# 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$^2$ (1 lb-worms/3 ft$^2$) and a feeding rate of 1.25 kg-feeds/kg-worm/day resulted in the highest bioconversion of the substrate into earthworm biomass while the best vermicompost was obtained at the same stocking density and a feeding rate of 0.75 kg-feeds/kg-worm/day.*

***Keywords***: Waste Streams, Bioconversion, Environment, Vermicomposting, Stocking Density, Feeding Rate, and Biosolids.

## INTRODUCTION

Scientific investigations have established the viability of using earthworms as a treatment technique for numerous waste streams (Hand, et al., 1988; Raymond et al., 1988; Logsdon, 1994; Harris, 1990). The action of earthworms in this process is both physical/mechanical and biochemical. The physical /mechanical processes include: substrate's aeration, mixing, as well as actual grinding, while 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 therefore saves on all these unit operations. Hand et al. (1988), thus defines 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.

Although the viability of vermicomposting is uncontestable, only a limited amount of work has been done on the actual application. This is especially so with respect to some critical design criteria of vermicomposting facilities. The studies presented herein investigated two such important parameters: the stocking density and the feeding rate.

## 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/$m^2$ (0.5, 0.75, 1.0 and 1.25 lbs-worms/3-$ft^2$), while the feeding rates were investigated at 0.75, 1.0 and 1.25 kg-feeds/kg-worm/day. Effects or responses to be investigated were: product stability, worms' 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.

## MATERIALS AND METHODS

Experiments were performed in worm-bins measuring 0.56 m X 0.38 m X 0.25 m (Length* Breadth* 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 respective similar worm-bins, to provide the desired stocking densities. To effect the four desired stocking densities mentioned above, earthworms live-biomass loading were 0.17 kg, 0.26 kg, 0.34 kg, 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-feeds/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, feeds consisted of 4 parts biosolids to 3 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 rest of the weekly feeds consisted entirely of biosolids. The experiments were conducted in an environment whose temperature ranged between 25±6$^0$ C. The substrate material were maintained moist by spraying/sprinkling the surface with water every two days using a spray can.

At every feeding, the following parameters were determined: moisture content of the feed material, pH, the volatile solids and the ash contents. These analyses were carried out immediately after the samples were obtained and where not possible, then the samples were refrigerated at 4 $^0$C to minimize microbiological decomposition, until the analyses were done.

Solids matter were determined as residue on drying at 80 $^0$C for 23 hours (APHA, 1989). Volatile solids were obtained by ashing the dried sample at 550 $^0$C for 8.5 hrs (APHA, 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 Ehart and Brian (1997). This suspension was placed on a mechanical shaker at 230 rpm for 30 minutes prior to pH measurement. In the Ehart and Brian procedure, a 0.01-M 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 $^0$C for 23 hours (APHA, 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 minutes. The mixture was then centrifuged at 4000 rpm for 10 minutes 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. 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 worms castings, digested, as well as undigested biosolids and paper mulch.

## RESULTS AND DISCUSSIONS

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 extracts parameters from the individual feedstock's 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. In all the worm bins, moisture was maintained at 76.3±1.6-% (w.b).

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 |
| Biosolid Water Extract | 1.69 | 0.21 | | |
| Paper Mulch Water Extract | 0.04 | 0.00 | | |

Tables 2 and 3, respectively, present 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. 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 pair-wise comparisons (T-tests) based on Least Significant Difference (LSD) method further established that, no significant difference (at $\alpha$=0.05) in earthworm biomass was observed between: 1.20 kg-worms/m$^2$ and 1.60 kg-worms/m$^2$; and between: 0.80 kg-worms/m$^2$ 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 kg-worms/m$^2$ 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. 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 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. Suffice it to say that, the stocking density is an important parameter in the growth of earthworm biomass, independent of the species.

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 kg-feed/kg-worm/day, and 1.25 kg-feed/kg-worm/day, feeding levels, a substantial amount of substrate that was still intact/undigested was observed at the end of the experiment.

Table 2: Percent Change in Earthworm Live-weight

| Earthworm Density (kg-worms/m$^2$) | Feed Levels (kg-feeds/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 |

Table 3. Pair-wise Comparisons: Earthworm Biomass Change

| Earthworm Density (kg-worms/m$^2$) | Mean Earthworm Biomass Change | Feed Level (kg-feeds/kg-worm/day) | Mean Earthworm Biomass Change |
|---|---|---|---|
| 0.80 | 32.68$^a$ | 0.75 | -0.06$^a$ |
| 1.20 | 75.64$^b$ | 1.0 | 22.27$^a$ |
| 1.60 | 79.59$^b$ | 1.25 | 107.75$^b$ |
| 2.00 | -14.63$^c$ | | |

$^{a,b,c,1,2}$ Means with the same letter were not significantly different at $\alpha$=0.05 level.

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. Table 5 presents the percent mean reductions in volatile solids and the pair-wise comparisons based on LSD method. Earthworm density at 1.60 kg/m$^2$ resulted in the highest reduction in the volatile solids. This would be expected, since this

Table 4. VS Reduction (Percent)

| Earthworm Density (kg-worms/m$^2$) | Feed Levels (kg-feeds/kg-worm/day) | | |
|---|---|---|---|
| | 0.75 | 1.0 | 1.25 |
| | 11.33 | 12.18 | 12.12 |
| 0.80 | 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 |

density also resulted in the highest growth of earthworm biomass. The reduction in VS did not significantly vary with substrate's feeding rate. But as previously noted, the1.0 kg-feed/kg-worm/day and the1.25 kg-feed/kg-worm/day feeding levels, had a substantial amount of substrate that was still intact at the end of experiment. For the purpose of treatment of the biosolids therefore, 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.

Table 5. Pair-wise Comparisons: VS Reduction (Percent)

| 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$^a$ |
| 1.20 | 11.38$^a$ | 1.0 | 11.82$^a$ |
| 1.60 | 12.98$^b$ | 1.25 | 11.48$^a$ |
| 2.00 | 10.20$^c$ | | |

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

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. 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.

Table 6. Vermicompost pH

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

Table 7. Pair-wise Comparisons: Vermicompost pH

| Earthworm Density (kg-worms/m$^2$) | Mean Vermicompost pH | Feed Level (kg-feeds/kg-worm/day) | Mean Vermicompost pH |
|---|---|---|---|
| 0.80 | 6.40[a] | 0.75 | 6.17[a] |
| 1.20 | 5.56[b] | 1.0 | 6.10[a,b] |
| 1.60 | 5.76[b] | 1.25 | 5.82[b] |
| 2.00 | 6.39[a] | | |

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

Tables 8 and 9 summarize the results of both the percent decrease in total solids and total bulk weight. 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), only total solids (TS) reduction varied 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 results in substantially lower handling and transport costs of the resulting product than the original raw substrate.

Table 8. TS and Total Weight Reduction (Percent)

| Earthworm Density (kg-worms/m$^2$) | Feed Levels (kg-feeds/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 Reduction(Percent)

| Earthworm Density (kg-worms/m$^2$) | Mean % Reduction | | Feed Level (kg-feeds/kg-worm/day) | Mean % Reduction | |
|---|---|---|---|---|---|
| | TS | Total wt | | TS | Total wt |
| 0.80 | 33.78[a] | 22.33[a] | 0.75 | 36.97[a] | 28.64[a] |
| 1.20 | 39.41[a,b] | 23.67[a] | 1.0 | 38.06[a] | 25.83[a] |
| 1.60 | 39.03[a,b] | 31.72[a] | 1.25 | 39.47[a] | 28.43[a] |
| 2.00 | 41.44[b] | 32.82[a] | | | |

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

Tables 10 to 13 show 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. A statistical ANOVA performed on the data showed that, for nitrogen, it is only the soluble N that did not vary significantly (at $\alpha$=0.05) with the earthworm density. 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 volatized. A look at the soluble portions of the two nutrients indicate 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.

## 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 while for the production of vermicompost, the same stocking density at a feeding rate of 0.75 kg-feed/kg-worm/day resulted in 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%. 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 percent N-content in the product but also substantially reduced the soluble portion, thus mitigating its impact on the environment. However, even after 8 weeks into the process, the reduction in VS was still low (at approximately 12%), meaning that the material was still not stable and continued treatment was perhaps desirable.

Table 10. Total N and Total P in Vermicompost

| Earthworm Density (kg-worms/m$^2$) | Feed Levels (kg-feeds/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 (Percent)

| Earthworm Density (kg-worms/m$^2$) | Mean Percent | | Feed Level (kg-feeds/kg-worm/day) | Mean Percent | |
|---|---|---|---|---|---|
| | N | P | | N | P |
| 0.80 | 3.81[a] | 1.74[a] | 0.75 | 3.89[a] | 2.02[a] |
| 1.20 | 3.56[b] | 1.98[a] | 1.0 | 3.63[b] | 1.93[a] |
| 1.60 | 3.73[a,b] | 2.12[a,b] | 1.25 | 3.54[b] | 1.95[a] |
| 2.00 | 3.65[a,b] | 2.02[a] | | | |

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

Table 12. Soluble Nitrogen and Phosphorus in Vermicompost (Percent)

| Earthworm Density (kg-worms/m$^2$) | Feed Levels (kg-feeds/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 |

Table 13. Pair-wise Comparisons: Soluble N and P in Vermicompost (Percent)

| Earthworm Density (kg-worms/m$^2$) | Mean Percent | | Feed Level (kg-feeds/kg-worm/day) | Mean Percent | |
|---|---|---|---|---|---|
| | N | P | | N | P |
| 0.80 | 0.59[a] | 0.15[a] | 0.75 | 0.66[a] | 0.16[a] |
| 1.20 | 0.51[a] | 0.14[a] | 1.0 | 0.54[b] | 0.15[a] |
| 1.60 | 0.61[a] | 0.16[a] | 1.25 | 0.52[b] | 0.14[a] |
| 2.00 | 0.57[a] | 0.17[a] | | | |

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

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