth week after which the worms were separated from vermicompost and total biomass of the worms determined. The eight-week experimental duration was chosen to coincide with the approximate generation time of *Eisenia foetida*, i.e. at the onset of the third generation-earthworms (Hartenstein and Hartenstein, 1981; Gaddie and Douglas, 1977; Edwards, 1988). Earthworm biomass growth was taken as the increase in total earthworm biomass collected from vermicomposted material and the bedding. Values were determined as live weight after hand sorting and removal of all extraneous material. The vermicompost was analyzed for the volatile solids, ash content, moisture content, pH, and the nutrients (N and P) using the methods already described. Vermicompost in this work refers to a mix of the worm castings, digested, as well as undigested biosolids and paper mulch.

4. Results and discussion

The feedstock components' parameters were individually determined (Table 1) and then combined on a weighted basis to provide a single representative feedstock parameter. The feedstock had a weighted N-content of 3.67%, a weighted P-content of 1.52%, a weighted pH of 7.47 and a weighted VS of 76%. Water extract parameters from the individual feedstock components were also determined individually and later combined on a weighted basis to parameterize the extracts. For the water extracts, the N-content was 1.03% while the P-content was 0.13%. The nutrient measurements were all on dry basis.

The percent change in earthworm biomass and the pair-wise comparisons of the mean percent change in earthworm biomass, with respect to the earthworm densities and feeding levels, are presented in Tables 2 and 3, respectively. The results from the two-way analysis of variance (ANOVA) procedure performed on data displayed in Table 2 showed that both the earthworm stocking densities and the feed levels resulted in significantly different earthworm biomass growth. The ANOVA also indicated significant interaction (at $\alpha = 0.05$) between stocking density and feeding rate. When interaction is significant, comparisons between means of one factor may be obscured by the interactions effects (Montgomery, 1991). To make comparison between means of one factor when significant interactions occur, Fisher's Least Significant Difference (LSD) procedure is one approach that is usually recommended for making

Table 3
Pair-wise comparisons: Earthworm biomass change (%) after eight weeks of vermicomposting

Initial earthworm density (kg-worms/m^2)	Mean earthworm biomass change (%)	Feed level (kg-feed/kg-worm/day)	Mean earthworm biomass change (%)
0.80	32.68 ^{a}	0.75	−0.06 $^\alpha$
1.20	75.64 ^{b}	1.0	22.27 $^\alpha$
1.60	79.59 ^{b}	1.25	107.75 $^\beta$
2.00	−14.63 ^{c}		

$^{a,b,c,\alpha,\beta}$ Means with the same letter were not significantly different at $\alpha = 0.05$ level.

Table 4
VS reduction (%) after eight weeks of vermicomposting

Initial earthworm density (kg-worms/m^2)	Feed levels (kg-feed/kg-worm/day)		
	0.75	1.0	1.25
0.80	11.33	12.18	12.12
	11.42	14.16	12.32
	10.44	10.10	10.24
1.20	12.62	12.33, 10.53	11.44, 12.46
	10.41	12.92, 11.40	10.07, 12.84
	10.81	9.38, 10.36	12.68, 13.01
1.60	12.21	12.68	13.32
	12.57	13.44	12.92
	12.08	13.85	13.76
2.00	11.19	12.26	9.72
	10.50	13.04	8.46
	10.12	10.13	6.41

any planned comparisons. The pair-wise comparisons (T-tests) based on Fisher's LSD procedure, further established that no significant difference (at $\alpha = 0.05$) in earthworm biomass was observed between 1.20 and 1.60 kg-worms/m^2; and between 0.80 and 1.20 kg-worms/m^2. The feed levels that did not result in significantly different earthworm biomass growth were at 0.75 and 1.0 kg-feed/kg-worm/day.

However, on the absolute scale, the differences are perhaps even more succinct. All the stocking densities (except, 1.20 and 1.60 kg-worms/m^2) and feeding levels resulted in substantial differences in the growth of earthworm biomass. The percent growth in earthworm biomass increased with stocking densities but dropped sharply at the 2.00 kg-worms/m^2 stocking density. More so, the individual earthworm's growth decreased with increase in stocking density. Datar et al. (1997), investigated effect of stocking density at three levels: 1.11, 1.85 and 2.59 kg-worms/m^2, of *Eudrilus eugeniae* (African Night Crawler) on the vermicomposting of Municipal Solid Waste (MSW). That study showed a general increase in the earthworm biomass but the increase decreased with the increase in stocking density. However, since the feed rate was also a variable, this makes it difficult to compare those studies with the studies presented here. Dominguez and Edwards (1997) also conducted a similar study on *Eisenia andrei* but on much smaller lab-scale plastic-flask-digesters, and with pig manure. In their studies, the increase in earthworm biomass increased with stocking density. They attributed this phenomenon to earlier sexual maturity of the earthworm at the higher stocking densities. Neuhauser et al. (1980) indirectly studied the effect of population density on growth and production, of *E. foetida*, and using linear regressions showed that growth declined with increase in population density, while production increased with population density. The results presented here agree with the general trend of the results obtained from the latter two studies.

The three feed levels investigated all seem to have resulted in a significant growth in earthworm biomass. The mean change in earthworm biomass increased with increasing feeding levels, in general (Table 3). These results suggest that a stocking density of 1.60 kg-worms/m^2 and a feeding level of 1.25 times the stocking density yields the highest earthworm biomass growth. It is important to note that, at 1.0 and 1.25 kg-feed/kg-worm/day, feeding levels, a substantial amount of the substrate, mainly the most recent, was still intact/unconverted at the end of the experiment.

A two-way ANOVA procedure conducted on results presented in Table 4 showed that the different earthworm densities produced significantly different volatile solids (VS) reductions, while the different feeding rates did not result in significantly different volatile solids reductions. This indicates some baseline conversion rate with respect to worm density. The percent mean reductions in volatile solids and the pair-wise comparisons based on Fisher's LSD method are presented in Table 5. Earthworm density at 1.60 kg/m^2 resulted in the highest reduction in the volatile solids. This would be expected, since this density also resulted in the highest growth of earthworm biomass. The reduction in VS did not significantly vary with substrate feeding rate. But as previously noted, the 1.0 and 1.25 kg-feed/kg-worm/day feeding levels, had a substantial amount of substrate that was still intact at the end of experiment. The relatively higher biomass growth in the higher feeding rates may perhaps explain this discrepancy. It is believed that, although there was substantially more undigested material in the higher feeding rates, the relatively higher growth of earthworm led to higher bioconversion rates, resulting in bigger reduction in VS, in the digested material. This evened out the VS reductions of the undi-

Table 5
Pair-wise comparisons: VS reduction (%) after eight weeks of vermicomposting

Initial earthworm density (kg/m^2)	Mean % VS reduction	Feed level (kg/kg-worm/day)	Mean % VS reduction
0.80	11.59 ^{a}	0.75	11.30 $^\alpha$
1.20	11.38 ^{a}	1.0	11.82 $^\alpha$
1.60	12.98 ^{b}	1.25	11.48 $^\alpha$
2.00	10.20 ^{c}		

$^{a,b,c,\alpha}$ Means with the same letter were not significantly different at $\alpha = 0.05$ level.

Table 6
Vermicompost pH after eight weeks of vermicomposting

Initial earthworm density (kg-worms/m^2)	Feed levels (kg-feed/kg-worm/day)		
	0.75	1.0	1.25
0.80	6.44	6.79	5.33
	6.30	7.17	5.70
	6.40	6.75	6.56
1.20	5.67	5.45, 5.45	5.46, 5.70
	5.78	6.01, 5.11	5.72, 5.32
	5.83	5.19, 5.38	5.36, 5.33
1.60	5.82	5.42	5.80
	5.75	5.64	5.63
	6.13	5.85	5.83
2.00	6.36	6.16	6.19
	6.98	5.94	6.27
	6.61	7.10	5.92

gested material. However, for the purpose of treatment of the biosolids, a stocking density of 1.60 kg-worm/m^2 and a feeding rate of 0.75 kg-feed/kg-worm/day, was found to be optimal.

The pH of the vermicompost is presented in Table 6. ANOVA indicated that the pH of the vermicompost significantly differed with both the stocking densities and the feeding rates. In general, there was a shift towards acidic conditions from the initial near neutral pH (7.47) of the substrate. The shifts appear to be directly related to the reductions in volatile solids and to the growth of earthworm biomass. The larger the increase in biomass growth, the greater the reduction in volatile solids, the more the shift towards the acidic situation.

These results however contradict an observation from the earlier work of Datar et al. (1997), whereby, the shift in pH was found to be in the opposite direction, and increasing with both worm density and process time. Most of the other work on vermicomposting (Albanell et al., 1988; Elvira et al., 1996, 1998; Hartenstein and Hartenstein, 1981; Mitchell, 1997) are in agreement with the studies presented here in as far as the lowering of pH during vermicomposting.

The pH-shift towards acidic conditions is believed to occur because of the resulting higher mineralization of the nitrogen and phosphorus into nitrites/nitrates and the orthophosphates, respectively. This pH shift could also be attributed to the bioconversion of the organic material into other various intermediate species of organic acids, which were neither qualified nor quantified in this study. It is also important to note that the pH shift is not only dynamic but is also substrate dependent. Further processing of the acidic intermediate products, as well as assimilation of the resulting acidic species will have the pH shift reversing. A different substrate could result in different intermediate species and hence portray a different behavior in pH shift.

The results of both the percent decrease in total solids and total bulk weights are summarized in Tables 7–9. The mean percent decrease in total solids, with respect to both the earthworm densities and the feeding rates, ranged from 33% to 42% while the total bulk weight decrease ranged between 22% and 33%. On analyzing the means displayed in Table 9 for any variation (ANOVA), both the total solids (TS) reduction and the total bulk weight were found to vary significantly with earthworm density. In general, the percent reduction in TS increased with an increase in earthworm density. These results are similar to those of studies conducted by Datar et al. (1997), on vermicomposting of Municipal Solid Waste (MSW). Arguably, these percentage reductions in both the TS and the bulk weight result in

Table 7
Pair-wise comparisons: Vermicompost pH after eight weeks of vermicomposting

Initial earthworm density (kg-worms/m^2)	Mean vermicompost pH	Feed level (kg-feed/kg-worm/day)	Mean vermicompost pH
0.80	6.40 [a]	0.75	6.17 [α]
1.20	5.56 [b]	1.0	6.10 [α,β]
1.60	5.76 [b]	1.25	5.82 [β]
2.00	6.39 [a]		

[a,b,α,β] Means with the same letter were not significantly different at $\alpha = 0.05$ level.

Table 8
TS (%) and total weight (%) reductions after eight weeks of vermicomposting

Initial earthworm density (kg-worms/m^2)	Feed levels (kg-feed/kg-worm/day)					
	0.75		1.0		1.25	
	TS	Total wt	TS	Total wt	TS	Total wt
0.80	31.48	25.92	34.08	18.50	35.77	22.56
1.20	40.56	22.73	32.74	18.91	39.63	25.84
			36.08	25.16	40.87	26.63
1.60	34.72	28.37	41.63	36.79	40.75	29.99
2.00	41.11	34.54	42.11	25.98	41.10	34.93

Table 9
Pair-wise comparisons: TS (%) and total weight (%) reductions after eight weeks of vermicomposting

Initial earthworm density (kg-worms/m^2)	Mean % reduction		Feed level (kg-feed/kg-worm/day)	Mean % reduction	
	TS	Total wt		TS	Total wt
0.80	33.78 [a]	22.33 [a]	0.75	36.97 [α]	28.64 [α]
1.20	37.77 [a,b]	24.04 [a]	1.0	37.37 [α]	25.81 [α]
1.60	39.03 [a,b]	31.72 [b]	1.25	39.47 [α]	28.78 [α]
2.00	41.44 [b]	32.82 [b]			

[a,b,c,α] Means with the same letter were not significantly different at $\alpha = 0.05$ level.

Table 10
Total N (%) and total P (%) in vermicompost after eight weeks

Initial earthworm density (kg-worms/m^2)	Feed levels (kg-feed/kg-worm/day)					
	0.75		1.0		1.25	
	N	P	N	P	N	P
0.80	3.99	2.13	3.84	2.16	3.44	1.99
	4.10	1.60	3.62	1.60	3.88	0.94
1.20	3.89	1.81	3.60, 3.61	1.97, 1.73	3.52, 2.94	2.18, 2.11
	3.49	2.12	3.56, 3.11	1.95, 1.80	3.64, 3.83	2.07, 1.98
1.60	3.74	2.24	3.99	2.27	3.78	2.22
	4.00	2.00	3.64	1.94	3.24	2.03
2.00	3.72	2.11	3.80	2.03	3.58	2.09
	4.20	2.12	3.30	1.84	3.31	1.95

Table 11
Pair-wise comparisons: Total N (%) and total P (%) in vermicompost after eight weeks

Initial earthworm density (kg-worms/m^2)	Mean (%)		Feed level (kg-feed/kg-worm/day)	Mean (%)	
	N	P		N	P
0.80	3.81 [a]	1.74 [a]	0.75	3.89 [α]	2.02 [α]
1.20	3.56 [b]	1.98 [a,b]	1.0	3.63 [β]	1.93 [α]
1.60	3.73 [a,b]	2.12 [b]	1.25	3.54 [β]	1.95 [α]
2.00	3.65 [a,b]	2.02 [a,b]			

[a,b,α,β] Means with the same letter were not significantly different at $\alpha = 0.05$ level.

Table 12
Soluble N (%) and P (%) in vermicompost after eight weeks

Initial earthworm density (kg-worms/m^2)	Feed levels (kg-feed/kg-worm/day)					
	0.75		1.0		1.25	
	N	P	N	P	N	P
1.80	0.72	0.13	0.51	0.17	0.55	0.14
1.20	0.59	0.13	0.49	0.14	0.39	0.08
			0.40	0.17	0.60	0.15
1.60	0.69	0.17	0.65	0.13	0.48	0.17
2.00	0.63	0.21	0.57	0.14	0.52	0.15

substantially lower handling and transport costs of the resulting product than the original raw substrate, from the waste-management viewpoint.

The contents of the nutrients, nitrogen and phosphorus, in the vermicompost product and water extracts from the vermicompost, as well as the respective results of statistical analyses, are shown in Tables 10–13. A statistical ANOVA performed on the data showed that, for nitrogen, it was only the soluble N that did not vary significantly (at $\alpha = 0.05$) with the earthworm density.

Table 13
Pair-wise comparisons: Soluble N (%) and P (%) in vermicompost after eight weeks

Initial earthworm density ($kg-worms/m^2$)	Mean (%)		Feed level (kg-feed/kg-worm/day)	Mean (%)	
	N	P		N	P
0.80	0.59^{a}	0.15^{a}	0.75	0.66^{α}	0.16^{α}
1.20	0.51^{a}	0.14^{a}	1.0	0.54^{β}	0.15^{α}
1.60	0.61^{a}	0.16^{a}	1.25	0.52^{β}	0.14^{α}
2.00	0.57^{a}	0.17^{a}			

$^{a,\alpha,\beta}$ Means with the same letter were not significantly different at $\alpha = 0.05$ level.

For P, ANOVA showed no significant variation amongst either the four stocking densities or amongst the three feeding levels investigated.

Although, the percent concentration of N (with respect to TS) remained the same in the vermicompost as in the feedstock, the total absolute amount decreased in parallel with the decrease in the TS during the process. On the other hand, the concentration of P increased in the vermicompost by between 14% and 39%, indicating that, the absolute amount of P did not substantially change during the vermicomposting. These results suggest that N and not P was either taken up and held in the worms' tissues or volatilized. A look at the soluble portions of the two nutrients indicates that soluble N was reduced by 35% to 50%, while the soluble P remained approximately the same. In this case, the potential environment impact from N in the vermicompost was substantially alleviated. Mitchell (1997) reports a similar decrease in concentrations of the soluble nutrients after vermicomposting of feedlot cattle manure.

5. Conclusions

For the bioconversion of biosolids into earthworm biomass, a stocking density of 1.60 $kg-worm/m^2$ at a feeding rate of 1.25 kg-feed/kg-worm/day seems the optimal combination. For the production of vermicompost, the same stocking density at a feeding rate of 0.75 kg-feed/kg-worm/day resulted in what appeared to be the most completely digested vermicompost. For all the stocking densities and feeding levels investigated in this study, substantial reduction of both the TS and total bulk weights were obtained, ranging from 22% to 42%. From the waste-management point of view, this translates into reduced handling and transport costs of the resulting product as opposed to the original raw substrate. The vermicomposting process not only maintained the N-content in the product but also substantially reduced the soluble portion, thus mitigating its impact on the environment. However, even after eight weeks into the process, the reduction in VS was still low (at $\approx$12%), meaning that the material was probably still not stable and continued treatment was perhaps desirable.

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