many attempts to identify and seal the leaks and run OUR tests without success, the OUR parameter was dropped from the experimental plan.

3.2.4 Laboratory Analyses - Water Extracts

Water compost extracts were obtained by mechanically shaking oven dried compost samples with distilled water for 2 hours (solid liquid ratio = 1/10). The extracts were centrifuged at 5,000g for 20 minutes, and filtered through a Watsman No. 1 filter paper (11 µm). The water extracts were developed using the method used by Garcia *et al.* (1991b).

The water extracts were analyzed immediately for NH_3 and organic nitrogen and were stored in teflon sealed glass bottles in a refrigerated room at 4°C until they were analyzed for carbon content.

3.2.4.1 Total Organic Carbon (TOC) Content

The total carbon (TC) and total inorganic carbon (TIC) content of the compost water extracts were determined by using a Dohrman DC-80 Organic Carbon Analyzer. The water extracts were diluted 10 fold prior to injection Using a volumetric pipet, 1 ml of compost water extract was transferred to a 10ml volumetric flask and topped up with. distilled water. The total organic carbon (TOC) content was calculated by subtracting the TIC value from TC value for each water extract sample. At least three syringe injections per extract were performed. Multiple extracts were developed and analyzed for selected samples to provide an indication of variance.

The compost water extracts were prepared from ground, oven-dried samples versus air dried samples. This sample preparation method may have introduced some possible errors in the TOC results. Drying the samples at the higher temperature would result in potential volatile organic and ammonia losses, and hence, affect the water extract results. Jimenez and Garcia (1992b) found there was only about a 1.2 to 1.8% more water soluble carbon in air dried and ground samples than in fresh samples. The volatile organic and ammonia losses may not be significant at the 103°C temperature. Tests would be required to assess the potential losses.

An additional source of error was the time required to filter the compost water extracts. To obtain enough water extract for analyses, the earlier grass-like samples required approximately 30 additional minutes of filtration time. The longer filtration times introduced possible losses in TOC and ammonia.

The errors introduced in obtaining the initial compost samples are perhaps larger in magnitude than the errors due to sample drying and water extract preparation.

3.2.4.2 Organic and Ammonia Nitrogen

The organic and ammonia nitrogen contents of the water extracts were determined by the Kjeldahl method described in Standard Methods for the Examination of Water and Wastewater 1989, 17th edition. Generally, duplicate aliquots of the water extracts were analyzed for NH_3 and organic nitrogen content.

4.0 RESULTS AND ANALYSIS

This section of the thesis reviews the results of the factorial experiments, discusses the decomposition kinetics of the various compost piles and the results of the ARIMA (Autoregressive integrated moving average) analyses of pile temperature data.

4.1 Factorial Experiments

The purpose of the field factorial experiments were to systematically evaluate the influence of key operational parameters on the decompostion rate of yard waste in a windrow type operation. The following sections describe the changes in operational and response variables and the results of the factorial experiments.

4.1.1 Trends in Operational Variables

4.1.1.1 C:N ratio

The C:N ratio of the various piles generally followed a decreasing trend throughout the first 112 days of the process, the active composting phase, and then remained fairly constant or varied slightly during the remaining 113 days, the maturation phase, of the process. Figures 4.1 to 4.8 show the C:N ratio versus composting days for the low, medium and high C:N ratio pile sections, as well as control piles C1 and C2 and the replicate piles R1 and R2.

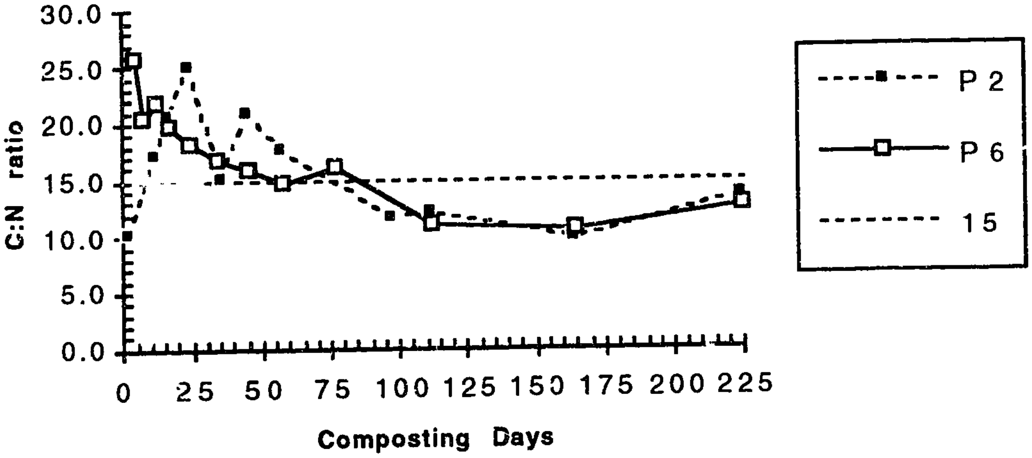


Figure 4.1 C:N ratio vs Composting Days - Piles 2 and 6

Hi C:N, Low M.C.

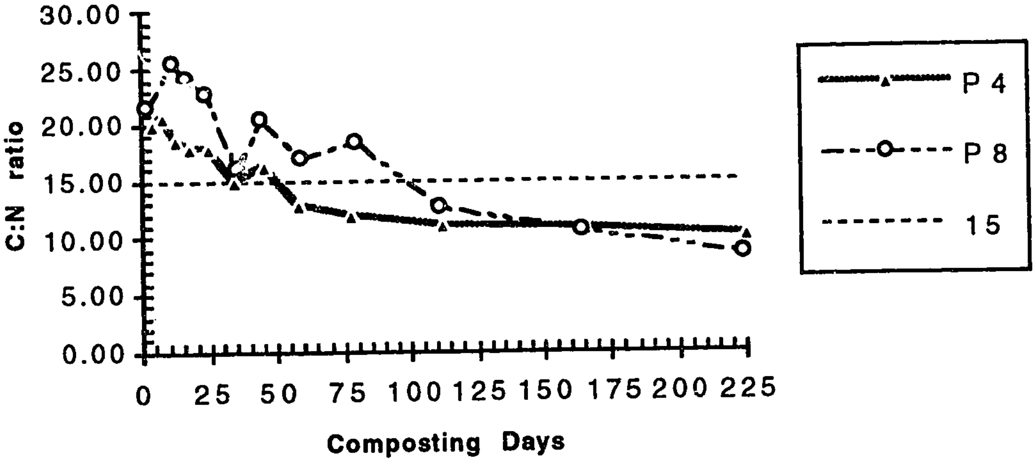


Figure 4.2 C:N ratio vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

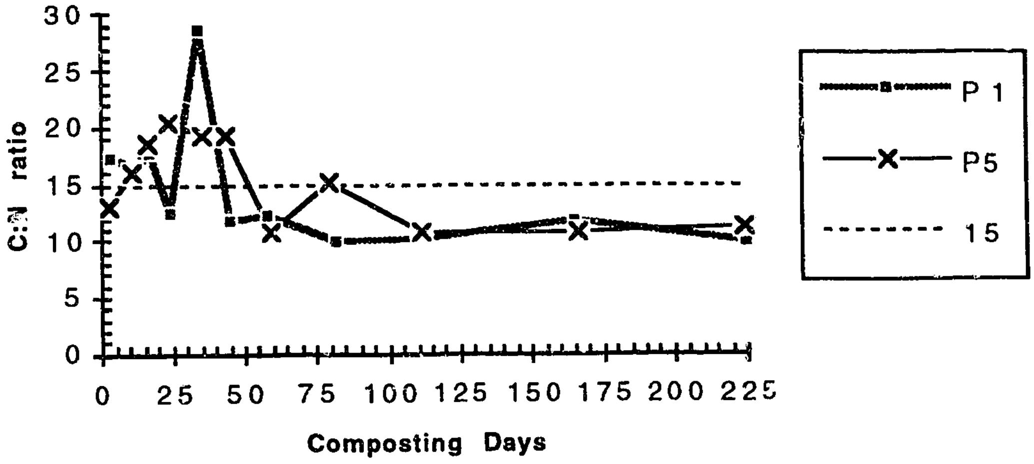


Figure 4.3 C:N ratio vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

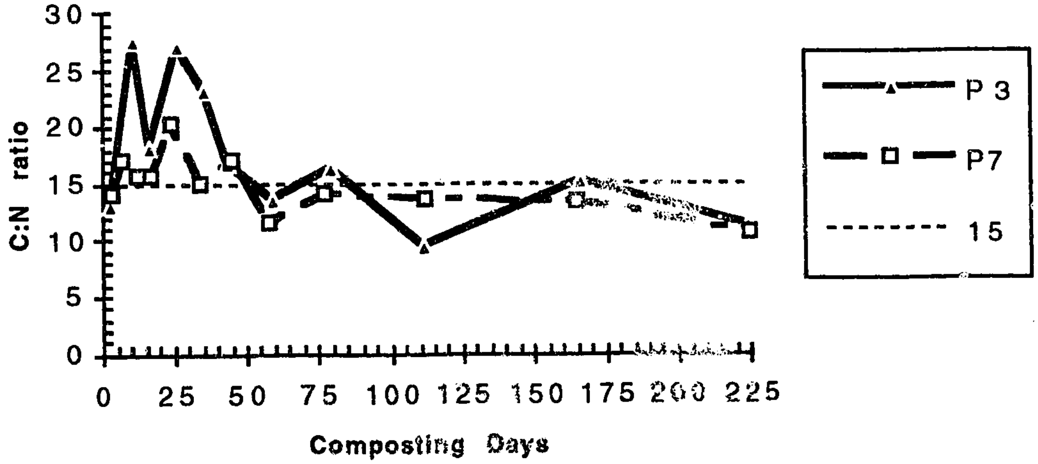


Figure 4.4 C:N ratio vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

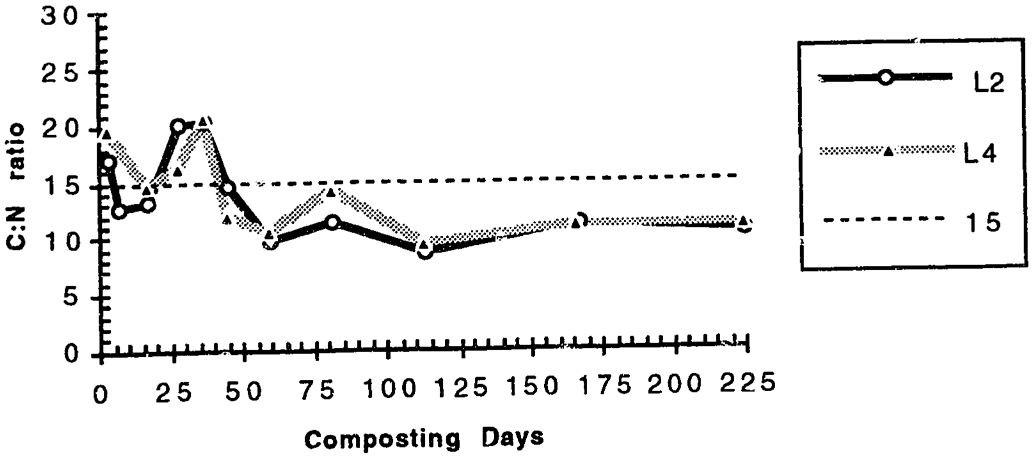


Figure 4.5 C:N ratio vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

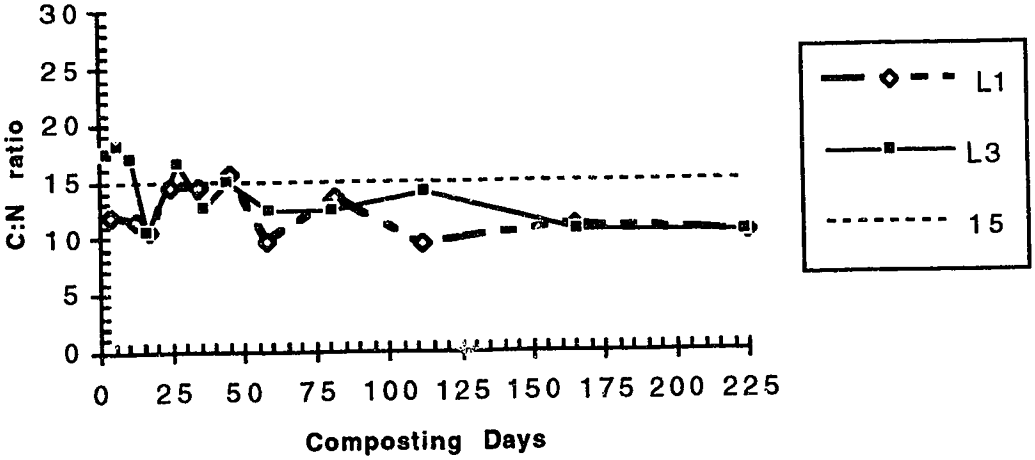


Figure 4.6 C:N ratio vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

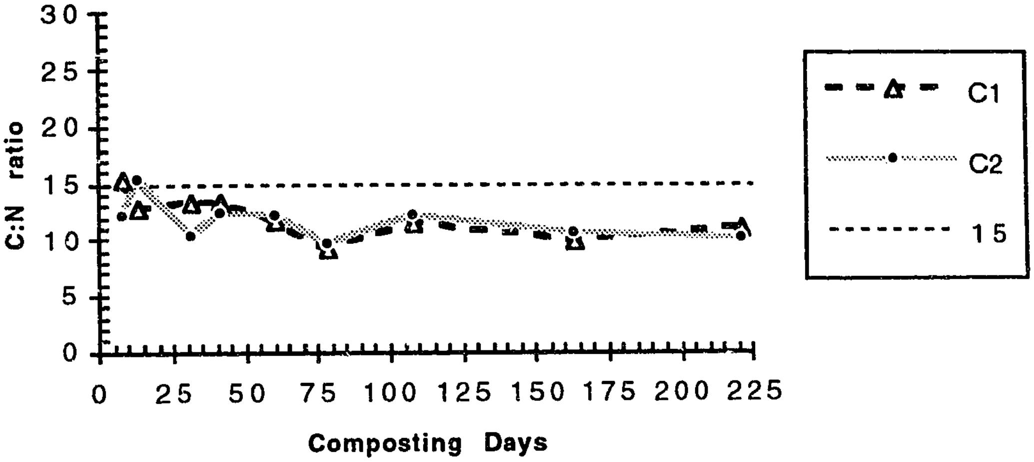


Figure 4.7 C:N ratio vs Composting Days - Piles C1 and C2

Control Piles

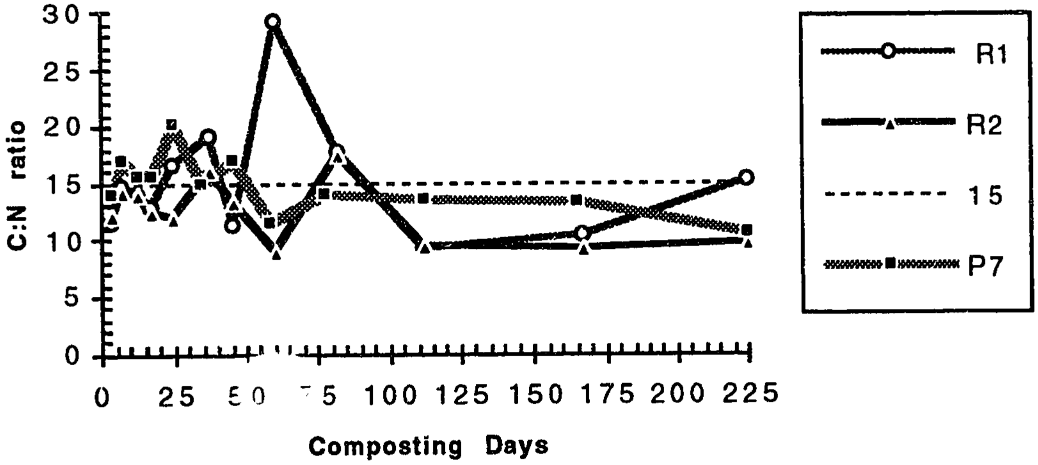


Figure 4.8 C:N ratio vs Composting Days - Piles 7, R1 and R2

Med C:N, Hi M.C.

Replicates

The C:N ratio values of the different piles generally fluctuated more during the first 35 to 45 days of the process and usually increased from the initial values during this period. Possible reasons for the fluctuations in the C:N ratio values are inadequate mixing, sampling errors, ammonia losses and the amount of straw added to the piles. Figure 4.8 clearly shows the variability in the C:N ratio data for piles with the same experimental design. Table 4.1 lists the initial and final C:N ratio values for the various piles.

Table 4.1 - Initial and Final Pile C:N Values

Pile No.	Pile Designation	Initial C:N ratio	Final C:N ratio
1	Med C:N, Low M.C., Low Por.	17.12	9.72
2	Hi C:N, Low M.C., Low Por.	10.19	13.49
3	Med C:N, Hi M.C., Low Por.	13.12	11.19
4	Hi C:N, Hi M.C., Low Por.	20.08	9.99
5	Med C:N, Low M.C., Hi Por.	13.13	11.11
6	Hi C:N, Low M.C., Hi Por.	25.80	12.57
7	Med C:N, Hi M.C., Hi Por.	13.92	10.52
8	Hi C:N, Hi M.C., Hi Por.	21.60	8.46
R1	Med C:N, Hi M.C., Hi Por.	11.45	15.15
R2	Med C:N, Hi M.C., Hi Por.	12.20	9.68
L1	Low C:N, Hi M.C., Low Por.	11.93	10.36
L2	Low C:N, Low M.C., Low Por.	17.03	10.29
L3	Low C:N, Hi M.C., Hi Por.	17.33	10.30
L4	Low C:N, Low M.C., Hi Por.	19.83	10.87
C1	Control Pile	15.27	11.07
C2	Control Pile	12.09	10.12

The initial C:N ratio values for piles sections L1 to L4 varied from 12:1 to 19:1. The final C:N ratio values for piles L1 to L4 were all approximately 10:1. The medium C:N ratio piles 3, 5 and 7 had initial values of about 13:1 and final C:N ratio values of approximately 11:1. Pile 1, the other medium C:N ratio pile section, had a starting value of about 17:1 and a final value of 13.5:1. The high C:N ratio piles 2, 4, 6 and 8 had initial C:N values from about 10:1 to 26:1 and final values varying from 8.5:1 to 13.5:1. The high

C:N ratio piles generally had higher C:N ratio values than the medium and low C:N ratio piles. The medium to low C:N ratio piles had similar values mainly because the amount of barley straw initially mixed with the respective pile sections did not increase the C:N ratio as much as expected. The C:N ratio of the barley straw was determined to be 55.7:1 by Norwest Labs, compared to literature values between 129 to 150:1 for wheat straw. At the time of the composting experiment, only barley straw was available. To increase the C:N ratio of piles 2 and 8 (on day 17) and piles 4 and 6 (on day 18) two front end loader buckets of wheat straw were added to each of these pile sections on August 17, 1992. On August 26, 1992 (days 26 and 27 respectively), an additional 3/4 of a bucket of wheat straw was mixed into each of the high C:N ratio piles. One bucket of barley straw was also added to piles 1 and 7 on composting day 18 and piles 3 and 7 on composting day 17 to increase the C:N ratio of the those pile sections. The initial C:N ratios of the City of Edmonton control piles C1 and C2 were 15.3 and 12.1, while the final values were 11.1 and 10.1 respectively.

4.1.1.2 Moisture Content

The factorial experiment included testing the affect of two different moisture content levels on the decomposition of the yard waste. The experimental design called for certain pile sections to be maintained at a moisture content of 60% and others at 40%. It was not possible to maintain the moisture content of the pile sections at the desired levels. As expected, the moisture content of the piles sections generally decreased dramatically during the first 2 to 3 weeks of the process due to evaporative losses as a result of the high temperatures. Water was added to the piles on five occasions to increase the moisture content during the first 73 days of the process. The moisture content generally followed a gradual decreasing trend for the remainder of the composting period. As the compost matured and the temperature of the piles cooled, evaporative losses decreased. The moisture content of the various piles are displayed in Figures 4.9 to 4.16. The vertical dashed lines in Figures 4.9 to 4.16 represent when the pile sections were watered.

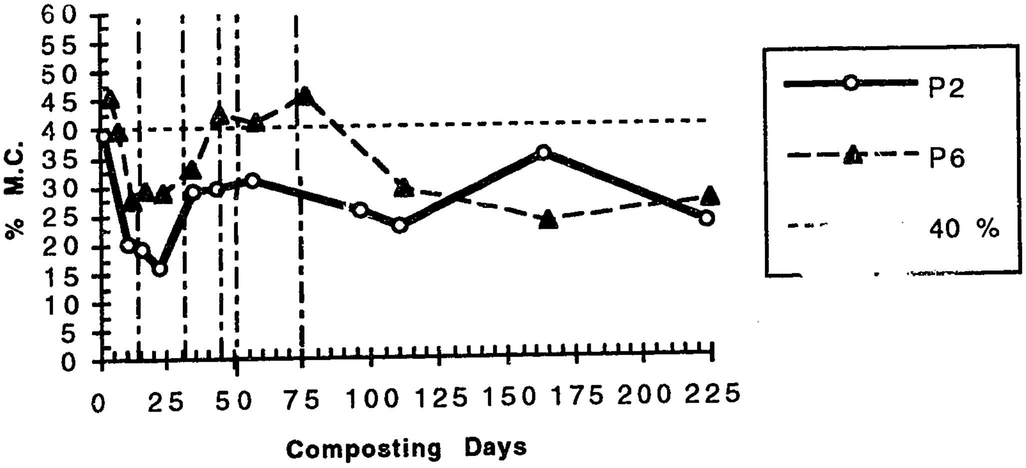


Figure 4.9 M.C. vs Composting Days - Piles 2 and 6
Hi C:N, Low M.C.

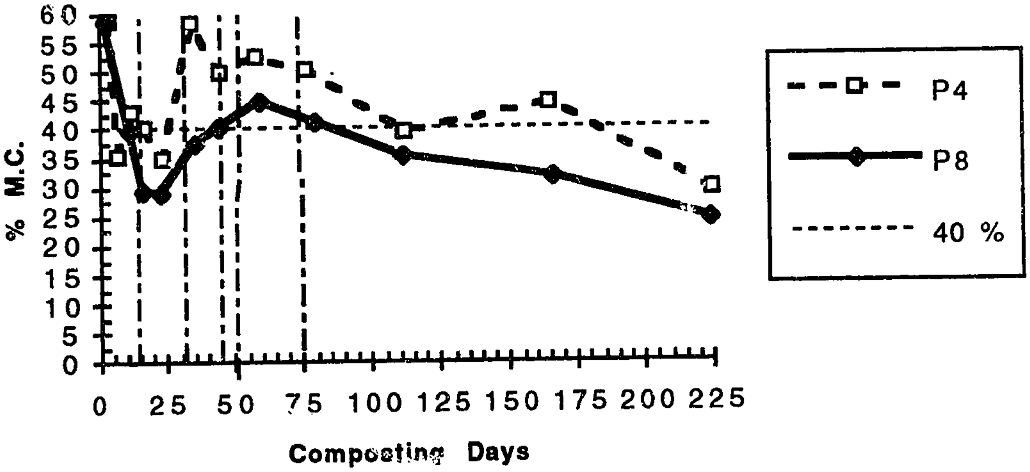


Figure 4.10 M.C. vs Composting Days - Piles 4 and 8
Hi C:N, Hi M.C.

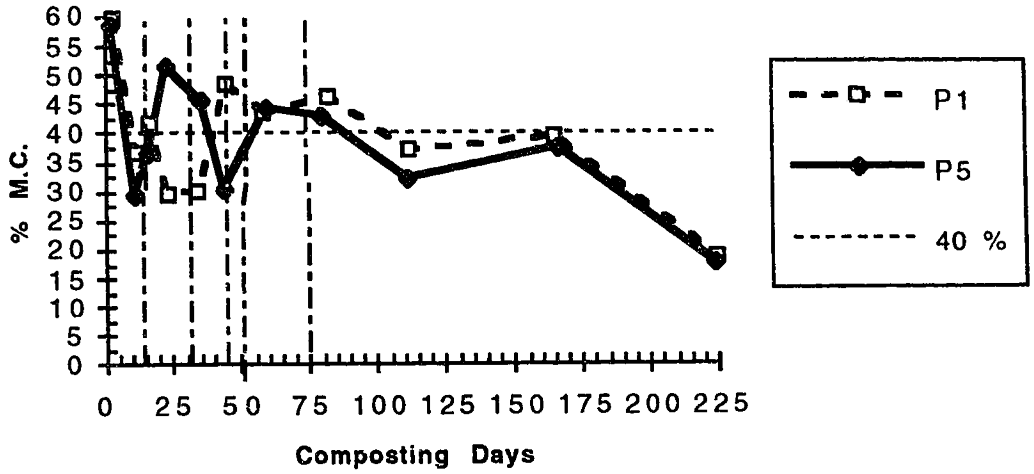


Figure 4.11 M.C. vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

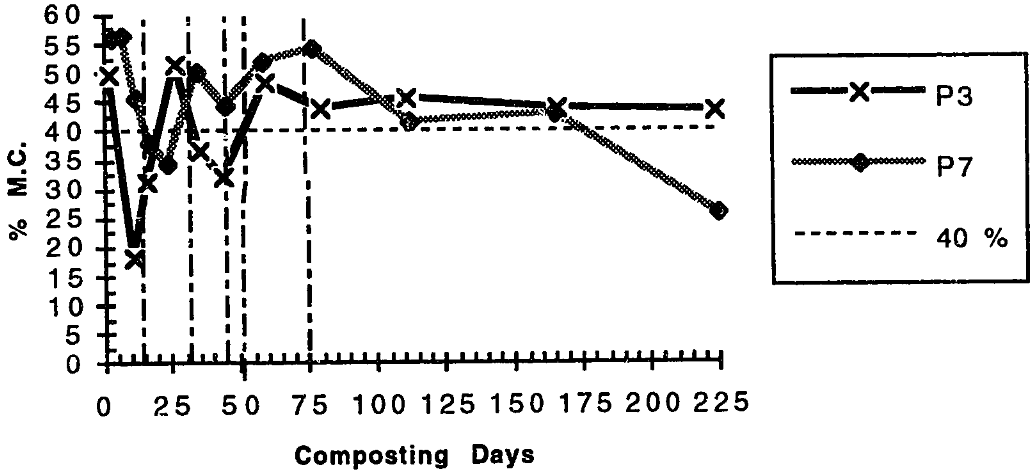


Figure 4.12 M.C. vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

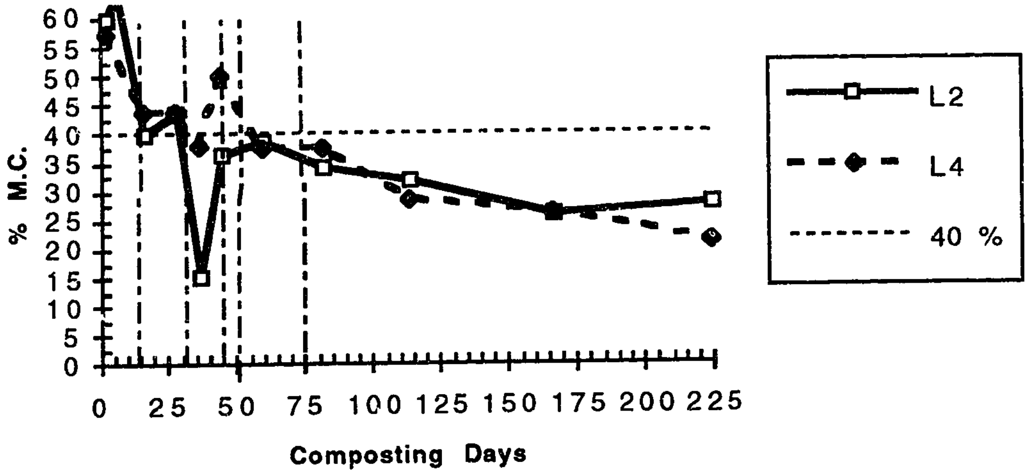


Figure 4.13 M.C. vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

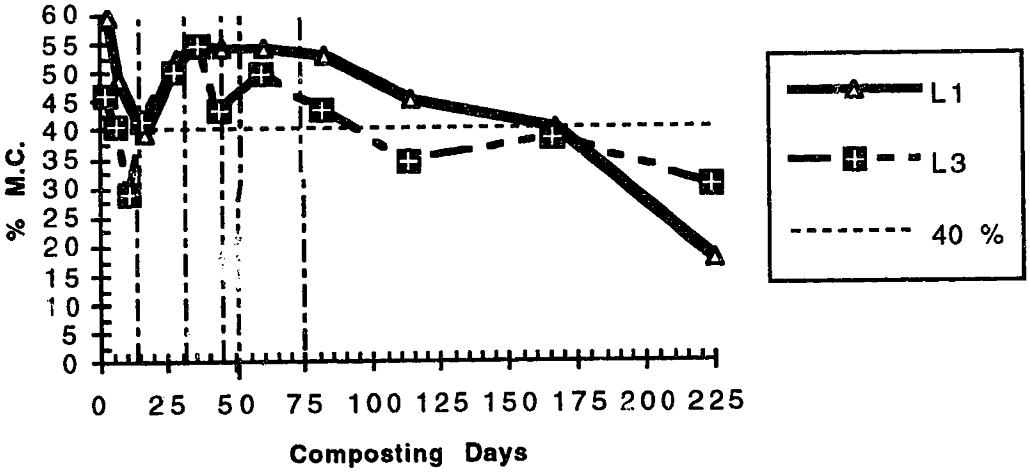


Figure 4.14 M.C. vs Composting Days - Piles L2 and L4

Low C:N, Hi M.C.

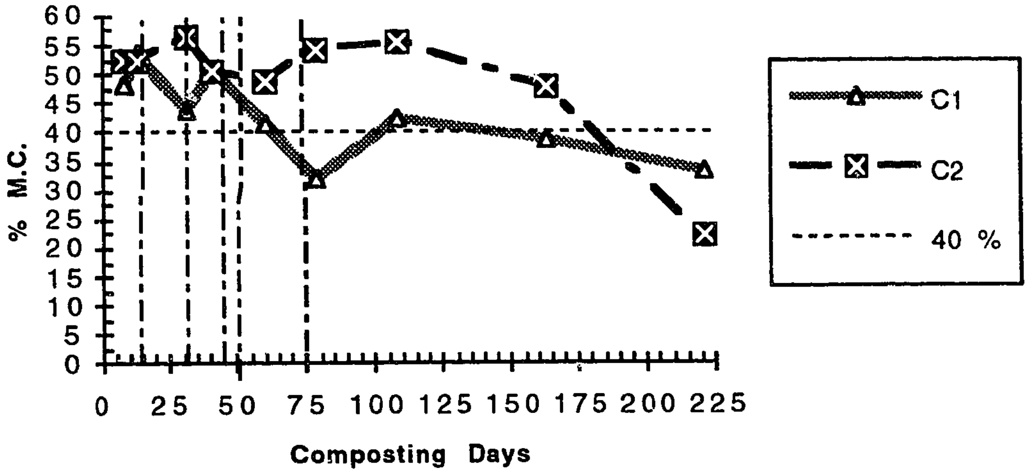


Figure 4.15 M.C. vs Composting Days - Piles C1 and C2

Control Piles

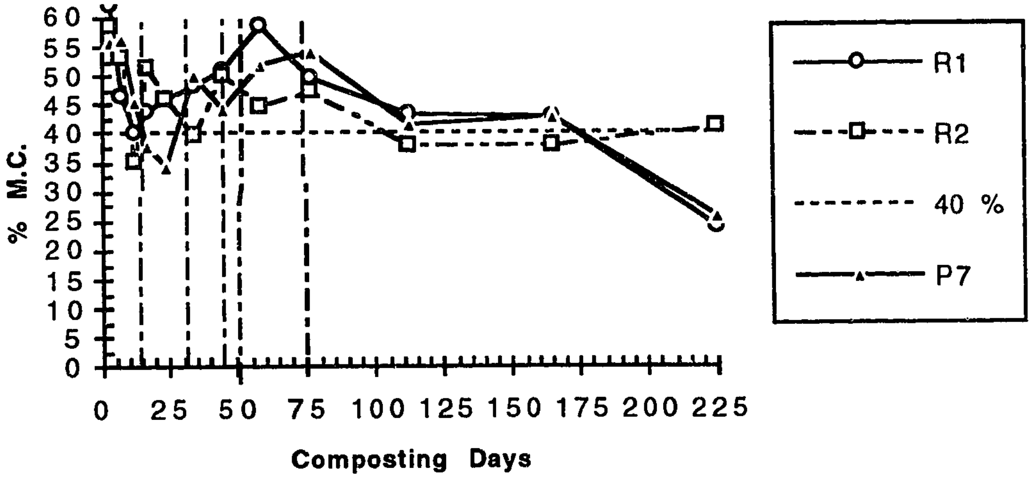


Figure 4.16 M.C. vs Composting Days - Piles R1 and R2 and 7

Med C:N, Hi M.C.- Replicate Piles

The directional changes in moisture content of the piles were consistent with changes described in the literature. Table 4.2 lists the weighted average % moisture contents for the various piles. The weighted average for each pile was calculated by the equation shown

$$\text{Avg \% M.C.} = \frac{\text{Days1*MC1} + \text{Days2*MC2} + \ldots + \text{Daysn*MCn}}{\text{Days1} + \text{Days2} + \ldots + \text{Daysn}} \qquad (26)$$

MCn = % M.C measurements at different intervals of the composting process.

Daysn = number of composting days between each % M.C. measurement.

Table 4.2 - Weighted Average % Moisture Content of the Compost Piles

Pile No.	Pile Designation	Planned Level	Weighted Avg Full Period	Weighted Avg Active Phase
1	Med C:N, Low M.C., Low Por.	40%	34.4%	40.5%
2	Hi C:N, Low M.C., Low Por.	40%	27.0%	25.2%
3	Med C:N, Hi M.C., Low Por.	60%	42.3%	41.1%
4	Hi C:N, Hi M.C., Low Por.	60%	41.0%	45.7%
5	Med C:N, Low M.C., Hi Por.	40%	32.8%	38.4%
6	Hi C:N, Low M.C., Hi Por.	40%	30.7%	35.9%
7	Med C:N, Hi M.C., Hi Por.	60%	40.1%	46.5%
8	Hi C:N, Hi M.C., Hi Por.	60%	33.1%	38.3%
R 1	Med C:N, Hi M.C., Hi Por.	60%	40.6%	48.4%
R 2	Med C:N, Hi M.C., Hi Por.	60%	41.7%	43.8%
L 1	Low C:N, Hi M.C., Low Por.	60%	39.2%	49.9%
L 2	Low C:N, Low M.C., Low Por.	40%	31.3%	35.7%
L 3	Low C:N, Hi M.C., Hi Por.	60%	30.6%	42.5%
L 4	Low C:N. Low M.C., Hi Por.	40%	30.7%	37.5%
C1	Control Pile	None	39.2%	42.6%
C2	Control Pile	None	43.8%	53.5%
		Avg High M.C. Pile	**38.6%**	**44.5%**
		Avg Low M.C. Pile	**31.2%**	**35.5%**

Active Phase - up to and including samples taken on November 19-21, 1992.

Although is was not possible to maintain the planned experimental moisture content levels, the moisture content for the 60% moisture content piles were generally higher than the 40% moisture piles. The overall weighted average moisture content for the 60% piles was 38.6% with a standard deviation of 3.86 for the full composting period compared to 31.2% with a standard deviation of 5.36 for the 40% moisture content piles. For the period up to and including the November 19-21, 1992 samples, referred to as the active stage, the overall weighted average moisture levels for both the high and low moisture piles were higher than the values calculated for the full composting period. The high moisture level piles had an overall average weighted moisture content of 44.5% for the active period with a standard deviation of 4.31. The overall average weighted moisture level for the low moisture experimental piles during the same period was 35.5% with a standard deviation of 2.49. These values reflect the fact the compost moisture contents of the various piles were higher during the active stages of the composting process, which is desired from an operational viewpoint. The overall weighted average moisture contents for the high and low M.C. piles were found to be significantly different using the Student t test at the 95% confidence level. The calculated t values were 2.86 and 4.95 respectively for the full and active composting period tests compared to t value from the table of 2.18.

In comparison, the overall weighted average moisture content for the control piles C1 and C2 was 2.9% higher for the full composting period and 3.6% higher for the active period than the values calculated for the experimental 60% moisture content pile sections. Piles 7, R1 and R2 having the same experimental treatment design, had an overall weighted average moisture content of 40.8% with a standard deviation of 0.82 for the full composting period. The difficulty experienced trying to maintain the experimental moisture levels may be due to the method of moisture addition, the characteristics of the composting materials, sampling and testing frequency and environmental factors. Environmental factors such as the amount of precipitation and ambient air temperatures may influence the moisture content. High ambient air temperatures will increase evaporation losses especially from the outer layers of the compost piles. Although it is difficult to quantify the impact of the precipitation, two observations were noted. Firstly, after a significant rain only the top 25 to 50mm (approximately) of the outer layer seemed to be wet. Secondly, when the snow cover melted in late March and early April, the top 100 to 150mm of the outer layer also seemed quite moist compared to the inner layers.

4.1.1.3 Porosity Adjustment

The porosity values for the various piles generally decreased throughout the process with the largest reduction observed in the first 60 days for most piles. This is consistent with the fact the rate of decomposition is higher during the first one or two months of the composting process when the easier degradable components are being broken down. Wood chips were added to pile 5 on composting day 70 and to piles 6 and 7 on composting day 71 to increase the porosity of the compost piles. Additional wood chips were also added to piles R1 and R2 on composting day 78 and to piles 8, L3 and L4 on composting day 77. The wood chip additions did not consistently create a significant increase in porosity values. Figures 4.17 to 4.20 display the porosity values versus composting time for the adjusted and maintained porosity piles.

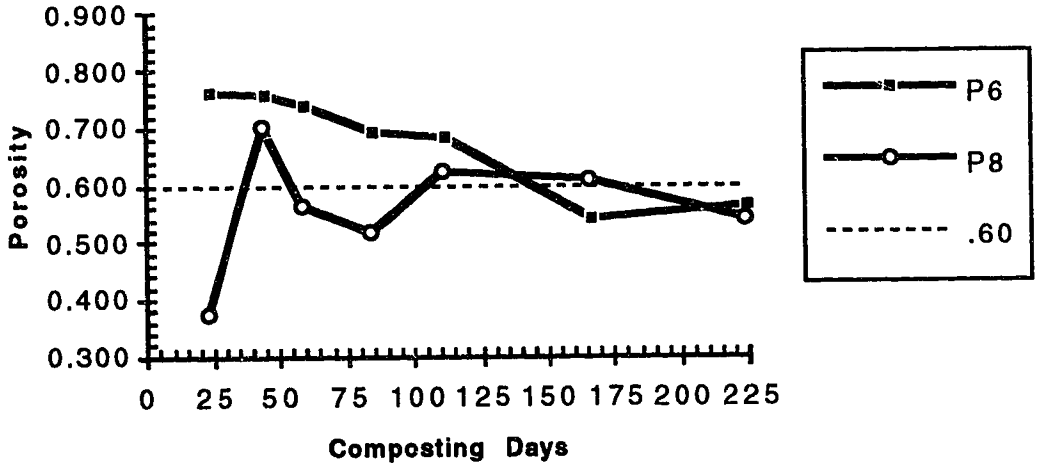


Figure 4.17 Porosity vs Composting Days - Piles 6 and 8
HI C:N, HI Por.

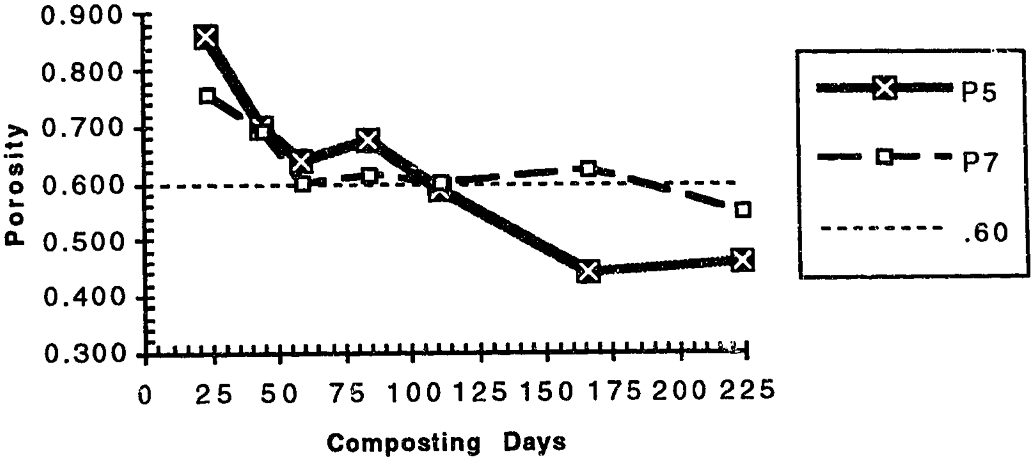


Figure 4.18 Porosity vs Composting Days - Piles 5 and 7

Med C:N, Hi Por

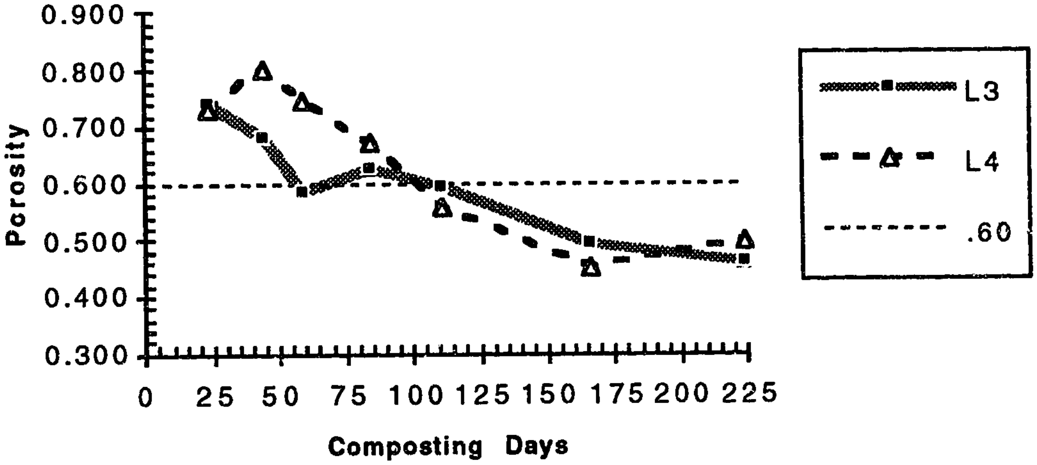


Figure 4.19 Porosity vs Composting Days - Piles L3 and L4

Low C:N, Hi Por.

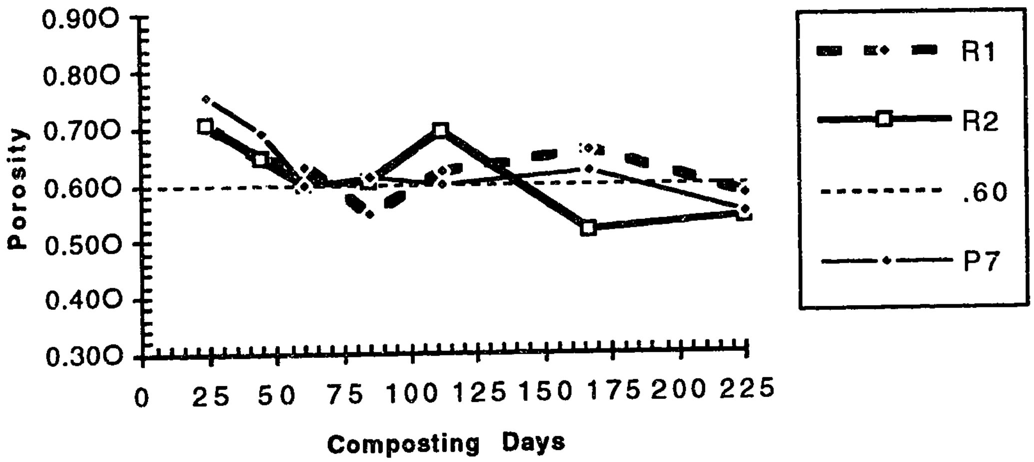
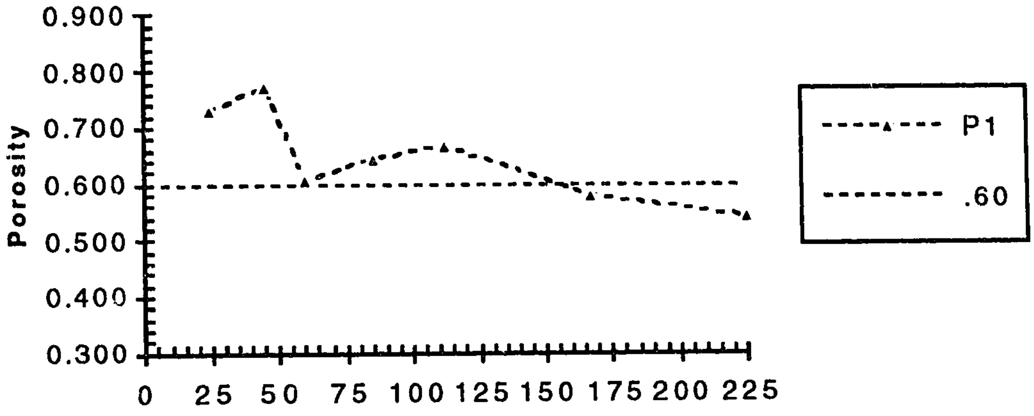


Figure 4.20 **Porosity vs Composting Days - Piles 7, R1 and R2**
Med C:N, Hi Por
Replicate Piles

Porosity values for piles 5, 6, 7, L4, R1, R2 and 8 generally decreased or remained fairly level for the first porosity measurements after the addition of more wood chips. The porosity values for Piles 8 and R1 increased for measurements taken in November and January. The porosity values for Pile 1, for example, increased for the October and November samples even though no additional wood chips were mixed into the pile section. Figure 4.21 shows the porosity measurements for Pile 1 vs composting days.



Composting Days

Figure 4.21 **Porosity vs Composting Days - Pile 1**
Med C:N - Porosity Adjusted and Maintained

There is no conclusive evidence indicating the addition of wood chips to certain experimental piles increased the porosity of these piles based on visual observation of the plots. Table 4.3 displays the first and final porosity measurements for the various experimental piles.

Table 4.3 - Pile Porosity Values

Pile No.	Pile Designation	Experimental Plan	Initial Porosity	Final Porosity
1	Med C:N, Low M.C., Low Por.	Initially Adjusted	0.732	0.543
2	Hi C:N, Low M.C., Low Por.	Initially Adjusted	0.685	0.501
3	Med C:N, Hi M.C., Low Por.	Initially Adjusted	0.725	0.579
4	Hi C:N, Hi M.C., Low Por.	Initially Adjusted	0.771	0.534
5	Med C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.861	0.458
6	Hi C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.761	0.561
7	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.753	0.548
8	Hi C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.372	0.540
R 1	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.703	0.578
R 2	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.702	0.537
L 1	Low C:N, Hi M.C., Low Por.	Initially Adjusted	0.756	0.371
L 2	Low C:N, Low M.C., Low Por.	Initially Adjusted	0.711	0.553
L 3	Low C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.740	0.460
L 4	Low C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.732	0.497
		Avg	**0.715**	**0.519**
		Stdev	**0.107**	**0.057**

The mean porosity value for the initial tests for the experimental piles was 0.72 with a standard deviation of 0.11. The mean final porosity value for the pile sections was 0.52 with a standard deviation of 0.06. The initial mean porosity value for the initially adjusted (low porosity) piles was 0.73 compared to a value of 0.70 for the porosity adjusted piles. The final mean porosity value for the initially adjusted (low porosity) piles was 0.51 compared to a value of 0.52 for the porosity adjusted (high porosity) piles. There was no statistical difference between the mean porosity values for the high and low porosity piles for both the initial and final porosity values using the t test. The control piles C1 and C2 had an average porosity value of 0.73 for the initial test with a standard deviation of 0.007. The mean final porosity value and standard deviation for the control piles was 0.67 and 0.016. The lower final mean porosity value determined for the experimental piles provides an indication the organic materials in the experimental piles had decomposed further than the yard waste in the control piles.

The porosity values measured for the various piles are similar to values observed by Fleming (1991) in the composting of mixtures of green waste, leaves and wood wastes in Florida. The initial mean porosity for her four experimental windrows was 0.70 compared to 0.72 determined for the experimental piles. The final mean porosity for her windrows was 0.30, which is lower than the final values observed for our composting piles. The difference may be explained by the type of organic materials, testing errors, degree of stabilization, the amount of wood wastes in the windrows. Fleming's two windrows containing approximately 50% wood wastes had final porosity values of 0.336 and 0.356, which supports the comment that the wood chips mixed into our experimental piles may increase the final porosity values.

4.1.2 Trends in Response Variables

The primary response variables used to measure the degree and rate of degradation of the organic materials in these experiments were the percent change in total carbon of solid samples and the percent change in TOC of compost water extracts as well as the more absolute indicator the ratio of Organic C/Organic N ($C:N_W$) of water extracts. The measurements of OUR were not successful, due to problems experienced during testing. No results are available for this parameter. Secondary, but less reliable indicators of maturity used in these studies, are average pile temperatures, percent increases in dry bulk density. Tables 4.4 and 4.5 list the results of the primary response variables as well as % increases in bulk densities over the full and active composting periods.

Table 4.4 - Pile Response Variable Values
Full composting period

		Response Variables		
Pile No.	**Pile Designation**	% Decrease in % C (SS)	% Decrease in TOC (WE)	% Increase in DBD
1	Med C:N, Low M.C., Low Por.	44.7	81.5	49.5
2	Hi C:N, Low M.C., Low Por.	42.7	84.8	55.8
3	Med C:N, Hi M.C., Low Por.	54.5	84.5	46.4
4	Hi C:N, Hi M.C., Low Por.	52.6	61.3	62.6
5	Med C:N, Low M.C., Hi Por.	49.5	80.1	71.3
6	Hi C:N, Low M.C., Hi Por.	56.6	68.2	63.4
7	Med C:N, Hi M.C., Hi Por.	56.1	78.3	47.6
8	Hi C:N, Hi M.C., Hi Por.	73.5	86.0	34.4
R 1	Med C:N, Hi M.C., Hi Por.	17.8	80.9	49.9
R 2	Med C:N, Hi M.C., Hi Por.	57.1	80.8	48.2
L 1	Low C:N, Hi M.C., Low Por.	37.9	83.8	68.3
L 2	Low C:N, Low M.C., Low Por.	66.4	82.1	56.9
L 3	Low C:N, Hi M.C., Hi Por.	53.3	73.8	60.7
L 4	Low C:N, Low M.C., Hi Por.	53.5	68.0	59.9
C 1	Control Pile	26.6	Not Tested	34.3
C 2	Control Pile	51.6	Not Tested	38.5

WE= Compost water extracts
SS = Compost solid samples

Table 4.5 - Pile Response Variable Values
Active composting period

Pile No.	Pile Designation	Response Variable % Decrease in % C (SS)	 % Decrease in TOC (WE)	 % Increase inDBD
1	Med C:N, Low M.C., Low Por.	48.3	80.2	39.6
2	Hi C:N, Low M.C., Low Por.	47.4	81.2	56.7
3	Med C:N, Hi M.C., Low Por.	46.8	81.4	46.7
4	Hi C:N, Hi M.C., Low Por.	50.7	67.6	59.5
5	Med C:N, Low M.C., Hi Por.	45.9	76.3	70.3
6	Hi C:N, Low M.C., Hi Por.	57.0	65.5	53.2
7	Med C:N, Hi M.C., Hi Por.	51.4	81.7	41.0
8	Hi C:N, Hi M.C., Hi Por.	65.9	84.8	30.9
R 1	Med C:N, Hi M.C., Hi Por.	37.0	76.5	45.8
R 2	Med C:N, Hi M.C., Hi Por.	52.3	65.0	39.9
L 1	Low C:N, Hi M.C., Low Por.	45.4	76.2	63.1
L 2	Low C:N, Low M.C., Low Por.	68.0	80.1	56.1
L 3	Low C:N, Hi M.C., Hi Por.	38.4	64.8	53.0
L 4	Low C:N, Low M.C., Hi Por.	48.9	53.1	55.4
C1	Control Pile	19.1	Not Tested	21.1
C2	Control Pile	36.4	Not Tested	-2.4

WE= Compost water extracts

4.1.2.1 Total Carbon

As expected, the percent total carbon (% C) of the various piles decreased throughout the composting period, with most of the decrease observed during the first 50 to 80 days of the process when the more available organic constituents are decomposed. The percent change in the total carbon content of the experimental piles varied from 17.8% for pile R1 to 66.4% for pile L2. The mean value was 51.8% with a standard deviation of 12.9. Control piles C1 and C2 observed a 26.6% and 51.6% decrease in % C. The large difference between the values for the control piles may be due to sampling or testing errors. Figures 4.22 to 4.29 display the percent carbon content over the composting duration for the various pile sections. The piles are organized according to their experimental C:N ratio and moisture levels.

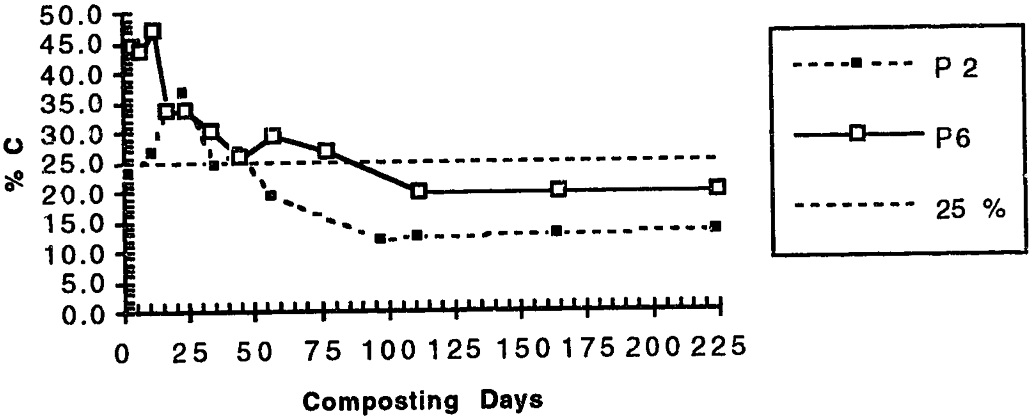


Figure 4.22 % C vs Composting Days - Piles 2 and 6

HI C:N, Low M.C.

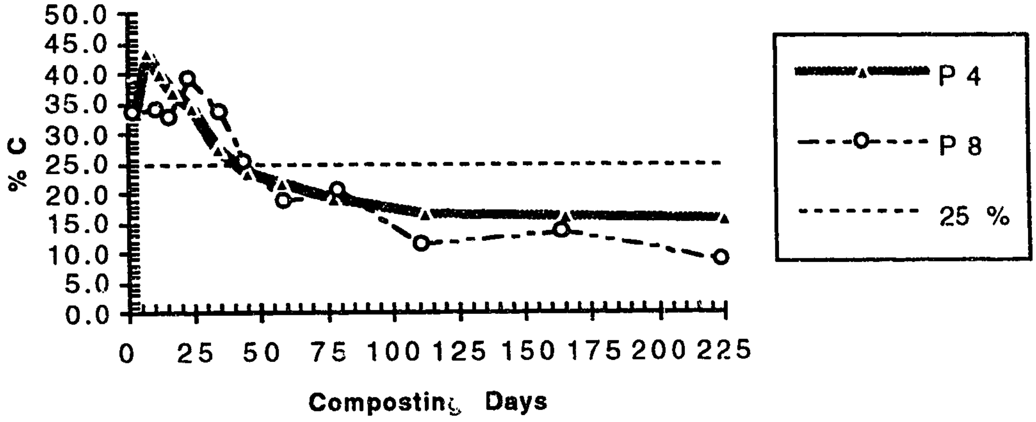


Figure 4.23 % C vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

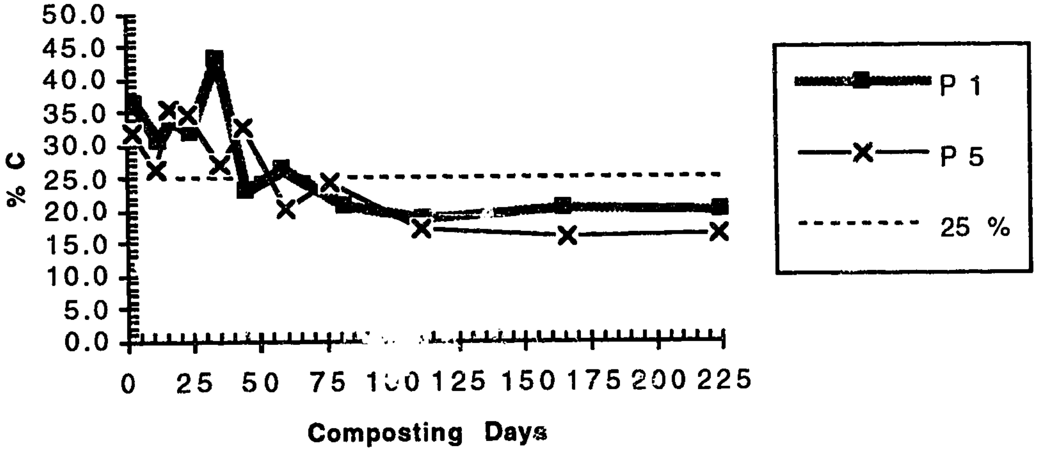


Figure 4.24 % C vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

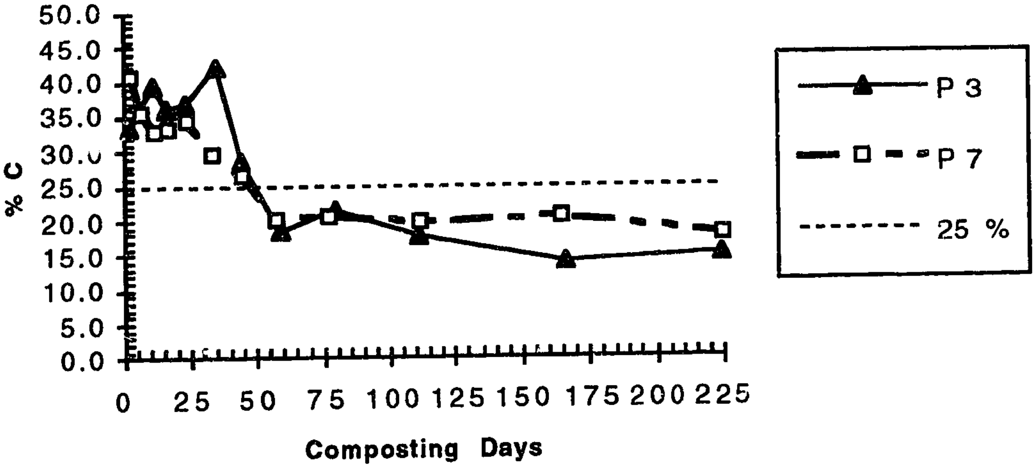


Figure 4.25 % C vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

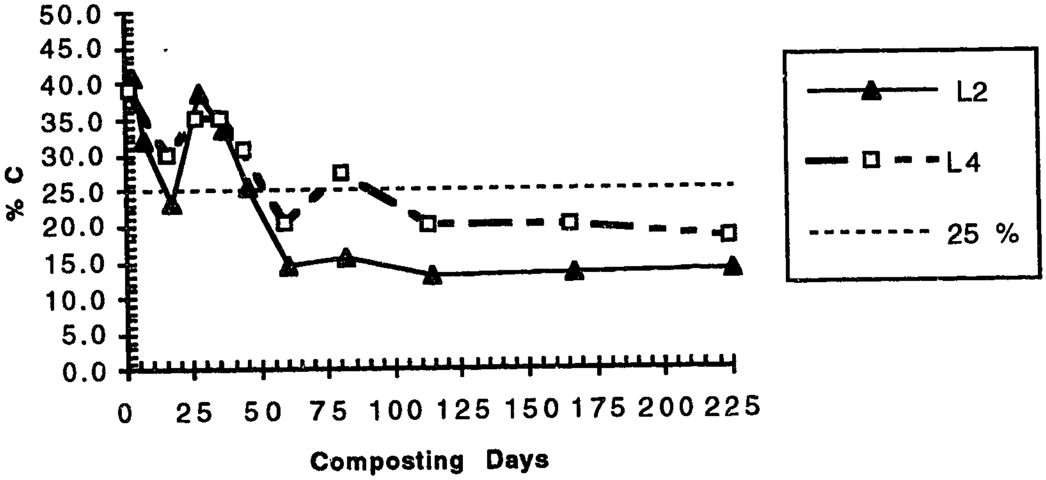


Figure 4.26 % C vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

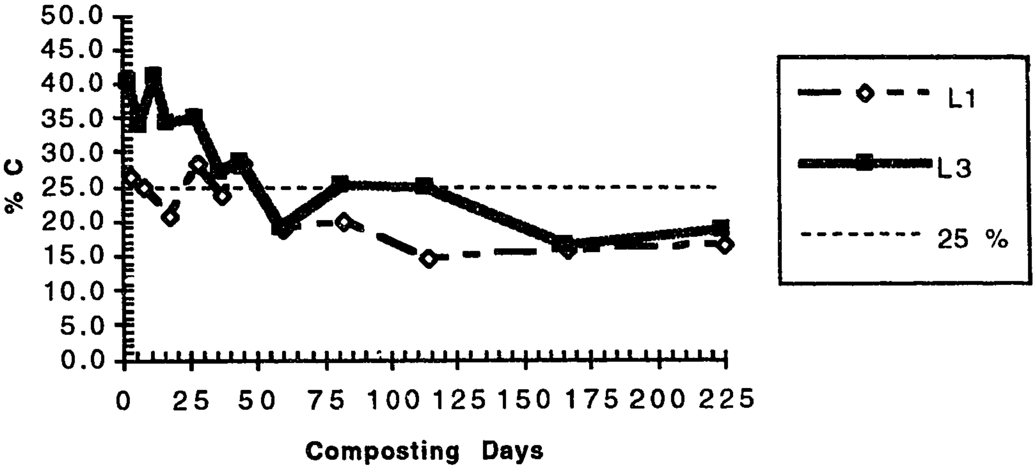


Figure 4.27 % C vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

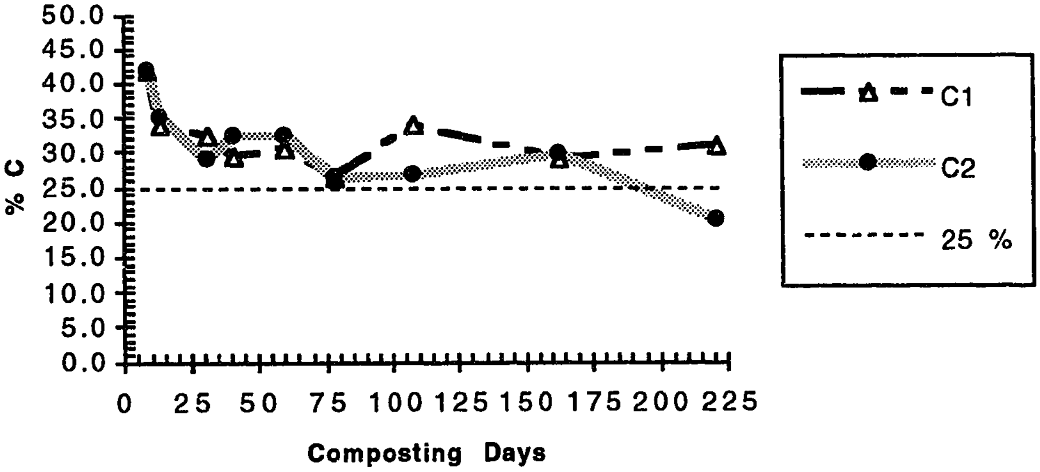


Figure 4.28 % C vs Composting Days - Piles C1 and C2

Control Piles

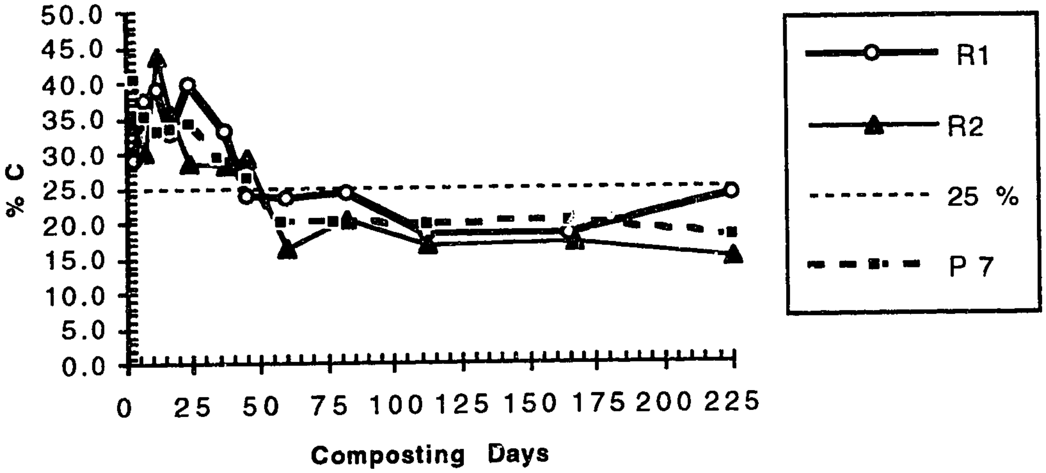


Figure 4.29 **% C vs Composting Days - Piles 7, R1 and R2**
Med C:N, Hi M.C.
Replicates

The values for the % change in total carbon content for each compost pile section are highly dependent on the reliability of the initial and final determinations for % C. The average % volatile solids values and their standard deviations are listed in Table A.1 in Appendix A. The % C values were determined by dividing the % volatile solids values by 1.8 as indicated in section 3.2.3.3.

Multiple samples were also collected for piles 1 to 8 and R1 and R2 to test for spatial differences in the compost material within the respective piles. The % volatile solids (% VS) parameter was used to evaluate the spatial differences in the compost material within a pile. Based on the multiple sample % VS results outlined in Table A.2, the samples collected for pile 2 on September 26, 1992 and pile 7 on October 10, 1992 showed the largest variation in % VS. The analysis of variance (ANOVA) method was used to test the null hypothesis (H_O) that the mean % VS values at the different locations within a pile are not different. The alternate hypothesis (H_A) is that the mean % VS values at the different locations within a pile are not the same. The results of the two ANOVA tests summarized in Table A.3 indicated the null hypothesis could not be rejected. Although statistically the mean % VS values at the different locations within the respective piles were not considered different, there was a significant amount of variability in the pile % VS values as indicated in Table A.2. For example, the mean % VS value for the multiple samples collected on September 26, 1992 for pile 2 was 34.81 ± 7.94 with a standard error of 3.44. The calculated confidence interval values for pile 2 on this sample date represents a ±22.80% of the pile mean value. The 95% confidence interval for most of the piles (as expressed as a percentage of the pile mean % VS values) were > ±10.00%. This variability might be explained by the heterogeneity of the pile material or errors introduced by the method of volatile solids determination. To ensure samples were not contaminated from materials of adjacent pile sections compost samples were randomly selected from the middle third of each pile section.

Table 4.6 outlines the % carbon values for the initial and final samples for the various compost pile sections.

Table 4.6 - Pile % Carbon values - Solid samples

Pile No.	Pile Designation	% C Initial values	% C Final values
1	Med C:N, Low M.C., Low Por.	36.2	20.0
3	Med C:N, Hi M.C., Low Por.	33.4	15.2
5	Med C:N, Low M.C., Hi Por.	31.9	16.1
7	Med C:N, Hi M.C., Hi Por.	40.6	17.8
R 1	Med C:N, Hi M.C., Hi Por.	29.1	24.0
R 2	Med C:N, Hi M.C., Hi Por.	35.0	15.0
2	Hi C:N, Low M.C., Low Por.	23.2	13.3
4	Hi C:N, Hi M.C., Low Por.	33.5	15.8
6	Hi C:N, Low M.C., Hi Por.	44.6	19.9
8	Hi C:N, Hi M.C., Hi Por.	33.5	8.9
L 1	Low C:N, Hi M.C., Low Por.	26.5	16.5
L 2	Low C:N, Low M.C., Low Por.	40.9	13.8
L 3	Low C:N, Hi M.C., Hi Por.	40.2	18.8
L 4	Low C:N, Low M.C., Hi Por.	39.0	18.1
C 1	Control Pile	42.1	30.9
C 2	Control Pile	42.1	20.4

The initial mean % C values for the high, medium and low C:N ratio piles were generally quite similar. The high C:N ratio piles 2, 4, 6 and 8 had a mean % C value of 33.7 with a standard deviation of 8.7. Pile section 2 had an initial % C content of 23.2, the lowest value of all the pile sections. The medium C:N ratio piles had a mean % C value of 34.4 with a standard deviation of 3.9. The low C:N ratio piles had the highest mean % C value of 36.7 with a standard deviation of 6.8. The high and medium C:N ratio piles were expected to have higher % C values due to the addition of straw. The mixing of 2 additional front end loader buckets of wheat straw to pile sections 4 and 6 (day 18), 2 and 8 (day 19) on August 17, 1992 did not seem to increase the % C values for the August 23, 1992 samples. The mean % C value for the high C:N ratio piles was 34.6 with a standard deviation of 1.5, compared to a mean and standard deviation of 34.4 and 3.8 for the medium C:N ratio piles. The initial % C results may be influenced by the heterogeneity of the mixed materials, sampling and test methods, or the amount of straw added to the piles.

The final % C contents also influence the % change in total carbon values. For example, pile R1 had a relatively high final % C content of 24.0%. compared to values of 17.8% and 15.0% for pile sections 7 and R2 which had the same treatment design. The high final % C content for pile R1 may be due to the possible contamination of the compost sample with the compost cover material. The burlap material used to separate the experimental compost material from the compost cover decomposed in most piles making it difficult to collect a true representative sample. This high final % C content for pile R1 results in a very low value for the % change in the total carbon.

The final % C contents for the control piles taken on day 221 varied considerably. The values for pile sections C1 and C2 were were 30.9% and 20.4% respectively. The most likely explanation for the large difference is sampling or testing errors. The % C content for piles C1 and C2 were 29.1% and 29.6% for the samples taken on day 163. The average pile temperatures for both C1 and C2 during the period between day 163 and day 221 were below 10°C. These low temperatures hindered the decomposition of the organic matter. It is unlikely the change in carbon content for pile section C2 observed during the period between day 163 and day 221 can be attributed to decomposition.

Given the results of the initial and final % C values, the % decrease in carbon content for the pile sections is not considered a reliable response indicator for this experiment. The % decrease in TOC of water extracts is a more reliable response factor because it better reflects the carbon available for microbial utilization.

4.1.2.2 Total Organic Carbon (TOC) - Compost Water Extracts

The TOC values for the various compost pile sections generally followed a decreasing trend throughout the composting period, with most of the decrease observed during the first 50 to 75 days of the process when the more available organic constituents are decomposed. The overall mean % change in TOC value was 73.9% with a standard deviation of 9.6. The highest % change in TOC was 84.8% for high C:N ratio pile 8 and the lowest was 53.1% for low C:N ratio pile section L4. Figures 4.30 to 4.36 display the TOC content (water extracts) versus the composting period for the various pile sections. The piles are organized according to their experimental C:N ratio and moisture levels.

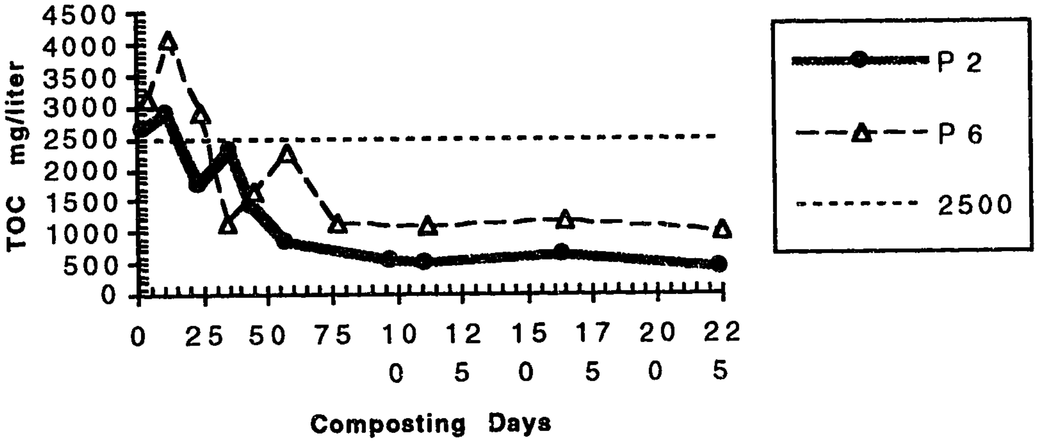


Figure 4.30 TOC vs Composting Days - Piles 2 and 6

HI C:N, Low M.C.

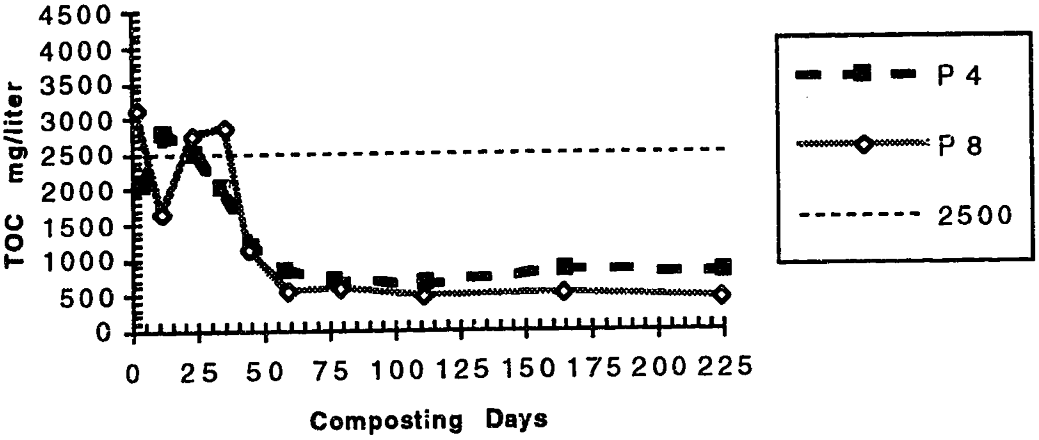


Figure 4.31 TOC vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

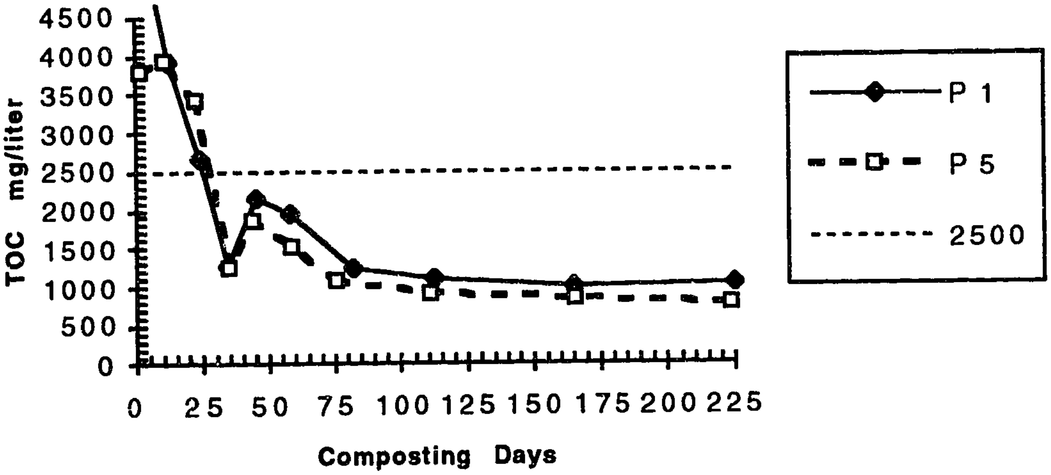


Figure 4.32 TOC vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

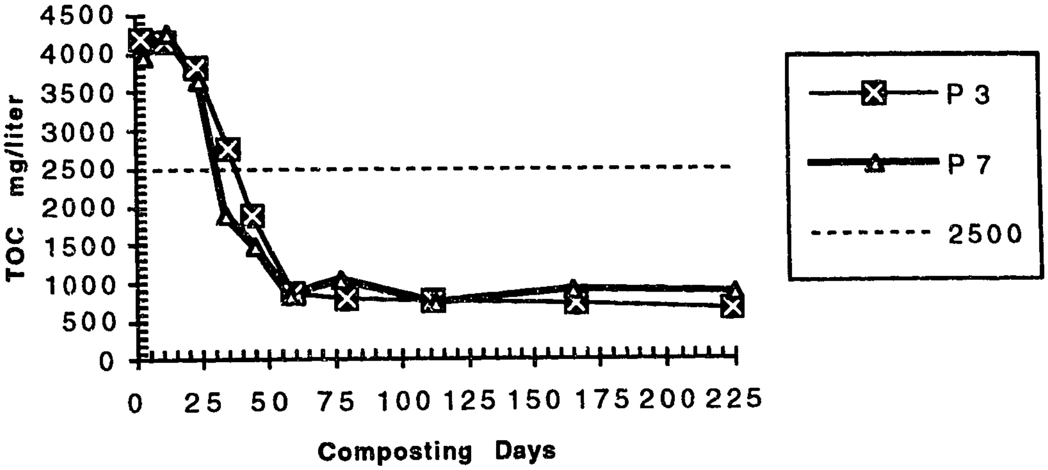


Figure 4.33 TOC vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

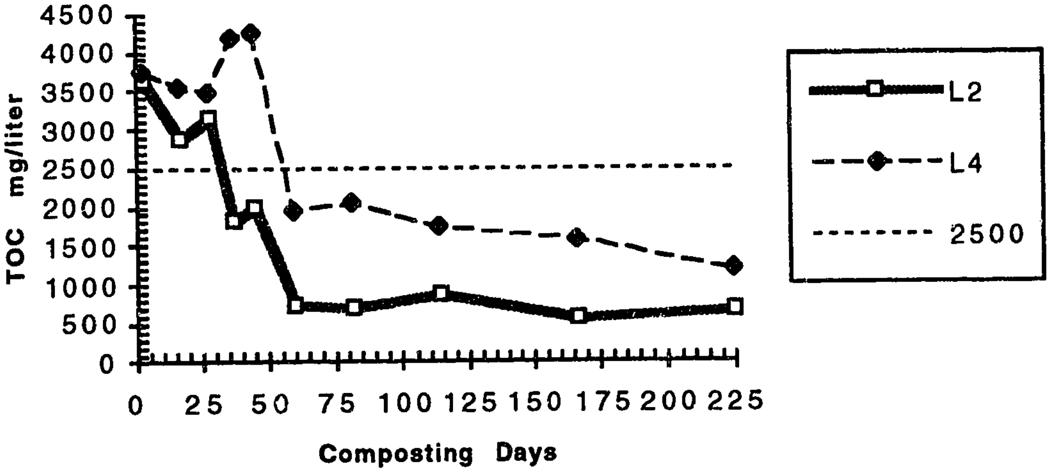


Figure 4.34 TOC vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

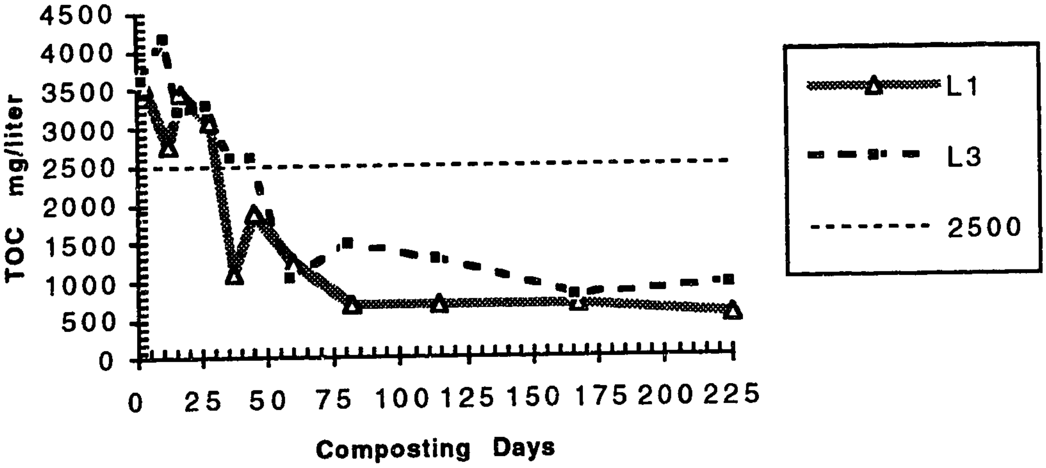


Figure 4.35 TOC vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

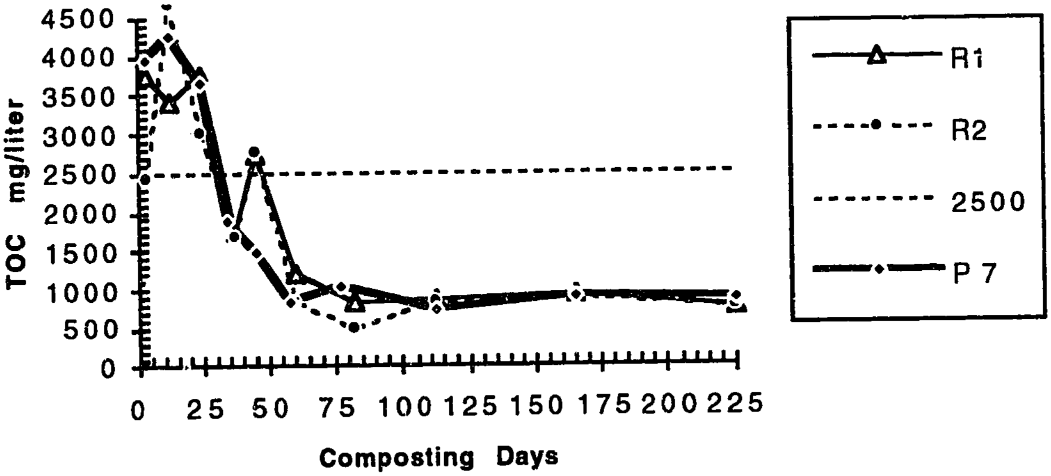


Figure 4.36 TOC vs Composting Days - Piles 7, R1 and R2

Med C:N, Hi M.C.

Replicates

The TOC values of the different piles sections fluctuated more during the first 36 days of the process and usually increased from the initial values. Piles 2, 4, 5, 6, 7, R2 and L3, for example, had higher TOC values on the samples taken on composting days 11 and 12, than determined from the initial samples. Riffaldi *et al* (1988) found the water soluble components initially increased during the first five days of composting a mixture of wastewater sludge from a paper factory and chopped straw. They attributed the initial increase to the increasing rate of decomposition by the microorganisms and they suggested the hydrolysis and solubilization of the complex substances initially predominated over mineralization and immobilization processes. The water soluble components of the compost water extract gradually decreased due to the microbial activity.

The values for the % change TOC content for each compost pile section are also highly dependent on the reliability of the initial and final determinations for TOC. The standard deviation of the average TOC value for multiple injections can be found in Appendix C.1. Table 4.7 outlines the TOC values for the initial and final samples for the various compost pile sections.

Table 4.7 - Pile TOC values - Water Extracts

Pile No.	Pile Designation	Initial TOC values mg/liter	Final TOC values mg/liter
1	Med C:N, Low M.C., Low Por.	5499.5	1017.8
3	Med C:N, Hi M.C., Low Por.	4137.7	649.6
5	Med C:N, Low M.C., Hi Por.	3778.1	752.0
7	Med C:N, Hi M.C., Hi Por.	3940.6	857.2
R1	Med C:N, Hi M.C., Hi Por.	3731.3	753.2
R2	Med C:N, Hi M.C., Hi Por.	2412.4	756.6
2	Hi C:N, Low M.C., Low Por.	2644.2	402.1
4	Hi C:N, Hi M.C., Low Por.	2053.7	793.9
6	Hi C:N, Low M.C., Hi Por.	3137.0	997.0
8	Hi C:N, Hi M.C., Hi Por.	3124.7	438.4
L1	Low C:N, Hi M.C., Low Por.	3536.3	571.4
L2	Low C:N, Low M.C., Low Por.	3608.8	646.1
L3	Low C:N, Hi M.C., Hi Por.	3602.1	944.4
L4	Low C:N, Low M.C., Hi Por.	3735.9	1195.0
C1	Control Pile		
C2	Control Pile		

The high C:N ratio piles 2, 4, 6 and 8 have a mean TOC value of 2739.9 with a standard deviation of 511.8. The medium C:N ratio piles have the highest mean TOC value of 3916.6 with a standard deviation of 987.0. The low C:N ratio piles have a mean TOC value of 3620.8 with a standard deviation of 83.4. As expected, the high C:N ratio piles had lower TOC values because straw has a lower relative proportion of water-soluble organic matter. Theoretically, the low C:N ratio piles should have had the highest initial TOC values because grass has a high relative proportion of water soluble organic matter. The differences in the mean values for the low and medium C:N ratio pile sections may be the result of heterogeneity of the compost material, sampling and or testing methods and procedures.

The % change in TOC values provide a relative indication of the level of maturity of the various piles and serves as a response variable in factorial design calculations to evaluate the influence of the key operational parameters on the decompostion rate. A more absolute indicator of maturity is the organic carbon to organic nitrogen ratio of water extracts. The following section discusses the organic carbon to organic nitrogen results for the various pile sections.

4.4.1.2.3 C:N_W ratio - Water Extracts

The organic carbon/organic nitrogen (C:N_W) values for the various pile sections fluctuated widely throughout the composting period although pile sections 2, 3, 4, 7, and L1 generally followed a decreasing trend. Garcia *et al.* (1991b) found the water soluble carbon/organic nitrogen ratio decreased considerably during the process for various mixtures of organic wastes consisting of aerobic sewage sludge, city refuse, grape debris and peat residue. Figures 4.37 to 4.43 show the C:N_W values versus the composting period for the various pile sections. The pile sections are organized according to their experimental C:N ratio and moisture levels.

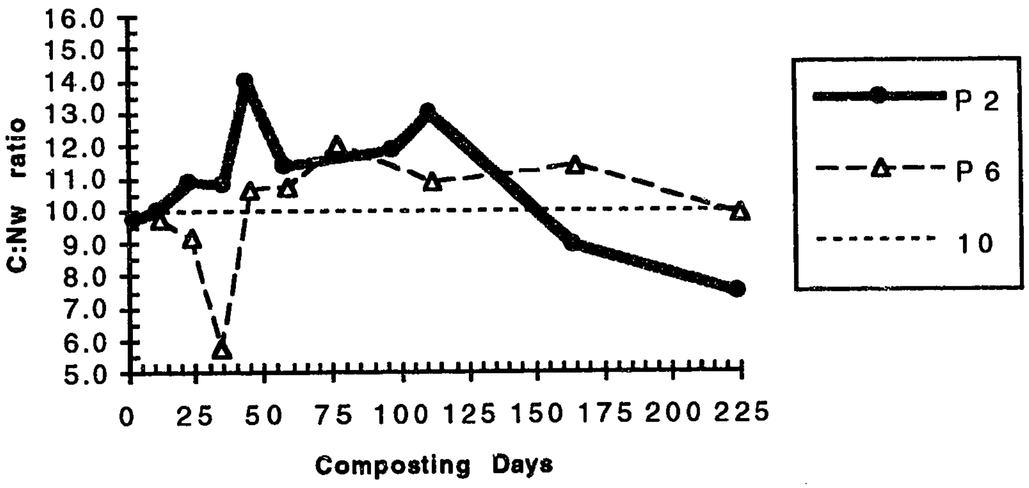


Figure 4.37 **C:N_W vs Composting Days - Piles 2 and 6**

Hi C:N, Low M.C.

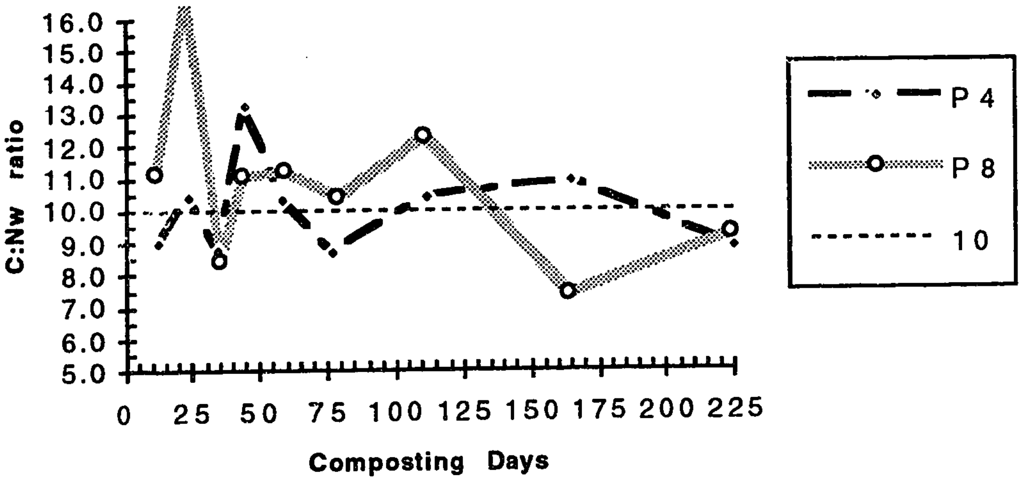


Figure 4.38 C:N_W vs Composting Days - Piles 4 and 8

HI C:N, HI M.C.

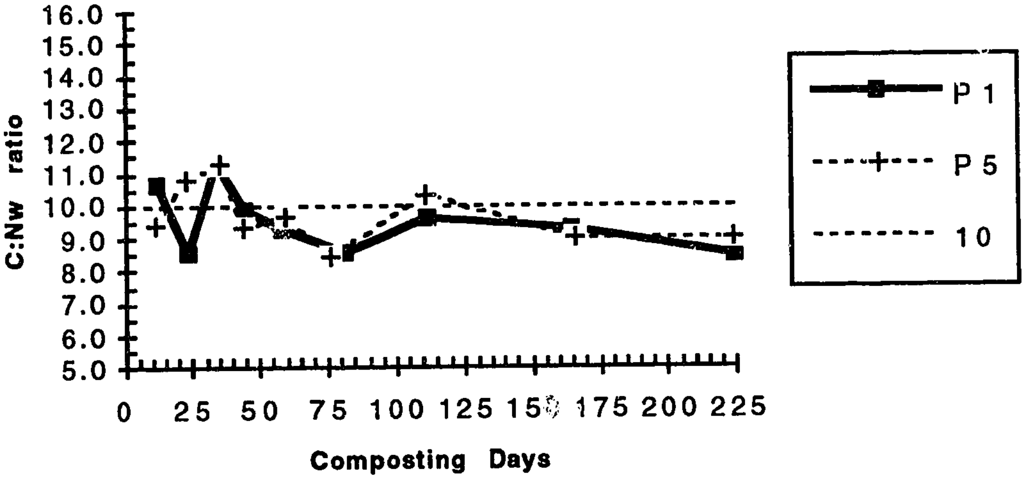


Figure 4.39 C:N_W vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

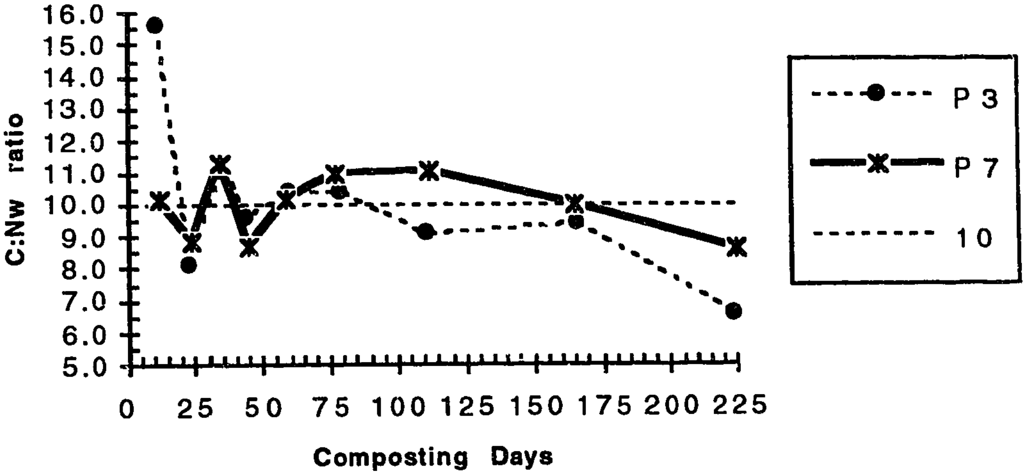


Figure 4.40 C:N_W vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

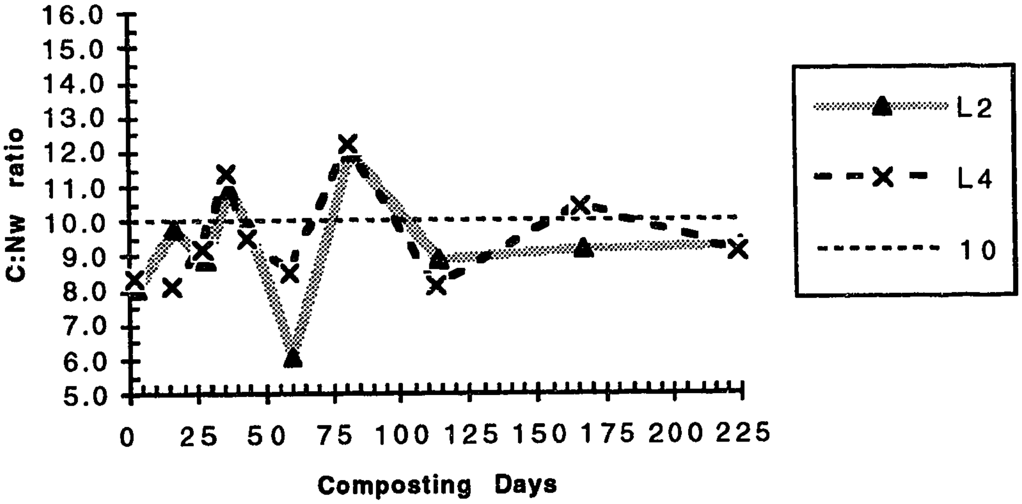


Figure 4.41 C:N_W vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

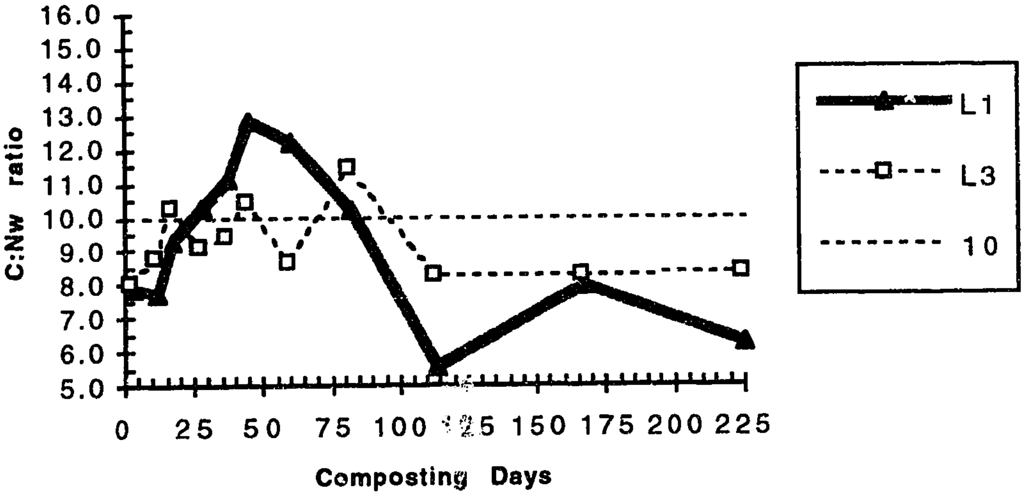


Figure 4.42 C:N_W vs Composting Days - Piles L1 and L3

Low C:N, HI M.C.

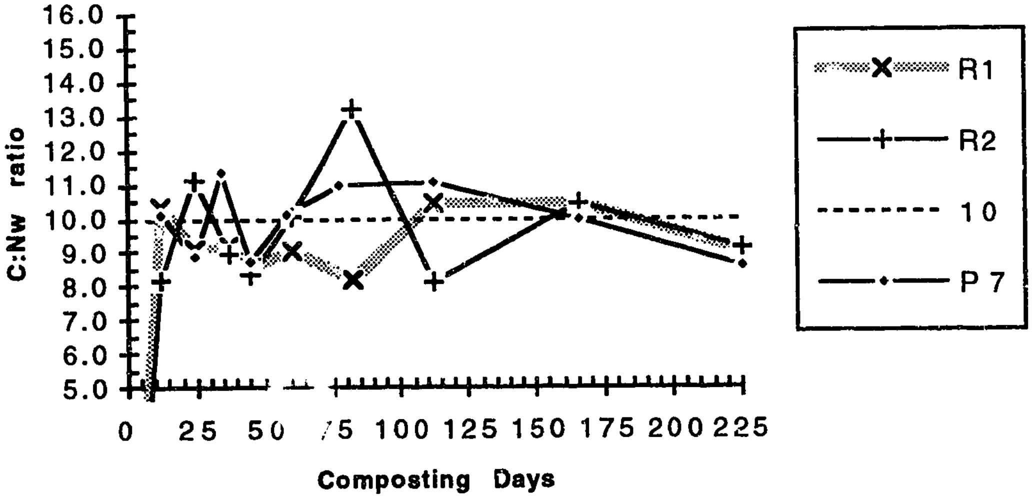


Figure 4.43 C:N_W vs Composting Days - Piles R1 and R2 and P 7

Med C:N, HI M.C.

Replicate Piles

The final $C:N_W$ ratio values for compost is considered an absolute indicator of compost maturity. Several authors have indicated a final $C:N_W$ ratio value between the 5 and 6 is as an absolute indicator of mature compost (Chanyasak and Kubota 1981; Chanyasak *et al.* 1982; Hirai *et al.* 1983; Riffaldi *et al.* 1988; Garcia *et al.* 1991). Table 4.8 outlines the initial and final $C:N_W$ values for the experimental piles. The initial $C:N_W$ values are from the August 11th and 16th, 1992 samples. There was not enough compost material remaining from the first samples to develop compost water extracts.

Table 4.8 - Pile Initial and Final $C:N_W$ ratios - Water Extracts

Pile No.	Pile Designation	Initial $C:N_W$	Final $C:N_W$
1	Med C:N, Low M.C., Low Por.	10.60	8.44
3	Med C:N, Hi M.C., Low Por.	15.57	6.60
5	Med C:N, Low M.C., Hi Por.	9.39	9.03
7	Med C:N, Hi M.C., Hi Por.	10.12	8.59
R 1	Med C:N, Hi M.C., Hi Por.	10.36	9.01
R 2	Med C:N, Hi M.C., Hi Por.	8.21	9.13
2	Hi C:N, Low M.C., Low Por.	9.97	7.50
4	Hi C:N, Hi M.C., Low Por.	9.00	8.80
6	Hi C:N, Low M.C., Hi Por.	9.77	9.88
8	Hi C:N, Hi M.C., Hi Por.	11.09	9.23
L 1	Low C:N, Hi M.C., Low Por.	7.75	6.25
L 2	Low C:N, Low M.C., Low Por.	8.86	9.24
L 3	Low C:N, Hi M.C., Hi Por.	8.84	8.33
L 4	Low C:N, Low M.C., Hi Por.	8.13	9.13

Initial values for piles L2 and L4 (92-08-16 sample)
Initial values for all other piles (92-08-11 sample)

The sole purpose for determining the final C:N_W ratio values was to identify which piles matured first. None of the final C:N_W ratio values were between 5 and 6, the range indicated for mature compost. The overall mean final C:N_W value for the experimental pile sections was 8.51 with a standard deviation of 1.0. The overall average initial (August 11, 1992 samples) C:N_W value for the experimental piles was 9.83 with a standard deviation of 1.92. The final C:N_W values were generally lower than the initial values. Pile section 3 had the lowest final value of 6.6, although piles L2 and 6 had values of 6.1 and 5.7 on days 60 and 34. The final C:N_W for pile sections L2 and 6 were 9.2 and 9.9. The C:N_W ratios do not provide an absolute indication of which pile sections matured first.

The experimental and literature C:N_W ratios differences may be due to the type of organic materials composted. The literature studies involving water extracts from air dried compost samples tested mature composts from a variety of organic mixtures but not grass and grass and straw composts. Grebus (1992) tested water extracts from fresh mature yard waste compost samples and found the C:N_W ratios to be higher than the literature values of between 5 and 6. The results obtained in this study may be representative of the true organic carbon to organic nitrogen ratios of mature grass and grass and straw composts. The most likely explanation for the differences in literature and experimental results are sample preparation and testing errors. For example, the final C:N_W values for pile sections 6 and L2 were much higher than the minimum values observed on days 34 and 60, respectively. The next section outlines the results of a secondary measure of organic degradation, the % increase in the compost dry bulk density.

4.1.2.4 Dry Bulk Density

As expected, the dry bulk density (DBD) of the various piles increased throughout the composting period, with most of the increase observed during the first 112 days, the active phase of the process and then remained fairly constant or increased slightly during the remaining 113 days or maturation phase. Low C:N ratio pile L1 had the highest % increase in DBD of 68.3%, while the lowest increase of 34.4% was observed for pile section 8. The mean % increase in DBD for the experimental pile sections was 55.3 with a standard deviation of 9.9 (from August 23, 1992 sample). This compares favorably to the mean value of 59.4% with a standard deviation of 8.0 observed by Fleming (1991) in the composting of mixtures of green waste, leaves and wood wastes in Florida. Control piles C1 and C2 had a lower mean % increase in dry bulk density of 36.4% with a standard deviation of 3.0 potentially indicating the organic materials did not degrade as much as the experimental piles. Multiple sample bulk density measurements were taken for piles 4 and 6 on October 16, 1992 to determine variability in bulk density measurements. Four wet bulk density measurements were taken for each pile. The average wet bulk density value for pile 4 was 434.0 Kg/m^3 with a standard deviation of 35.37. Pile 6 had an average wet bulk density value of 654.8 Kg/m^3 with a standard deviation of 36.29. Figures 4.44 to 4.51 display the DBD versus the composting period for the various pile sections. The pile sections are organized according to their experimental C:N ratio and moisture levels.

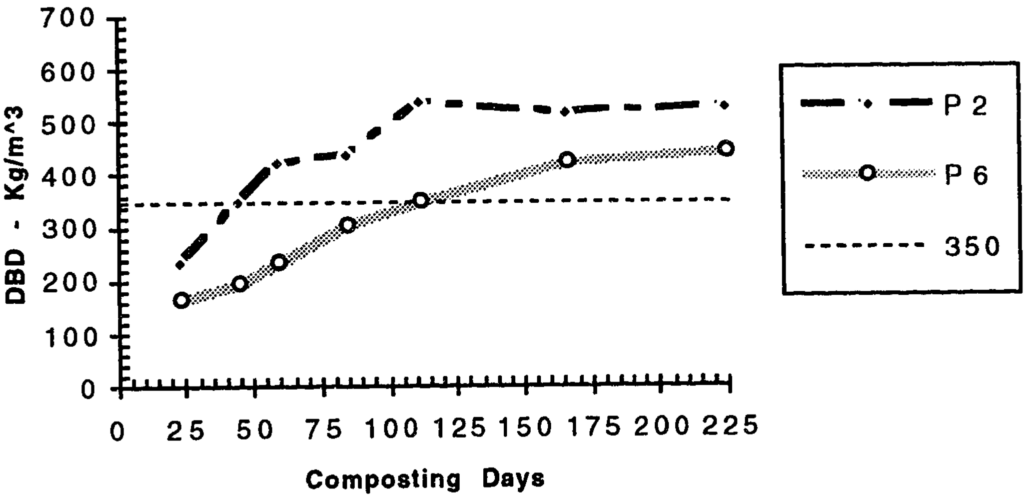


Figure 4.44 DBD vs Composting Days - Piles 2 and 6

HI C:N, Low M.C.

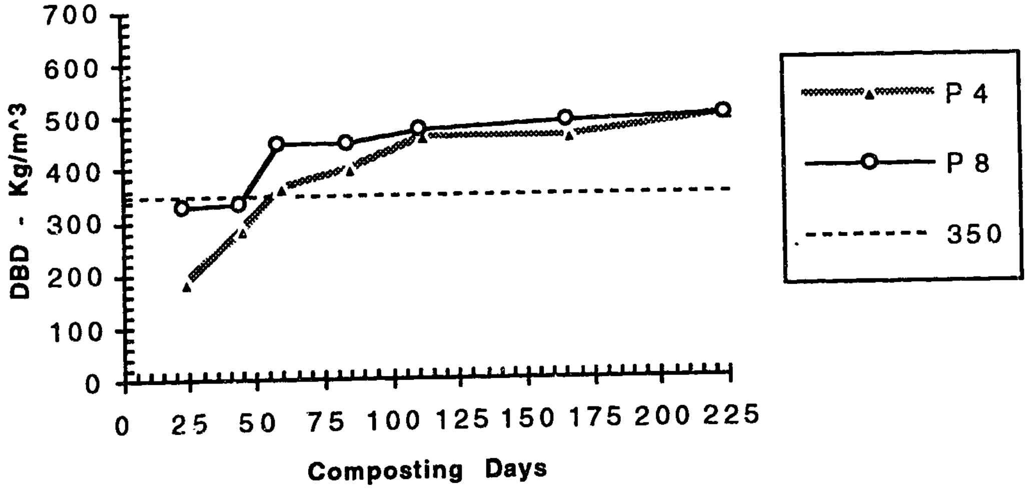


Figure 4.45 DBD vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

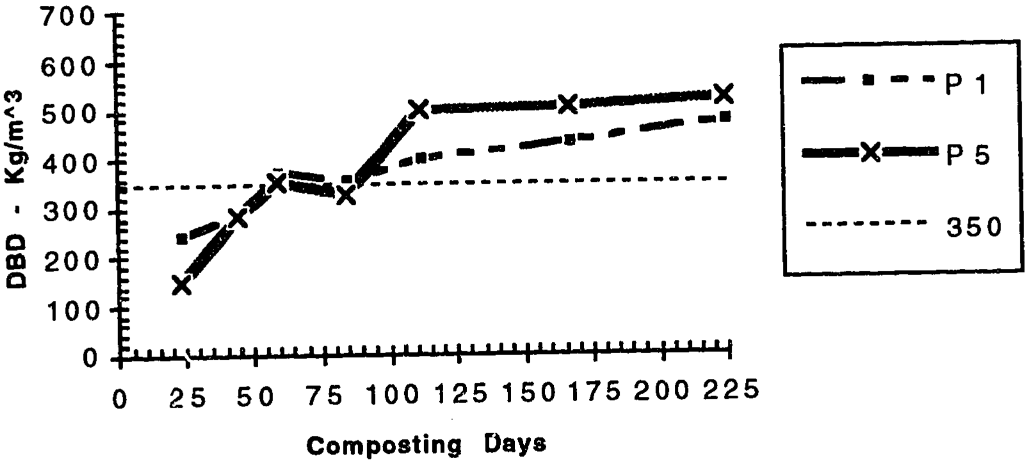


Figure 4.46 DBD vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

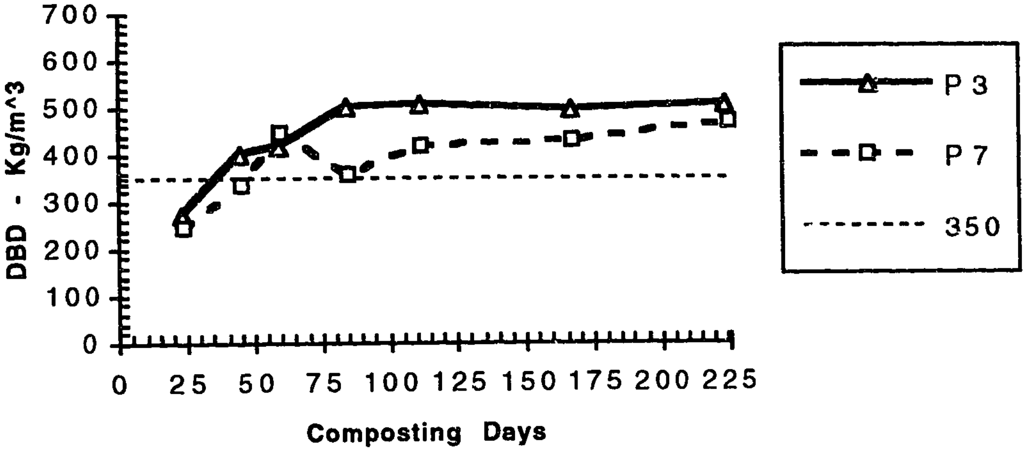


Figure 4.47 DBD vs Composting Days - Piles 3 and 7

Med C:N, HI M.C.

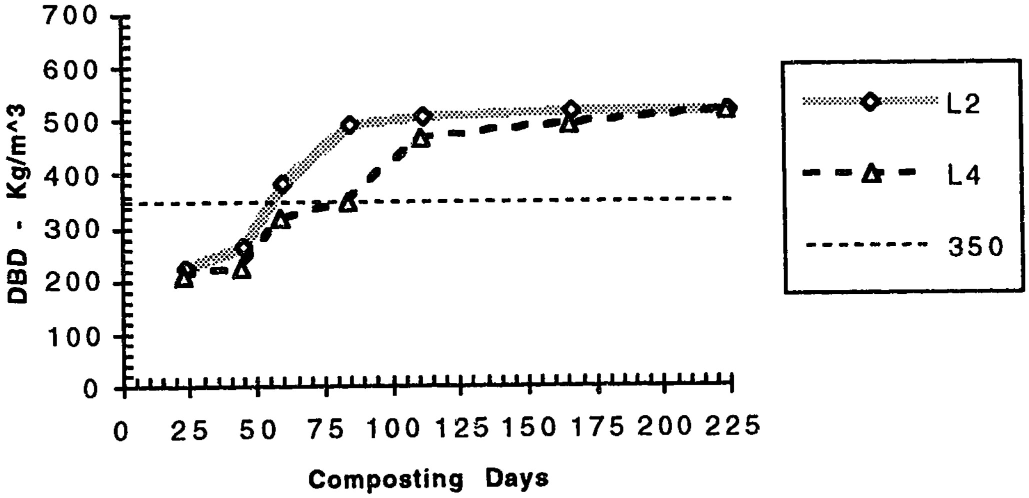


Figure 4.48 DBD vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

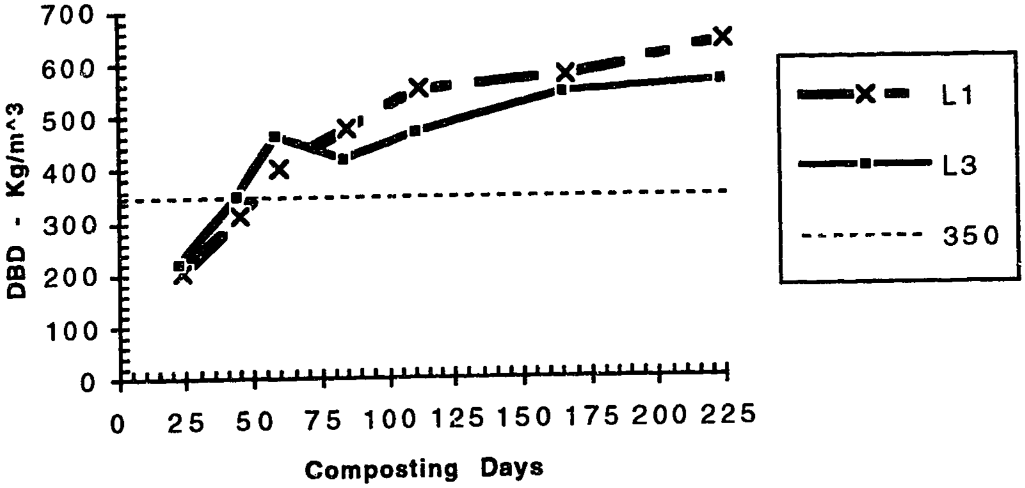


Figure 4.49 DBD vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

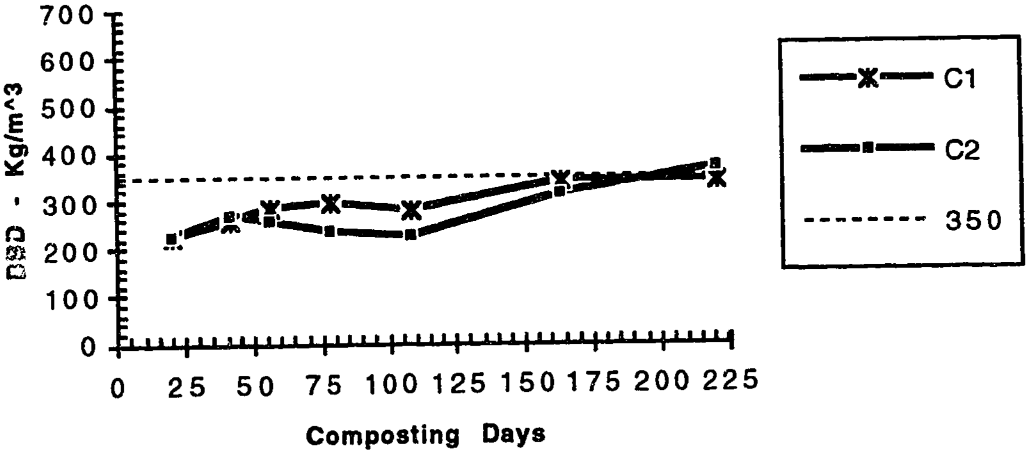


Figure 4.50 DBD vs Composting Days - Piles C1 and C2

Control Piles

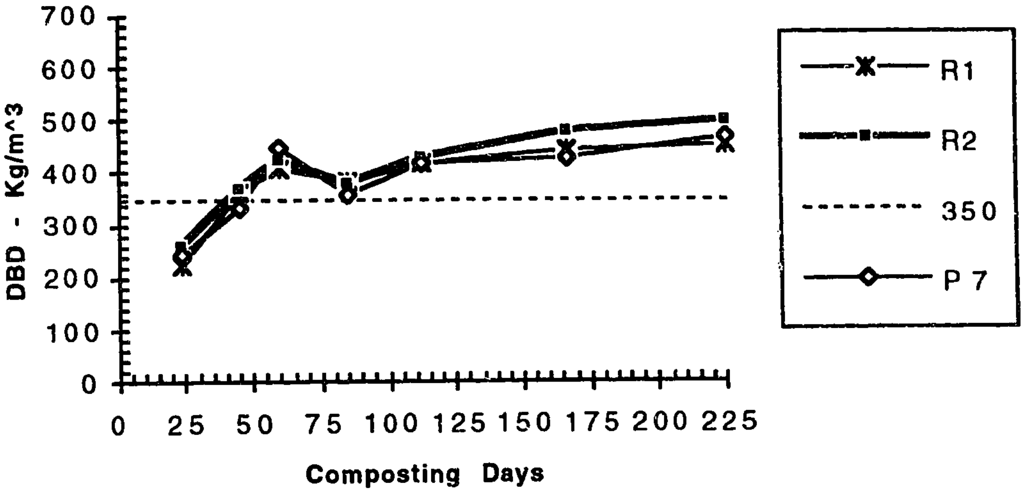


Figure 4.51 DBD vs Composting Days - Piles 7, R1 and R2

Med C:N, Hi M.C.

Replicate Piles

Pile sections 4, 5, 6, 7, 8, L3 and L4, R1 and R2, which had wood chips added to adjust porosity, generally have lower values of dry bulk density than the piles with the same experimental moisture and C:N levels. Wood chips were added to pile 5, on day 70 and piles 6, 7, on day 71 and to piles 8, L3 and L4 on day 77 and Piles R1 and R2 on day 78. The wood chips are less dense than the existing compost mixtures so the lower dry bulk density values for the porosity adjusted piles are expected. Table 4.10 outlines the dry bulk density values for the August 23, 1992 samples and the final samples for the various compost pile sections.

Table 4.9 - Pile Dry Bulk Density values (DBD)

Pile	Pile Designation	DBD Kg/m^3 92-08-23	DBD Kg/m^3 93-03-13
1	Med C:N, Low M.C., Low Por.	237.7	470.7
3	Med C:N, Hi M.C., Low Por.	270.5	504.4
5	Med C:N, Low M.C., Hi Por.	148.3	517.1
7	Med C:N, Hi M.C., Hi Por.	245.3	467.7
R1	Med C:N, Hi M.C., Hi Por.	225.8	451.0
R2	Med C:N, Hi M.C., Hi Por.	256.6	495.0
2	Hi C:N, Low M.C., Low Por.	232.3	526.1
4	Hi C:N, Hi M.C., Low Por.	184.9	493.9
6	Hi C:N, Low M.C., Hi Por.	162.3	443.0
8	Hi C:N, Hi M.C., Hi Por.	326.6	496.2
L1	Low C:N, Hi M.C., Low Por.	202.8	640.6
L2	Low C:N, Low M.C., Low Por.	222.8	516.9
L3	Low C:N, Hi M.C., Hi Por.	219.7	559.4
L4	Low C:N, Low M.C., Hi Por.	207.9	518.3
C1	Control Pile	221.2	336.9
C2	Control Pile	226.0	367.8

The dry bulk density values for the high C:N ratio piles on August 23, 1992 varied from 162.3 Kg/m^3 for pile 6 to a high value of 326.6 Kg/m^3 for pile section 8. The mean value was 226.5 Kg/m^3 with a standard deviation of 72.8. The medium C:N ratio piles have a mean DBD value on August 23, 1992 of 230.7 Kg/m^3 with a standard deviation of 43.2. The low C:N ratio piles have a mean value of 213.3 Kg/m^3 with a standard deviation of 9.5. The large variation in DBD values observed for the high C:N ratio piles on August 23, 1992 may be explained by the heterogeneity of the mixtures of straw and grass.

The mean final DBD for the high C:N piles was 489.8 Kg/m^3 with a standard deviation of 34.5. The medium C:N ratio piles had a similar final value of 484.3 Kg/m^3 with a standard deviation of 25.2. The highest mean final DBD of 558.8 Kg/m^3 with a standard deviation of 58.0 was observed for the low C:N ratio piles. The dry bulk densities were comparable to values observed by Fleming (1991). In her study, the initial and final mean DBD were 259.6 Kg/m^3 and 639.4 Kg/m^3 with standard deviations of 87.3 and 56.8.

The % increase in DBD provides a relative indication of the level of maturity of the various piles and serves as a response variable in factorial design calculations to evaluate the influence of the key operational parameters on the decomposition rate. Although it is not considered a primary indicator of compost maturity, it may be useful in the confirmation of the results of more recognized maturity parameters.

4.1.3 Factorial Design Results

Because the experimental moisture levels were not able to be maintained the design matrix was adjusted to reflect the actual moisture levels measured in the different compost piles. The adjusted factorial design matrices are referred to as botched factorials. The +1 and -1 levels for the moisture content variable are replaced by values representing the actual pile moisture content as a percentage of the planned experimental levels. For example, the weighted average moisture content for pile 2 for the full composting period was 27.0% which is 0.68 of the planned experimental level of 40%. Instead of +1 and -1 levels ±0.68 is used in the design matrix. The factorial design was analysed using the % decrease in TOC and the % increase in dry bulk density for both the active and full composting periods as the response variables. The results for the active composting period reflect the importance of the operational variables during the period when most of the decomposition of organic materials takes place. As stated earlier the % decrease in TOC is considered the most reliable response variable. The % increase in dry bulk density is a secondary and less reliable response variable. The following section summarizes the results of the factorial experiment for both response variables.

4.1.3.1 Factorial Experiment - Results

The results of the factorial design, using % decrease in TOC as the response variable, indicate none of the main effects and their interactions were found to significantly effect the decomposition of the organic materials. Based on the calculated 95% confidence intervals of the regression coefficient ß values, none of the factors are significantly different from zero. All the ß values have both positive and negative confidence interval values, indicating zero is a possible value. The ß values measure the effect of a unit change in the variable on the mean response (Montgomery 1984). The main effects and their interactions represent a change from -1 to +1, a change of 2 units. To calculate the main effects and their interactions, the ß values are doubled. The results of the factorial experiment are shown in Table E.1 in Appendix E. Table 4.10 summarizes the significant factors for both response variables based on the 95% and 90% confidence intervals, as well as the results from the half normal plots.

Table 4.10 - Factorial Experiment - Significant Effects

Significant Effects and Interactions

Response Variable	% Decrease in TOC			% Increase in Dry Bulk Density		
Period	**95% CI**	**90% CI**	**Half Normal Plot**	**95% CI**	**90% CI**	**Half Normal Plot**
Full	None	13 23 123	13 123	23	23	3 123
Active	None	None	2 12 13	23	23	3 13 23

The confidence interval results are considered more reliable because the results of the half normal plot are dependent upon how the straight line is drawn through the points. Although the 95 %

confidence interval results, using % decrease in TOC as the response variable, indicate no factor is significant, results from the 90 % confidence interval calculations and the half normal plots for both response variables provide some indication that some factors marginally influenced the decomposition process. In addition, ranking the effects from the highest to lowest value after normalization also provides a measure of relative importance. The higher the normalized value the larger the effect on the decomposition rate. The effects are normalized by dividing the value of the effect by the standard error at the 5% significance level.

For the full composting period, the 90% confidence interval calculations of the ß values for the response variable % decrease in TOC, suggest the interactions 13 (C:N ratio-Porosity), 23 (MC-Porosity) and 123 (C:N ratio-MC-Porosity) marginally influenced the decomposition of the organic materials. The results of the half normal plot also indicate the 13 and 123 interactions are significant. The factorial design results, using % increase in dry bulk density as the response variable, found the 23 interaction (MC-Porosity) to be significant. Table 4.11 summarizes the rankings of the effects for both response variable factorials for the full composting period.

Table 4.11 - Ranking of Effects - Full Period

% Decrease in TOC			% Increase in Dry Bulk Density		
Effects	**Value**	**Value/S.E.**	**Effects**	**Value**	**Value/S.E.**
23	-9.14	-4.60	23	-13.77	-5.58
123	-12.16	-4.56	1	-8.82	-3.36
13	-8.2	-3.90	12	-10.70	-3.22
3	3.24	2.02	2	-6.57	-2.66
12	4.46	1.68	123	-8.70	-2.62
1	0.99	0.46	13	-5.11	-1.96
2	-0.27	-0.14	3	-1.27	-0.64

Interactions 23 and 123 and 13 have the highest values of the normalized effects for the % decrease in TOC factorial. The 23 interaction has the highest value of the normalized effects for the dry bulk density factorial. The negative value for the 23 effect for the DBD factorial indicates, this effect has a negative influence on the increase in dry bulk density. A negative value for an effect for the TOC factorial indicates the effect increases the percent decrease in TOC. Based on the overall results of the 90% confidence intervals, half normal plots and rankings, there are indications that the 13, 23 and 123 interactions marginally influenced the decomposition of the organic materials. The factorial results from the TOC response variable are considered more reliable than the dry bulk density results; therefore the conclusions are mainly based on the TOC factorial results.

For the active period, none of the factors were found to influence the decomposition of the organic materials, based on the 90% confidence interval calculations of the ß values for the response variable % decrease in TOC. The half normal plot indicated the main effect 2 (MC) and the interactions 12 (C:N ratio-MC) and 13 (C:N ratio-Porosity) were significant. The dry bulk density factorial confidence interval results indicated the 23 interaction was significant. Table 4.12 summarizes the rankings of the effects for both response variable factorials for the active composting period.

Table 4.12 - Ranking of Effects - Active Period

% Decrease in TOC			% Increase in Dry Bulk Density		
Effects	**Value**	**Value/S.E.**	**Effects**	**Value**	**Value/S.E.**
3	7.78	3.68	23	-15.01	-4.94
13	-10.08	-3.64	1	-7.92	-2.46
23	-8.99	-3.44	2	-6.23	-2.06
1	-6.80	-2.46	13	-6.02	-1.86
123	-5.80	-1.66	12	-7.02	-1.72
2	-1.69	-0.64	3	-3.99	-1.62
12	0.92	0.26	123	-6.3	-1.54

The main effect 3 (Porosity) and interactions 13 and 23 have the highest values of the normalized effects for the % decrease in TOC factorial. The 23 interaction has the highest value of the normalized effects for the dry bulk density factorial. Main effects 1 (C:N ratio) and 2 (MC) have the second and third highest values. Overall the factorial results for the active period do not consistently indicate any of the factors influence the decomposition of the organic materials. The following section discusses the factorial results of the 90% confidence intervals, half normal plots and rankings for the full composting period.

4.1.3.2 Factorial Results Discussion

None of the operational factors were found to significantly effect the decomposition of the organic materials based on the calculated 95% confidence intervals of the ß's for the % decrease in TOC factorial. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13, 23 and 123 interactions marginally influenced the decomposition of the organic materials. The following paragraphs discuss the theoretical importance of these interactions and outlines possible explanations for the factorial results.

The factorial results suggest the operational factors are interelated which is consistent with theory. The 23 interaction (MC-Porosity) which had the highest normalized effect value is considered to have the largest affect on the response variable If the moisture content is too high, the the void space available for air will be reduced. This will result in a lower supply of oxygen which will reduce the rate of biological activity. When the the moisture content is low and the void space available for air is high, the rate of biological activity is also reduced. The flow of air through the void space results in moisture losses and potential cooling of the compost mass. A balance between adequate moisture content and porosity is important for optimizing the decomposition process.

The second and third highest normalized effects based on the TOC factorial results for the full period are the interaction 123 (C:N ratio-MC-Porosity) and 13 (C:N ratio- Porosity). These results suggest a relationship exists between the moisture content, porosity and the C:N ratio of the materials. A potential explanation may be the variable C:N ratio actually represents the physical nature of the material. The void space in the compost pile is related to the physical nature of the compost materials and not the C:N ratio. Fibrous or bulky materials such as straw and wood chips are able to maintain adequate porosity compared to grass clippings. Golueke (1977) indicated the maximum permissible percent moisture is also a function of the physical nature of the materials. For example, fibrous or bulky materials such as straw and wood chips can absorb relatively large amounts of water and still maintain adequate porosity (Haug 1980).

Finally the lowest normalized effects based on the TOC factorial results for the full period are the main effects 2(MC) and 1(C:N ratio). This may suggest that these factors alone do not influence the decomposition of the organic materials. The normalized effect value for the main effect 3(Porosity) was ranked 4th for the full period and first for the active period for the TOC factorial results. Based on the actual measured porosity values for piles 5, 6, 7, L4, R1, R2 and 8 the porosity generally decreased or remained fairly level for the first porosity measurements after the addition of more wood chips. Possible reasons for the inconsistent results could include errors introduced in measurement, sampling or testing, improper mixing of wood chips, compost cover contamination of the samples or the volume of wood chips added did not significantly alter the porosity of the piles. The most likely explanation are errors introduced in the determination of the porosity measurements. Since there appears to be no standard method of determining compost porosity, the accuracy of the method used in this study can not be determined.

4.1.3.3 Summary and Explanations

In summary, the factorial results based on the calculated 95% confidence intervals of the ß's for the % decrease in TOC factorial found none of the factors influenced the decomposition rate of the organic materials. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13 (C:N ratio-Porosity), 23 (MC-Porosity) and 123 (C:N ratio-MC-Porosity) marginally influenced the decomposition of the organic materials. The results do not support the hypotheses that the operating variables C:N ratio, moisture content and porosity adjustment individually effect the decomposition rate of the organic materials. Possible explanations for these experimental results are: 1) the response variables used in the study were not able to measure the effects, 2) the effect of C:N ratio, M.C. and porosity on degradation did not occur within the ranges tested or 3) the difficulties encountered in maintaining and operating a field level experiment impacted the results. The most likely reasons are the difficulties in maintaining and operating a field level experiment.

For example, the difficulty experienced trying to maintain the experimental moisture levels may have effected the factorial results. It was not possible to maintain the moisture content of the pile sections at the desired levels. For the full composting period the average weighted mean pile moisture content for the high MC piles was 38.6% compared to the experimental level of 60%. For the 40% MC piles, the average weighted mean pile moisture content was 31.2% for the full composting period. The moisture differences may not have been significant enough to create a real difference in the experimental conditions. Although the -1 and +1 levels for the MC variable in the factorial design matrix were adjusted to reflect the calculated values of the pile average weighted moisture contents, these values may not provide a good representation of the actual moisture conditions.

In addition, the amount of straw added to the experimental piles may not have been sufficient enough to create a significant difference in the C:N ratio of the piles. The experimental C:N ratio levels were based on the number of front end loader buckets instead of the mass of the different organic materials.

4.2 Decomposition

The purpose of monitoring the decomposition of the organic materials for the various compost piles was to: **1**. evaluate and model the biological degradation of these materials over time and provide a tool for optimization of the process; **2**. determine the magnitude and rate of decomposition of the various compost piles.and compare the results with expected behavior. The following sections summarize the decomposition behavior of the experimental compost piles and compares the results to a physical model proposed by Haug (1980).

4.2.1 Decomposition Modelling

Determining the overall reaction rate for the active composting period for the various experimental piles may be useful in identifying differences and process optimization opportunities. Generally the decomposition rate of organic residues especially in soils is considered to follow first order rate kinetics (Paul and Clark 1989). In this study, the parameters % total carbon (% C) in solid compost samples and TOC of compost water extracts were used as measures of the degradation of the organic materials. The measured % C values reported in this study includes the carbon content of substrate as well as biomass. The actual substrate % C is usually determined by subtracting the carbon content of the biomass.

The kinetic rates for the decomposition of the organic materials can be calculated by determining the slope of the line for the different plots of substrate parameters versus time. Instead of plotting the data, linear regression techniques using the least-squares method were used to determine the slope and R^2 value of the fitted line. The R^2 value is the square of the Pearson product moment correlation coefficient. The slope of the fitted line of substrate concentration versus time determined the zero order kinetic rate. For first order kinetics, the slope of the ln of % C and ln of TOC versus time determined the reaction rate constants. The slope of the fitted line of 1/% C and 1/TOC versus time determined the second order kinetic rates. Table 4.13 on the following page summarizes the modelling results for % C of compost solid samples.

The zero order model has the lowest R^2 value of 0.68 while the average R^2 value for the second order model was highest at 0.76. The first order R^2 value was slightly lower than the second order model at a value of 0.74. The calculated R^2 value is a measure of how well the plotted plots fit the straight line relationship. The closer the R^2 value is to 1.0 the better the data fits the straight line relationship. An analysis of variance test was used to statistically determine, if the average R^2 values for the different models are significantly different. The results outlined in Table F.1 indicated, that collectively there was a difference somewhere in the data of the three groups, but a group by group comparison using the Student-Newman-Keuls test with a 5% significance level found the zero order average R^2 value was significantly different than the first and second order average R^2 values. There was no significant difference found between the first and second order average values. Based on the comparison of the average R^2 values, the % C data for the experimental piles suggests the decomposition process follows either first or second order kinetics. The first order model is the more likely case because other authors have indicated the composting process and decomposition of plant residues generally follow first order rate kinetics (Paul and Clark 1989; Haug 1993).

Table 4.13 - Rate Constants for % Carbon - solid samples

Active Period- all values up to and including November 19-21, 1992 samples.

Pile No.	Pile Designations	Zero Order			First Order			Second Order		
		k %C day^{-1}	R^2	Rank	k day^{-1}	R^2	Rank	k %C^{-1}day^{-1}	R^2	Rank
1	Med C:N, Low M.C., Low Por.	-0.1706	0.59	8	0.0064	0.69	8	2.497E-04	0.77	8
2	Hi C:N, Low M.C., Low Por.	-0.1800	0.65	7	0.0040	0.76	14	4.981E-04	0.82	2
3	Med C:N, Hi M.C., Low Por.	-0.2139	0.67	5	0.0080	0.72	4	3.097E-04	0.75	6
4	Hi C:N, Hi M.C., Low Por.	-0.2425	0.81	1	0.0090	0.89	3	3.556E-04	0.95	4
5	Med C:N, Low M.C., Hi Por.	-0.0871	0.68	14	0.0057	0.66	10	2.373E-04	0.69	11
6	Hi C:N, Low M.C., Hi Por.	-0.2256	0.75	4	0.0072	0.83	6	2.438E-04	0.88	9
7	Med C:N, Hi M.C., Hi Por.	-0.0903	0.66	13	0.0070	0.84	7	2.658E-04	0.86	7
8	Hi C:N, Hi M.C., Hi Por.	-0.2346	0.83	3	0.0104	0.87	1	5.115E-04	0.85	1
R1	Med C:N, Hi M.C., Hi Por.	-0.1697	0.66	9	0.0062	0.72	9	2.354E-04	0.77	12
R2	Med C:N, Hi M.C., Hi Por.	-0.2027	0.69	6	0.0079	0.74	5	3.230E-04	0.75	5
L1	Low C:N, Hi M.C., Low Por.	-0.0958	0.55	12	0.0047	0.61	13	2.419E-04	0.65	10
L2	Low C:N, Low M.C., Low Por.	-0.2352	0.66	2	0.0102	0.73	2	4.843E-04	0.77	3
L3	Low C:N, Hi M.C., Hi Por.	-0.1548	0.60	11	0.0051	0.57	12	2.061E-04	0.65	13
L4	Low C:N, Low M.C., Hi Por.	-0.1549	0.67	10	0.0056	0.66	11	1.741E-04	0.51	14
C1	Control Pile	-0.0664	0.23	15	0.0019	0.23	16	5.751E-05	0.22	16
C2	Control Pile	0.3117	0.29	16	0.0037	0.66	15	1.153E-04	0.68	15
	Averages	-0.1755	0.68		0.0070	0.74		0.00031	0.75	

The average % C first order reaction rate constant is 0.0070/day. The rate constants listed in Table 2.7 are generally a few magnitudes higher than determined from the the % C data for the experimental piles. For example, the k values for grass/leaves and grass/cardboard mixtures using first order rate equation for the rate of disappearance of compost mass, ranged from 0.165/day to 0.190/day for Marugg (1993). A possible explanation for these results is the measured % C values of the compost includes not only the amount of carbon in the organic residues and the intermediate products, but also the carbon content of the microbes. The measured % C is higher than actual % carbon of the substrate. As the composting process proceeds, the substrate concentration is decreasing and the biomass concentration increases to a certain point in the process. In the latter stages, the biomass concentration starts to decrease as the amount of available substrate decreases. The calculated decomposition rate using % C is probably lower than the actual rate. If the biomass carbon content was subtracted from the total carbon, the actual decomposition rate could of been calculated.

Table 4.14 summarizes the modelling results for the TOC of compost water extracts.

Table 4.14 - Rate Constants for TOC - water extract

Active Period- all values up to and including November 19-21, 1992 samples.

Pile	Pile Designations	Zero Order k mg $L^{-1}day^{-1}$	Zero Order R^2	Zero Order Rank	First Order k day^{-1}	First Order R^2	First Order Rank	Second Order k L $mg^{-1}day^{-1}$	Second Order R^2	Second Order Rank
1	Med C:N, Low M.C., Low Por.	-32.87	0.62	3	0.0132	0.71	11	6.334E-06	0.74	11
2	Hi C:N, Low M.C., Low Por.	-22.22	0.84	11	0.0174	0.93	4	1.691E-05	0.94	2
3	Med C:N, Hi M.C., Low Por.	-37.94	0.83	1	0.0192	0.86	1	1.211E-05	0.86	5
4	Hi C:N, Hi M.C., Low Por.	-20.19	0.73	13	0.0147	0.82	9	1.228E-05	0.87	4
5	Med C:N, Low M.C., Hi Por.	-30.08	0.72	5	0.0147	0.79	10	8.400E-06	0.84	10
6	Hi C:N, Low M.C., Hi Por.	-23.53	0.56	10	0.0112	0.59	13	6.032E-06	0.58	12
7	Med C:N, Hi M.C., Hi Por.	-35.40	0.56	2	0.0182	0.83	3	1.163E-05	0.88	7
8	Hi C:N, Hi M.C., Hi Por.	-10.95	0.64	14	0.0189	0.75	2	1.855E-05	0.81	1
R1	Med C:N, Hi M.C., Hi Por.	-30.63	0.79	4	0.0174	0.66	5	1.336E-05	0.59	3
R2	Med C:N, Hi M.C., Hi Por.	-29.34	0.58	6	0.0161	0.84	8	9.959E-06	0.85	9
L1	Low C:N, Hi M.C., Low Por.	-28.05	0.75	7	0.0166	0.82	6	1.201E-05	0.85	6
L2	Low C:N, Low M.C., Low Por.	-27.77	0.77	8	0.0162	0.76	7	1.126E-05	0.70	8
L3	Low C:N, Hi M.C., Hi Por.	-26.88	0.77	9	0.0119	0.74	12	5.851E-06	0.65	13
L4	Low C:N, Low M.C., Hi Por.	-22.20	0.60	12	0.0083	0.66	14	3.242E-06	0.72	14
	Averages	**-27.00**	**0.70**		**0.0153**	**0.77**		**0.0000106**	**0.78**	

The zero order model has the lowest R^2 value of 0.70 while the average R^2 value for the second order model was highest at 0.78. The first order R^2 value was slightly lower than the second order model at a value of 0.77. An analysis of variance test was again used to statistically determine, if the average R^2 values for the different models are significantly different. The results indicated that collectively there was a difference somewhere in the data of the three groups but a group by group comparison using the Student-Newman-Keuls test with a 5% significance level found there was no significant difference between the average R^2 values. Based on the comparison of the average R^2 values, the TOC data for the experimental piles suggests the decomposition of the organic materials follows either zero, first or second order kinetics. The first order model is again the more likely case but a discussion of a potential second order model will be reviewed in the section titled Comparison to Theoretical Models.

The average TOC first order reaction rate constant is -0.0153/day. The rate constants listed in Table 2.7 are generally one magnitude higher than determined from the the TOC data for the experimental piles. The TOC data for this study includes the organic carbon content of the biomass. This may explain the differences in the magnitude of the rate constants. The measured TOC value is higher than the actual TOC of just the substrate. If the biomass TOC content was subtracted from the experimental measured value,.the actual decomposition rate could of been determined.

In comparing the first order rate constants for the % C and TOC parameters, the average pile TOC rate constant is over 10 times higher than the average pile rate constant for % C. This higher rate constant value is expected because the TOC parameter measures the readily available water soluble organic carbon content. The measured % C content includes the organic carbon content of all constituents including the more resistant compounds cellulose, hemicellulose and lignin. Paul and Clark (1989) outline the rate constants for plant residues in soils under laboratory conditions. They indicate for easily decomposable compounds -k = 0.2 compared to -k = 0.08 for slowly decomposable constituents. The multicomponent empirical models proposed by Murayama *et al.* (1990) and Van Veen *et al.* (1984) support the argument that different fractions of plant residues decompose at different rates. The reaction rate of the easily decomposable fraction is higher than the more resistant fraction of the plant residue. The following section compares the decomposition modelling results with the theoretical physical model proposed by Haug (1980).

4.2.2 Comparison to Theoretical Model

The modelling results for the parameters % C and TOC over time indicated the the decomposition of the organic materials followed either first or second order kinetics. Generally, the decomposition of organic material is considered to follow first order kinetics Haug (1980), (Paul and Clark 1989). The following section reviews the model proposed by Haug (1980) and discusses the model in relation to experimental decomposition rates and changes in compost substrate and biomass. The composting kinetic model proposed by Haug (1980) is shown below.

$$-\frac{ds}{dt} = \frac{k\,A_V\,X}{K_X + X} \tag{25}$$

-ds/dt = rate of hydrolysis of solid substrate
k = maximum rate of hydrolysis occurring at high microbial population.
A_V = Available surface area (substrate) per unit volume
K_X = half velocity coefficient The microbial concentration at 1/2 the maximum reaction rate.

Haug (1993) indicated that the solubilization of the solid substrate through hydrolysis is probably the rate limiting mechanism during composting. Based on his model, the rate of hydrolysis is a function of the size of the microbial population **X**, and the available substrate surface area per unit volume **A_V**. Haug (1980) described two general cases of the model. Case 1 when the concentration of microbes is much less than **K_X** (the half-rate constant) the rate of hydrolysis of the solid substrate is a first order reaction with respect to the microbial concentration. Case **2** when the concentration of microbes is much greater than the half rate constant the change in solid substrate over time is a zero order reaction with respect to microbial concentration.

Haug (1980) noted that different decomposition rates observed for different substrate materials are probably due to differences in the value of **kA_V**. For example, a more resistant substrate such as wood fiber would have a lower value of **kA_V**. Haug (1980) suggested this may be interpreted as a lower number of available enzyme binding sites or a lower number of successful enzyme reactions in a more resistant substrate. The product kA_V appears to be a measure of substrate availability and the value changes throughout the composting process. Haug (1993) indicated that during the early stages of composting, the substrates with high kA_V values (**kA_{V1}**) are decomposing resulting in an increase in microbial population. As the composting process proceeds, the more resistant substrates with low kA_V values (**kA_{V2}**) are encountered. The rate of hydrolysis of the more complex substrates are the rate determining step of the overall process. The more recalcitrant substrates decompose at lower rates for a longer period of time (Haug 1993; Marugg *et al.* 1993). The changes in % C in solid samples and TOC in water extracts over time provided evidence that the decomposition rate is higher during the active phase and lower during the maturation phase based on the change in slope of the curves. Haug (1993) also suggested the values of **K_X** are likely a function of the type of substrate and should increase as the number of active sites per unit volume increases. Based on this suggestion, the values of **K_X** would also change as the compost substrate changes.

In addition to changes in substrate, the concentration and the types of microorganisms also change during the composting process. During the early mesophilic stage, when the more easily available substrates are consumed, the microbial population especially bacteria increases exponentially (Biddlestone *et al.* 1987). As the temperature increases above $40^{o}C$ the mesophilic organisms die off and the thermophilic organisms flourish. During the thermophilic stage, the compost pile temperature continues to increase to above 60°C (Biddlestone *et al.* 1987). Above 60°C, microbial activity decreases significantly as the fungi are deactivated, and spore-forming bacteria and actinomycetes prevail. The microbial concentration or biomass during the early stages of composting (mainly bacteria) will be represented by the term **X_1**. After the peak temperature period is reached, the compost mass enters a cooling stage marked by a decrease in compost pile temperature and represents a decrease in available substrate. During the cooling stage, fungi and actinomycetes attack the more resistant hemicellulose and cellulose fractions breaking them down to simple sugars which may be used by variety of microorganisms (Biddlestone *et al.* 1987). The biomass concentration in the maturation phase of composting when fungi and actinomycetes dominate will be represented by the term **X_2**.

In the later stages of composting a mixture of solid waste and sewage sludge, de Bertoldi *et al.* (1983) observed a continuous decrease in the number of cellulolytic bacteria to about 10^2 per gram dry weight (50 days). The maximum cellulolytic bacteria count was between 10^3 to 10^4 per gram dry weight, after about 25 days of composting. de Bertoldi *et al.* (1983) indicated the number of cellulolytic fungi increased to approximately 10^8 per gram dry weight in the later stages of composting (50 days) The cellulolytic fungi count was approximately 10^5 per gram dry weight at the start of the composting process. The number of actinomycetes also increased to between 10^6 to 10^7per gram dry weight in the later stages of the composting process from the initial.count of approximately10^4 per gram dry weight (de Bertoldi *et al.* 1983). The compost pile temperature continues to drop to ambient conditions due to lower microbial activity and decomposition rate. Although the concentrations of fungi and actinomycetes increased in the later stages of composting, the overall biomass concentration is expected to decrease, due to a reduction in available substrate. None of referenced composting literature sources specifically noted the fact the concentration of biomass decreased during the maturation phase.

Table 4.15 summarizes the relative values for the various terms in Haug's model for both the active and maturation phases of the composting process.

Table 4.15 - Composting Model Conditions

Term	**Active Phase**	**Maturation Phase**
k	High	Low
S	High S	Low S
A_v	High A_{v1}	High A_{v2} Low A_{v1}
X	High X_1 Low X_2	High X_2 Low X_1
Model Case		
$X << K_x$	$\frac{ds}{dt} = \frac{k\ Av\ X}{K_x}$	$\frac{ds}{dt} = \frac{k\ Av\ X}{K_x}$
$X >> K_x$	$\frac{ds}{dt} = k\ Av$	$\frac{ds}{dt} = k\ Av$

Based on this discussion of Haug's model and its parameters, it appears the rate of hydrolysis, A_v, biomass concentration and type, K_x and the kinetic rate vary throughout the different stages of the process. The two general model cases apply to both the active and maturation stage. Haug's proposed model provides valuable insight into the composting process, but it looks mainly at biomass concentration and does not deal with the relationship between the biomass concentration and the available substrate. The biomass concentration **X** is a function of the available substrate through the the yield coefficient **Y**. The yield coefficient is defined as the ratio of mass of cells formed to the mass of substrate consumed (Metcalf and Eddy, Inc. 1991). Haug (1980) stated the term **A_V** is likely related to the total number of enzyme absorption sites on the substrate. Therefore, the available substrate concentration is a function of the available surface area per volume (**A_V**). With respect to substrate, the two general cases are reviewed below.

Case 1 when the concentration of microbes is much less than **K_X** (the half-rate constant) the rate of hydrolysis of the solid substrate is a second order reaction with respect to **A_V** (related to substrate concentration) and **X** which is a function of the substrate concentration through the yield coeffficient. Case 2 when the concentration of microbes is much greater than the half rate constant the change in solid substrate over time is a first order reaction with respect **A_V.**

In summary, the kinetic rates determined for the various experimental compost piles indicated the overall decomposition rate during the active phase may be either first or second order.with respect to substrate concentration. A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon **A_V** (related to substrate concentration) and microbial concentration **X** which is a function of the available substrate concentration through the yield coefficient. A second possible explanation is the measured % C and TOC values included the carbon content of both substrate and the biomass.

Future research opportunities include determining values for the various kinetic model variables and testing the kinetic model.

4.2.3 Comparison of Individual Piles

The first order decomposition rates for the various piles are generally quite similar and only a few piles are deemed to be significantly different. Multiple t tests were performed to determine which piles were significantly different based on the first order decomposition rate constants (k). The statistical results are summarized in Tables F.2 and F.3 in Appendix F. Table 4.16 outlines the piles than are significantly different for the % C data.

Table 4.16 - Piles found to be Significantly Different - % C data

1st Order k values for % C data

Rank by k value	Pile No.	Pile Designations	Piles Significantly different
1(Highest)	8	Hi C:N, Hi M.C., Hi Por.	Piles 5, L1, L3, L4
2	L2	Low C:N, Low M.C., Low Por.	Piles L1, L3, L4
3	4	Hi C:N, Hi M.C., Low Por.	
4	3	Med C:N, Hi M.C., Low Pc	
5	R2	Med C:N, Hi M.C., Hi Por.	
6	6	Hi C:N, Low M.C., Hi Por.	
7	7	Med C:N, Hi M.C., Hi Por.	
8	1	Med C:N, Low M.C., Low Por.	
9	R1	Med C:N, Hi M.C., Hi Por.	
10	5	Med C:N, Low M.C., Hi Por.	Pile 8
11	L4	Low C:N, Low M.C., Hi Por.	Piles 8, L2
12	L3	Low C:N, Hi M.C., Hi Por.	Piles 8, L2
13	L1	Low C:N, Hi M.C., Low Por.	Piles 2, 8, L2
14 (Lowest)	2	Hi C:N, Low M.C., Low Por.	Pile L1

Piles 8 and L2 had the largest decomposition k values and were found to be significantly different than the low C:N ratio piles L1, L3, and L4. Pile 8 was also different than Pile 5. Pile 2 a high C:N ratio, low moisture content pile had the lowest decomposition rate and was found to be significantly different than pile L1. There appears to be no consistent reasoning, based on the experimental levels of the operating variables, to explain the ranking order and significant differences between the decomposition rates of the piles. The decomposition rates for the high C:N ratio, high moisture content piles 8 and 4 were expected to be high in comparison to the other piles. However, Pile L2 a low C:N ratio, high moisture content pile was not expected to have the second largest decomposition rate. Pile L3 the other low C:N ratio, high moisture content pile was ranked 12 overall. The decomposition rates for the low C:N ratio piles except for Pile L2 were generally low in the rankings. Table 4.17 outlines the piles that are significantly different for the TOC data.

Table 4.17 - Piles Significantly Different - TOC data

1st Order k values for TOC data

Rank by k value	**Pile No.**	**Pile Designations**	**Piles Significantly different**
1(Highest)	3	Med C:N, Hi M.C., Low Por.	Pile L4
2	8	Hi C:N, Hi M.C., Hi Por.	Pile L4
3	7	Med C:N, Hi M.C., Hi Por.	Pile L4
4	2	Hi C:N, Low M.C., Low Por.	
5	R 1	Med C:N, Hi M.C., Hi Por.	
6	L 1	Low C:N, Hi M.C., Low Por.	
7	L 2	Low C:N, Low M.C., Low Por.	
8	R 2	Med C:N, Hi M.C., Hi Por.	
9	4	Hi C:N, Hi M.C., Low Por.	
10	5	Med C:N, Low M.C., Hi Por.	
11	1	Med C:N, Low M.C., Low Por.	
12	L 3	Low C:N, Hi M.C., Hi Por.	
13	6	Hi C:N, Low M.C., Hi Por.	
14 (Lowest)	L 4	Low C:N, Low M.C., Hi Por.	

Piles 3, 8 and 7 had the largest 1st order decomposition k values and were found to be significantly different than L4 which had the lowest value. Again there appears to be no consistent reasoning, based on the experimental levels of the operating variables, to explain the ranking order and significant differences between the decomposition rates of the piles. The maturity parameter $C:N_W$ cannot be used to indicate which piles matured first as none of the values were between the range of 5 to 6. Possible reasons for the differences observed between the experimental and literature values are sample preparation techniques, testing errors, possible sample contamination, and different organic materials.

4.2.4 Summary and Explanations

In summary, the decomposition rates for the parameters % C and TOC over time were found to follow either first or second order kinetics. Based on ANOVA tests there were no differences between the average pile R^2 values for the first and second order kinetic models. Generally the decomposition of organic materials is considered to follow first order kinetics. The first order decomposition rate constants for both parameters were lower than literature values.

A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon A_v and microbial concentration X which is a function of the available substrate concentration through the yield coefficient

Finally the first order decomposition rates for the various piles were compared using an ANOVA. Although there were some significant differences between some of the piles, there was no consistent reasoning based on the experimental levels to explain the results. The ranking of the piles by first order decomposition rate constants, therefore, cannot be used to verify which operational parameters influenced the rate of decomposition. Possible reasons for these experimental results are: inadequate material mixing, actual C:N ratio levels, sampling and testing errors and the difficulties experienced in trying to control moisture content of the piles.

4.3 Temperature and % Oxygen Results

Compost pile temperatures were measured to: **1**. identify the different stages of the composting process; **2**. provide an indication of process performance; **3**. to evaluate the the effectiveness of rebuilding the compost piles; **4**. serve as a secondary indicator of compost maturity. The following sections discuss the trends in compost pile temperatures and % oxygen readings and the results of the ARIMA (Autoregressive integrated moving average) analysis.

4.3.1 Trends in Pile Temperature and % Oxygen Readings

The average pile temperature for the various piles generally followed a decreasing trend throughout the first 65 days of the process and then increased to over 60^{0}C after the piles are rebuilt and covered with burlap and mature compost. The initial average temperatures for the compost piles were approximately 65^{0}C. No mesophilic stage was observed. Based on the fact the yard waste was picked up from the different areas of the city on a weekly basis it is highly possible the degradation process had already started prior to the development of the windrows. The peak thermophilic stage for most of the piles was approximately 16-20 days in length. After this period, the average pile temperatures generally followed a decreasing trend until the piles were rebuilt and covered. The average pile temperatures prior to rebuilding ranged from 28.9^{0}C for pile 1 to 54.3^{0}C for pile 7. Most of the piles had an average temperature of approximately 30^{0}C with mean ambient temperatures in the 3 to 8^{0}C range. The cooling stage is generally characterized as the period, when the compost pile temperature decreases to ambient conditions due to lower microbial activity (Biddlestone *et al.* 1987). The compost piles were rebuilt prior to the conclusion of the initial cooling stage. As indicated, after the compost piles were rebuilt the average pile temperature increased to over 60^{0}C and stayed above 50^{0}C for most of November 1992 when the mean ambient temperatures were in the range of -2 to 2^{0}C. The pile temperatures then gradually decreased to ambient temperatures after approximately 180 days signalling the start of the maturation stage. The average pile temperature serves as a secondary and approximate indicator of maturity. Figures D.1 to D.16 show changes in the average pile temperatures for the various piles. Table D.1 in Appendix D summarizes the average monthly pile temperatures. The average monthly temperatures for most of the piles were close in value except for piles 3, 6 and 8 during the November 1992 to January 1993 time frame. Control piles C1 and C2 generally had higher average monthly temperatures in September and October of 1992 than most of the experimental piles. The most likely explanation for these higher temperatures is the control piles were not as far along as the experimental piles in the composting process. Conversely the average monthly temperatures for the control piles were lower during December and January. The differences are probably due to the installation of the passive aeration system, rebuilding and covering of the experimental piles.

The % oxygen content of the various piles fluctuated for the first 130-140 days and then levelled off at values close to ambient conditions. Figures D.17 to D.32 show changes in the average % oxygen readings for the various piles. The oxygen readings ranged from values of 10 to 20.9%. which are much higher than the minimum value of 5%. The method of measurement may have introduced oxygen into the pile resulting in a higher readings. The next section discusses the results of the time series ARIMA analyses for compost pile temperature data.

4.3.2 Arima Analyses - Results

Arima (Autoregressive integrated moving average) analysis was used to investigate the influence interventions such as turning, watering, rebuilding and adding additional wood chips to the experimental piles had on the average pile temperatures over the composting period. The main purpose of these interventions were to try to maintain the experimental levels of the operational variables for the factorial experiments. For example, the piles were watered to try to increase the moisture content to the desired levels. Usually the piles were mechanically turned the same day to homogenize the compost materials therefore more than one intervention was carried on the same day or prior to the next temperature reading. This experiment was not specifically designed to evaluate the various interventions using Arima analysis therefore the results must be fairly consistent in order to support any conclusions. Installing the passive aeration system, rebuilding and covering the experimental piles was the only intervention that was not directly connected to maintaining the experimental levels.

Arima models are used to mathematically describe the random disturbances in a time series. These models can involve the use of three different processes namely autoregression, differencing (integration) and moving averages. Not all models involve the use of all three processes. For example, the appropriate model for the compost temperature time series was an Arima (1,0,0) model. The usual nomenclature defining an Arima model is Arima (p,d,q). The p defines the order of autoregression, d the degree of differencing and q the order of moving average. The Arima (1,0,0) model is a first order autoregressive process and does not involve differencing and moving average processes. In the autoregression process, each value in a time series is a function of one or more preceding values. The equation shown below defines the relationship for a first order autoregressive process (SPSS for Windows Trends Manual 1993).

$$\text{Value}_t = \text{disturbance}_t + \text{ARI coefficient} * \text{Value}_{t-1} \qquad (29)$$

ARI coefficient = autoregressive coefficient

The value of the ARI coefficient indicates how strongly the value at time t is dependent on the preceding value (1993). ARI coefficient values close to 1 as calculated in these analyses indicates there is a strong relationship between the series value at time t and the preceding value. The model coefficients for the various interactions are listed in Table 4.18. A negative value indicates the pile temperature increased as a result of the intervention. Based on 95% probability the coefficients highlighted in bold were considered significant.

Table 4.18 - ARIMA Analyses - Results
Variable- Average Pile temperatures

Pile	**AR1**	**Mixing**	**Watering**	**Rebuild**	**Porosity**
Pile 1	**0.9695**	0.785	**-7.586**	**-14.850**	
Pile 2	**0.9186**	-1.861	-0.270	-9.990	
Pile 3	**0.9227**	-1.323	3.322	**-12.788**	
Pile 4	**0.9459**	-0.114	-3.718	**-12.298**	
Pile 5	**0.9127**	-1.668	1.691	-9.986	-8.696
Pile 6	**0.9635**	0.789	**-7.467**	**-14.751**	-0.440
Pile 7	**0.9801**	2.661	**-5.418**	1.152	**9.669**
Pile 8	**0.9274**	-0.652	-2.203	5.019	-5.430
Pile R1	**0.9705**	1.101	1.700	**-13.200**	**-10.705**
Pile R2	**0.9724**	2.189	1.619	-6.551	1.494
Pile L1	**0.9721**	-3.304	**-4.730**	-5.802	
Pile L2	**0.9456**	-4.818	0.447	0.114	

Based on the model coefficient values the mixing, watering and porosity adjustment interventions did not consistently influence the average pile temperatures. For example, seven piles with negative model coefficients indicated mixing increased the temperature. Five piles with positive values suggested mixing decreased the average pile temperature. Five piles had significant negative model coefficients for the intervention pile rebuilding. These results support the conclusion that the installation of a passive aeration system, and the rebuilding and covering of the compost piles resulted in higher compost temperatures. The average pile temperature after the intervention was higher than the temperature before the intervention.

5.0 SUMMARY AND CONCLUSIONS

The objectives of this study were to 1) systematically evaluate the influence of key operational parameters on the decomposition rate of yard waste and 2) identify a practical indicator of compost stability and maturity. A factorial experiment was selected to evaluate the influence of the operational variables, because it is the most efficient method to estimate the effects of two or more factors and the their interactions. The factorial results using the % decrease in the TOC as the response variable found none of the effects to be significant at the 5% significance level. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13, (C:N ratio-Porosity) 23 (MC-Porosity) and the 123 (C:N ratio-MC-Porosity) interactions marginally influenced the decomposition rate of the organic materials. Generally, the results do not support the hypotheses that the operating variables C:N ratio, moisture content and porosity adjustment individually affected the decomposition rate of the organic materials. Possible explanations for these experimental results are: 1) the response variables used in the study were not able to measure the effects , 2) the effect of C:N ratio, M.C. and porosity on degradation did not occur within the ranges tested or 3) the difficulties encountered in maintaining and operating a field level experiment impacted the results. The most likely reasons are the difficulties in maintaining and operating a field level experiment. For example, the difficulty experienced trying to maintain the experimental moisture levels may have effected the factorial results. It was not possible to maintain the moisture content of the pile sections at the desired levels.

The purpose of monitoring the decomposition of the organic materials for the various compost piles was to: 1) evaluate and model the biological degradation of these materials over time and provide a tool for optimization of the process, 2) determine the magnitude and rate of decomposition of the various compost piles and compare the results with expected behavior. The decomposition rates for the parameters % C and TOC over time were found to follow either first or second order kinetics with respect to substrate concentration. A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon A_v (related to substrate concentration) and microbial concentration which is a function of the available substrate concentration through the yield coefficient. A second explanation is the % C and TOC data included both the carbon content of substrate and biomass. The data does not represent the change in just substrate carbon over time. The first order decomposition rates for the various piles were compared using multiple t tests. Although there were some significant differences between some of the piles, there was no consistent reasoning based on the experimental levels to explain the results. The ranking of the piles by first order decomposition rate constants, therefore, cannot be used to verify which operational parameters influenced the decomposition rate.

An Arima analysis of the average pile temperature data indicated the average pile temperature increased as a result of rebuilding, covering and installing a passive aeration system. The average monthly temperatures for the control piles were lower during December and January than the rebuilt experimental piles. The results support the hypothesis that building up the compost piles will result in higher pile temperatures during the cooler ambient conditions. The degradation of the organic materials; therefore, is not greatly reduced by the cold ambient temperatures. By retaining enough heat, higher compost temperatures are maintained which promotes the continued optimal decomposition of the organic materials.

The second objective of this study was to identify a practical indicator of compost stability and maturity. The final $C:N_W$ ratio values for the experimental piles did not fall between the range of 5 to 6 indicated by others as the absolute indication of maturity. The OUR parameter was dropped from the experimental plan, after several attempts to solve the problem of leaks in the tubing were not successful. The change in % C and TOC over time provided some indication, when the active composting period had ended and the maturation stage had started. At this point, there is a definite change in the slope of the curve for the various piles. Finally, the average pile temperatures gradually decreased to ambient temperatures after approximately 180 days signalling the start of the maturation stage. In summary, no parameter used in this study was identified as a absolute indicator of compost maturity.

Suggestions to improve future research efforts include grinding up the straw prior to mixing, weighting the mass of each organic material, and developing more replicate piles. In addition, the use of the D.O. oxygen meter to measure the OUR rates of the compost should be investigated and evaluated. It is critical to establish more than one reliable response variable to verify the experimental results.

Future areas of research may include determining values for the terms k, A_v, X and K_X for Haug's kinetic model and testing the model with respect to substrate concentration.

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7.0 APPENDICES

Appendix A - Solid Sample Parameter Data

Table A.1- Solid Sample Parameter Data

Pile 1

								Multiple Sample Data					
Sample Date	Days	%MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-02	3	59.54	65.20	5.09	36.22	2.12	17.12	92-09-26	X	51.11	40.91	5.49	22.73
92-08-11	12	36.74	55.39	5.76	30.77	1.85	16.59		Y	33.30	54.60	3.13	30.33
92-08-16	17	41.56	19.50	19.50	33.88	1.92	17.66		Z	45.32	47.47	4.79	26.37
92-08-23	24	29.27	57.45	3.45	31.92	2.59	12.34		Pile Avg	43.24	47.66		26.48
92-09-02	34	30.05	77.57	22.38	43.09	1.52	28.40		S	9.09			
92-09-13	45	48.12	41.47	3.06	23.04	1.99	11.56						
92-09-26	58	43.24	47.66	6.73	26.48	2.20	12.04	92-10-20	X	47.38	36.20	2.78	20.11
92-10-20	82	46.22	37.09	3.24	20.60	2.07	9.94		Y	43.02	37.47	4.93	20.81
92-11-19	112	36.97	33.73	0.91	18.74	1.85	10.15		Z	48.27	37.59	2.87	20.88
93-01-12	165	39.42	36.22	0.23	20.12	1.74	11.58		Pile Avg	46.22	37.09		20.60
93-03-13	225	18.71	36.05	0.47	20.03	2.06	9.72		S	2.81			

Pile 2

92-08-02	2	38.63	41.84	2.31	23.24	2.28	10.19	92-09-26	X	27.72	44.63	13.04	24.79
92-08-11	11	19.96	47.90	17.39	26.61	1.54	17.29		Y	33.68	29.32	6.08	16.29
92-08-16	16	18.96	60.99	1.56	33.88	1.65	20.56		Z	30.64	30.49	0.45	16.94
92-08-23	23	15.97	66.09	7.54	36.72	1.47	25.04		Pile Avg	30.68	34.81		19.34
92-09-04	35	28.84	43.91	12.49	24.39	1.62	15.02		S	2.98			
92-09-13	44	29.28	48.32	6.90	26.85	1.28	20.93						
92-09-26	57	30.68	34.81	10.31	19.34	1.10	17.65						
92-11-05	97	25.22	21.45	0.43	11.92	1.03	11.59						
92-11-19	111	22.88	21.99	0.92	12.21	1.01	12.06						
93-01-12	164	34.90	22.83	0.92	12.68	1.28	9.91						
93-03-13	224	23.29	23.96	0.87	13.31	0.99	13.49						

Pile 3

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	49.51	60.17	10.69	33.43	2.55	13.12
92-08-11	11	18.02	71.10	9.77	39.50	1.43	27.53
92-08-16	16	31.13	64.75	0.90	35.97	1.99	18.06
92-08-26	26	51.26	66.35	6.54	36.86	1.36	27.02
92-09-04	35	36.66	75.53	2.77	41.96	1.81	23.21
92-09-13	44	32.09	51.71	4.76	28.73	1.71	16.85
92-09-28	59	48.09	33.56	4.78	18.65	1.37	13.58
92-10-18	79	43.69	38.86	6.05	21.59	1.33	16.26
92-11-19	111	45.63	32.04	0.94	17.80	1.91	9.34
92-01-14	166	43.72	25.40	0.23	14.11	0.94	15.04
92-03-13	224	43.41	27.38	0.13	15.21	1.36	11.19

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-28	X	47.45	33.29	0.25	18.49
	Y	46.03	28.90	1.03	16.05
	Z	50.80	38.51	3.10	21.39
	Pile Avg	48.09	33.56		18.65
	S	2.45			
92-10-18	X	44.60	32.46	6.21	18.04
	Y	41.71	41.83	5.68	23.24
	Z	44.76	42.29	1.25	23.49
	Pile Avg	43.69	38.86		21.59
	S	1.71			

Pile 4

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-03	4	58.55	60.21	19.38	33.45	1.67	20.08
92-08-06	7	35.08	78.96	4.12	43.86	2.11	20.77
92-08-11	12	42.86	72.14	19.50	40.08	2.17	18.50
92-08-16	17	39.98	66.79	6.73	37.11	2.07	17.92
92-08-23	24	34.90	61.06	2.92	34.54	1.93	17.86
92-09-02	34	58.29	49.68	12.29	27.60	1.85	14.92
92-09-13	45	49.71	42.63	4.83	23.68	1.46	16.23
92-09-26	58	52.38	39.22	7.43	21.79	1.70	12.80
92-10-15	77	50.15	33.55	5.71	19.19	1.60	12.01
92-11-19	112	39.32	29.71	1.79	16.51	1.50	11.00
93-01-12	165	44.27	29.04	0.14	16.13	1.49	10.81
93-03-13	225	29.30	28.53	0.25	15.85	1.59	9.99

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	54.08	37.58	6.46	20.88
	Y	52.91	45.55	8.72	25.31
	Z	50.15	34.54	2.42	19.19
	Pile Avg	52.38	39.22		21.79
	S	2.02			
92-10-15	X	48.88	29.05	2.42	16.14
	Y	50.98	34.42	8.68	19.12
	Y'	51.86	36.41	7.22	20.23
	Z	48.78	34.34	0.95	19.08
	Pile Avg	50.12	33.55		18.64
	S	1.54			

Pile 5

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	58.43	57.46	16.16	31.92	2.43	13.13
92-08-11	11	29.23	47.50	15.79	26.39	1.65	16.04
92-08-16	16	36.79	64.05	2.82	35.58	1.91	18.60
92-08-23	23	51.43	62.31	8.56	34.62	1.69	20.43
92-09-04	35	45.46	48.61	6.39	27.01	1.40	19.30
92-09-13	44	30.21	58.82	0.38	32.68	1.69	19.29
92-09-28	59	44.31	36.47	5.68	20.26	1.88	10.77
92-10-18	79	42.97	43.45	4.15	24.14	1.60	15.04
92-11-19	111	32.05	31.06	2.63	17.26	1.59	10.84
93-01-14	166	37.54	28.80	0.30	16.00	1.50	10.67
93-03-13	224	17.70	29.02	0.80	16.12	1.45	11.11

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-28	X	47.60	41.85	1.84	23.25
	Y	43.09	33.97	7.56	18.87
	Z	42.25	33.58	4.37	18.65
	Pile Avg	44.31	36.47		20.26
	S	2.88			
92-10-18	X	30.06	41.02	1.00	22.79
	Y	49.86	44.47	4.25	24.70
	Z	48.98	44.86	2.45	24.92
	Pile Avg	42.97	43.45		24.14
	S	11.18			

Pile 6

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-03	4	45.70	80.20	2.71	44.56	1.73	25.80
92-08-06	7	39.67	78.35	1.00	43.53	2.14	20.35
92-08-11	12	27.42	85.04	7.51	47.24	2.17	21.74
92-08-16	17	29.46	60.44	6.92	33.58	1.71	19.66
92-08-23	24	29.11	60.33	3.97	33.52	1.85	18.15
92-09-02	34	33.02	54.36	5.68	30.20	1.80	16.74
92-09-13	45	42.53	46.18	0.55	25.66	1.62	15.85
92-09-26	53	41.20	52.73	4.29	29.30	2.01	14.58
92-10-15	77	45.44	48.34	9.65	26.86	1.67	16.05
92-11-19	112	29.42	35.36	4.69	19.65	1.79	10.99
93-01-12	165	23.63	35.41	1.67	19.67	1.85	10.62
93-03-13	225	27.27	35.74	1.64	19.86	1.58	12.57

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	39.33	49.82	4.64	27.68
	Y	39.94	52.33	2.84	29.07
	Z	44.32	56.04	4.89	31.13
	Pile Avg	41.20	52.73		29.30
	S	2.72			
92-10-15	X	54.52	52.57	2.81	29.21
	Y	46.55	54.54	5.50	30.30
	Y'	37.02	44.52	18.28	24.73
	Z	43.69	41.74	3.75	23.19
	Pile Avg	45.44	48.34		26.86
	S	4.89			

Pile 7

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	55.83	73.01	1.81	40.56	2.91	13.92
92-08-06	7	56.24	63.60	22.42	35.33	2.08	17.02
92-08-11	12	45.59	59.17	9.77	32.87	2.11	15.59
92-08-16	17	37.94	59.84	8.27	33.24	2.14	15.54
92-08-23	24	34.24	61.63	2.37	34.24	1.70	20.15
92-09-02	34	49.94	52.99	4.87	29.44	1.96	14.99
92-09-13	45	44.38	47.72	2.18	26.51	1.56	17.04
92-09-26	58	52.07	35.87	4.27	19.93	1.74	11.45
92-10-15	77	54.32	32.54	12.82	20.26	1.46	13.91
92-11-19	112	41.68	35.48	2.52	19.71	1.46	13.53
93-01-12	165	42.76	36.40	0.83	20.22	1.53	13.25
93-03-13	225	25.88	32.06	0.62	17.81	1.69	10.52

Pile 8

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	58.64	60.21	19.38	33.45	1.55	21.60
92-08-11	11	39.76	61.30	4.06	34.06	1.34	25.50
92-08-16	16	29.25	58.78	9.35	32.66	1.36	24.03
92-08-23	23	29.07	62.76	6.82	39.24	1.73	22.63
92-09-04	35	37.34	60.53	7.26	33.63	2.10	16.04
92-09-13	44	40.16	45.80	2.47	25.44	1.24	20.55
92-09-28	59	44.48	32.60	8.42	19.00	1.12	16.96
92-10-18	79	40.98	36.16	6.47	20.39	1.11	18.29
92-11-19	111	35.44	20.56	2.04	11.42	0.91	12.58
93-01-12	164	31.73	24.16	2.45	13.63	1.29	10.56
93-03-13	224	24.67	15.98	14.35	8.88	1.05	8.46

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	47.77	34.74	1.67	19.30
	Y	56.07	40.82	3.15	22.68
	Z	52.37	32.05	2.95	17.81
	Pile Avg	52.07	35.87		19.93
	S	4.16			
	X	54.03	20.77	23.49	11.54
	Y	58.84	38.28	1.89	21.26
	Y'	52.50	33.25	6.49	18.47
	Z	51.63	37.88	2.43	21.04
	Pile Avg	54.32	32.54		20.26
	S	3.22			
92-09-28	X	41.03	23.94	1.01	13.30
	Y	44.06	33.04	7.79	20.85
	Z	48.32	40.80	6.61	22.84
	Pile Avg	44.48	32.60		19.00
	S	3.66			
92-10-18	X	44.07	33.73	7.12	18.74
	Y	40.86	40.26	5.63	21.00
	Z	38.01	34.50	8.24	21.43
	Pile Avg	40.98	36.16		20.39
	S	3.03			

Pile R1

								Multiple Sample Data					
Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-02	3	62.13	52.44	6.35	29.13	2.54	11.45	92-10-20	X	44.07	43.01	1.81	23.90
92-08-06	7	46.28	6 .76	5.43	37.64	2.56	14.72		Y	52.45	41.95	2.47	23.31
92-08-11	12	40.14	69.89	3.21	38.83	2.78	13.99		Z	52.02	46.24	2.76	25.69
92-08-16	17	43.62	58.89	12.35	32.72	2.56	12.79		Pile Avg	49.52	43.74		24.30
92-08-23	24	45.81	71.69	9.78	39.83	2.42	16.47		S	4.72			
92-09-05	37	48.37	59.71	1.80	33.17	1.74	19.04						
92-09-13	45	50.75	42.88	1.28	23.82	2.11	11.29						
92-09-29	60	58.79	42.26	3.53	23.48	0.80	29.26						
92-10-20	82	49.52	43.74	2.67	24.30	1.37	17.77						
92-11-19	112	43.56	33.04	4.49	18.36	2.02	9.11						
93-01-12	165	43.09	33.05	0.56	18.36	1.77	10.35						
93-03-13	225	23.89	43.13	0.94	23.96	1.58	15.15						
Pile R2													
92-08-02	3	58.41	63.07	1.66	35.04	2.87	12.20	92-10-20	X	52.92	44.07	3.03	24.48
92-08-06	7	53.17	54.18	36.55	30.10	2.14	14.10		Y	41.88	32.32	1.36	17.95
92-08-11	12	35.06	78.57	15.39	43.65	3.10	14.08		Z	47.09	33.70	3.72	18.72
92-08-16	17	51.64	64.43	2.79	35.80	2.89	12.39		Pile Avg	47.30	36.69		20.39
92-08-23	24	45.81	51.81	29.01	28.78	2.41	11.93		S	5.52			
92-09-05	37	39.78	50.58	1.40	28.10	1.74	16.13						
92-09-13	45	50.14	53.39	0.42	29.66	2.24	13.25						
92-09-28	60	44.72	29.75	2.76	16.53	1.87	8.86						
92-10-20	82	47.30	36.69	5.75	20.39	1.17	17.38						
92-11-19	112	37.96	30.09	2.34	16.72	1.80	9.31						
93-01-14	167	38.03	30.79	0.16	17.11	1.86	9.20						
93-03-13	225	41.09	27.05	0.18	15.03	1.55	9.68						

Pile L1

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	59.36	47.74	0.50	26.52	2.22	11.93
92-08-06	7	46.51	44.94	18.24	24.97	2.20	11.36
92-08-16	17	39.51	37.43	4.24	20.79	1.97	10.54
92-08-27	28	52.52	50.60	13.00	28.11	1.96	14.32
92-09-05	37	54.64	42.95	5.22	23.86	1.66	14.34
92-09-13	45	53.98	51.01	1.40	28.34	1.83	15.48
92-09-28	60	54.11	33.67	3.79	18.71	1.96	9.56
92-10-20	82	52.59	35.83	1.45	19.90	1.48	13.41
92-11-21	114	45.28	29.05	2.41	14.47	1.55	9.32
93-01-14	167	40.02	28.48	0.36	15.82	1.45	10.91
93-03-13	225	17.53	29.67	0.04	16.49	1.59	10.36

Pile L2

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	3	59.53	73.64	9.39	40.91	2.40	17.03
92-08-06	7	63.97	57.77	21.42	32.10	2.53	12.67
92-08-16	17	39.59	42.21	4.24	23.45	1.79	13.09
92-08-27	28	43.30	69.34	3.36	38.52	1.93	19.92
92-09-05	37	15.13	60.15	15.57	33.42	1.65	20.31
92-09-13	45	36.08	45.90	1.66	25.50	1.78	14.33
92-09-28	60	38.27	25.72	3.28	14.29	1.48	9.65
92-10-20	82	34.06	27.77	3.06	15.43	1.37	11.28
92-11-21	114	31.80	23.56	3.68	13.09	1.53	8.55
93-01-14	167	25.95	23.84	0.50	13.24	1.21	10.93
93-03-13	225	27.41	24.76	0.56	13.75	1.34	10.29

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C

Pile L3

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	46.13	72.35	3.46	40.20	2.32	17.33
92-08-06	6	40.69	61.06	3.77	33.92	1.87	18.11
92-08-11	11	28.85	74.13	4.07	41.18	2.43	16.97
92-08-16	16	41.40	61.84	1.58	34.36	3.24	10.61
92-08-27	27	49.90	63.16	7.80	35.09	2.12	16.58
92-09-05	36	54.73	48.77	2.48	27.09	2.15	12.63
92-09-13	44	43.42	51.50	2.00	28.61	1.91	15.00
92-09-28	59	49.77	34.17	7.88	18.98	1.54	12.34
92-10-20	81	43.49	45.33	0.37	25.18	2.02	12.46
92-11-21	113	34.53	44.60	6.94	24.78	1.77	13.96
93-01-14	166	38.50	29.92	0.85	16.62	1.58	10.49
93-03-13	224	30.20	33.76	0.35	18.75	1.82	10.30

Pile L4

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	57.46	70.19	7.91	38.99	1.97	19.83
92-08-16	16	43.60	53.63	7.98	29.79	2.03	14.71
92-08-27	27	43.96	62.87	1.67	34.93	2.13	16.39
92-09-05	36	37.78	62.75	7.87	34.86	1.69	20.61
92-09-13	44	49.96	55.19	12.31	30.66	2.59	11.86
92-09-28	59	37.44	36.67	2.65	20.37	1.93	10.55
92-10-20	81	37.40	49.29	3.54	27.39	1.93	14.22
92-11-21	113	28.41	35.88	3.47	19.93	2.15	9.26
93-01-14	166	26.35	36.16	0.55	20.09	1.84	10.94
93-03-13	224	21.28	32.64	0.99	18.13	1.67	10.87

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C

Pile C1

								Multiple Sample Data					
Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-11	8	48.27	75.74		42.08	2.76	15.27						
92-08-16	13	53.63	60.89	26.76	33.83	2.65	12.79						
92-09-03	31	43.83	58.05	13.18	32.25	2.42	13.35						
92-09-13	41	50.83	52.99	1.23	29.44	2.20	13.39						
92-10-02	60	41.65	55.27	2.33	30.71	2.62	11.73						
92-10-20	78	32.28	47.39	4.01	26.33	2.86	9.22						
92-11-19	108	42.37	61.29	6.70	34.05	2.99	11.39						
93-01-14	163	38.74	52.36	0.16	29.09	2.96	9.83						
93-03-13	221	33.28	55.61	0.54	30.90	2.79	11.07						

Pile C2

92-08-11	8	52.46	75.74	6.57	42.08	3.48	12.09
92-08-16	13	52.46	63.37	3.45	35.21	2.29	15.35
92-09-03	31	56.50	52.00	8.80	28.89	2.81	10.30
92-09-13	41	50.73	58.43	4.89	32.46	2.62	12.38
92-10-02	60	48.80	58.44	8.65	32.47	2.66	12.20
92-10-20	78	54.28	47.69	4.32	26.49	2.77	9.56
92-11-19	108	55.64	48.16	3.66	26.76	2.22	12.05
93-01-14	163	47.61	53.36	0.28	29.64	2.83	10.47
93-03-13	221	22.09	36.69	1.52	20.38	2.02	10.12

Table A.2 - Multiple Sample % Volatile Solids Statistics

Pile	Sample Date	Mean % VS	S	n	SE of Mean	95 % CI ±	95 % CI % of Mean Value ±
1	92-09-26	47.56	6.73	9	2.24	5.18	10.87
1	92-10-20	37.09	3.24	9	1.08	2.50	6.73
2	92-09-26	34.81	10.31	9	3.44	7.94	22.80
3	92-09-28	34.81	4.78	9	1.59	3.68	10.97
3	92-10-18	38.86	6.05	9	2.02	4.66	11.98
4	92-09-26	39.22	7.43	9	2.48	5.72	14.58
4	92-10-15	33.55	[illegible]71	12	1.65	3.62	10.80
5	92-09-28	3[illegible]	[illegible]	9	1.89	4.37	11.98
5	92-10-18	[illegible]	[illegible]	9	1.38	3.19	7.35
6	92-09-26	[illegible]	[illegible]	9	1.43	3.30	6.26
6	92-10-15	[illegible]	[illegible]	[illegible]	2.79	6.13	12.67
7	92-09-26	[illegible]	[illegible]	[illegible]	1.42	3.29	9.16
7	92-10-15	3[illegible]	[illegible]	[illegible]	3.70	8.14	25.02
8	92-09-28	32.[illegible]	[illegible]	[illegible]	2.81	6.48	19.89
8	92-10-18	36.1	[illegible]	[illegible]	2.16	4.99	13.78
R1	92-10-20	43.7[illegible]	[illegible]	[illegible]	0.89	2.05	4.69
R2	92-10-20	36.69	[illegible]	9	1.92	4.42	12.06
						Average	**12.45**

many attempts to identify and seal the leaks and run OUR tests without success, the OUR parameter was dropped from the experimental plan.

3.2.4 Laboratory Analyses - Water Extracts

Water compost extracts were obtained by mechanically shaking oven dried compost samples with distilled water for 2 hours (solid liquid ratio = 1/10). The extracts were centrifuged at 5,000g for 20 minutes, and filtered through a Watsman No. 1 filter paper (11 µm). The water extracts were developed using the method used by Garcia *et al.* (1991b).

The water extracts were analyzed immediately for NH_3 and organic nitrogen and were stored in teflon sealed glass bottles in a refrigerated room at 4°C until they were analyzed for carbon content.

3.2.4.1 Total Organic Carbon (TOC) Content

The total carbon (TC) and total inorganic carbon (TIC) content of the compost water extracts were determined by using a Dohrman DC-80 Organic Carbon Analyzer. The water extracts were diluted 10 fold prior to injection Using a volumetric pipet, 1 ml of compost water extract was transferred to a 10ml volumetric flask and topped up with. distilled water. The total organic carbon (TOC) content was calculated by subtracting the TIC value from TC value for each water extract sample. At least three syringe injections per extract were performed. Multiple extracts were developed and analyzed for selected samples to provide an indication of variance.

The compost water extracts were prepared from ground, oven-dried samples versus air dried samples. This sample preparation method may have introduced some possible errors in the TOC results. Drying the samples at the higher temperature would result in potential volatile organic and ammonia losses, and hence, affect the water extract results. Jimenez and Garcia (1992b) found there was only about a 1.2 to 1.8% more water soluble carbon in air dried and ground samples than in fresh samples. The volatile organic and ammonia losses may not be significant at the 103°C temperature. Tests would be required to assess the potential losses.

An additional source of error was the time required to filter the compost water extracts. To obtain enough water extract for analyses, the earlier grass-like samples required approximately 30 additional minutes of filtration time. The longer filtration times introduced possible losses in TOC and ammonia.

The errors introduced in obtaining the initial compost samples are perhaps larger in magnitude than the errors due to sample drying and water extract preparation.

3.2.4.2 Organic and Ammonia Nitrogen

The organic and ammonia nitrogen contents of the water extracts were determined by the Kjeldahl method described in Standard Methods for the Examination of Water and Wastewater 1989, 17th edition. Generally, duplicate aliquots of the water extracts were analyzed for NH_3 and organic nitrogen content.

4.0 RESULTS AND ANALYSIS

This section of the thesis reviews the results of the factorial experiments, discusses the decomposition kinetics of the various compost piles and the results of the ARIMA (Autoregressive integrated moving average) analyses of pile temperature data.

4.1 Factorial Experiments

The purpose of the field factorial experiments were to systematically evaluate the influence of key operational parameters on the decompostion rate of yard waste in a windrow type operation. The following sections describe the changes in operational and response variables and the results of the factorial experiments.

4.1.1 Trends in Operational Variables

4.1.1.1 C:N ratio

The C:N ratio of the various piles generally followed a decreasing trend throughout the first 112 days of the process, the active composting phase, and then remained fairly constant or varied slightly during the remaining 113 days, the maturation phase, of the process. Figures 4.1 to 4.8 show the C:N ratio versus composting days for the low, medium and high C:N ratio pile sections, as well as control piles C1 and C2 and the replicate piles R1 and R2.

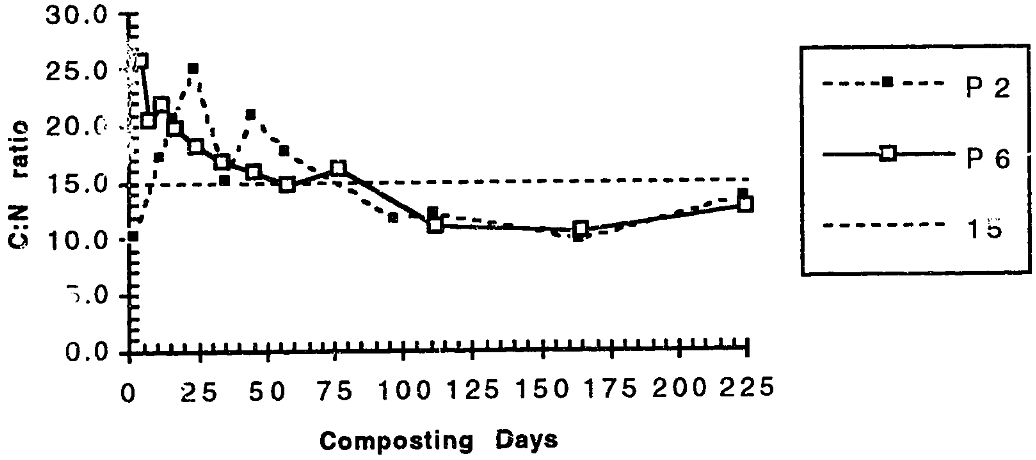

Figure 4.1 C:N ratio vs Composting Days - Piles 2 and 6

Hi C:N, Low M.C.

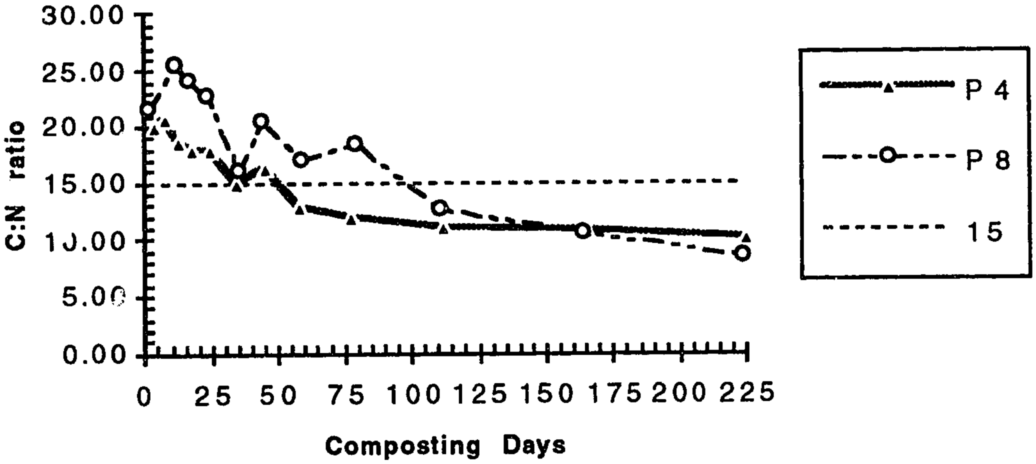

Figure 4.2 C:N ratio vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

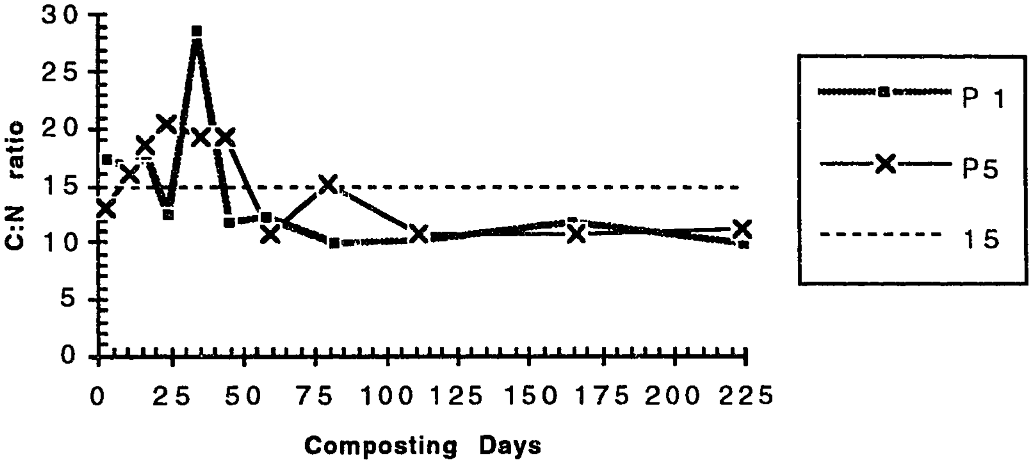

Figure 4.3 C:N ratio vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

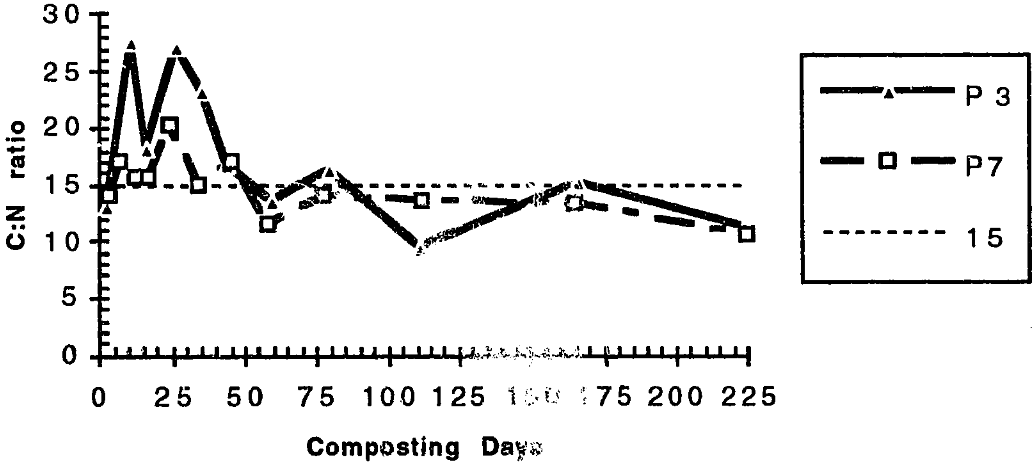

Figure 4.4 C:N ratio vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

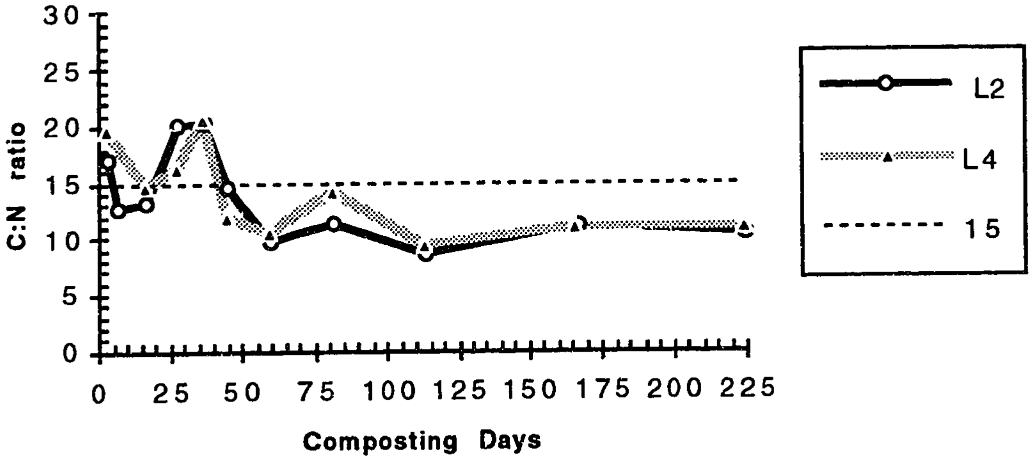

Figure 4.5 C:N ratio vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

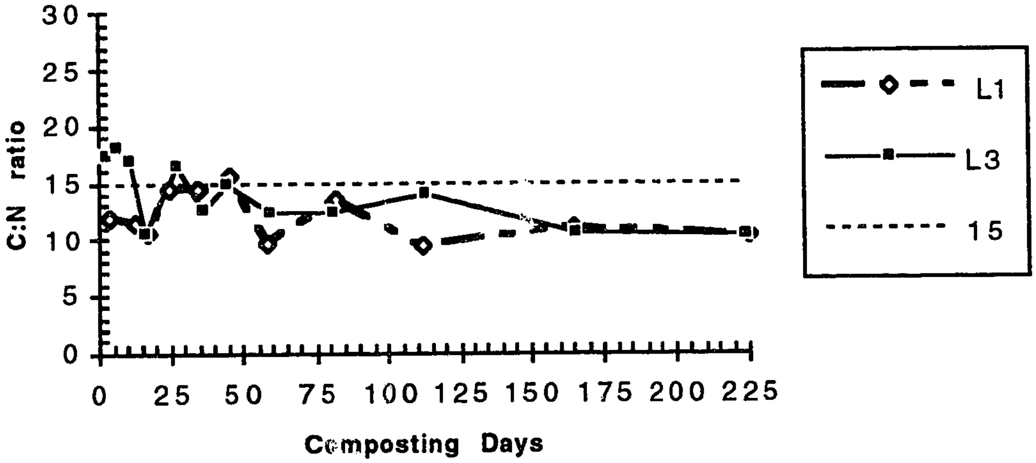

Figure 4.6 C:N ratio vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

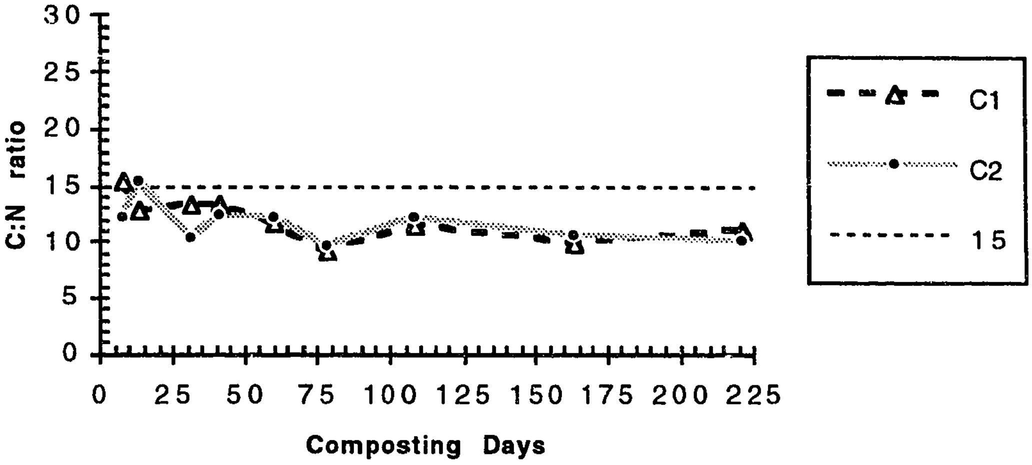

Figure 4.7 C:N ratio vs Composting Days - Piles C1 and C2

Control Piles

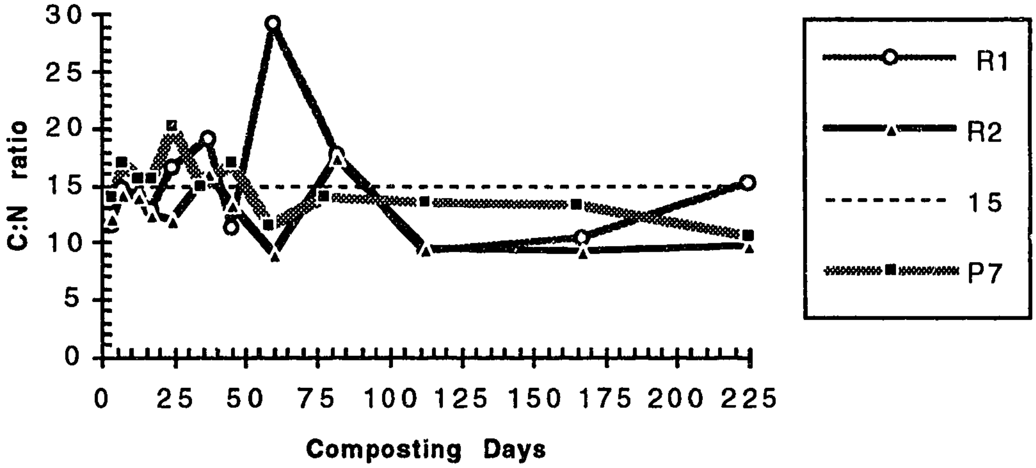

Figure 4.8 C:N ratio vs Composting Days - Piles 7, R1 and R2

Med C:N, Hi M.C.

Replicates

The C:N ratio values of the different piles generally fluctuated more during the first 35 to 45 days of the process and usually increased from the initial values during this period. Possible reasons for the fluctuations in the C:N ratio values are inadequate mixing, sampling errors, ammonia losses and the amount of straw added to the piles. Figure 4.8 clearly shows the variability in the C:N ratio data for piles with the same experimental design. Table 4.1 lists the initial and final C:N ratio values for the various piles.

Table 4.1 - Initial and Final Pile C:N Values

Pile No.	Pile Designation	Initial C:N ratio	Final C:N ratio
1	Med C:N, Low M.C., Low Por.	17.12	9.72
2	Hi C:N, Low M.C., Low Por.	10.19	13.49
3	Med C:N, Hi M.C., Low Por.	13.12	11.19
4	Hi C:N, Hi M.C., Low Por.	20.08	9.99
5	Med C:N, Low M.C., Hi Por.	13.13	11.11
6	Hi C:N, Low M.C., Hi Por.	25.80	12.57
7	Med C:N, Hi M.C., Hi Por.	13.92	10.52
8	Hi C:N, Hi M.C., Hi Por.	21.60	8.46
R1	Med C:N, Hi M.C., Hi Por.	11.45	15.15
R2	Med C:N, Hi M.C., Hi Por.	12.20	9.68
L1	Low C:N, Hi M.C., Low Por.	11.93	10.36
L2	Low C:N, Low M.C., Low Por.	17.03	10.29
L3	Low C:N, Hi M.C., Hi Por.	17.33	10.30
L4	Low C:N, Low M.C., Hi Por.	19.83	10.87
C1	Control Pile	15.27	11.07
C2	Control Pile	12.09	10.12

The initial C:N ratio values for piles sections L1 to L4 varied from 12:1 to 19:1. The final C:N ratio values for piles L1 to L4 were all approximately 10:1. The medium C:N ratio piles 3, 5 and 7 had initial values of about 13:1 and final C:N ratio values of approximately 11:1. Pile 1, the other medium C:N ratio pile section, had a starting value of about 17:1 and a final value of 13.5:1. The high C:N ratio piles 2, 4, 6 and 8 had initial C:N values from about 10:1 to 26:1 and final values varying from 8.5:1 to 13.5:1. The high

C:N ratio piles generally had higher C:N ratio values than the medium and low C:N ratio piles. The medium to low C:N ratio piles had similar values mainly because the amount of barley straw initially mixed with the respective pile sections did not increase the C:N ratio as much as expected. The C:N ratio of the barley straw was determined to be 55.7:1 by Norwest Labs, compared to literature values between 129 to 150:1 for wheat straw. At the time of the composting experiment, only barley straw was available. To increase the C:N ratio of piles 2 and 8 (on day 17) and piles 4 and 6 (on day 18) two front end loader buckets of wheat straw were added to each of these pile sections on August 17, 1992. On August 26, 1992 (days 26 and 27 respectively), an additional 3/4 of a bucket of wheat straw was mixed into each of the high C:N ratio piles. One bucket of barley straw was also added to piles 1 and 7 on composting day 18 and piles 3 and 7 on composting day 17 to increase the C:N ratio of the those pile sections. The initial C:N ratios of the City of Edmonton control piles C1 and C2 were 15.3 and 12.1, while the final values were 11.1 and 10.1 respectively.

4.1.1.2 Moisture Content

The factorial experiment included testing the affect of two different moisture content levels on the decomposition of the yard waste. The experimental design called for certain pile sections to be maintained at a moisture content of 60% and others at 40%. It was not possible to maintain the moisture content of the pile sections at the desired levels. As expected, the moisture content of the piles sections generally decreased dramatically during the first 2 to 3 weeks of the process due to evaporative losses as a result of the high temperatures. Water was added to the piles on five occasions to increase the moisture content during the first 73 days of the process. The moisture content generally followed a gradual decreasing trend for the remainder of the composting period. As the compost matured and the temperature of the piles cooled, evaporative losses decreased. The moisture content of the various piles are displayed in Figures 4.9 to 4.16. The vertical dashed lines in Figures 4.9 to 4.16 represent when the pile sections were watered.

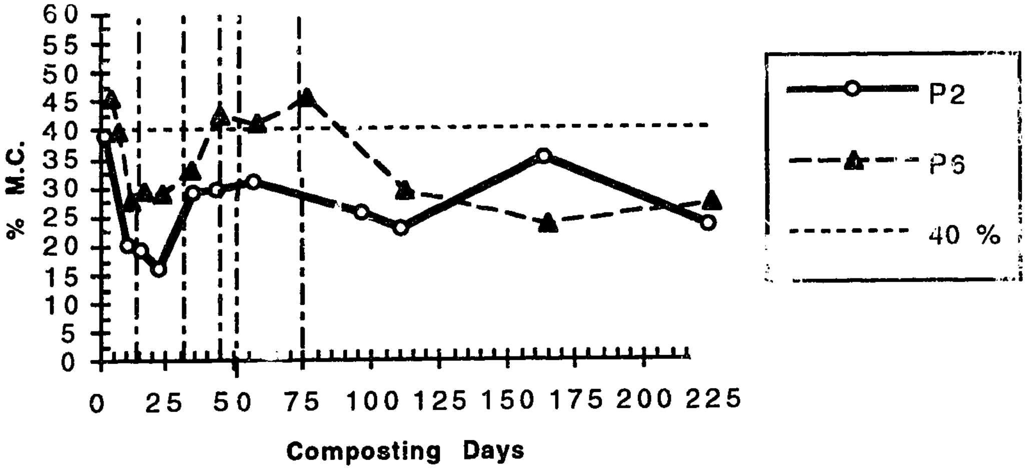

Figure 4.9 M.C. vs Composting Days - Piles 2 and 6
Hi C:N, Low M.C.

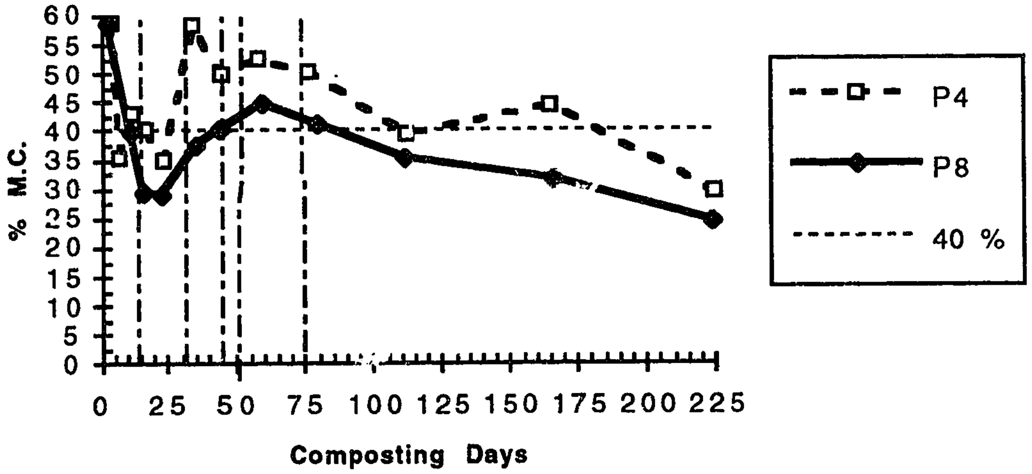

Figure 4.10 M.C. vs Composting Days - Piles 4 and 8
Hi C:N, Hi M.C.

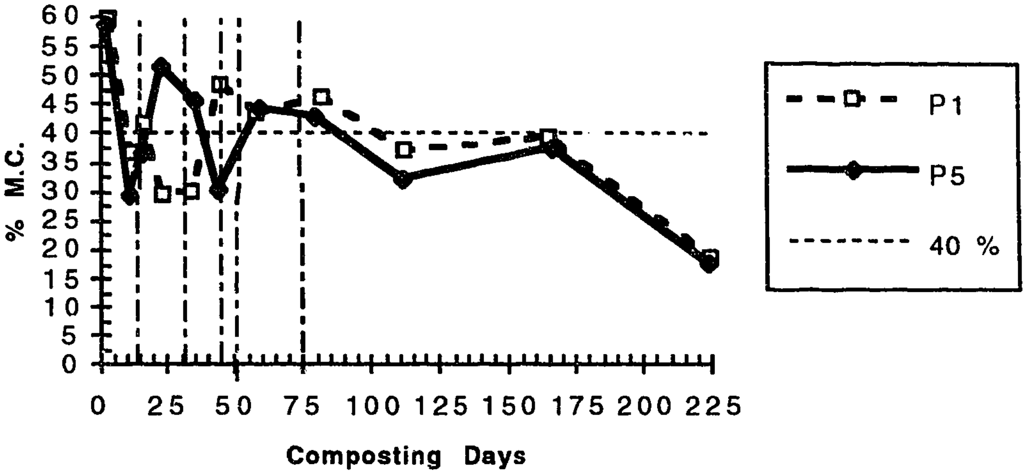

Figure 4.11 M.C. vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

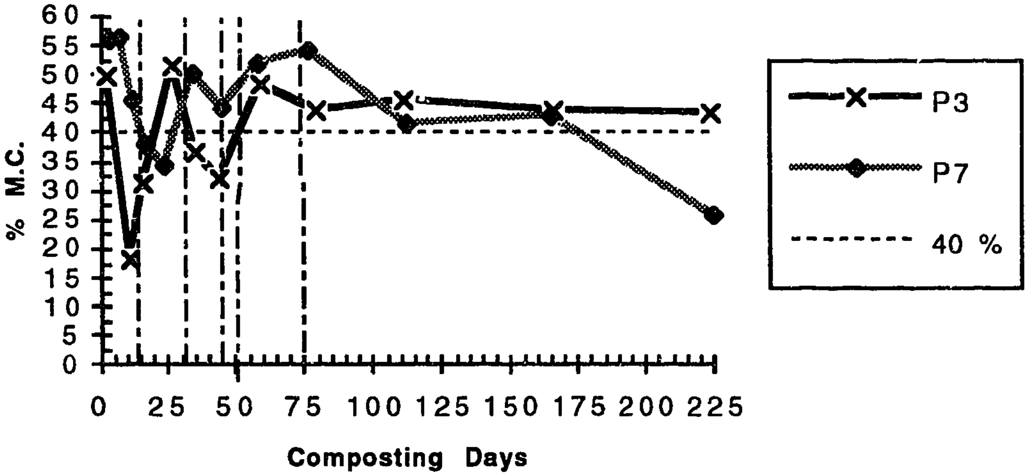

Figure 4.12 M.C. vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

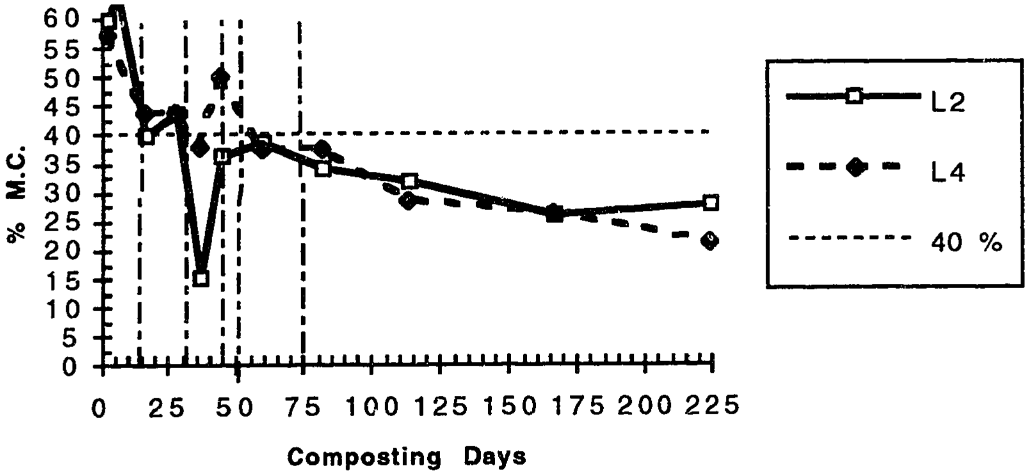

Figure 4.13 M.C. vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

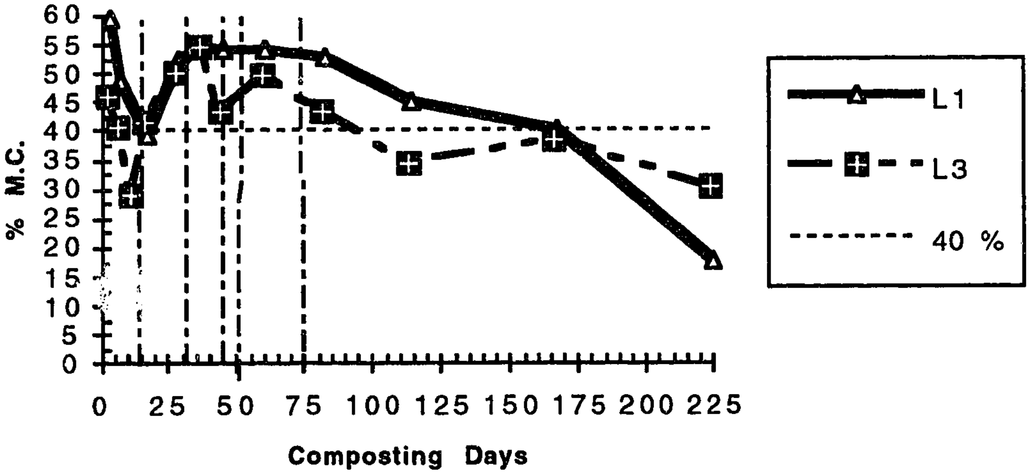

Figure 4.14 M.C. vs Composting Days - Piles L2 and L4

Low C:N, Hi M.C.

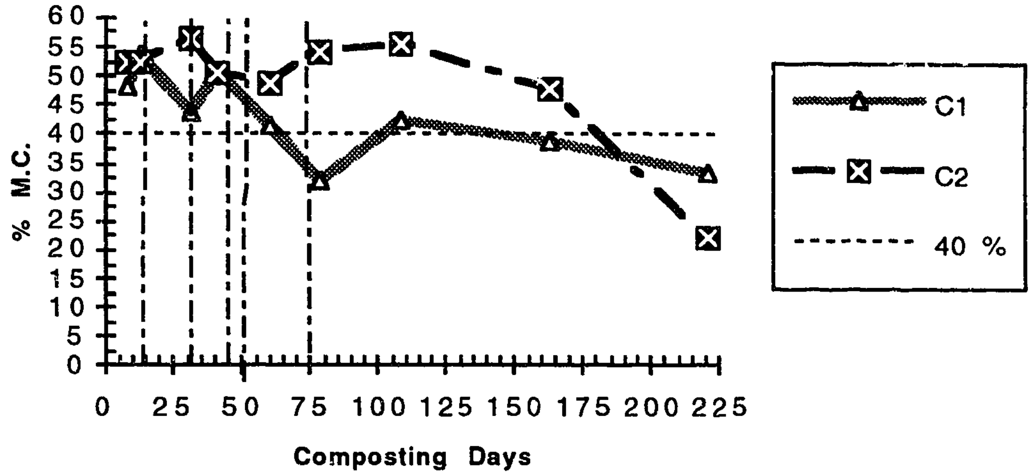

Figure 4.15 M.C. vs Composting Days - Piles C1 and C2

Control Piles

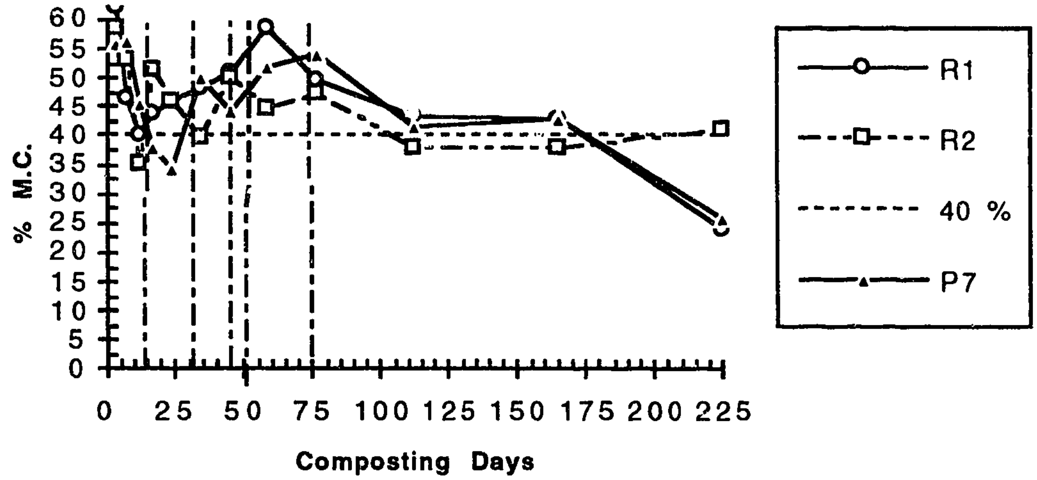

Figure 4.16 M.C. vs Composting Days - Piles R1 and R2 and 7

Med C:N, Hi M.C.- Replicate Piles

The directional changes in moisture content of the piles were consistent with changes described in the literature. Table 4.2 lists the weighted average % moisture contents for the various piles. The weighted average for each pile was calculated by the equation shown

$$\text{Avg \% M.C.} = \frac{\text{Days1*MC1} + \text{Days2*MC2} + \ldots + \text{Daysn*MCn}}{\text{Days1} + \text{Days2} + \ldots + \text{Daysn}} \qquad (26)$$

MCn = % M.C measurements at different intervals of the composting process.

Daysn = number of composting days between each % M.C. measurement.

Table 4.2 - Weighted Average % Moisture Content of the Compost Piles

Pile No.	Pile Designation	Planned Level	Weighted Avg Full Period	Weighted Avg Active Phase
1	Med C:N, Low M.C., Low Por.	40%	34.4%	40.5%
2	Hi C:N, Low M.C., Low Por.	40%	27.0%	25.2%
3	Med C:N, Hi M.C., Low Por.	60%	42.3%	41.1%
4	Hi C:N, Hi M.C., Low Por.	60%	41.0%	45.7%
5	Med C:N, Low M.C., Hi Por.	40%	32.8%	38.4%
6	Hi C:N, Low M.C., Hi Por.	40%	30.7%	35.9%
7	Med C:N, Hi M.C., Hi Por.	60%	40.1%	46.5%
8	Hi C:N, Hi M.C., Hi Por.	60%	33.1%	38.3%
R 1	Med C:N, Hi M.C., Hi Por.	60%	40.6%	48.4%
R 2	Med C:N, Hi M.C., Hi Por.	60%	41.7%	43.8%
L 1	Low C:N, Hi M.C., Low Por.	60%	39.2%	49.9%
L 2	Low C:N, Low M.C., Low Por.	40%	31.3%	35.7%
L 3	Low C:N, Hi M.C., Hi Por.	60%	30.6%	42.5%
L 4	Low C:N, Low M.C., Hi Por.	40%	30.7%	37.5%
C1	Control Pile	None	39.2%	42.6%
C2	Control Pile	None	43.8%	53.5%
		Avg High M.C. Pile	**38.6%**	**44.5%**
		Avg Low M.C. Pile	**31.2%**	**35.5%**

Active Phase - up to and including samples taken on November 19-21, 1992.

Although is was not possible to maintain the planned experimental moisture content levels, the moisture content for the 60% moisture content piles were generally higher than the 40% moisture piles. The overall weighted average moisture content for the 60% piles was 38.6% with a standard deviation of 3.86 for the full composting period compared to 31.2% with a standard deviation of 5.36 for the 40% moisture content piles. For the period up to and including the November 19-21, 1992 samples, referred to as the active stage, the overall weighted average moisture levels for both the high and low moisture piles were higher than the values calculated for the full composting period. The high moisture level piles had an overall average weighted moisture content of 44.5% for the active period with a standard deviation of 4.31. The overall average weighted moisture level for the low moisture experimental piles during the same period was 35.5% with a standard deviation of 2.49. These values reflect the fact the compost moisture contents of the various piles were higher during the active stages of the composting process, which is desired from an operational viewpoint. The overall weighted average moisture contents for the high and low M.C. piles were found to be significantly different using the Student t test at the 95% confidence level. The calculated t values were 2.86 and 4.95 respectively for the full and active composting period tests compared to t value from the table of 2.18.

In comparison, the overall weighted average moisture content for the control piles C1 and C2 was 2.9% higher for the full composting period and 3.6% higher for the active period than the values calculated for the experimental 60% moisture content pile sections. Piles 7, R1 and R2 having the same experimental treatment design, had an overall weighted average moisture content of 40.8% with a standard deviation of 0.82 for the full composting period. The difficulty experienced trying to maintain the experimental moisture levels may be due to the method of moisture addition, the characteristics of the composting materials, sampling and testing frequency and environmental factors. Environmental factors such as the amount of precipitation and ambient air temperatures may influence the moisture content. High ambient air temperatures will increase evaporation losses especially from the outer layers of the compost piles. Although it is difficult to quantify the impact of the precipitation, two observations were noted. Firstly, after a significant rain only the top 25 to 50mm (approximately) of the outer layer seemed to be wet. Secondly, when the snow cover melted in late March and early April, the top 100 to 150mm of the outer layer also seemed quite moist compared to the inner layers.

4.1.1.3 Porosity Adjustment

The porosity values for the various piles generally decreased throughout the process with the largest reduction observed in the first 60 days for most piles. This is consistent with the fact the rate of decomposition is higher during the first one or two months of the composting process when the easier degradable components are being broken down. Wood chips were added to pile 5 on composting day 70 and to piles 6 and 7 on composting day 71 to increase the porosity of the compost piles. Additional wood chips were also added to piles R1 and R2 on composting day 78 and to piles 8, L3 and L4 on composting day 77. The wood chip additions did not consistently create a significant increase in porosity values. Figures 4.17 to 4.20 display the porosity values versus composting time for the adjusted and maintained porosity piles.

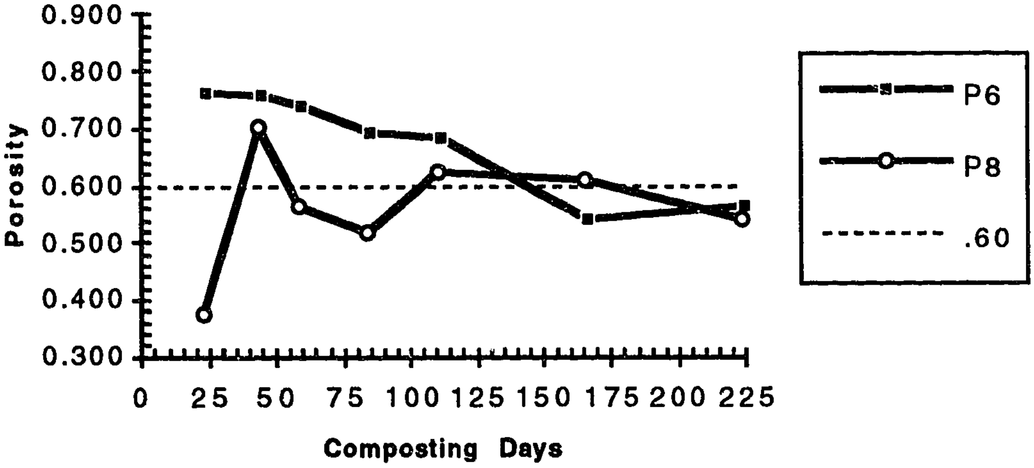

Figure 4.17 **Porosity vs Composting Days - Piles 6 and 8 HI C:N, HI Por.**

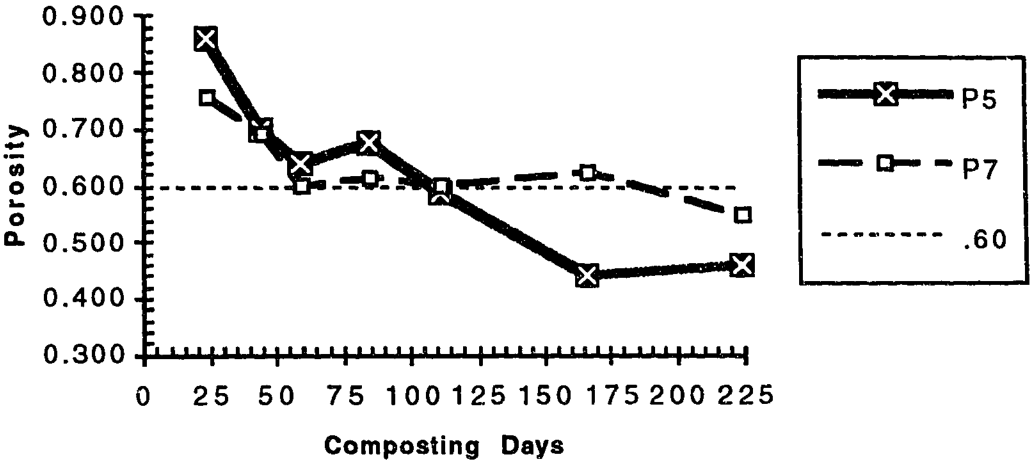

Figure 4.18 Porosity vs Composting Days - Piles 5 and 7

Med C:N, Hi Por

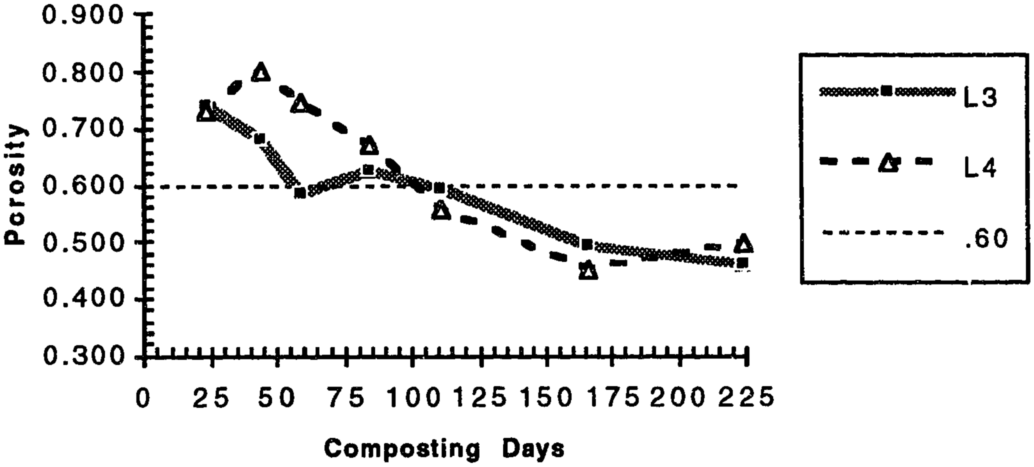

Figure 4.19 Porosity vs Composting Days - Piles L3 and L4

Low C:N, Hi Por.

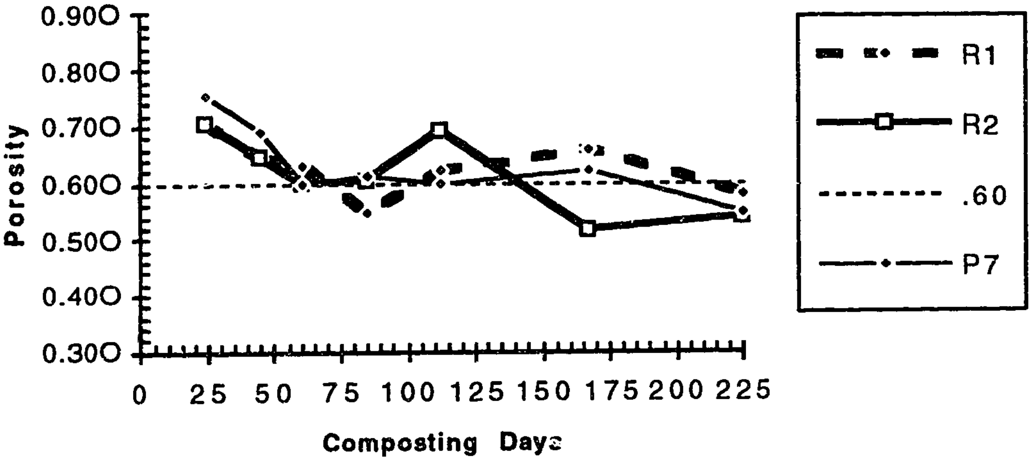

Figure 4.20 Porosity vs Composting Days - Piles 7, R1 and R2
Med C:N, Hi Por
Replicate Piles

Porosity values for piles 5, 6, 7, L4, R1, R2 and 8 generally decreased or remained fairly level for the first porosity measurements after the addition of more wood chips. The porosity values for Piles 8 and R1 increased for measurements taken in November and January. The porosity values for Pile 1, for example, increased for the October and November samples even though no additional wood chips were mixed into the pile section. Figure 4.21 shows the porosity measurements for Pile 1 vs composting days.

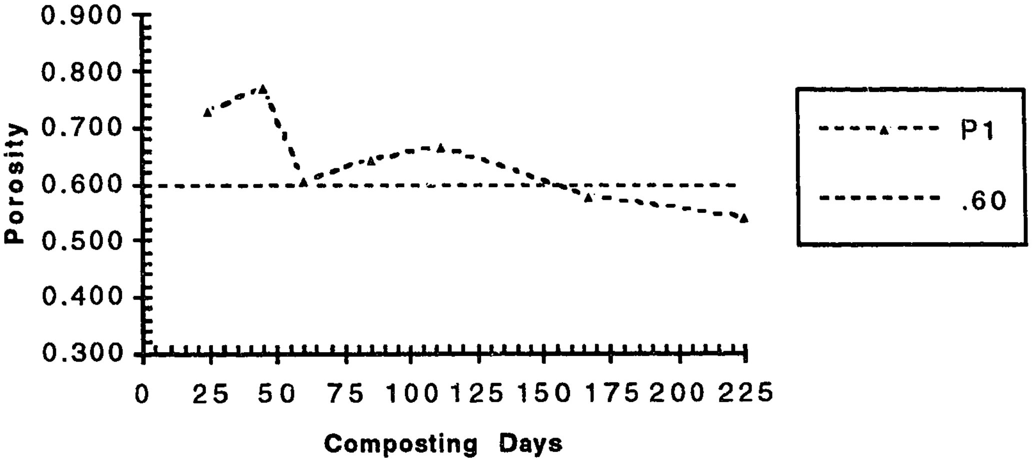

Figure 4.21 **Porosity vs Composting Days - Pile 1**
Med C:N - Porosity Adjusted and Maintained

There is no conclusive evidence indicating the addition of wood chips to certain experimental piles increased the porosity of these piles based on visual observation of the plots. Table 4.3 displays the first and final porosity measurements for the various experimental piles.

Table 4.3 - Pile Porosity Values

Pile No.	Pile Designation	Experimental Plan	Initial Porosity	Final Porosity
1	Med C:N, Low M.C., Low Por.	Initially Adjusted	0.732	0.543
2	Hi C:N, Low M.C., Low Por.	Initially Adjusted	0.685	0.501
3	Med C:N, Hi M.C., Low Por.	Initially Adjusted	0.725	0.579
4	Hi C:N, Hi M.C., Low Por.	Initially Adjusted	0.771	0.534
5	Med C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.861	0.458
6	Hi C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.761	0.561
7	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.753	0.548
8	Hi C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.3[illegible]	0.540
R 1	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.703	0.578
R 2	Med C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.702	0.537
L 1	Low C:N, Hi M.C., Low Por.	Initially Adjusted	0.756	0.371
L 2	Low C:N, Low M.C., Low Por.	Initially Adjusted	0.711	0.553
L 3	Low C:N, Hi M.C., Hi Por.	Adjusted and Maintained	0.740	0.460
L 4	Low C:N, Low M.C., Hi Por.	Adjusted and Maintained	0.732	0.497
		Avg	0.715	0.519
		Stdev	0.107	0.057

The mean porosity value for the initial tests for the experimental piles was 0.72 with a standard deviation of 0.11. The mean final porosity value for the pile sections was 0.52 with a standard deviation of 0.06. The initial mean porosity value for the initially adjusted (low porosity) piles was 0.73 compared to a value of 0.70 for the porosity adjusted piles. The final mean porosity value for the initially adjusted (low porosity) piles was 0.51 compared to a value of 0.52 for the porosity adjusted (high porosity) piles. There was no statistical difference between the mean porosity values for the high and low porosity piles for both the initial and final porosity values using the t test. The control piles C1 and C2 had an average porosity value of 0.73 for the initial test with a standard deviation of 0.007. The mean final porosity value and standard deviation for the control piles was 0.67 and 0.016. The lower final mean porosity value determined for the experimental piles provides an indication the organic materials in the experimental piles had decomposed further than the yard waste in the control piles.

The porosity values measured for the various piles are similar to values observed by Fleming (1991) in the composting of mixtures of green waste, leaves and wood wastes in Florida. The initial mean porosity for her four experimental windrows was 0.70 compared to 0.72 determined for the experimental piles. The final mean porosity for her windrows was 0.30, which is lower than the final values observed for our composting piles. The difference may be explained by the type of organic materials, testing errors, degree of stabilization, the amount of wood wastes in the windrows. Fleming's two windrows containing approximately 50% wood wastes had final porosity values of 0.336 and 0.356, which supports the comment that the wood chips mixed into our experimental piles may increase the final porosity values.

4.1.2 Trends in Response Variables

The primary response variables used to measure the degree and rate of degradation of the organic materials in these experiments were the percent change in total carbon of solid samples and the percent change in TOC of compost water extracts as well as the more absolute indicator the ratio of Organic C/Organic N ($C:N_W$) of water extracts. The measurements of OUR were not successful, due to problems experienced during testing. No results are available for this parameter. Secondary, but less reliable indicators of maturity used in these studies, are average pile temperatures, percent increases in dry bulk density. Tables 4.4 and 4.5 list the results of the primary response variables as well as % increases in bulk densities over the full and active composting periods.

Table 4.4 - Pile Response Variable Values
Full composting period

		Response Variables		
Pile No.	**Pile Designation**	% Decrease in % C (SS)	% Decrease in TOC (WE)	% Increase in DBD
1	Med C:N, Low M.C., Low Por.	44.7	81.5	49.5
2	Hi C:N, Low M.C., Low Por.	42.7	84.8	55.8
3	Med C:N, Hi M.C., Low Por.	54.5	84.5	46.4
4	Hi C:N, Hi M.C., Low Por.	52.6	61.3	62.6
5	Med C:N, Low M.C., Hi Por.	49.5	80.1	71.3
6	Hi C:N, Low M.C., Hi Por.	56.6	68.2	63.4
7	Med C:N, Hi M.C., Hi Por.	56.1	78.3	47.6
8	Hi C:N, Hi M.C., Hi Por.	73.5	86.0	34.4
R 1	Med C:N, Hi M.C., Hi Por.	17.8	80.9	49.9
R 2	Med C:N, Hi M.C., Hi Por.	57.1	80.8	48.2
L 1	Low C:N, Hi M.C., Low Por.	37.9	83.8	68.3
L 2	Low C:N, Low M.C., Low Por.	66.4	82.1	56.9
L 3	Low C:N, Hi M.C., Hi Por.	53.3	73.8	60.7
L 4	Low C:N, Low M.C., Hi Por.	53.5	68.0	59.9
C1	Control Pile	26.6	Not Tested	34.3
C2	Control Pile	51.6	Not Tested	38.5

WE= Compost water extracts
SS = Compost solid samples

Table 4.5 - Pile Response Variable Values
Active composting period

Pile No.	Pile Designation	% Decrease in % C (SS)	% Decrease in TOC (WE)	% Increase inDBD
		Response Variable		
1	Med C:N, Low M.C., Low Por.	48.3	80.2	39.6
2	Hi C:N, Low M.C., Low Por.	47.4	81.2	56.7
3	Med C:N, Hi M.C., Low Por.	46.8	81.4	46.7
4	Hi C:N, Hi M.C., Low Por.	50.7	67.6	59.5
5	Med C:N, Low M.C., Hi Por.	45.9	76.3	70.3
6	Hi C:N, Low M.C., Hi Por.	57.0	65.5	53.2
7	Med C:N, Hi M.C., Hi Por.	51.4	81.7	41.0
8	Hi C:N, Hi M.C., Hi Por.	65.9	84.8	30.9
R1	Med C:N, Hi M.C., Hi Por.	37.0	76.5	45.8
R2	Med C:N, Hi M.C., Hi Por.	52.3	65.0	39.9
L1	Low C:N, Hi M.C., Low Por.	45.4	76.2	63.1
L2	Low C:N, Low M.C., Low Por.	68.0	80.1	56.1
L3	Low C:N, Hi M.C., Hi Por.	38.4	64.8	53.0
L4	Low C:N, Low M.C., Hi Por.	48.9	53.1	55.4
C1	Control Pile	19.1	Not Tested	21.1
C2	Control Pile	36.4	Not Tested	-2.4

WE= Compost water extracts

4.1.2.1 Total Carbon

As expected, the percent total carbon (% C) of the various piles decreased throughout the composting period, with most of the decrease observed during the first 50 to 80 days of the process when the more available organic constituents are decomposed. The percent change in the total carbon content of the experimental piles varied from 17.8% for pile R1 to 66.4% for pile L2. The mean value was 51.8% with a standard deviation of 12.9. Control piles C1 and C2 observed a 26.6% and 51.6% decrease in % C. The large difference between the values for the control piles may be due to sampling or testing errors. Figures 4.22 to 4.29 display the percent carbon content over the composting duration for the various pile sections. The piles are organized according to their experimental C:N ratio and moisture levels.

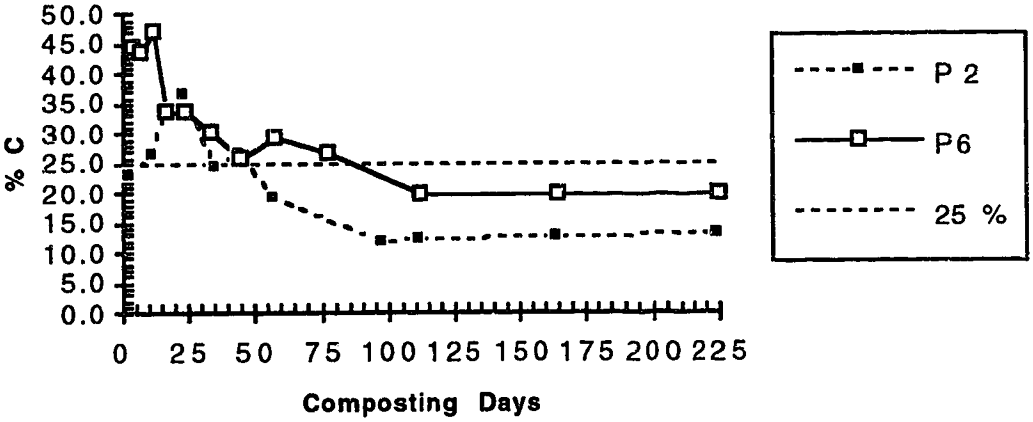

Figure 4.22 % C vs Composting Days - Piles 2 and 6

Hi C:N, Low M.C.

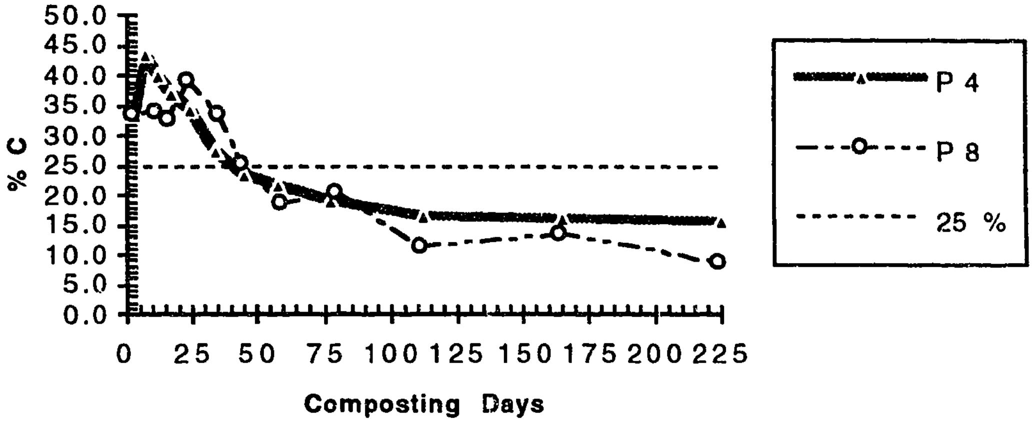

Figure 4.23 % C vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

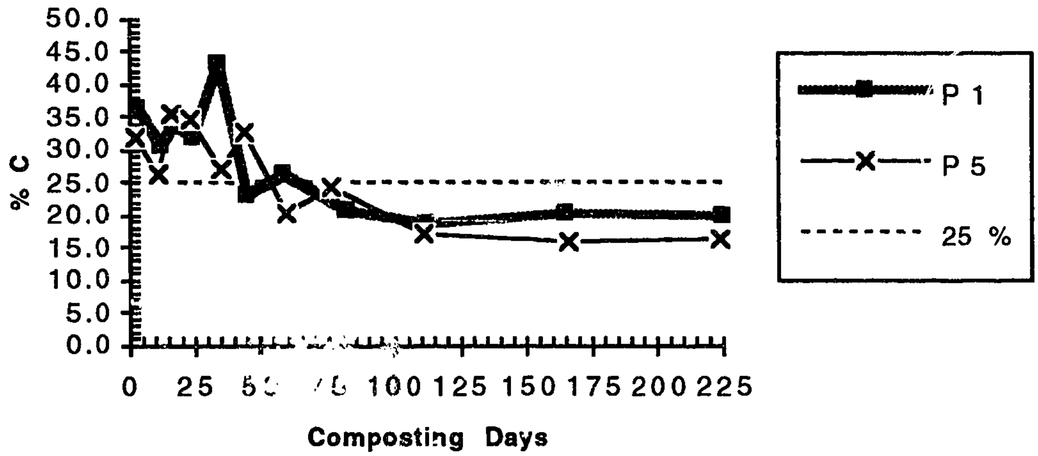

Figure 4.24 % C vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

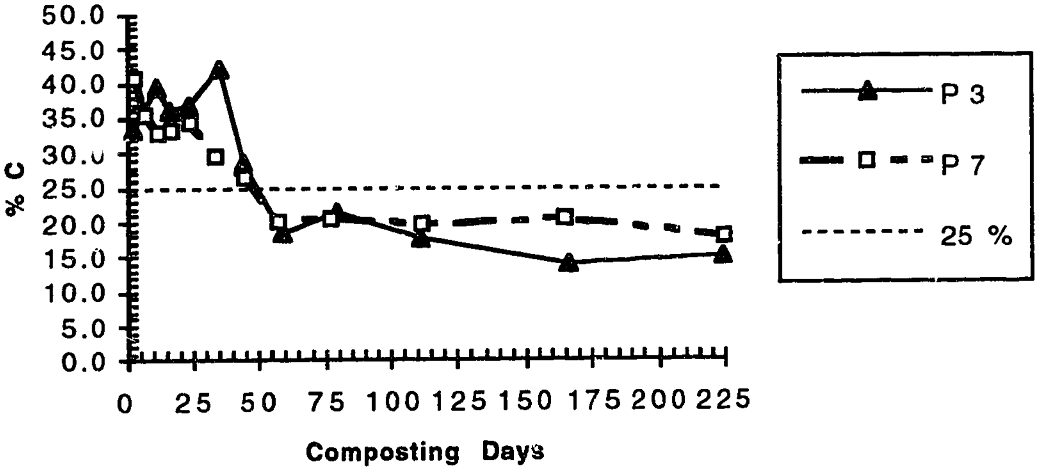

Figure 4.25 % C vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

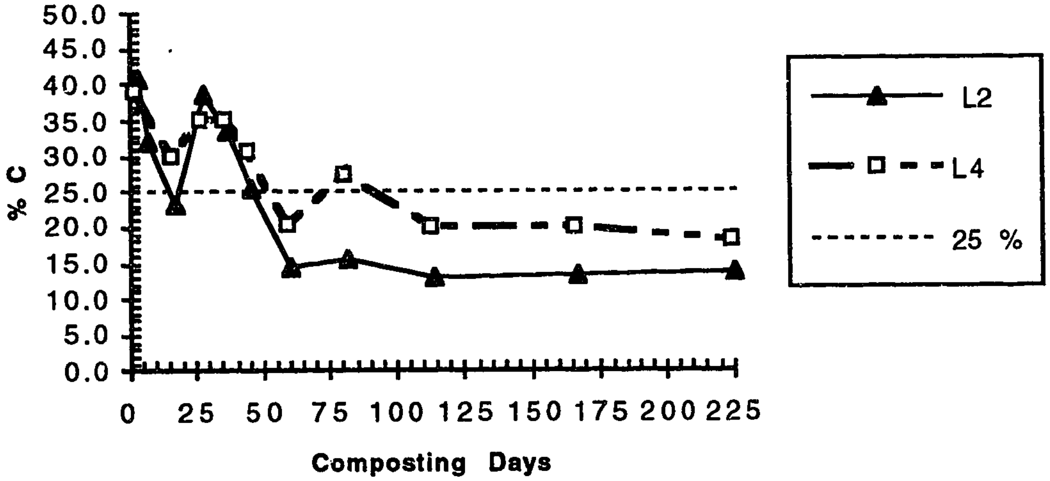

Figure 4.26 % C vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

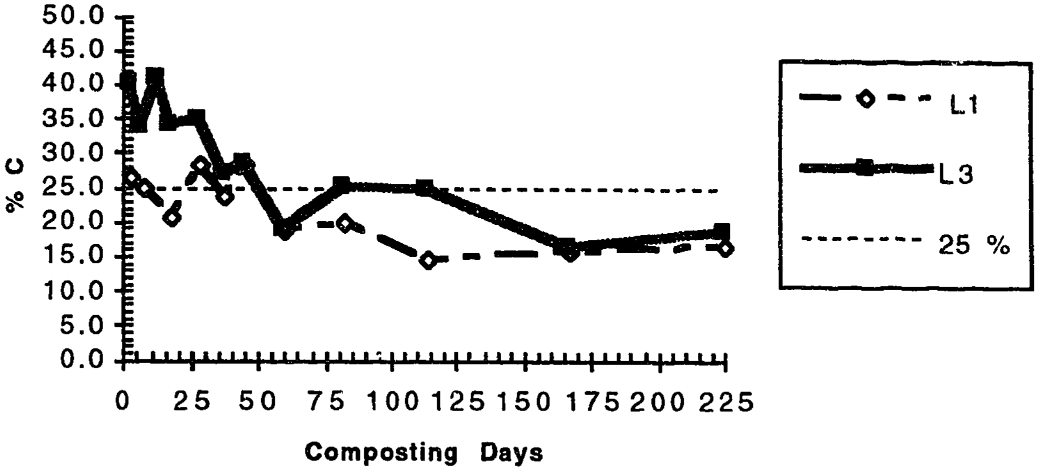

Figure 4.27 % C vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

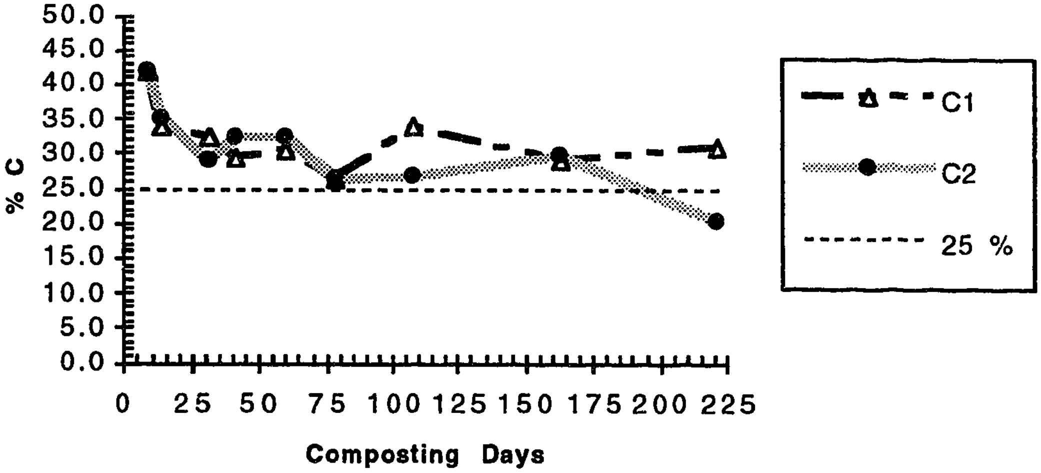

Figure 4.28 % C vs Composting Days - Piles C1 and C2

Control Piles

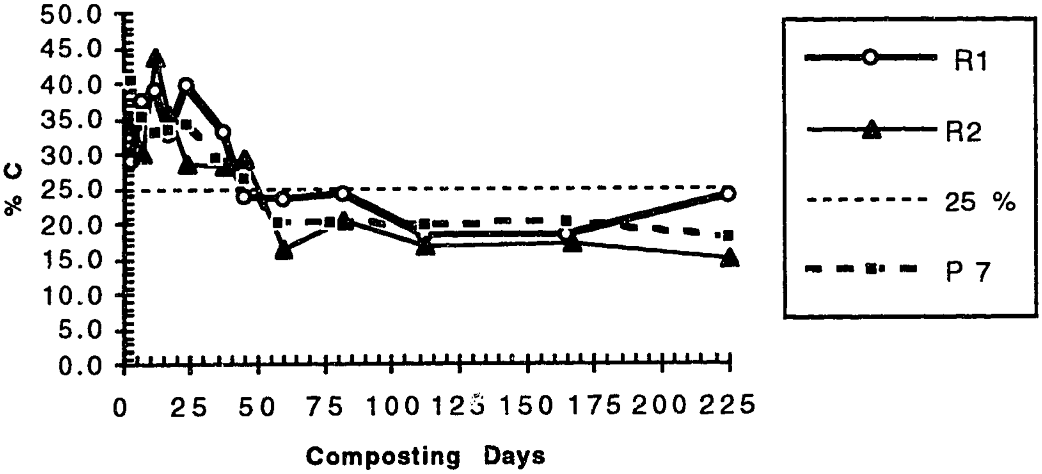

Figure 4.29 % C vs Composting Days - Piles 7, R1 and R2
Med C:N, Hi M.C.
Replicates

The values for the % change in total carbon content for each compost pile section are highly dependent on the reliability of the initial and final determinations for % C. The average % volatile solids values and their standard deviations are listed in Table A.1 in Appendix A. The % C values were determined by dividing the % volatile solids values by 1.8 as indicated in section 3.2.3.3.

Multiple samples were also collected for piles 1 to 8 and R1 and R2 to test for spatial differences in the compost material within the respective piles. The % volatile solids (% VS) parameter was used to evaluate the spatial differences in the compost material within a pile. Based on the multiple sample % VS results outlined in Table A.2, the samples collected for pile 2 on September 26, 1992 and pile 7 on October 10, 1992 showed the largest variation in % VS. The analysis of variance (ANOVA) method was used to test the null hypothesis (H_O) that the mean % VS values at the different locations within a pile are not different. The alternate hypothesis (H_A) is that the mean % VS values at the different locations within a pile are not the same. The results of the two ANOVA tests summarized in Table A.3 indicated the null hypothesis could not be rejected. Although statistically the mean % VS values at the different locations within the respective piles were not considered different, there was a significant amount of variability in the pile % VS values as indicated in Table A.2. For example, the mean % VS value for the multiple samples collected on September 26, 1992 for pile 2 was 34.81 ± 7.94 with a standard error of 3.44. The calculated confidence interval values for pile 2 on this sample date represents a ±22.80% of the pile mean value. The 95% confidence interval for most of the piles (as expressed as a percentage of the pile mean % VS values) were > ±10.00%. This variability might be explained by the heterogeneity of the pile material or errors introduced by the method of volatile solids determination. To ensure samples were not contaminated from materials of adjacent pile sections compost samples were randomly selected from the middle third of each pile section.

Table 4.6 outlines the % carbon values for the initial and final samples for the various compost pile sections.

Table 4.6 - Pile % Carbon values - Solid samples

Pile No.	Pile Designation	% C Initial values	% C Final values
1	Med C:N, Low M.C., Low Por.	36.2	20.0
3	Med C:N, Hi M.C., Low Por.	33.4	15.2
5	Med C:N, Low M.C., Hi Por.	31.9	16.1
7	Med C:N, Hi M.C., Hi Por.	40.6	17.8
R 1	Med C:N, Hi M.C., Hi Por.	29.1	24.0
R 2	Med C:N, Hi M.C., Hi Por.	35.0	15.0
2	Hi C:N, Low M.C., Low Por.	23.2	13.3
4	Hi C:N, Hi M.C., Low Por.	33.5	15.8
6	Hi C:N, Low M.C., Hi Por.	44.6	19.9
8	Hi C:N, Hi M.C., Hi Por.	33.5	8.9
L 1	Low C:N, Hi M.C., Low Por.	26.5	16.5
L 2	Low C:N, Low M.C., Low Por.	40.9	13.8
L 3	Low C:N, Hi M.C., Hi Por.	40.2	18.8
L 4	Low C:N, Low M.C., Hi Por.	39.0	18.1
C1	Control Pile	42.1	30.9
C2	Control Pile	42.1	20.4

The initial mean % C values for the high, medium and low C:N ratio piles were generally quite similar. The high C:N ratio piles 2, 4, 6 and 8 had a mean % C value of 33.7 with a standard deviation of 8.7. Pile section 2 had an initial % C content of 23.2, the lowest value of all the pile sections. The medium C:N ratio piles had a mean % C value of 34.4 with a standard deviation of 3.9. The low C:N ratio piles had the highest mean % C value of 36.7 with a standard deviation of 6.8. The high and medium C:N ratio piles were expected to have higher % C values due to the addition of straw. The mixing of 2 additional front end loader buckets of wheat straw to pile sections 4 and 6 (day 18), 2 and 8 (day 19) on August 17, 1992 did not seem to increase the % C values for the August 23, 1992 samples. The mean % C value for the high C:N ratio piles was 34.6 with a standard deviation of 1.5, compared to a mean and standard deviation of 34.4 and 3.8 for the medium C:N ratio piles. The initial % C results may be influenced by the heterogeneity of the mixed materials, sampling and test methods, or the amount of straw added to the piles.

The final % C contents also influence the % change in total carbon values. For example, pile R1 had a relatively high final % C content of 24.0%. compared to values of 17.8% and 15.0% for pile sections 7 and R2 which had the same treatment design. The high final % C content for pile R1 may be due to the possible contamination of the compost sample with the compost cover material. The burlap material used to separate the experimental compost material from the compost cover decomposed in most piles making it difficult to collect a true representative sample. This high final % C content for pile R1 results in a very low value for the % change in the total carbon.

The final % C contents for the control piles taken on day 221 varied considerably. The values for pile sections C1 and C2 were were 30.9% and 20.4% respectively. The most likely explanation for the large difference is sampling or testing errors. The % C content for piles C1 and C2 were 29.1% and 29.6% for the samples taken on day 163. The average pile temperatures for both C1 and C2 during the period between day 163 and day 221 were below 10^{0}C. These low temperatures hindered the decomposition of the organic matter. It is unlikely the change in carbon content for pile section C2 observed during the period between day 163 and day 221 can be attributed to decomposition.

Given the results of the initial and final % C values, the % decrease in carbon content for the pile sections is not considered a reliable response indicator for this experiment. The % decrease in TOC of water extracts is a more reliable response factor because it better reflects the carbon available for microbial utilization.

4.1.2.2 Total Organic Carbon (TOC) - Compost Water Extracts

The TOC values for the various compost pile sections generally followed a decreasing trend throughout the composting period, with most of the decrease observed during the first 50 to 75 days of the process when the more available organic constituents are decomposed. The overall mean % change in TOC value was 73.9% with a standard deviation of 9.6. The highest % change in TOC was 84.8% for high C:N ratio pile 8 and the lowest was 53.1% for low C:N ratio pile section L4. Figures 4.30 to 4.36 display the TOC content (water extracts) versus the composting period for the various pile sections. The piles are organized according to their experimental C:N ratio and moisture levels.

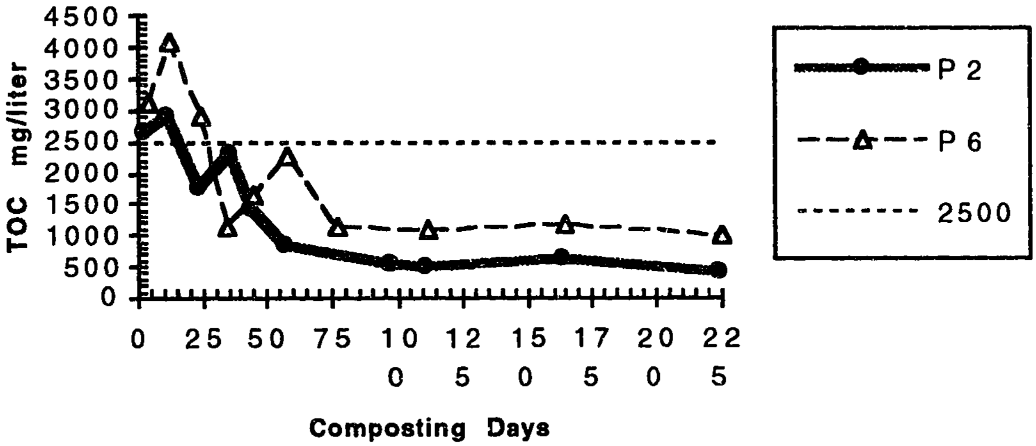

Figure 4.30 **TOC vs Composting Days - Piles 2 and 6**

Hi C:N, Low M.C.

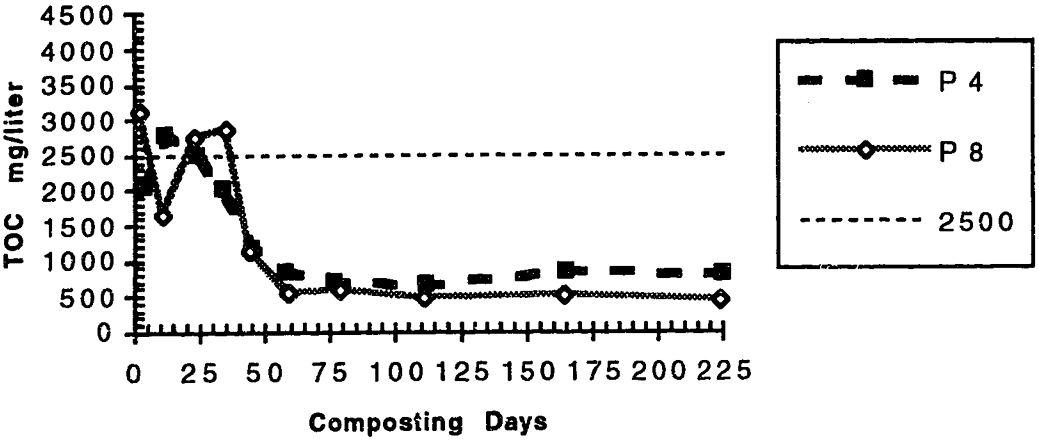

Figure 4.31 TOC vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

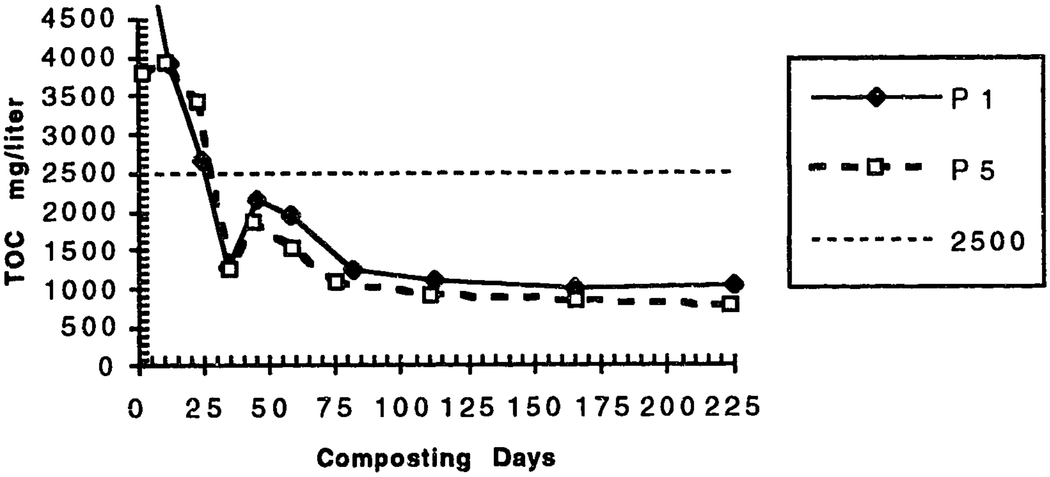

Figure 4.32 TOC vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

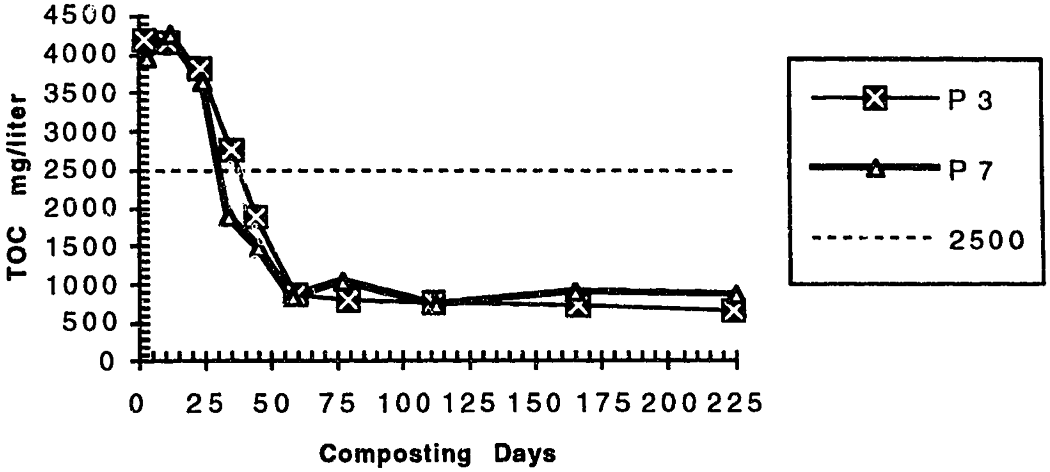

Figure 4.33 TOC vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

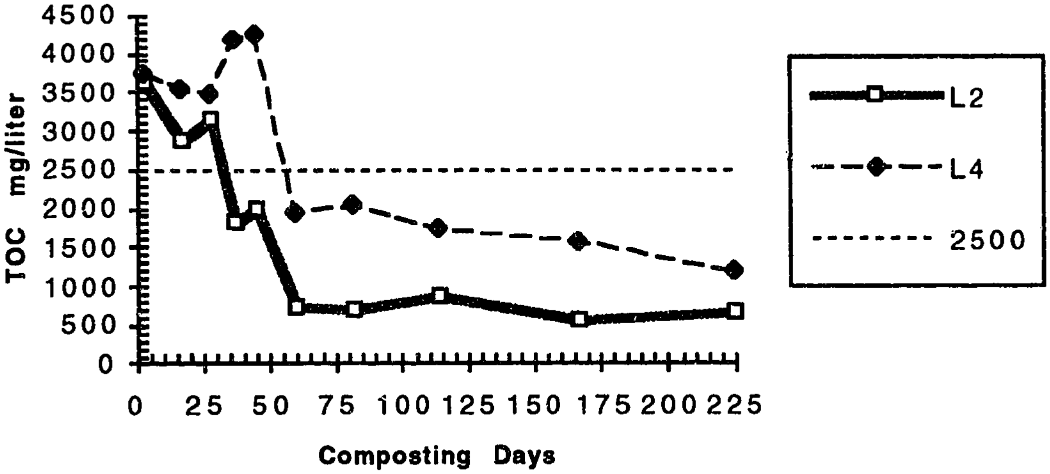

Figure 4.34 TOC vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

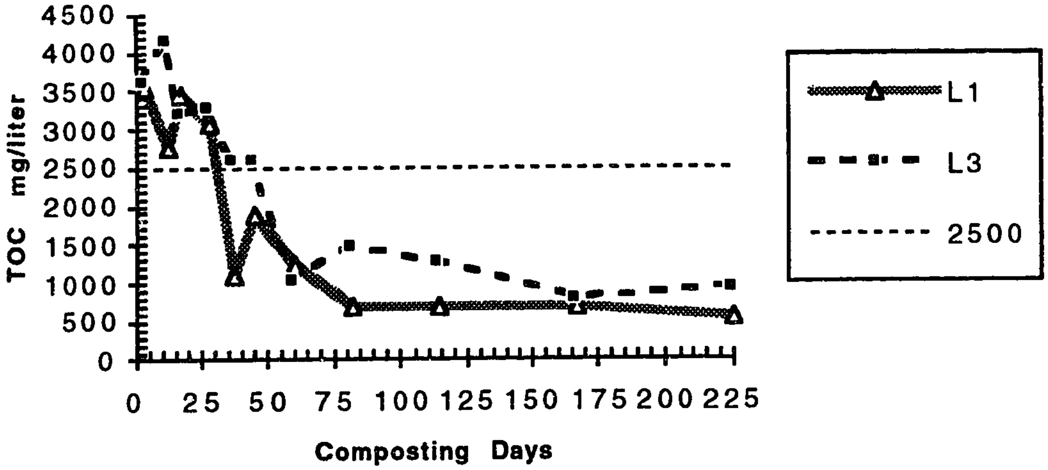

Figure 4.35 TOC vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

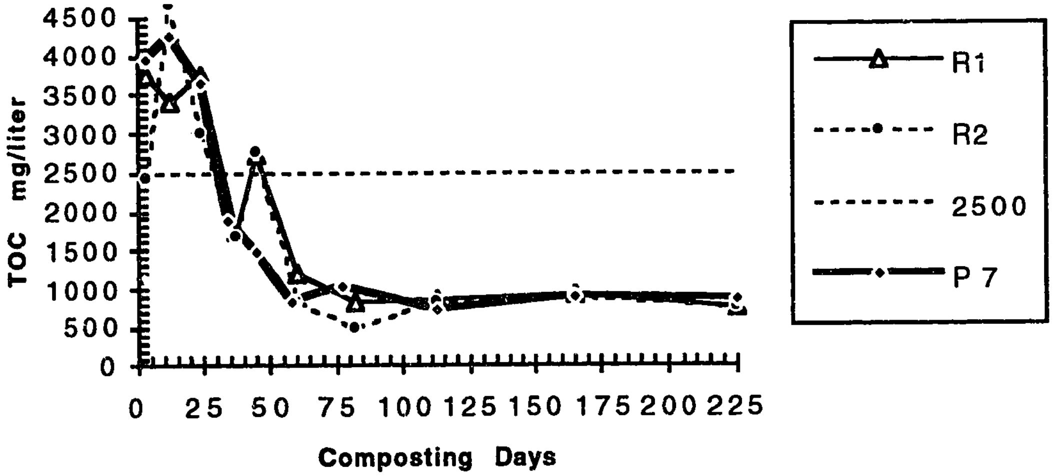

Figure 4.36 TOC vs Composting Days - Piles 7, R1 and R2

Med C:N, Hi M.C.

Replicates

The TOC values of the different piles sections fluctuated more during the first 36 days of the process and usually increased from the initial values. Piles 2, 4, 5, 6, 7, R2 and L3, for example, had higher TOC values on the samples taken on composting days 11 and 12, than determined from the initial samples. Riffaldi *et al* (1988) found the water soluble components initially increased during the first five days of composting a mixture of wastewater sludge from a paper factory and chopped straw. They attributed the initial increase to the increasing rate of decomposition by the microorganisms and they suggested the hydrolysis and solubilization of the complex substances initially predominated over mineralization and immobilization processes. The water soluble components of the compost water extract gradually decreased due to the microbial activity.

The values for the % change TOC content for each compost pile section are also highly dependent on the reliability of the initial and final determinations for TOC. The standard deviation of the average TOC value for multiple injections can be found in Appendix C.1. Table 4.7 outlines the TOC values for the initial and final samples for the various compost pile sections.

Table 4.7 - Pile TOC values - Water Extracts

Pile No.	Pile Designation	Initial TOC values mg/liter	Final TOC values mg/liter
1	Med C:N, Low M.C., Low Por.	5499.5	1017.8
3	Med C:N, Hi M.C., Low Por.	4137.7	649.6
5	Med C:N, Low M.C., Hi Por.	3778.1	752.0
7	Med C:N, Hi M.C., Hi Por.	3940.6	857.2
R1	Med C:N, Hi M.C., Hi Por.	3731.3	753.2
R2	Med C:N, Hi M.C., Hi Por.	2412.4	756.6
2	Hi C:N, Low M.C., Low Por.	2644.2	402.1
4	Hi C:N, Hi M.C., Low Por.	2053.7	793.9
6	Hi C:N, Low M.C., Hi Por.	3137.0	997.0
8	Hi C:N, Hi M.C., Hi Por.	3124.7	438.4
L1	Low C:N, Hi M.C., Low Por.	3536.3	571.4
L2	Low C:N, Low M.C., Low Por.	3608.8	646.1
L3	Low C:N, Hi M.C., Hi Por.	3602.1	944.4
L4	Low C:N, Low M.C., Hi Por.	3735.9	1195.0
C1	Control Pile		
C2	Control Pile		

The high C:N ratio piles 2, 4, 6 and 8 have a mean TOC value of 2739.9 with a standard deviation of 511.8. The medium C:N ratio piles have the highest mean TOC value of 3916.6 with a standard deviation of 987.0. The low C:N ratio piles have a mean TOC value of 3620.8 with a standard deviation of 83.4. As expected, the high C:N ratio piles had lower TOC values because straw has a lower relative proportion of water-soluble organic matter. Theoretically, the low C:N ratio piles should have had the highest initial TOC values because grass has a high relative proportion of water soluble organic matter. The differences in the mean values for the low and medium C:N ratio pile sections may be the result of heterogeneity of the compost material, sampling and or testing methods and procedures.

The % change in TOC values provide a relative indication of the level of maturity of the various piles and serves as a response variable in factorial design calculations to evaluate the influence of the key operational parameters on the decompostion rate. A more absolute indicator of maturity is the organic carbon to organic nitrogen ratio of water extracts. The following section discusses the organic carbon to organic nitrogen results for the various pile sections.

4.4.1.2.3 C:N_W ratio - Water Extracts

The organic carbon/organic nitrogen (C:N_W) values for the various pile sections fluctuated widely throughout the composting period although pile sections 2, 3, 4, 7, and L1 generally followed a decreasing trend. Garcia *et al.* (1991b) found the water soluble carbon/organic nitrogen ratio decreased considerably during the process for various mixtures of organic wastes consisting of aerobic sewage sludge, city refuse, grape debris and peat residue. Figures 4.37 to 4.43 show the C:N_W values versus the composting period for the various pile sections. The pile sections are organized according to their experimental C:N ratio and moisture levels.

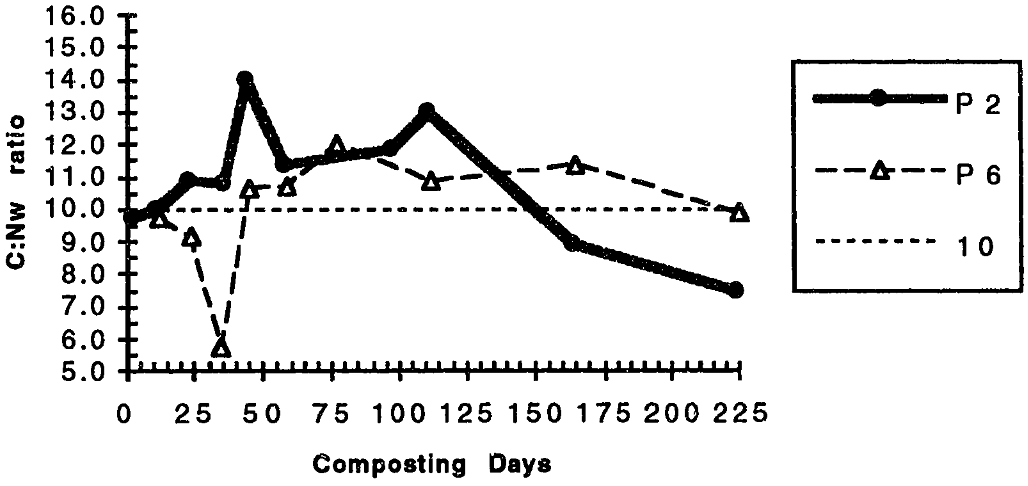

Figure 4.37 C:N_W vs Composting Days - Piles 2 and 6

Hi C:N, Low M.C.

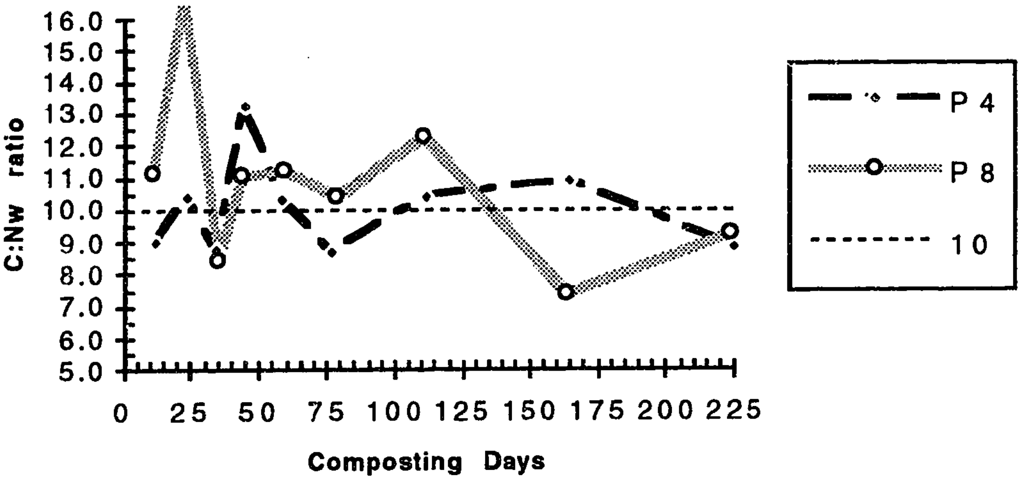

Figure 4.38 C:N_W vs Composting Days - Piles 4 and 8

HI C:N, HI M.C.

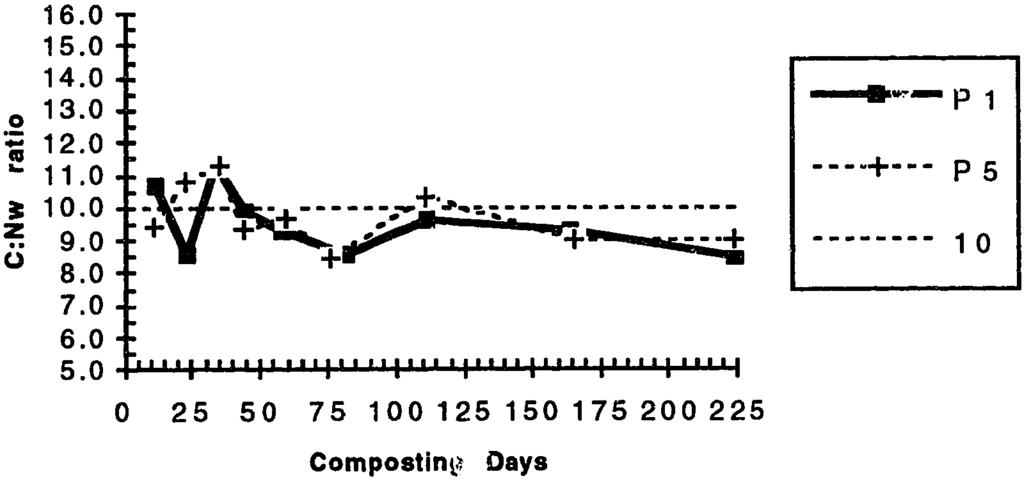

Figure 4.39 C:N_W vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

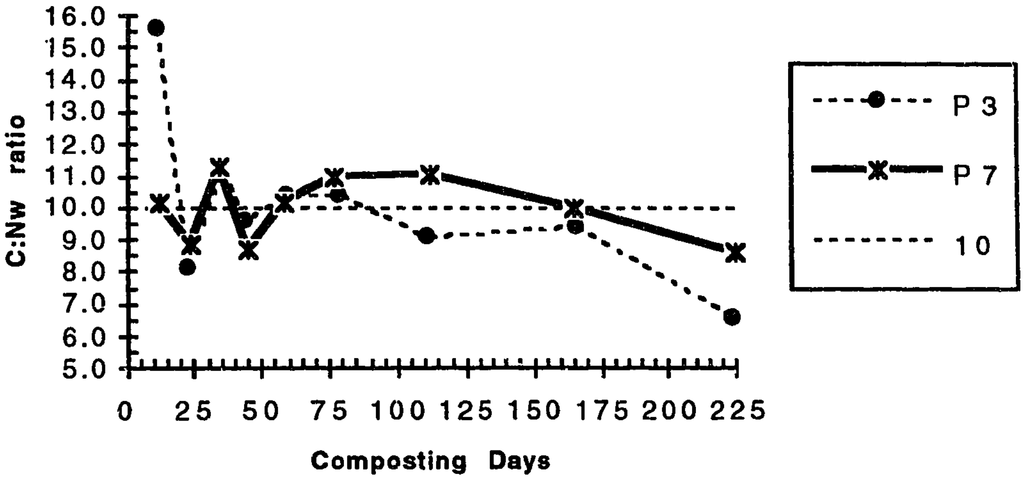

Figure 4.40 C:N_W vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

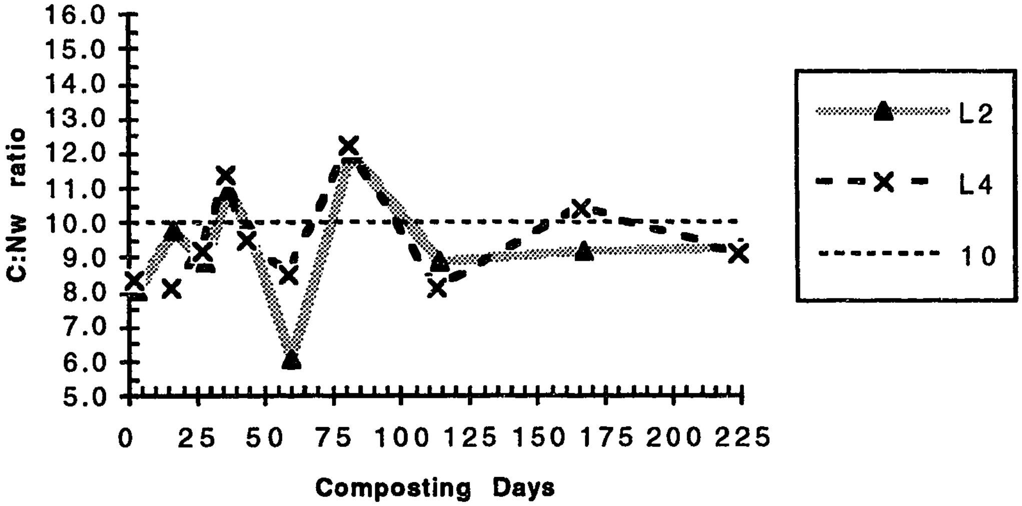

Figure 4.41 C:N_W vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

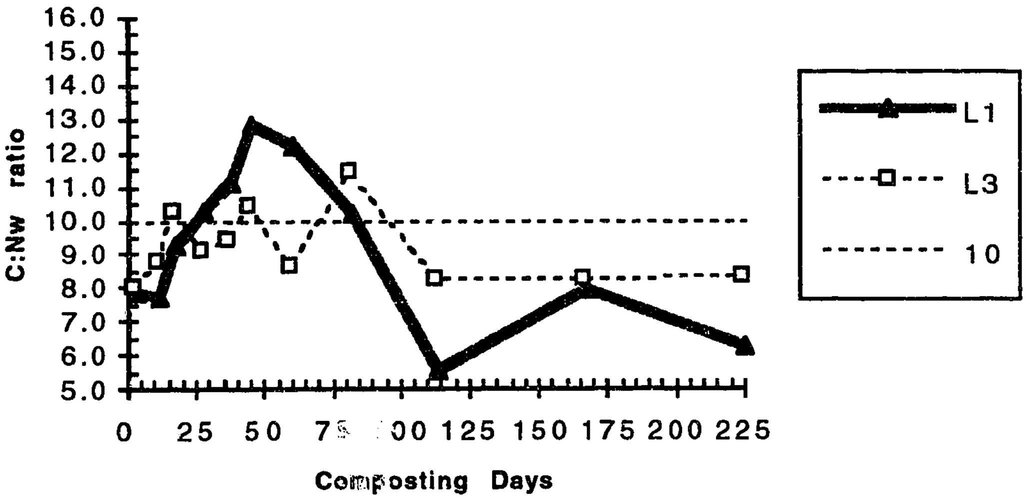

Figure 4.42 C:N_W vs Composting Days - Piles L1 and L3

Low C:N, HI M.C.

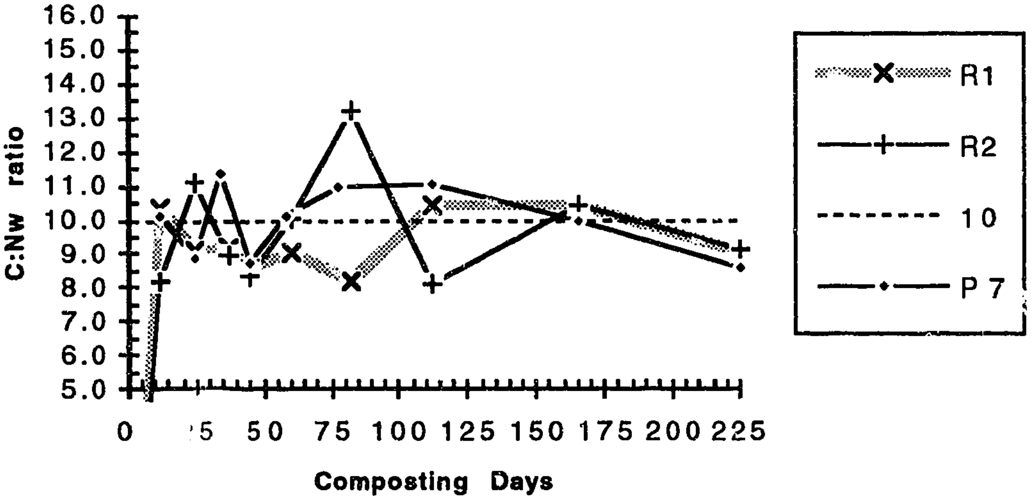

Figure 4.43 C:N_W vs Composting Days - Piles R1 and R2 and P 7

Med C:N, HI M.C.

Replicate Piles

The final $C:N_W$ ratio values for compost is considered an absolute indicator of compost maturity. Several authors have indicated a final $C:N_W$ ratio value between the 5 and 6 is as an absolute indicator of mature compost (Chanyasak and Kubota 1981; Chanyasak *et al.* 1982; Hirai *et al.* 1983; Riffaldi *et al.* 1988; Garcia *et al.* 1991). Table 4.8 outlines the initial and final $C:N_W$ values for the experimental piles. The initial $C:N_W$ values are from the August 11th and 16th, 1992 samples. There was not enough compost material remaining from the first samples to develop compost water extracts.

Table 4.8 - Pile Initial and Final $C:N_W$ ratios - Water Extracts

Pile No.	Pile Designation	Initial $C:N_W$	Final $C:N_W$
1	Med C:N, Low M.C., Low Por.	10.60	8.44
3	Med C:N, Hi M.C., Low Por.	15.57	6.60
5	Med C:N, Low M.C., Hi Por.	9.39	9.03
7	Med C:N, Hi M.C., Hi Por.	10.12	8.59
R1	Med C:N, Hi M.C., Hi Por.	10.36	9.01
R2	Med C:N, Hi M.C., Hi Por.	8.21	9.13
2	Hi C:N, Low M.C., Low Por.	9.97	7.50
4	Hi C:N, Hi M.C., Low Por.	9.00	8.80
6	Hi C:N, Low M.C., Hi Por.	9.77	9.88
8	Hi C:N, Hi M.C., Hi Por.	11.09	9.23
L1	Low C:N, Hi M.C., Low Por.	7.75	6.25
L2	Low C:N, Low M.C., Low Por.	8.86	9.24
L3	Low C:N, Hi M.C., Hi Por.	8.84	8.33
L4	Low C:N, Low M.C., Hi Por.	8.13	9.13

Initial values for piles L2 and L4 (92-08-16 sample)
Initial values for all other piles (92-08-11 sample)

The sole purpose for determining the final C:N_W ratio values was to identify which piles matured first. None of the final C:N_W ratio values were between 5 and 6, the range indicated for mature compost. The overall mean final C:N_W value for the experimental pile sections was 8.51 with a standard deviation of 1.0. The overall average initial (August 11, 1992 samples) C:N_W value for the experimental piles was 9.83 with a standard deviation of 1.92. The final C:N_W values were generally lower than the initial values. Pile section 3 had the lowest final value of 6.6, although piles L2 and 6 had values of 6.1 and 5.7 on days 60 and 34. The final C:N_W for pile sections L2 and 6 were 9.2 and 9.9. The C:N_W ratios do not provide an absolute indication of which pile sections matured first.

The experimental and literature C:N_W ratios differences may be due to the type of organic materials composted. The literature studies involving water extracts from air dried compost samples tested mature composts from a variety of organic mixtures but not grass and grass and straw composts. Grebus (1992) tested water extracts from fresh mature yard waste compost samples and found the C:N_W ratios to be higher than the literature values of between 5 and 6. The results obtained in this study may be representative of the true organic carbon to organic nitrogen ratios of mature grass and grass and straw composts. The most likely explanation for the differences in literature and experimental results are sample preparation and testing errors. For example, the final C:N_W values for pile sections 6 and L2 were much higher than the minimum values observed on days 34 and 60, respectively. The next section outlines the results of a secondary measure of organic degradation, the % increase in the compost dry bulk density.

4.1.2.4 Dry Bulk Density

As expected, the dry bulk density (DBD) of the various piles increased throughout the composting period, with most of the increase observed during the first 112 days, the active phase of the process and then remained fairly constant or increased slightly during the remaining 113 days or maturation phase. Low C:N ratio pile L1 had the highest % increase in DBD of 68.3%, while the lowest increase of 34.4% was observed for pile section 8. The mean % increase in DBD for the experimental pile sections was 55.3 with a standard deviation of 9.9 (from August 23, 1992 sample). This compares favorably to the mean value of 59.4% with a standard deviation of 8.0 observed by Fleming (1991) in the composting of mixtures of green waste, leaves and wood wastes in Florida. Control piles C1 and C2 had a lower mean % increase in dry bulk density of 36.4% with a standard deviation of 3.0 potentially indicating the organic materials did not degrade as much as the experimental piles. Multiple sample bulk density measurements were taken for piles 4 and 6 on October 16, 1992 to determine variability in bulk density measurements. Four wet bulk density measurements were taken for each pile. The average wet bulk density value for pile 4 was 434.0 Kg/m^3 with a standard deviation of 35.37. Pile 6 had an average wet bulk density value of 654.8 Kg/m^3 with a standard deviation of 36.29. Figures 4.44 to 4.51 display the DBD versus the composting period for the various pile sections. The pile sections are organized according to their experimental C:N ratio and moisture levels.

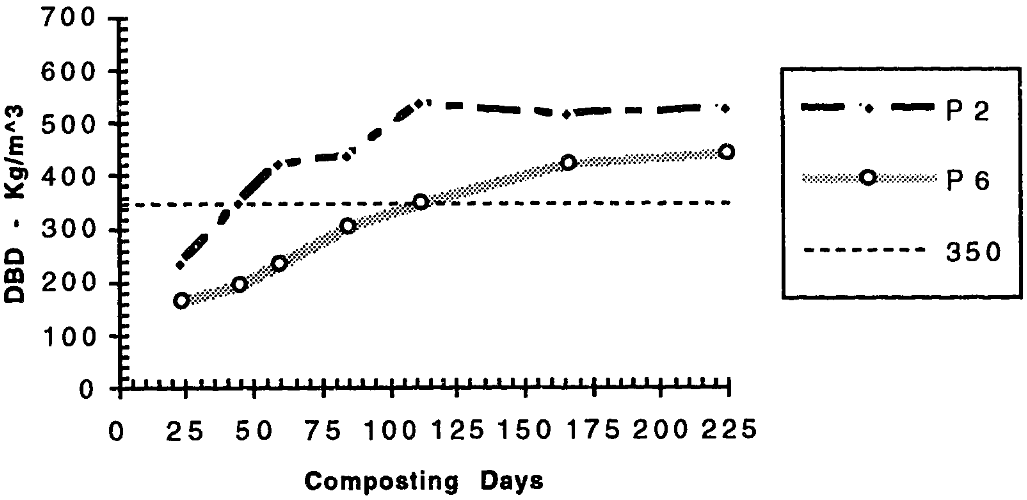

Figure 4.44 DBD vs Composting Days - Piles 2 and 6

HI C:N, Low M.C.

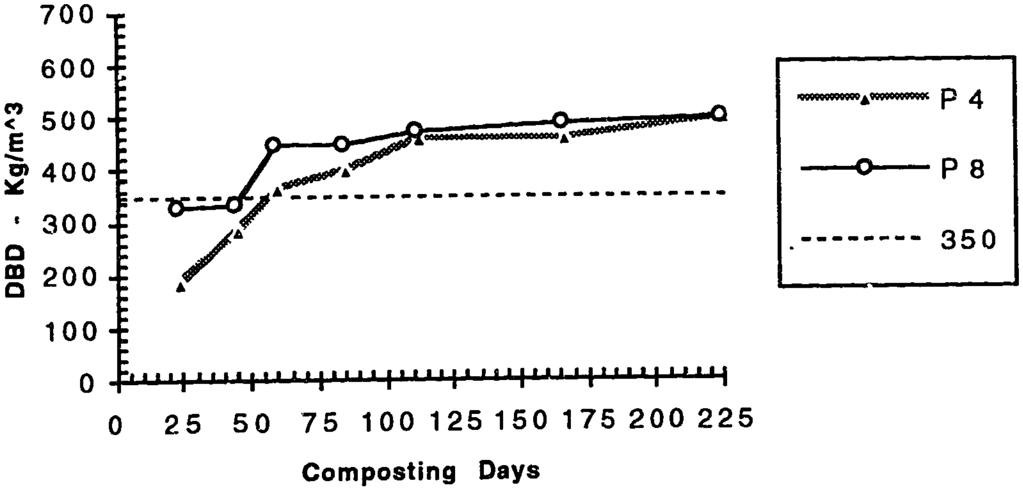

Figure 4.45 DBD vs Composting Days - Piles 4 and 8

Hi C:N, Hi M.C.

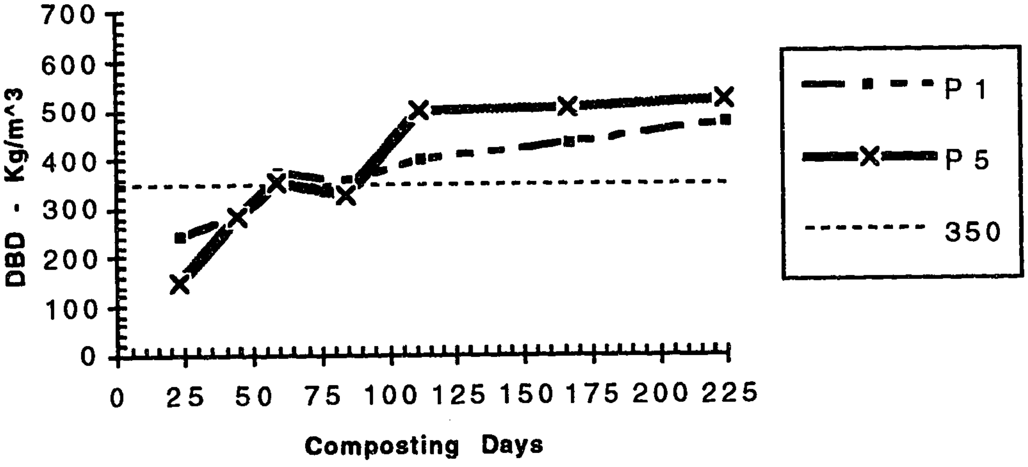

Figure 4.46 DBD vs Composting Days - Piles 1 and 5

Med C:N, Low M.C.

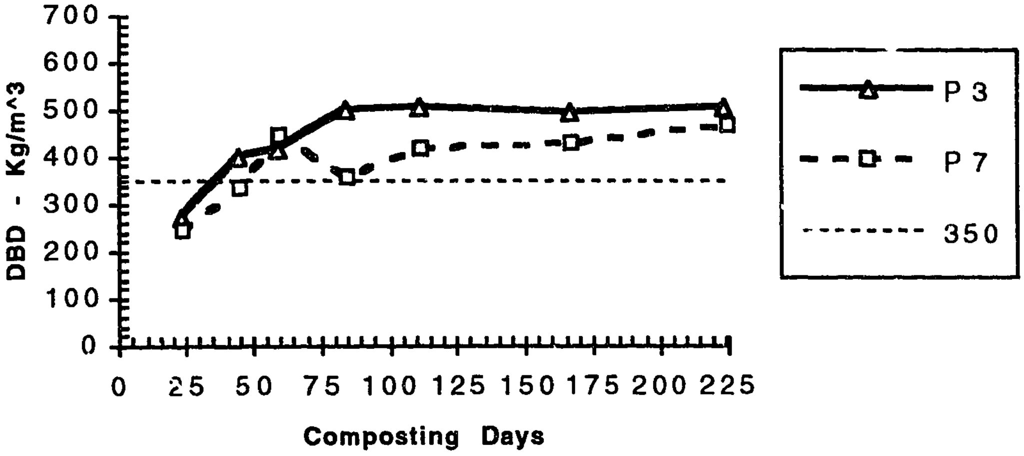

Figure 4.47 DBD vs Composting Days - Piles 3 and 7

Med C:N, Hi M.C.

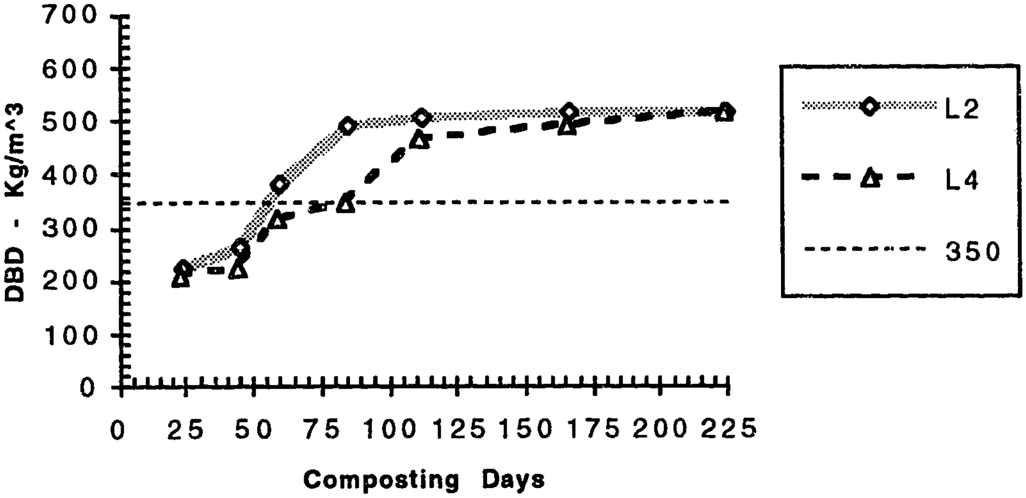

Figure 4.48 DBD vs Composting Days - Piles L2 and L4

Low C:N, Low M.C.

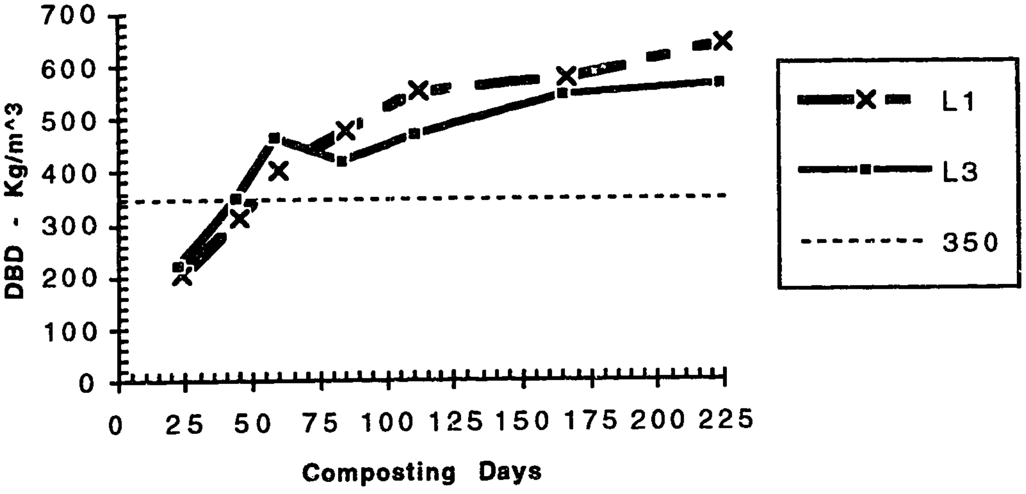

Figure 4.49 DBD vs Composting Days - Piles L1 and L3

Low C:N, Hi M.C.

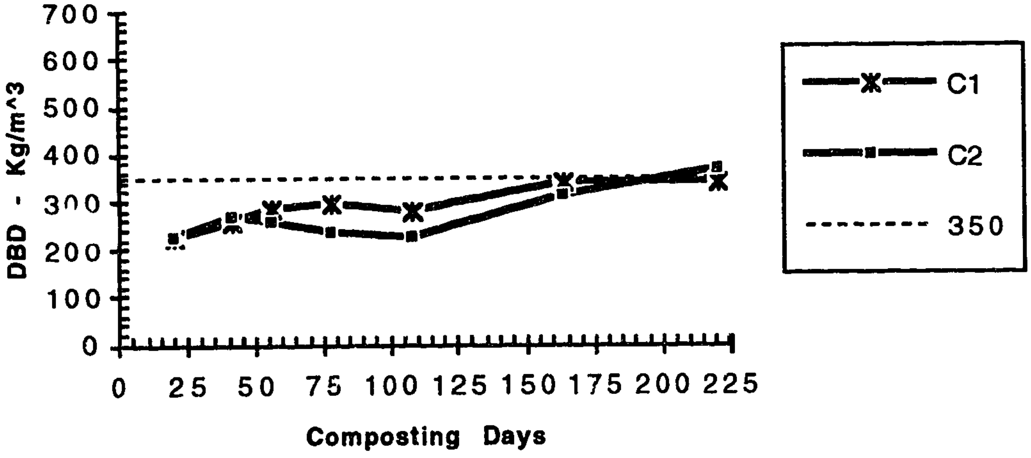

Figure 4.50 DBD vs Composting Days - Piles C1 and C2

Control Piles

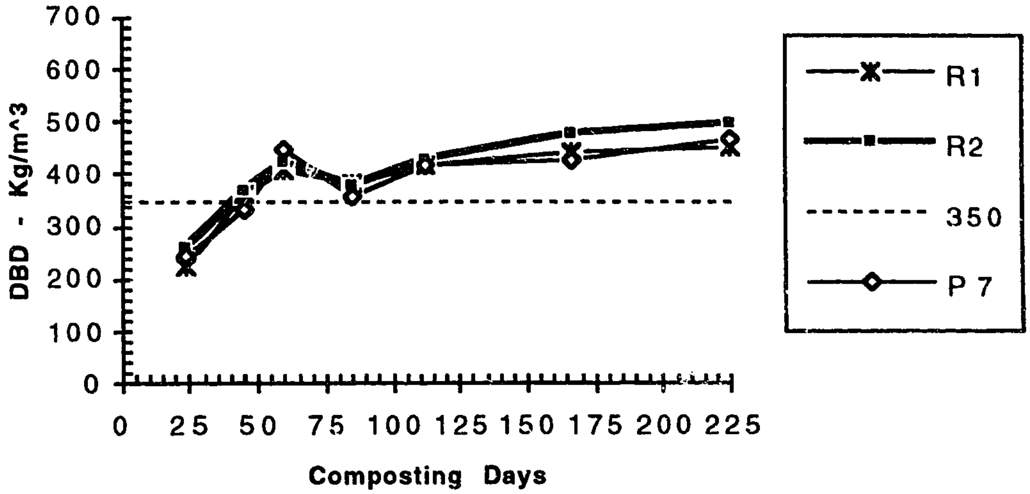

Figure 4.51 DBD vs Composting Days - Piles 7, R1 and R2

Med C:N, Hi M.C.

Replicate Piles

Pile sections 4, 5, 6, 7, 8, L3 and L4, R1 and R2, which had wood chips added to adjust porosity, generally have lower values of dry bulk density than the piles with the same experimental moisture and C:N levels. Wood chips were added to pile 5, on day 70 and piles 6, 7, on day 71 and to piles 8, L3 and L4 on day 77 and Piles R1 and R2 on day 78. The wood chips are less dense than the existing compost mixtures so the lower dry bulk density values for the porosity adjusted piles are expected. Table 4.10 outlines the dry bulk density values for the August 23, 1992 samples and the final samples for the various compost pile sections.

Table 4.9 - Pile Dry Bulk Density values (DBD)

Pile	Pile Designation	DBD Kg/m^3 92-08-23	DBD Kg/m^3 93-03-13
1	Med C:N, Low M.C., Low Por.	237.7	470.7
3	Med C:N, Hi M.C., Low Por.	270.5	504.4
5	Med C:N, Low M.C., Hi Por.	148.3	517.1
7	Med C:N, Hi M.C., Hi Por.	245.3	467.7
R 1	Med C:N, Hi M.C., Hi Por.	225.8	451.0
R 2	Med C:N, Hi M.C., Hi Por.	256.6	495.0
2	Hi C:N, Low M.C., Low Por.	232.3	526.1
4	Hi C:N, Hi M.C., Low Por.	184.9	493.9
6	Hi C:N, Low M.C., Hi Por.	162.3	443.0
8	Hi C:N, Hi M.C., Hi Por.	326.6	496.2
L 1	Low C:N, Hi M.C., Low Por.	202.8	640.6
L 2	Low C:N, Low M.C., Low Por.	222.8	516.9
L 3	Low C:N, Hi M.C., Hi Por.	219.7	559.4
L 4	Low C:N, Low M.C., Hi Por.	207.9	518.3
C1	Control Pile	221.2	336.9
C2	Control Pile	226.0	367.8

The dry bulk density values for the high C:N ratio piles on August 23, 1992 varied from 162.3 Kg/m^3 for pile 6 to a high value of 326.6 Kg/m^3 for pile section 8. The mean value was 226.5 Kg/m^3 with a standard deviation of 72.8. The medium C:N ratio piles have a mean DBD value on August 23, 1992 of 230.7 Kg/m^3 with a standard deviation of 43.2. The low C:N ratio piles have a mean value of 213.3 Kg/m^3 with a standard deviation of 9.5. The large variation in DBD values observed for the high C:N ratio piles on August 23, 1992 may be explained by the heterogeneity of the mixtures of straw and grass.

The mean final DBD for the high C:N piles was 489.8 Kg/m^3 with a standard deviation of 34.5. The medium C:N ratio piles had a similar final value of 484.3 Kg/m^3 with a standard deviation of 25.2. The highest mean final DBD of 558.8 Kg/m^3 with a standard deviation of 58.0 was observed for the low C:N ratio piles. The dry bulk densities were comparable to values observed by Fleming (1991). In her study, the initial and final mean DBD were 259.6 Kg/m^3 and 639.4 Kg/m^3 with standard deviations of 87.3 and 56.8.

The % increase in DBD provides a relative indication of the level of maturity of the various piles and serves as a response variable in factorial design calculations to evaluate the influence of the key operational parameters on the decomposition rate. Although it is not considered a primary indicator of compost maturity, it may be useful in the confirmation of the results of more recognized maturity parameters.

4.1.3 Factorial Design Results

Because the experimental moisture levels were not able to be maintained the design matrix was adjusted to reflect the actual moisture levels measured in the different compost piles. The adjusted factorial design matrices are referred to as botched factorials. The +1 and -1 levels for the moisture content variable are replaced by values representing the actual pile moisture content as a percentage of the planned experimental levels. For example, the weighted average moisture content for pile 2 for the full composting period was 27.0% which is 0.68 of the planned experimental level of 40%. Instead of +1 and -1 levels ± 0.68 is used in the design matrix. The factorial design was analysed using the % decrease in TOC and the % increase in dry bulk density for both the active and full composting periods as the response variables. The results for the active composting period reflect the importance of the operational variables during the period when most of the decomposition of organic materials takes place. As stated earlier the % decrease in TOC is considered the most reliable response variable. The % increase in dry bulk density is a secondary and less reliable response variable. The following section summarizes the results of the factorial experiment for both response variables.

4.1.3.1 Factorial Experiment - Results

The results of the factorial design, using % decrease in TOC as the response variable, indicate none of the main effects and their interactions were found to significantly effect the decomposition of the organic materials. Based on the calculated 95% confidence intervals of the regression coefficient β values, none of the factors are significantly different from zero. All the β values have both positive and negative confidence interval values, indicating zero is a possible value. The β values measure the effect of a unit change in the variable on the mean response (Montgomery 1984). The main effects and their interactions represent a change from -1 to +1, a change of 2 units. To calculate the main effects and their interactions, the β values are doubled. The results of the factorial experiment are shown in Table E.1 in Appendix E. Table 4.10 summarizes the significant factors for both response variables based on the 95% and 90% confidence intervals, as well as the results from the half normal plots.

Table 4.10 - Factorial Experiment - Significant Effects

Significant Effects and Interactions

Response Variable	% Decrease in TOC			% Increase in Dry Bulk Density		
Period	**95% CI**	**90% CI**	**Half Normal Plot**	**95% CI**	**90% CI**	**Half Normal Plot**
Full	None	13 23 123	13 123	23	23	3 123
Active	None	None	2 12 13	23	23	3 13 23

The confidence interval results are considered more reliable because the results of the half normal plot are dependent upon how the straight line is drawn through the points. Although the 95 %

confidence interval results, using % decrease in TOC as the response variable, indicate no factor is significant, results from the 90 % confidence interval calculations and the half normal plots for both response variables provide some indication that some factors marginally influenced the decomposition process. In addition, ranking the effects from the highest to lowest value after normalization also provides a measure of relative importance. The higher the normalized value the larger the effect on the decomposition rate. The effects are normalized by dividing the value of the effect by the standard error at the 5% significance level.

For the full composting period, the 90% confidence interval calculations of the ß values for the response variable % decrease in TOC, suggest the interactions 13 (C:N ratio-Porosity), 23 (MC-Porosity) and 123 (C:N ratio-MC-Porosity) marginally influenced the decomposition of the organic materials. The results of the half normal plot also indicate the 13 and 123 interactions are significant. The factorial design results, using % increase in dry bulk density as the response variable, found the 23 interaction (MC-Porosity) to be significant. Table 4.11 summarizes the rankings of the effects for both response variable factorials for the full composting period.

Table 4.11 - Ranking of Effects - Full Period

% Decrease in TOC			% Increase in Dry Bulk Density		
Effects	**Value**	**Value/S.E.**	**Effects**	**Value**	**Value/S.E.**
23	-9.14	-4.60	23	-13.77	-5.58
123	-12.16	-4.56	1	-8.82	-3.36
13	-8.2	-3.90	12	-10.70	-3.22
3	3.24	2.02	2	-6.57	-2.66
12	4.46	1.68	123	-8.70	-2.62
1	0.99	0.46	13	-5.11	-1.96
2	-0.27	-0.14	3	-1.27	-0.64

Interactions 23 and 123 and 13 have the highest values of the normalized effects for the % decrease in TOC factorial. The 23 interaction has the highest value of the normalized effects for the dry bulk density factorial. The negative value for the 23 effect for the DBD factorial indicates, this effect has a negative influence on the increase in dry bulk density. A negative value for an effect for the TOC factorial indicates the effect increases the percent decrease in TOC. Based on the overall results of the 90% confidence intervals, half normal plots and rankings, there are indications that the 13, 23 and 123 interactions marginally influenced the decomposition of the organic materials. The factorial results from the TOC response variable are considered more reliable than the dry bulk density results; therefore the conclusions are mainly based on the TOC factorial results.

For the active period, none of the factors were found to influence the decomposition of the organic materials, based on the 90% confidence interval calculations of the ß values for the response variable % decrease in TOC. The half normal plot indicated the main effect 2 (MC) and the interactions 12 (C:N ratio-MC) and 13 (C:N ratio-Porosity) were significant. The dry bulk density factorial confidence interval results indicated the 23 interaction was significant. Table 4.12 summarizes the rankings of the effects for both response variable factorials for the active composting period.

Table 4.12 - Ranking of Effects - Active Period

% Decrease in TOC			% Increase in Dry Bulk Density		
Effects	**Value**	**Value/S.E.**	**Effects**	**Value**	**Value/S.E.**
3	7.78	3.68	23	-15.01	-4.94
13	-10.08	-3.64	1	-7.92	-2.46
23	-8.99	-3.44	2	-6.23	-2.06
1	-6.80	-2.46	13	-6.02	-1.86
123	-5.80	-1.66	12	-7.02	-1.72
2	-1.69	-0.64	3	-3.99	-1.62
12	0.92	0.26	123	-6.3	-1.54

The main effect 3 (Porosity) and interactions 13 and 23 have the highest values of the normalized effects for the % decrease in TOC factorial. The 23 interaction has the highest value of the normalized effects for the dry bulk density factorial. Main effects 1 (C:N ratio) and 2 (MC) have the second and third highest values. Overall the factorial results for the active period do not consistently indicate any of the factors influence the decomposition of the organic materials. The following section discusses the factorial results of the 90% confidence intervals, half normal plots and rankings for the full composting period.

4.1.3.2 Factorial Results Discussion

None of the operational factors were found to significantly effect the decomposition of the organic materials based on the calculated 95% confidence intervals of the ß's for the % decrease in TOC factorial. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13, 23 and 123 interactions marginally influenced the decomposition of the organic materials. The following paragraphs discuss the theoretical importance of these interactions and outlines possible explanations for the factorial results.

The factorial results suggest the operational factors are interelated which is consistent with theory. The 23 interaction (MC-Porosity) which had the highest normalized effect value is considered to have the largest affect on the response variable If the moisture content is too high, the the void space available for air will be reduced. This will result in a lower supply of oxygen which will reduce the rate of biological activity. When the the moisture content is low and the void space available for air is high, the rate of biological activity is also reduced. The flow of air through the void space results in moisture losses and potential cooling of the compost mass. A balance between adequate moisture content and porosity is important for optimizing the decomposition process.

The second and third highest normalized effects based on the TOC factorial results for the full period are the interaction 123 (C:N ratio-MC-Porosity) and 13 (C:N ratio- Porosity). These results suggest a relationship exists between the moisture content, porosity and the C:N ratio of the materials. A potential explanation may be the variable C:N ratio actually represents the physical nature of the material. The void space in the compost pile is related to the physical nature of the compost materials and not the C:N ratio. Fibrous or bulky materials such as straw and wood chips are able to maintain adequate porosity compared to grass clippings. Golueke (1977) indicated the maximum permissible percent moisture is also a function of the physical nature of the materials. For example, fibrous or bulky materials such as straw and wood chips can absorb relatively large amounts of water and still maintain adequate porosity (Haug 1980).

Finally the lowest normalized effects based on the TOC factorial results for the full period are the main effects 2(MC) and 1(C:N ratio). This may suggest that these factors alone do not influence the decomposition of the organic materials. The normalized effect value for the main effect 3(Porosity) was ranked 4th for the full period and first for the active period for the TOC factorial results. Based on the actual measured porosity values for piles 5, 6, 7, L4, R1, R2 and 8 the porosity generally decreased or remained fairly level for the first porosity measurements after the addition of more wood chips. Possible reasons for the inconsistent results could include errors introduced in measurement, sampling or testing, improper mixing of wood chips, compost cover contamination of the samples or the volume of wood chips added did not significantly alter the porosity of the piles. The most likely explanation are errors introduced in the determination of the porosity measurements. Since there appears to be no standard method of determining compost porosity, the accuracy of the method used in this study can not be determined.

4.1.3.3 Summary and Explanations

In summary, the factorial results based on the calculated 95% confidence intervals of the ß's for the % decrease in TOC factorial found none of the factors influenced the decomposition rate of the organic materials. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13 (C:N ratio-Porosity), 23 (MC-Porosity) and 123 (C:N ratio-MC-Porosity) marginally influenced the decomposition of the organic materials. The results do not support the hypotheses that the operating variables C:N ratio, moisture content and porosity adjustment individually effect the decomposition rate of the organic materials. Possible explanations for these experimental results are: 1) the response variables used in the study were not able to measure the effects, 2) the effect of C:N ratio, M.C. and porosity on degradation did not occur within the ranges tested or 3) the difficulties encountered in maintaining and operating a field level experiment impacted the results. The most likely reasons are the difficulties in maintaining and operating a field level experiment.

For example, the difficulty experienced trying to maintain the experimental moisture levels may have effected the factorial results. It was not possible to maintain the moisture content of the pile sections at the desired levels. For the full composting period the average weighted mean pile moisture content for the high MC piles was 38.6% compared to the experimental level of 60%. For the 40% MC piles, the average weighted mean pile moisture content was 31.2% for the full composting period. The moisture differences may not have been significant enough to create a real difference in the experimental conditions. Although the -1 and +1 levels for the MC variable in the factorial design matrix were adjusted to reflect the calculated values of the pile average weighted moisture contents, these values may not provide a good representation of the actual moisture conditions.

In addition, the amount of straw added to the experimental piles may not have been sufficient enough to create a significant difference in the C:N ratio of the piles. The experimental C:N ratio levels were based on the number of front end loader buckets instead of the mass of the different organic materials.

4.2 Decomposition

The purpose of monitoring the decomposition of the organic materials for the various compost piles was to: **1**. evaluate and model the biological degradation of these materials over time and provide a tool for optimization of the process; **2**. determine the magnitude and rate of decomposition of the various compost piles.and compare the results with expected behavior. The following sections summarize the decomposition behavior of the experimental compost piles and compares the results to a physical model proposed by Haug (1980).

4.2.1 Decomposition Modelling

Determining the overall reaction rate for the active composting period for the various experimental piles may be useful in identifying differences and process optimization opportunities. Generally the decomposition rate of organic residues especially in soils is considered to follow first order rate kinetics (Paul and Clark 1989). In this study, the parameters % total carbon (% C) in solid compost samples and TOC of compost water extracts were used as measures of the degradation of the organic materials. The measured % C values reported in this study includes the carbon content of substrate as well as biomass. The actual substrate % C is usually determined by subtracting the carbon content of the biomass.

The kinetic rates for the decomposition of the organic materials can be calculated by determining the slope of the line for the different plots of substrate parameters versus time. Instead of plotting the data, linear regression techniques using the least-squares method were used to determine the slope and R^2 value of the fitted line. The R^2 value is the square of the Pearson product moment correlation coefficient. The slope of the fitted line of substrate concentration versus time determined the zero order kinetic rate. For first order kinetics, the slope of the ln of % C and ln of TOC versus time determined the reaction rate constants. The slope of the fitted line of 1/% C and 1/TOC versus time determined the second order kinetic rates. Table 4.13 on the following page summarizes the modelling results for % C of compost solid samples.

The zero order model has the lowest R^2 value of 0.68 while the average R^2 value for the second order model was highest at 0.76. The first order R^2 value was slightly lower than the second order model at a value of 0.74. The calculated R^2 value is a measure of how well the plotted plots fit the straight line relationship. The closer the R^2 value is to 1.0 the better the data fits the straight line relationship. An analysis of variance test was used to statistically determine, if the average R^2 values for the different models are significantly different. The results outlined in Table F.1 indicated, that collectively there was a difference somewhere in the data of the three groups, but a group by group comparison using the Student-Newman-Keuls test with a 5% significance level found the zero order average R^2 value was significantly different than the first and second order average R^2 values. There was no significant difference found between the first and second order average values. Based on the comparison of the average R^2 values, the % C data for the experimental piles suggests the decomposition process follows either first or second order kinetics. The first order model is the more likely case because other authors have indicated the composting process and decomposition of plant residues generally follow first order rate kinetics (Paul and Clark 1989; Haug 1993).

Table 4.13 - Rate Constants for % Carbon - solid samples

Active Period- all values up to and including November 19-21, 1992 samples.

		Zero Order			First Order			Second Order		
Pile No.	**Pile Designations**	**k** %C day^{-1}	**R^2**	**Rank**	**k** day^{-1}	**R^2**	**Rank**	**k** %C^{-1}day^{-1}	**R^2**	**Rank**
1	Med C:N, Low M.C., Low Por.	-0.1706	0.59	8	0.0064	0.69	8	2.497E-04	0.77	8
2	Hi C:N, Low M.C., Low Por.	-0.1800	0.65	7	0.0040	0.76	14	4.981E-04	0.82	2
3	Med C:N, Hi M.C., Low Por.	-0.2139	0.67	5	0.0080	0.72	4	3.097E-04	0.75	6
4	Hi C:N, Hi M.C., Low Por.	-0.2425	0.81	1	0.0090	0.89	3	3.556E-04	0.95	4
5	Med C:N, Low M.C., Hi Por.	-0.0871	0.68	14	0.0057	0.66	10	2.373E-04	0.69	11
6	Hi C:N, Low M.C., Hi Por.	-0.2256	0.75	4	0.0072	0.83	6	2.438E-04	0.88	9
7	Med C:N, Hi M.C., Hi Por.	-0.0903	0.66	13	0.0070	0.84	7	2.658E-04	0.86	7
8	Hi C:N, Hi M.C., Hi Por.	-0.2346	0.83	3	0.0104	0.87	1	5.115E-04	0.85	1
R1	Med C:N, Hi M.C., Hi Por.	-0.1697	0.66	9	0.0062	0.72	9	2.354E-04	0.77	12
R2	Med C:N, Hi M.C., Hi Por.	-0.2027	0.69	6	0.0079	0.74	5	3.230E-04	0.75	5
L1	Low C:N, Hi M.C., Low Por.	-0.0958	0.55	12	0.0047	0.61	13	2.419E-04	0.65	10
L2	Low C:N, Low M.C., Low Por.	-0.2352	0.66	2	0.0102	0.73	2	4.843E-04	0.77	3
L3	Low C:N, Hi M.C., Hi Por.	-0.1548	0.60	11	0.0051	0.57	12	2.061E-04	0.65	13
L4	Low C:N, Low M.C., Hi Por.	-0.1549	0.67	10	0.0056	0.66	11	1.741E-04	0.51	14
C1	Control Pile	-0.0664	0.23	15	0.0019	0.23	16	5.751E-05	0.22	16
C2	Control Pile	0.3117	0.29	16	0.0037	0.66	15	1.453E-04	0.68	15
	Averages	**-0.1755**	**0.68**		**0.0070**	**0.74**		**0.00031**	**0.76**	

The average % C first order reaction rate constant is 0.0070/day. The rate constants listed in Table 2.7 are generally a few magnitudes higher than determined from the the % C data for the experimental piles. For example, the k values for grass/leaves and grass/cardboard mixtures using first order rate equation for the rate of disappearance of compost mass, ranged from 0.165/day to 0.190/day for Marugg (1993). A possible explanation for these results is the measured % C values of the compost includes not only the amount of carbon in the organic residues and the intermediate products, but also the carbon content of the microbes. The measured % C is higher than actual % carbon of the substrate. As the composting process proceeds, the substrate concentration is decreasing and the biomass concentration increases to a certain point in the process. In the latter stages, the biomass concentration starts to decrease as the amount of available substrate decreases. The calculated decomposition rate using % C is probably lower than the actual rate. If the biomass carbon content was subtracted from the total carbon, the actual decomposition rate could of been calculated.

Table 4.14 summarizes the modelling results for the TOC of compost water extracts.

Table 4.14 - Rate Constants for TOC - water extract

Active Period- all values up to and including November 19-21, 1992 samples.

		Zero Order			First Order			Second Order		
Pile	Pile Designations	k mg $L^{-1}day^{-1}$	R^2	Rank	k day^{-1}	R^2	Rank	k L $mg^{-1}day^{-1}$	R^2	Rank
1	Med C:N, Low M.C., Low Por.	-32.87	0.62	3	0.0132	0.71	11	6.334E-06	0.74	11
2	Hi C:N, Low M.C., Low Por.	-22.22	0.84	11	0.0174	0.93	4	1.691E-05	0.94	2
3	Med C:N, Hi M.C., Low Por.	-37.94	0.83	1	0.0192	0.86	1	1.211E-05	0.86	5
4	Hi C:N, Hi M.C., Low Por.	-20.19	0.73	13	0.0147	0.82	9	1.228E-05	0.87	4
5	Med C:N, Low M.C., Hi Por.	-30.08	0.72	5	0.0147	0.79	10	8.400E-06	0.84	10
6	Hi C:N, Low M.C., Hi Por.	-23.53	0.56	10	0.0112	0.59	13	6.032E-06	0.58	12
7	Med C:N, Hi M.C., Hi Por.	-35.40	0.56	2	0.0182	0.83	3	1.163E-05	0.88	7
8	Hi C:N, Hi M.C., Hi Por.	-10.95	0.64	14	0.0189	0.75	2	1.855E-05	0.81	1
R1	Med C:N, Hi M.C., Hi Por.	-30.63	0.79	4	0.0174	0.66	5	1.336E-05	0.59	3
R2	Med C:N, Hi M.C., Hi Por.	-29.34	0.53	6	0.0161	0.84	8	9.959E-06	0.85	9
L1	Low C:N, Hi M.C., Low Por.	-28.05	0.75	7	0.0166	0.82	6	1.201E-05	0.85	6
L2	Low C:N, Low M.C., Low Por.	-27.77	0.77	8	0.0162	0.76	7	1.126E-05	0.70	8
L3	Low C:N, Hi M.C., Hi Por.	-26.88	0.77	9	0.0119	0.74	12	5.851E-06	0.65	13
L4	Low C:N, Low M.C., Hi Por.	-22.20	0.60	12	0.0083	0.66	14	3.242E-06	0.72	14
	Averages	**-27.00**	**0.70**		**0.0153**	**0.77**		**0.0000106**	**0.78**	

The zero order model has the lowest R^2 value of 0.70 while the average R^2 value for the second order model was highest at 0.78. The first order R^2 value was slightly lower than the second order model at a value of 0.77. An analysis of variance test was again used to statistically determine, if the average R^2 values for the different models are significantly different. The results indicated that collectively there was a difference somewhere in the data of the three groups but a group by group comparison using the Student-Newman-Keuls test with a 5% significance level found there was no significant difference between the average R^2 values. Based on the comparison of the average R^2 values, the TOC data for the experimental piles suggests the decomposition of the organic materials follows either zero, first or second order kinetics. The first order model is again the more likely case but a discussion of a potential second order model will be reviewed in the section titled Comparison to Theoretical Models.

The average TOC first order reaction rate constant is -0.0153/day. The rate constants listed in Table 2.7 are generally one magnitude higher than determined from the the TOC data for the experimental piles. The TOC data for this study includes the organic carbon content of the biomass. This may explain the differences in the magnitude of the rate constants. The measured TOC value is higher than the actual TOC of just the substrate. If the biomass TOC content was subtracted from the experimental measured value,.the actual decomposition rate could of been determined.

In comparing the first order rate constants for the % C and TOC parameters, the average pile TOC rate constant is over 10 times higher than the average pile rate constant for % C. This higher rate constant value is expected because the TOC parameter measures the readily available water soluble organic carbon content. The measured % C content includes the organic carbon content of all constituents including the more resistant compounds cellulose, hemicellulose and lignin. Paul and Clark (1989) outline the rate constants for plant residues in soils under laboratory conditions. They indicate for easily decomposable compounds -k = 0.2 compared to -k = 0.08 for slowly decomposable constituents. The multicomponent empirical models proposed by Murayama *et al.* (1990) and Van Veen *et al.* (1984) support the argument that different fractions of plant residues decompose at different rates. The reaction rate of the easily decomposable fraction is higher than the more resistant fraction of the plant residue. The following section compares the decomposition modelling results with the theoretical physical model proposed by Haug (1980).

4.2.2 Comparison to Theoretical Model

The modelling results for the parameters % C and TOC over time indicated the the decomposition of the organic materials followed either first or second order kinetics. Generally, the decomposition of organic material is considered to follow first order kinetics Haug (1980), (Paul and Clark 1989). The following section reviews the model proposed by Haug (1980) and discusses the model in relation to experimental decomposition rates and changes in compost substrate and biomass. The composting kinetic model proposed by Haug (1980) is shown below.

$$-\frac{ds}{dt} = \frac{k A_V X}{K_X + X} \qquad (25)$$

-ds/dt = rate of hydrolysis of solid substrate

k = maximum rate of hydrolysis occurring at high microbial population.

A_V = Available surface area (substrate) per unit volume

K_X = half velocity coefficient The microbial concentration at 1/2 the maximum reaction rate.

Haug (1993) indicated that the solubilization of the solid substrate through hydrolysis is probably the rate limiting mechanism during composting. Based on his model, the rate of hydrolysis is a function of the size of the microbial population **X**, and the available substrate surface area per unit volume **A_V**. Haug (1980) described two general cases of the model. Case 1 when the concentration of microbes is much less than $\mathbf{K_X}$ (the half-rate constant) the rate of hydrolysis of the solid substrate is a first order reaction with respect to the microbial concentration. Case **2** when the concentration of microbes is much greater than the half rate constant the change in solid substrate over time is a zero order reaction with respect to microbial concentration.

Haug (1980) noted that different decomposition rates observed for different substrate materials are probably due to differences in the value of $\mathbf{kA_V}$. For example, a more resistant substrate such as wood fiber would have a lower value of $\mathbf{kA_V}$. Haug (1980) suggested this may be interpreted as a lower number of available enzyme binding sites or a lower number of successful enzyme reactions in a more resistant substrate. The product kA_V appears to be a measure of substrate availability and the value changes throughout the composting process. Haug (1993) indicated that during the early stages of composting, the substrates with high kA_V values ($\mathbf{kA_{V1}}$) are decomposing resulting in an increase in microbial population. As the composting process proceeds, the more resistant substrates with low kA_V values ($\mathbf{kA_{V2}}$) are encountered. The rate of hydrolysis of the more complex substrates are the rate determining step of the overall process. The more recalcitrant substrates decompose at lower rates for a longer period of time (Haug 1993; Marugg *et al.* 1993). The changes in % C in solid samples and TOC in water extracts over time provided evidence that the decomposition rate is higher during the active phase and lower during the maturation phase based on the change in slope of the curves. Haug (1993) also suggested the values of **Kx** are likely a function of the type of substrate and should increase as the number of active sites per unit volume increases. Based on this suggestion, the values of **Kx** would also change as the compost substrate changes.

In addition to changes in substrate, the concentration and the types of microorganisms also change during the composting process. During the early mesophilic stage, when the more easily available substrates are consumed, the microbial population especially bacteria increases exponentially (Biddlestone *et al.* 1987). As the temperature increases above $40^{o}C$ the mesophilic organisms die off and the thermophilic organisms flourish. During the thermophilic stage, the compost pile temperature continues to increase to above 60°C (Biddlestone *et al.* 1987). Above 60°C, microbial activity decreases significantly as the fungi are deactivated, and spore-forming bacteria and actinomycetes prevail. The microbial concentration or biomass during the early stages of composting (mainly bacteria) will be represented by the term $\mathbf{X_1}$. After the peak temperature period is reached, the compost mass enters a cooling stage marked by a decrease in compost pile temperature and represents a decrease in available substrate. During the cooling stage, fungi and actinomycetes attack the more resistant hemicellulose and cellulose fractions breaking them down to simple sugars which may be used by variety of microorganisms (Biddlestone *et al.* 1987). The biomass concentration in the maturation phase of composting when fungi and actinomycetes dominate will be represented by the term $\mathbf{X_2}$.

In the later stages of composting a mixture of solid waste and sewage sludge, de Bertoldi *et al.* (1983) observed a continuous decrease in the number of cellulolytic bacteria to about 10^2 per gram dry weight (50 days). The maximum cellulolytic bacteria count was between 10^3 to 10^4 per gram dry weight, after about 25 days of composting. de Bertoldi *et al.* (1983) indicated the number of cellulolytic fungi increased to approximately 10^8 per gram dry weight in the later stages of composting (50 days) The cellulolytic fungi count was approximately 10^5 per gram dry weight at the start of the composting process. The number of actinomycetes also increased to between 10^6 to 10^7per gram dry weight in the later stages of the composting process from the initial.count of approximately10^4 per gram dry weight (de Bertoldi *et al.* 1983). The compost pile temperature continues to drop to ambient conditions due to lower microbial activity and decomposition rate. Although the concentrations of fungi and actinomycetes increased in the later stages of composting, the overall biomass concentration is expected to decrease, due to a reduction in available substrate. None of referenced composting literature sources specifically noted the fact the concentration of biomass decreased during the maturation phase.

Table 4.15 summarizes the relative values for the various terms in Haug's model for both the active and maturation phases of the composting process.

Table 4.15 - Composting Model Conditions

Term	Active Phase	Maturation Phase
k	High	Low
S	High S	Low S
Av	High A_{v1}	High A_{v2} Low A_{v1}
X	High X_1 Low X_2	High X_2 Low X_1
Model Case		
$X << K_x$	$\frac{ds}{dt} = \frac{k\ Av\ X}{K_x}$	$\frac{ds}{dt} = \frac{k\ Av\ X}{K_x}$
$X >> K_x$	$\frac{ds}{dt} = k\ Av$	$\frac{ds}{dt} = k\ Av$

Based on this discussion of Haug's model and its parameters, it appears the rate of hydrolysis, A_V, biomass concentration and type, K_X and the kinetic rate vary throughout the different stages of the process. The two general model cases apply to both the active and maturation stage. Haug's proposed model provides valuable insight into the composting process, but it looks mainly at biomass concentration and does not deal with the relationship between the biomass concentration and the available substrate. The biomass concentration **X** is a function of the available substrate through the the yield coefficient **Y**. The yield coefficient is defined as the ratio of mass of cells formed to the mass of substrate consumed (Metcalf and Eddy, Inc. 1991). Haug (1980) stated the term $\mathbf{A_V}$ is likely related to the total number of enzyme absorption sites on the substrate. Therefore, the available substrate concentration is a function of the available surface area per volume ($\mathbf{A_V}$). With respect to substrate, the two general cases are reviewed below.

Case 1 when the concentration of microbes is much less than $\mathbf{K_X}$ (the half-rate constant) the rate of hydrolysis of the solid substrate is a second order reaction with respect to $\mathbf{A_V}$ (related to substrate concentration) and $\mathbf{X}$ which is a function of the substrate concentration through the yield coeffficient. Case 2 when the concentration of microbes is much greater than the half rate constant the change in solid substrate over time is a first order reaction with respect $\mathbf{A_V}$.

In summary, the kinetic rates determined for the various experimental compost piles indicated the overall decomposition rate during the active phase may be either first or second order.with respect to substrate concentration. A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon $\mathbf{A_V}$ (related to substrate concentration) and microbial concentration $\mathbf{X}$ which is a function of the available substrate concentration through the yield coefficient. A second possible explanation is the measured % C and TOC values included the carbon content of both substrate and the biomass.

Future research opportunities include determining values for the various kinetic model variables and testing the kinetic model.

4.2.3 Comparison of Individual Piles

The first order decomposition rates for the various piles are generally quite similar and only a few piles are deemed to be significantly different. Multiple t tests were performed to determine which piles were significantly different based on the first order decomposition rate constants (k). The statistical results are summarized in Tables F.2 and F.3 in Appendix F. Table 4.16 outlines the piles that are significantly different for the % C data.

Table 4.16 - Piles found to be Significantly Different - % C data

1st Order values for % C data

Rank by k value	**Pile No.**	**Pile Designations**	**Piles Significantly different**
1(Highest)	8	Hi C:N, Hi M.C., Hi Por.	Piles 5, L1, L3, L4
2	L2	Low C:N, Low M.C., Low Por.	Piles L1, L3, L4
3	4	Hi C:N, Hi M.C., Low Por.	
4	3	Med C:N, Hi M.C., Low Por.	
5	R2	Med C:N, Hi M.C., Hi Por.	
6	6	Hi C:N, Low M.C., Hi Por.	
7	7	Med C:N, Hi M.C., Hi Por.	
8	1	Med C:N, Low M.C., Low Por.	
9	R1	Med C:N, Hi M.C., Hi Por.	
10	5	Med C:N, Low M.C., Hi Por.	Pile 8
11	L4	Low C:N, Low M.C., Hi Por.	Piles 8, L2
12	L3	Low C:N, Hi M.C., Hi Por.	Piles 8, L2
13	L1	Low C:N, Hi M.C., Low Por.	Piles 2, 8, L2
14 (Lowest)	2	Hi C:N, Low M.C., Low Por.	Pile L1

Piles 8 and L2 had the largest decomposition k values and were found to be significantly different than the low C:N ratio piles L1, L3, and L4. Pile 8 was also different than Pile 5. Pile 2 a high C:N ratio, low moisture content pile had the lowest decomposition rate and was found to be significantly different than pile L1. There appears to be no consistent reasoning, based on the experimental levels of the operating variables, to explain the ranking order and significant differences between the decomposition rates of the piles. The decomposition rates for the high C:N ratio, high moisture content piles 8 and 4 were expected to be high in comparison to the other piles. However, Pile L2 a low C:N ratio, high moisture content pile was not expected to have the second largest decomposition rate. Pile L3 the other low C:N ratio, high moisture content pile was ranked 12 overall. The decomposition rates for the low C:N ratio piles except for Pile L2 were generally low in the rankings. Table 4.17 outlines the piles that are significantly different for the TOC data.

Table 4.17 - Piles Significantly Different - TOC data

1st Order k values for TOC data

Rank by k value	**Pile No.**	**Pile Designations**	**Piles Significantly different**
1(Highest)	**3**	Med C:N, Hi M.C., Low Por.	Pile L4
2	**8**	Hi C:N, Hi M.C., Hi Por.	Pile L4
3	**7**	Med C:N, Hi M.C., Hi Por.	Pile L4
4	**2**	Hi C:N, Low M.C., Low Por.	
5	**R 1**	Med C:N, Hi M.C., Hi Por.	
6	**L 1**	Low C:N, Hi M.C., Low Por.	
7	**L 2**	Low C:N, Low M.C., Low Por.	
8	**R 2**	Med C:N, Hi M.C., Hi Por.	
9	**4**	Hi C:N, Hi M.C., Low Por.	
1 0	**5**	Med C:N, Low M.C., Hi Por.	
1 1	**1**	Med C:N, Low M.C., Low Por.	
1 2	**L 3**	Low C:N, Hi M.C., Hi Por.	
1 3	**6**	Hi C:N, Low M.C., Hi Por.	
14 (Lowest)	**L 4**	Low C:N, Low M.C., Hi Por.	

Piles 3, 8 and 7 had the largest 1st order decomposition k values and were found to be significantly different than L4 which had the lowest value. Again there appears to be no consistent reasoning, based on the experimental levels of the operating variables, to explain the ranking order and significant differences between the decomposition rates of the piles. The maturity parameter $C:N_W$ cannot be used to indicate which piles matured first as none of the values were between the range of 5 to 6 Possible reasons for the differences observed between the experimental and literature values are sample preparation techniques, testing errors, possible sample contamination, and different organic materials.

4.2.4 Summary and Explanations

In summary, the decomposition rates for the parameters % C and TOC over time were found to follow either first or second order kinetics. Based on ANOVA tests there were no differences between the average pile R^2 values for the first and second order kinetic models. Generally the decomposition of organic materials is considered to follow first order kinetics. The first order decomposition rate constants for both parameters were lower than literature values.

A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon $\mathbf{A_v}$ and microbial concentration **X** which is a function of the available substrate concentration through the yield coefficient

Finally the first order decomposition rates for the various piles were compared using an ANOVA. Although there were some significant differences between some of the piles, there was no consistent reasoning based on the experimental levels to explain the results. The ranking of the piles by first order decomposition rate constants, therefore, cannot be used to verify which operational parameters influenced the rate of decomposition. Possible reasons for these experimental results are: inadequate material mixing, actual C:N ratio levels, sampling and testing errors and the difficulties experienced in trying to control moisture content of the piles.

4.3 Temperature and % Oxygen Results

Compost pile temperatures were measured to: **1**. identify the different stages of the composting process; **2**. provide an indication of process performance; **3**. to evaluate the the effectiveness of rebuilding the compost piles; **4**. serve as a secondary indicator of compost maturity. The following sections discuss the trends in compost pile temperatures and % oxygen readings and the results of the ARIMA (Autoregressive integrated moving average) analysis.

4.3.1 Trends in Pile Temperature and % Oxygen Readings

The average pile temperature for the various piles generally followed a decreasing trend throughout the first 65 days of the process and then increased to over 60°C after the piles are rebuilt and covered with burlap and mature compost. The initial average temperatures for the compost piles were approximately 65°C. No mesophilic stage was observed. Based on the fact the yard waste was picked up from the different areas of the city on a weekly basis it is highly possible the degradation process had already started prior to the development of the windrows. The peak thermophilic stage for most of the piles was approximately 16-20 days in length. After this period, the average pile temperatures generally followed a decreasing trend until the piles were rebuilt and covered. The average pile temperatures prior to rebuilding ranged from 28.9°C for pile 1 to 54.3°C for pile 7. Most of the piles had an average temperature of approximately 30°C with mean ambient temperatures in the 3 to 8°C range. The cooling stage is generally characterized as the period, when the compost pile temperature decreases to ambient conditions due to lower microbial activity (Biddlestone *et al.* 1987). The compost piles were rebuilt prior to the conclusion of the initial cooling stage. As indicated, after the compost piles were rebuilt the average pile temperature increased to over 60°C and stayed above 50°C for most of November 1992 when the mean ambient temperatures were in the range of -2 to 2°C. The pile temperatures then gradually decreased to ambient temperatures after approximately 180 days signalling the start of the maturation stage. The average pile temperature serves as a secondary and approximate indicator of maturity. Figures D.1 to D.16 show changes in the average pile temperatures for the various piles. Table D.1 in Appendix D summarizes the average monthly pile temperatures. The average monthly temperatures for most of the piles were close in value except for piles 3, 6 and 8 during the November 1992 to January 1993 time frame. Control piles C1 and C2 generally had higher average monthly temperatures in September and October of 1992 than most of the experimental piles. The most likely explanation for these higher temperatures is the control piles were not as far along as the experimental piles in the composting process. Conversely the average monthly temperatures for the control piles were lower during December and January. The differences are probably due to the installation of the passive aeration system, rebuilding and covering of the experimental piles.

The % oxygen content of the various piles fluctuated for the first 130-140 days and then levelled off at values close to ambient conditions. Figures D.17 to D.32 show changes in the average % oxygen readings for the various piles. The oxygen readings ranged from values of 10 to 20.9%. which are much higher than the minimum value of 5%. The method of measurement may have introduced oxygen into the pile resulting in a higher readings. The next section discusses the results of the time series ARIMA analyses for compost pile temperature data.

4.3.2 Arima Analyses - Results

Arima (Autoregressive integrated moving average) analysis was used to investigate the influence interventions such as turning, watering, rebuilding and adding additional wood chips to the experimental piles had on the average pile temperatures over the composting period. The main purpose of these interventions were to try to maintain the experimental levels of the operational variables for the factorial experiments. For example, the piles were watered to try to increase the moisture content to the desired levels. Usually the piles were mechanically turned the same day to homogenize the compost materials therefore more than one intervention was carried on the same day or prior to the next temperature reading. This experiment was not specifically designed to evaluate the various interventions using Arima analysis therefore the results must be fairly consistent in order to support any conclusions. Installing the passive aeration system, rebuilding and covering the experimental piles was the only intervention that was not directly connected to maintaining the experimental levels.

Arima models are used to mathematically describe the random disturbances in a time series. These models can involve the use of three different processes namely autoregression, differencing (integration) and moving averages. Not all models involve the use of all three processes. For example, the appropriate model for the compost temperature time series was an Arima (1,0,0) model. The usual nomenclature defining an Arima model is Arima (p,d,q). The p defines the order of autoregression, d the degree of differencing and q the order of moving average. The Arima (1,0,0) model is a first order autoregressive process and does not involve differencing and moving average processes. In the autoregression process, each value in a time series is a function of one or more preceding values. The equation shown below defines the relationship for a first order autoregressive process (SPSS for Windows Trends Manual 1993).

$$\text{Value}_t = \text{disturbance}_t + \text{ARI coefficient} * \text{Value}_{t-1} \qquad (29)$$

ARI coefficient = autoregressive coefficient

The value of the ARI coefficient indicates how strongly the value at time t is dependent on the preceding value (1993). ARI coefficient values close to 1 as calculated in these analyses indicates there is a strong relationship between the series value at time t and the preceding value. The model coefficients for the various interactions are listed in Table 4.18. A negative value indicates the pile temperature increased as a result of the intervention. Based on 95% probability the coefficients highlighted in bold were considered significant.

Table 4.18 - ARIMA Analyses - Results
Variable- Average Pile temperatures

Pile	**AR1**	**Mixing**	**Watering**	**Rebuild**	**Porosity**
Pile 1	**0.9695**	0.785	**-7.586**	**-14.850**	
Pile 2	**0.9136**	-1.861	-0.270	-9.990	
Pile 3	**0.9227**	-1.323	3.322	**-12.788**	
Pile 4	**0.9459**	-0.114	-3.718	**-12.298**	
Pile 5	**0.9127**	-1.668	1.691	-9.986	-8.696
Pile 6	**0.9635**	0.789	**-7.467**	**-14.751**	-0.440
Pile 7	**0.9801**	2.661	**-5.418**	1.152	**9.669**
Pile 8	**0.9274**	-0.652	-2.203	5.019	-5.430
Pile R1	**0.9705**	1.101	1.700	**-13.200**	**-10.705**
Pile R2	**0.9724**	2.189	1.619	-6.551	1.494
Pile L1	**0.9721**	-3.304	**-4.730**	-5.802	
Pile L2	**0.9456**	-4.818	0.447	0.114	

Based on the model coefficient values the mixing, watering and porosity adjustment interventions did not consistently influence the average pile temperatures. For example, seven piles with negative model coefficients indicated mixing increased the temperature. Five piles with positive values suggested mixing decreased the average pile temperature. Five piles had significant negative model coefficients for the intervention pile rebuilding. These results support the conclusion that the installation of a passive aeration system, and the rebuilding and covering of the compost piles resulted in higher compost temperatures. The average pile temperature after the intervention was higher than the temperature before the intervention.

5.0 SUMMARY AND CONCLUSIONS

The objectives of this study were to **1)** systematically evaluate the influence of key operational parameters on the decomposition rate of yard waste and **2)** identify a practical indicator of compost stability and maturity. A factorial experiment was selected to evaluate the influence of the operational variables, because it is the most efficient method to estimate the effects of two or more factors and the their interactions. The factorial results using the % decrease in the TOC as the response variable found none of the effects to be significant at the 5% significance level. The 90% confidence intervals, half normal plots and effect rankings for the full composting period provided indications the 13. (C:N ratio-Porosity) 23 (MC-Porosity) and the 123 (C:N ratio-MC-Porosity) interactions marginally influenced the decomposition rate of the organic materials. Generally, the results do not support the hypotheses that the operating variables C:N ratio, moisture content and porosity adjustment individually affected the decomposition rate of the organic materials. Possible explanations for these experimental results are: 1) the response variables used in the study were not able to measure the effects , 2) the effect of C:N ratio, M.C. and porosity on degradation did not occur within the ranges tested or 3) the difficulties encountered in maintaining and operating a field level experiment impacted the results. The most likely reasons are the difficulties in maintaining and operating a field level experiment. For example, the difficulty experienced trying to maintain the experimental moisture levels may have effected the factorial results. It was not possible to maintain the moisture content of the pile sections at the desired levels.

The purpose of monitoring the decomposition of the organic materials for the various compost piles was to: **1)** evaluate and model the biological degradation of these materials over time and provide a tool for optimization of the process, **2)** determine the magnitude and rate of decomposition of the various compost piles and compare the results with expected behavior. The decomposition rates for the parameters % C and TOC over time were found to follow either first or second order kinetics with respect to substrate concentration. A possible explanation for the second order results is the rate of hydrolysis of the substrate may depend upon $\mathbf{A_v}$ (related to substrate concentration) and microbial concentration which is a function of the available substrate concentration through the yield coefficient. A second explanation is the % C and TOC data included both the carbon content of substrate and biomass. The data does not represent the change in just substrate carbon over time. The first order decomposition rates for the various piles were compared using multiple t tests. Although there were some significant differences between some of the piles, there was no consistent reasoning based on the experimental levels to explain the results. The ranking of the piles by first order decomposition rate constants, therefore, cannot be used to verify which operational parameters influenced the decomposition rate.

An Arima analysis of the average pile temperature data indicated the average pile temperature increased as a result of rebuilding, covering and installing a passive aeration system. The average monthly temperatures for the control piles were lower during December and January than the rebuilt experimental piles. The results support the hypothesis that building up the compost piles will result in higher pile temperatures during the cooler ambient conditions. The degradation of the organic materials; therefore, is not greatly reduced by the cold ambient temperatures. By retaining enough heat, higher compost temperatures are maintained which promotes the continued optimal decomposition of the organic materials.

The second objective of this study was to identify a practical indicator of compost stability and maturity. The final $C:N_W$ ratio values for the experimental piles did not fall between the range of 5 to 6 indicated by others as the absolute indication of maturity. The OUR parameter was dropped from the experimental plan, after several attempts to solve the problem of leaks in the tubing were not successful. The change in % C and TOC over time provided some indication, when the active composting period had ended and the maturation stage had started. At this point, there is a definite change in the slope of the curve for the various piles. Finally, the average pile temperatures gradually decreased to ambient temperatures after approximately 180 days signalling the start of the maturation stage. In summary, no parameter used in this study was identified as a absolute indicator of compost maturity.

Suggestions to improve future research efforts include grinding up the straw prior to mixing, weighting the mass of each organic material, and developing more replicate piles. In addition, the use of the D.O. oxygen meter to measure the OUR rates of the compost should be investigated and evaluated. It is critical to establish more than one reliable response variable to verify the experimental results.

Future areas of research may include determining values for the terms k, A_v, X and K_X for Haug's kinetic model and testing the model with respect to substrate concentration.

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7.0 APPENDICES

Appendix A - Solid Sample Parameter Data

Table A.1- Solid Sample Parameter Data

								Multiple Sample Data					
Pile 1													
Sample Date	Days	%MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-02	3	59.54	65.20	5.09	36.22	2.12	17.12	92-09-26	X	51.11	40.91	5.49	22.73
92-08-11	12	36.74	55.39	5.76	30.77	1.85	16.59		Y	33.30	54.60	3.13	30.33
92-08-16	17	41.56	19.50	19.50	33.88	1.92	17.66		Z	45.32	47.47	4.79	26.37
92-08-23	24	29.27	57.45	3.45	31.92	2.59	12.34		Pile Avg	43.24	47.66		26.48
92-09-02	34	30.05	77.57	22.38	43.09	1.52	25.10		S	9.09			
92-09-13	45	48.12	41.47	3.06	23.04	1.99	11.56						
92-09-26	58	43.24	47.66	6.73	26.48	2.20	12.04	92-10-20	X	47.38	36.20	2.78	20.11
92-10-20	82	46.22	37.09	3.24	20.60	2.07	9.94		Y	43.02	37.47	4.93	20.81
92-11-19	112	36.97	33.73	0.91	18.74	1.85	10.15		Z	48.27	37.59	2.87	20.88
93-01-12	165	39.42	36.22	0.23	20.12	1.74	11.58		Pile Avg	46.22	37.09		20.60
93-03-13	225	18.71	36.05	0.47	20.03	2.06	9.72		S	2.81			
Pile 2													
92-08-02	2	38.63	41.84	2.31	23.24	2.28	10.19	92-09-26	X	27.72	44.63	13.04	24.79
92-08-11	11	19.96	47.90	17.39	26.61	1.54	17.29		Y	33.68	29.32	6.08	16.29
92-08-16	16	18.96	60.99	1.56	33.88	1.65	20.56		Z	30.64	30.49	0.45	16.94
92-08-23	23	15.97	65.09	7.54	36.72	1.47	25.04		Pile Avg	30.68	34.81		19.34
92-09-04	35	28.84	43.91	12.49	24.39	1.62	15.02		S	2.98			
92-09-13	44	29.28	48.32	6.90	26.85	1.28	20.93						
92-09-26	57	30.68	34.81	10.31	19.34	1.10	17.65						
92-11-05	97	25.22	21.45	0.43	11.92	1.03	11.59						
92-11-19	111	22.88	21.99	0.92	12.21	1.01	12.06						
93-01-12	164	34.90	22.83	0.92	12.68	1.28	9.91						
93-03-13	224	23.29	23.96	0.87	13.31	0.99	13.49						

Multiple Sample Data

Pile 3

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-02	2	49.51	60.17	10.69	33.43	2.55	13.12	92-09-28	X	47.45	33.29	0.25	18.49
92-08-11	11	18.02	71.10	9.77	39.50	1.43	27.53		Y	46.03	28.90	1.03	16.05
92-08-16	16	31.13	64.75	0.90	35.97	1.99	18.06		Z	50.80	38.51	3.10	21.39
92-08-26	26	51.26	66.35	6.54	36.86	1.36	27.02		Pile Avg	48.09	33.56		18.65
92-09-04	35	36.66	75.53	2.77	41.96	1.81	23.21		S	2.45			
92-09-13	44	32.09	51.71	4.76	28.73	1.71	16.85						
92-09-28	59	48.09	33.56	4.78	18.65	1.37	13.58	92-10-18	X	44.60	32.46	6.21	18.04
92-10-18	79	43.69	38.86	6.05	21.59	1.33	16.26		Y	41.71	41.83	5.68	23.24
92-11-19	111	45.63	32.04	0.94	17.80	1.91	9.34		Z	44.76	42.29	1.25	23.49
92-01-14	166	43.72	25.40	0.23	14.11	0.94	15.04		Pile Avg	43.69	38.86		21.59
92-03-13	224	43.41	27.38	0.13	15.21	1.36	11.19		S	1.71			

Pile 4

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-03	4	58.55	60.21	19.38	33.45	1.67	20.08	92-09-26	X	54.08	37.58	6.46	20.88
92-08-06	7	35.08	78.96	4.12	43.86	2.11	20.77		Y	52.91	45.55	8.72	25.31
92-08-11	12	42.86	72.14	19.50	40.08	2.17	18.50		Z	50.15	34.54	2.42	19.19
92-08-16	17	39.98	66.79	6.73	37.11	2.07	17.92		Pile Avg	52.38	39.22		21.79
92-08-23	24	34.90	61.06	2.92	34.54	1.93	17.86		S	2.02			
92-09-02	34	58.29	49.66	12.29	27.60	1.85	14.92						
92-09-13	45	49.71	42.63	4.83	23.68	1.46	16.23	92-10-15	X	48.88	29.05	2.42	16.14
92-09-26	58	52.38	39.22	7.43	21.79	1.70	12.80		Y	50.98	34.42	8.68	19.12
92-10-15	77	50.15	33.55	5.71	19.19	1.60	12.01		Y'	51.86	36.41	7.22	20.23
92-11-19	112	39.32	29.71	1.79	16.51	1.50	11.00		Z	48.78	34.34	0.95	19.08
93-01-12	165	44.27	29.04	0.14	16.13	1.49	10.81		Pile Avg	50.12	33.55		18.64
93-03-13	225	29.30	28.53	0.25	15.85	1.59	9.99		S	1.54			

Pile 5

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-02	2	58.43	57.46	16.16	31.92	2.43	13.13
92-08-11	11	29.23	47.50	15.79	26.39	1.65	16.04
92-08-16	16	36.79	64.05	2.82	35.58	1.91	18.60
92-08-23	23	51.43	62.31	8.56	34.62	1.69	20.43
92-09-04	35	45.46	48.61	6.39	27.01	1.40	19.30
92-09-13	44	30.21	58.82	0.38	32.68	1.69	19.29
92-09-28	59	44.31	36.47	5.68	20.26	1.88	10.77
92-10-18	79	42.97	43.45	4.15	24.14	1.60	15.04
92-11-19	111	32.05	31.06	2.63	17.26	1.59	10.84
93-01-14	166	37.54	28.80	0.30	16.00	1.50	10.67
93-03-13	224	17.70	29.02	0.80	16.12	1.45	11.11

Multiple Sample Data

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-28	X	47.60	41.85	1.84	23.25
	Y	43.09	33.97	7.56	18.87
	Z	42.25	33.58	4.37	18.65
	Pile Avg	44.31	36.47		20.26
	S	2.88			
92-10-18	X	30.06	41.02	1.00	22.79
	Y	49.86	44.47	4.25	24.70
	Z	48.98	44.86	2.45	24.92
	Pile Avg	42.97	43.45		24.14
	S	11.18			

Pile 6

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio
92-08-03	4	45.70	80.20	2.71	44.56	1.73	25.80
92-08-06	7	39.67	78.35	1.00	43.53	2.14	20.35
92-08-11	12	27.42	85.04	7.51	47.24	2.17	21.74
92-08-16	17	29.46	60.44	6.92	33.58	1.71	19.66
92-08-23	24	29.11	60.33	3.97	33.52	1.85	18.15
92-09-02	34	33.02	54.36	5.68	30.20	1.80	16.74
92-09-13	45	42.53	46.18	0.55	25.66	1.62	15.85
92-09-26	58	41.20	52.73	4.29	29.30	2.01	14.58
92-10-15	77	45.44	48.34	9.65	26.86	1.67	16.05
92-11-19	112	29.42	35.36	4.69	19.65	1.79	10.99
93-01-12	165	23.63	35.41	1.67	19.67	1.85	10.62
93-03-13	225	27.27	35.74	1.64	19.86	1.58	12.57

Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-09-26	X	39.33	49.82	4.64	27.68
	Y	39.94	52.33	2.84	29.07
	Z	44.32	56.04	4.89	31.13
	Pile Avg	41.20	52.73		29.30
	S	2.72			
92-10-15	X	54.52	52.57	2.81	29.21
	Y	46.55	54.54	5.50	30.30
	Y'	37.02	44.52	18.28	24.73
	Z	43.69	41.74	3.75	23.19
	Pile Avg	45.44	48.34		26.86
	S	4.89			

Pile 7

Multiple Sample Data

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-02	3	55.83	73.01	1.81	40.56	2.91	13.92	92-09-26	X	47.77	34.74	1.67	19.30
92-08-06	7	56.24	63.60	22.42	35.33	2.08	17.02		Y	56.07	40.82	3.15	22.68
92-08-11	12	45.59	59.17	9.77	32.87	2.11	15.59		Z	52.37	32.05	2.95	17.81
92-08-16	17	37.94	59.84	8.27	33.24	2.14	15.54		Pile Avg	52.07	35.87		19.93
92-08-23	24	34.24	61.63	2.37	34.24	1.70	20.15		S	4.16			
92-09-02	34	49.94	52.99	4.87	29.44	1.96	14.99						
92-09-13	45	44.38	47.72	2.18	26.51	1.56	17.04		X	54.03	20.77	23.49	11.54
92-09-26	58	52.07	35.87	4.27	19.93	1.74	11.45		Y	58.84	38.28	1.89	21.26
92-10-15	77	54.32	32.54	12.82	20.26	1.46	13.91		Y'	52.50	33.25	6.49	18.47
92-11-19	112	41.68	35.48	2.52	19.71	1.46	13.53		Z	51.63	37.88	2.43	21.04
93-01-12	165	42.76	36.40	0.83	20.22	1.53	13.25		Pile Avg	54.32	32.54		20.26
93-03-13	225	25.88	32.06	0.62	17.81	1.69	10.52		S	3.22			

Pile 8

92-08-02	2	58.64	60.21	19.38	33.45	1.55	21.60	92-09-28	X	41.03	23.94	1.01	13.30
92-08-11	11	39.76	61.30	4.06	34.06	1.34	25.50		Y	44.08	33.04	7.79	20.85
92-08-16	16	29.25	58.78	9.35	32.66	1.36	24.03		Z	48.32	40.80	6.61	22.84
92-08-23	23	29.07	62.76	6.82	39.24	1.73	22.63		Pile Avg	44.48	32.60		19.00
92-09-04	35	37.34	60.53	7.26	33.63	2.10	16.04		S	3.66			
92-09-13	44	40.16	45.80	2.47	25.44	1.24	20.55						
92-09-28	59	44.48	32.60	8.42	19.00	1.12	16.96	92-10-18	X	44.07	33.73	7.12	18.74
92-10-18	79	40.98	36.16	6.47	20.39	1.11	18.29		Y	40.86	40.26	5.63	21.00
92-11-19	111	35.44	20.56	2.04	11.42	0.91	12.58		Z	38.01	34.50	8.24	21.43
93-01-12	164	31.73	24.16	2.45	13.63	1.29	10.56		Pile Avg	40.98	36.16		20.39
93-03-13	224	24.67	15.98	14.35	8.88	1.05	8.46		S	3.03			

Pile R1

								Multiple Sample Data					
Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-02	3	62.1[illegible]	52.44	6.35	29.13	2.54	11.45	92-10-20	X	44.07	43.01	1.81	23.90
92-08-06	7	46.28	67.76	5.43	37.64	2.56	14.72		Y	52.45	41.95	2.47	23.31
92-08-11	12	40.14	69.89	3.21	38.83	2.78	13.99		Z	52.02	46.24	2.76	25.69
92-08-16	17	43.62	58.89	12.35	32.72	2.56	12.79		Pile Avg	49.52	43.74		24.30
92-08-23	24	45.81	71.69	9.78	39.83	2.42	16.47		S	4.72			
92-09-05	37	48.37	59.71	1.80	33.17	1.74	19.04						
92-09-13	45	50.75	42.88	1.28	23.82	2.11	11.29						
92-09-28	60	58.79	42.26	3.53	23.48	0.80	29.26						
92-10-20	82	49.52	43.74	2.67	24.30	1.37	17.77						
92-11-19	112	43.56	33.04	4.49	18.36	2.02	9.11						
93-01-12	165	43.09	33.05	0.56	18.36	1.77	10.35						
93-03-13	225	23.89	43.13	0.94	23.96	1.58	15.15						
Pile R2													
92-08-02	3	58.41	63.07	1.66	35.04	2.87	12.20	92-10-20	X	52.92	44.07	3.03	24.48
92-08-06	7	53.17	54.18	36.55	30.10	2.14	14.10		Y	41.88	32.32	1.36	17.95
92-08-11	12	35.06	78.57	15.39	43.65	3.10	14.08		Z	47.09	33.70	3.72	18.72
92-08-16	17	51.64	64.43	2.79	35.80	2.89	12.39		Pile Avg	47.30	36.69		20.39
92-08-23	24	45.81	51.81	29.01	28.78	2.41	11.93		S	5.52			
92-09-05	37	39.78	50.58	1.40	28.10	1.74	16.13						
92-09-13	45	50.14	53.39	0.42	29.66	2.24	13.25						
92-09-28	60	44.72	29.75	2.76	16.53	1.87	8.86						
92-10-20	82	47.30	36.69	5.75	20.39	1.17	17.38						
92-11-19	112	37.96	30.09	2.34	16.72	1.80	9.31						
93-01-14	167	38.03	30.79	0.16	17.11	1.86	9.20						
93-03-13	225	41.09	27.05	0.18	15.03	1.55	9.68						

Pile L1

Multiple Sample Data

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-02	3	59.36	47.74	0.50	26.52	2.22	11.93						
92-08-06	7	48.51	44.94	18.24	24.97	2.20	11.36						
92-08-16	17	39.51	37.43	4.24	20.79	1.97	10.54						
92-08-27	28	52.52	50.60	13.00	28.11	1.96	14.32						
92-09-05	37	54.64	42.95	5.22	23.86	1.66	14.34						
92-09-13	45	53.98	51.01	1.40	28.34	1.83	15.48						
92-09-28	60	54.11	33.67	3.79	18.71	1.96	9.56						
92-10-20	82	52.59	35.83	1.45	19.90	1.48	13.41						
92-11-21	114	45.28	26.05	2.41	14.47	1.55	9.32						
93-01-14	167	40.02	28.48	0.36	15.82	1.45	10.91						
93-03-13	225	17.59	29.67	0.04	16.49	1.59	10.36						

Pile L2

92-08-02	3	59.53	73.64	9.39	40.91	2.40	17.03
92-08-06	7	63.97	57.77	21.42	32.10	2.53	12.67
92-08-16	17	39.59	42.21	4.24	23.45	1.79	13.09
92-08-27	28	43.30	69.34	3.36	38.52	1.93	19.92
92-09-05	37	15.13	60.15	15.57	33.42	1.65	20.31
92-09-13	45	36.08	45.90	1.66	25.50	1.78	14.33
92-09-28	60	38.27	25.72	3.28	14.29	1.48	9.65
92-10-20	82	34.06	27.77	3.06	15.43	1.37	11.28
92-11-21	114	31.80	23.56	3.68	13.09	1.53	8.55
93-01-14	167	25.95	23.84	0.50	13.24	1.21	10.93
93-03-13	225	27.41	24.76	0.56	13.75	1.34	10.29

Pile L3

Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
								Multiple Sample Data					
92-08-02	2	46.13	72.35	3.46	40.20	2.32	17.33						
92-08-06	6	40.69	61.06	3.77	33.92	1.87	18.11						
92-08-11	11	28.85	74.13	4.07	41.18	2.43	16.97						
92-08-16	16	41.40	61.84	1.58	34.36	3.24	10.61						
92-08-27	27	49.90	63.16	7.80	35.09	2.12	16.58						
92-09-05	36	54.73	48.77	2.48	27.09	2.15	12.63						
92-09-13	44	43.42	51.50	2.00	28.61	1.91	15.00						
92-09-28	59	49.77	34.17	7.88	18.98	1.54	12.34						
92-10-20	81	43.49	45.33	0.37	25.18	2.02	12.46						
92-11-21	113	34.53	44.60	6.94	24.78	1.77	13.96						
93-01-14	166	38.50	29.92	0.85	16.62	1.58	10.49						
93-03-13	224	30.20	33.76	0.35	18.75	1.82	10.30						
Pile L4													
92-08-02	2	57.46	70.19	7.91	38.99	1.97	19.83						
92-08-16	16	43.60	53.63	7.98	29.79	2.03	14.71						
92-08-27	27	43.96	62.87	1.67	34.93	2.13	16.39						
92-09-05	36	37.78	62.75	7.87	34.86	1.69	20.61						
92-09-13	44	49.96	55.19	12.31	30.66	2.59	11.86						
92-09-28	59	37.44	36.67	2.65	20.37	1.93	10.55						
92-10-20	81	37.40	49.29	3.54	27.39	1.93	14.22						
92-11-21	113	28.41	35.88	3.47	19.93	2.15	9.26						
93-01-14	166	26.35	36.16	0.55	20.09	1.84	10.94						
93-03-13	224	21.28	32.64	0.99	18.13	1.67	10.87						

Pile C1

								Multiple Sample Data					
Sample Date	Days	% MC	Avg % VS	S	Avg % C	% N	Avg C:N ratio	Sample Date	Position	% MC	Avg % VS	S	Avg % C
92-08-11	8	48.27	75.74		42.08	2.76	15.27						
92-08-16	13.	53.63	60.89	26.75	33.83	2.65	12.79						
92-09-03	31	43.83	58.05	13.18	32.25	2.42	13.35						
92-09-13	41	50.83	52.99	1.23	29.44	2.20	13.39						
92-10-02	60	41.65	55.27	2.33	30.71	2.62	11.73						
92-10-20	78	32.28	47.39	4.01	26 33	2.86	9.22						
92-11-19	108	42.37	61.29	6.70	34.05	2.99	11.39						
93-01-14	163	38.74	52.36	0.16	29.09	2.96	9.83						
93-03-13	221	33.28	55.61	0.54	30.90	2.79	11.07						
Pile C2													
92-08-11	8	52.46	75.74	6.57	42.08	3.48	12.09						
92-08-16	13	52.46	63.37	3.45	35.21	2.29	15.35						
92-09-03	31	56.50	52.00	8.80	28.89	2.81	10.30						
92-09-13	41	50.73	58.43	4.89	32.46	2.62	12.38						
92-10-02	60	48.80	58.44	8.65	32.47	2.66	12.20						
92-10-20	78	54.28	47.69	4.32	26.49	2.77	9.56						
92-11-19	108	55.64	48.16	3.66	26.76	2.22	12.05						
93-01-14	163	47.61	53.36	0.28	29.64	2.83	10.47						
93-03-13	221	22.09	36.69	1.52	20.38	2.02	10.12						

Table A.2 - Multiple Sample % Volatile Solids Statistics

Pile	Sample Date	Mean % VS	S	n	SE of Mean	95 % CI ±	95 % CI % of Mean Value ±
1	92-09-26	47.66	6.73	9	2.24	5.18	10.87
1	92-10-20	37.09	3.24	9	1.08	2.50	6.73
2	92-09-26	34.81	10.31	9	3.44	7.94	22.80
3	92-09-28	34.81	4.78	9	1.59	3.68	10.97
3	92-10-18	38.86	6.05	9	2.02	4.66	11.98
4	92-09-26	39.22	7.43	9	2.48	5.72	14.58
4	92-10-15	3[illegible]	[illegible]	12	1.65	3.62	10.80
5	92-09-28	[illegible]	[illegible]	9	1.89	4.37	11.98
5	92-10-18	[illegible]	[illegible]	9	1.38	3.19	7.35
6	92-09-26	[illegible]	[illegible]	9	1.43	3.30	6.26
6	92-10-15	[illegible]	[illegible]	[illegible]	2.79	6.13	12.67
7	92-09-26	3[illegible]	[illegible]	[illegible]	1.42	3.29	9.16
7	92-10-15	32[illegible]	[illegible]	[illegible]	3.70	8.14	25.02
8	92-09-28	32.[illegible]	[illegible]	[illegible]	2.81	6.48	19.89
8	92-10-18	36.[illegible]	[illegible]	[illegible]	2.16	4.99	13.78
R1	92-10-20	43.7	[illegible]	9	0.89	2.05	4.69
R2	92-10-20	36.69	5.75	9	1.92	4.42	12.06
						Average	**12.45**

Table A.3 - ANOVA - Mean % Volatile Solids Values

Pile 2

sample date 92-09-26
sample locations X,Y,Z

source of variation	sum of squares	degrees of freedom	mean square	ratio s_L^2/s_R^2	$F_{2,6}$ (0.005)
within location	S_R=414.49	6	s_R^2=69.80	2.10	5.14
between locations	S_L=290.42	2	s_L^2=145.21		cannot reject H_o
total about the grand average	S_D=704.91	8			

Pile 7

sample date 92-10-15
sample locations X,Y,Y',Z

source of variation	sum of squares	degrees of freedom	mean square	ratio s_L^2/s_R^2	$F_{3,8}$ (0.005)
within locations	S_R=1207.01	8	s_R^2=150.87	0.885	4.07
between locations	S_L=400.70	3	s_L^2=133.57		cannot reject H_o
total about the grand average	S_D=1607.71				

Appendix B - Density and Porosity Data

Table B.1 - Compost Densities and Porosity Data

Pile 1

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg ρ_c Kg/m^3	S	Porosity
92-08-23	24	307	238	92-08-23	885.5	110.6	0.732
92-09-13	45	419	283	92-09-13	1247.5	46.0	0.773
92-09-28	60	529	369	92-09-26	943.9	2.40	0.609
92-10-20	85	519	355	92-10-20	1000.2	15.7	0.645
92-11-19	112	539	393	92-11-19	1184.5	66.4	0.668
93-01-14	167	599	429	93-01-12	1022.3	26.3	0.580
93-03-13	225	559	471	93-03-13	1030.1	10.0	0.543

Pile 2

92-08-23	23	269	232	92-08-23	737.2	16.5	0.685
92-09-13	44	449	347	92-09-13	779.0	6.6	0.554
92-09-28	59	549	420	92-09-26	955.5	7.3	0.561
92-10-20	84	549	438	92-11-05	1028.4	10.3	0.574
92-11-19	111	659	536	92-11-19	1221.9	11.9	0.561
93-01-14	166	698	518	93-01-12	1211.4	10.9	0.573
93-03-13	224	649	526	93-03-13	1053.3	23.9	0.501

Pile 3

92-08-23	23	409	270	92-08-23	984.4	72.4	0.725
92-09-13	44	524	397	92-09-13	1042.9	12.3	0.620
92-09-28	59	639	417	92-09-28	1124.9	12.7	0.629
92-10-20	84	718	500	92-10-18	1074.8	9.8	0.535
92-11-19	111	738	507	92-11-19	1295.0	30.7	0.608
93-01-14	166	708	493	93-01-14	1263.6	103.4	0.610
93-03-13	224	723	504	93-03-13	1197.4	5.0	0.579

Pile 4

92-08-23	24	249	185	92-08-23	805.8	56.0	0.771
92-09-13	45	429	285	92-09-13	1078.4	117.0	0.736
92-09-28	60	549	360	92-09-26	1234.9	97.3	0.708
92-10-20	85	599	399	92-10-15	1052.6	60.2	0.621
92-11-19	112	669	456	92-11-19	1221.2	15.5	0.626
93-01-14	167	659	456	93-01-12	1172.5	103.0	0.611
93-03-13	225	639	494	93-03-13	1060.1	41.5	0.534

Pile 5

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg ρ_c Kg/m^3	S	Porosity
92-08-23	23	225	148	92-08-23	1063.9	174.7	0.861
92-09-13	44	369	284	92-09-13	946.1	23.3	0.700
92-09-28	59	509	353	92-09-28	976.7	20.6	0.639
92-10-20	84	469	328	92-10-15	1017.3	26.4	0.678
92-11-19	111	659	499	92-11-19	1206.6	6.5	0.587
93-01-14	166	693	504	93-01-14	902.1	103.1	0.441
93-03-13	224	609	517	93-03-13	953.6	10.4	0.458

Pile 6

92-08-23	24	210	162	92-08-23	677.9	26.3	0.761
92-09-13	45	249	196	92-09-13	805.3	5.6	0.757
92-09-28	60	329	232	92-09-26	884.2	136.9	0.738
92-10-20	85	439	302	92-10-15	971.3	93.4	0.689
92-11-19	112	449	347	92-11-19	1079.2	69.1	0.679
93-01-14	167	524	424	93-01-12	913.5	36.1	0.536
93-03-13	225	564	443	93-03-13	1010.1	22.4	0.561

Pile 7

92-08-23	24	329	245	92-08-23	991.4	32.5	0.753
92-09-13	45	479	332	92-09-13	1075.3	45.1	0.691
92-09-28	60	679	446	92-09-26	1115.4	65.0	0.600
92-10-20	85	549	356	92-10-15	922.2	62.4	0.614
92-11-19	112	589	416	92-11-19	1038.9	212.4	0.600
93-01-14	167	609	426	93-01-12	1122.4	16.6	0.620
93-03-13	225	589	468	93-03-13	1035.3	70.3	0.548

Pile 8

92-08-23	23	434	326	92-08-23	518.8	4.2	0.372
92-09-13	44	469	335	92-09-13	1111.3	12.1	0.699
92-09-28	59	649	445	92-09-28	1008.2	7.9	0.559
92-10-20	84	629	446	92-10-18	917.6	96.3	0.514
92-11-19	111	639	471	92-11-19	1239.5	26.6	0.620
93-01-14	166	639	485	93-01-12	1233.6	106.2	0.607
93-03-13	224	619	496	93-03-13	1078.4	29.9	0.540

Pile R1

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg ρ_c Kg/m^3	S	Porosity
92-08-23	24	329	226	92-08-23	761.55	39.5	0.703
92-09-13	45	544	361	92-09-13	1006.78	4.7	0.642
92-09-28	60	649	408	92-09-28	1108.48	26.1	0.632
92-10-20	85	569	380	92-10-20	836.45	105.2	0.545
92-11-19	112	599	417	92-11-19	1097.72	41.9	0.620
93-01-14	167	629	439	93-01-12	1280.86	350.9	0.657
93-03-13	225	559	451	93-03-13	1069.25	11.9	0.578
Pile R2							
92-08-23	24	374	257	92-08-23	862.00	12.6	0.702
92-09-13	45	554	369	92-09-13	1039.28	6.7	0.645
92-09-28	60	609	421	92-09-28	1050.36	17.2	0.600
92-10-20	85	559	379	92-10-20	956.96	8.9	0.604
92-11-19	112	589	427	92-11-19	1368.04	132.0	0.688
93-01-14	167	659	477	93-01-14	986.08	127.2	0.516
93-03-13	225	698	495	93-03-13	1069.31	87.4	0.537
Pile L1							
92-08-23	24	309	203	92-08-27	830.87	19.6	0.756
92-09-13	45	479	311	92-09-13	1102.16	17.4	0.718
92-09-28	60	619	401	92-09-28	1139.35	24.6	0.648
92-10-20	85	728	477	92-10-20	1209.07	34.6	0.605
92-11-19	112	798	549	92-11-21	1154.14	43.9	0.524
93-01-14	167	808	577	93-01-14	1168.88	74.6	0.506
93-03-13	225	753	641	93-03-13	1018.26	270.4	0.371
Pile L2							
92-08-23	24	319	223	92-08-27	772.12	152.7	0.711
92-09-13	45	359	264	92-09-13	873.00	20.4	0.698
92-09-28	60	529	382	92-09-28	1197.36	2.4	0.681
92-10-20	85	659	491	92-10-20	974.34	221.9	0.496
92-11-19	112	669	507	92-11-21	1156.13	66.5	0.561
93-01-14	167	649	515	93-01-14	1140.82	51.6	0.549
93-03-13	225	659	517	93-03-13	1156.72	170.0	0.553

Pile L3

Sample Date	Days	Wet Bulk Density Kg/m^3	Dry Bulk Density Kg/m^3	Sample Date	Avg ρc Kg/m^3	S	Porosity
92-08-23	23	329	220	92-08-27	844.9	30.0	0.740
92-09-13	44	499	348	92-09-13	1089.8	14.2	0.681
92-09-28	59	688	460	92-09-28	1107.1	10.3	0.585
92-10-20	84	599	417	92-10-20	1117.2	50.1	0.627
92-11-19	111	629	467	92-11-21	1147.1	104.6	0.593
93-01-14	166	748	540	93-01-14	1058.8	16.5	0.490
93-03-13	224	728	559	93-03-13	1036.9	49.6	0.460

Pile L4

92-08-23	23	299	208	92-08-27	777.3	126.3	0.732
92-09-13	44	337	225	92-09-13	1114.7	94.6	0.799
92-09-28	59	439	319	92-09-28	1262.8	17.2	0.747
92-10-20	84	479	349	92-10-20	1066.1	33.5	0.673
92-11-19	111	599	466	92-11-21	1053.6	112.2	0.558
93-01-14	166	619	490	93-01-14	891.2	10.7	0.451
93-03-13	224	629	518	93-03-13	1029.9	10.9	0.497

Pile C1

92-08-23	20	329	221	92-09-03	844.1	13.4	0.738
92-09-13	41	384	255	92-09-13	1056.5	39.6	0.759
92-09-28	56	399	282	92-10-02	1050.8	7.9	0.732
92-10-20	78	389	294	92-10-20	1027.7	15.2	0.714
92-11-19	108	399	280	92-11-19	967.7	91.7	0.710
93-01-14	163	469	338	93-01-14	1040.2	137.3	0.675
93-03-13	221	449	337	93-03-13	973.9	176.3	0.654

Pile C2

92-08-23	20	339	226	92-09-03	832.2	10.7	0.728
92-09-13	41	399	265	92-09-13	976.1	6.6	0.729
92-09-28	56	379	255	92-10-02	1052.2	11.4	0.758
92-10-20	78	359	233	92-10-20	1026.3	52.6	0.773
92-11-19	108	299	221	92-11-19	1148.0	25.4	0.808
93-01-14	163	459	311	93-01-14	911.4		0.659
93-03-13	221	449	368	93-03-13	1140.3	31.2	0.677

Appendix C - Water Extract Parameter Data

Table C.1 - Water Extract Parameter Data

Pile 1

Date	Days	Avg TOC mg/l	n i	S	Avg NH3 mg/l	Avg Org N mg/l	n	S	TOC/ Org N
92-08-02	3	5499.49	3	8.54					
92-08-11	12	3913.53	2	12.02	38.29	369.10	2	9.16	10.60
92-08-23	24	2656.30	3	6.66	33.64	310.82	2	3.99	8.55
92-09-02	34	1271.76	3	9.54	10.14	112.76	2	1.79	11.28
92-09-13	45	2137.49	3	2.83	35.20	217.70	2	0.69	9.82
92-09-26	58	1957.72	3	10.69	24.54	210.78	3	7.04	9.29
92-10-18	82	1245.23	2	2.12	6.87	145.73	2	0.64	8.54
92-11-19	112	1091.20	6	15.74	5.75	113.55	2	0.12	9.61
93-01-12	165	1016.90	3	1.15	8.79	110.20	2	0.23	9.23
93-03-13	225	1017.79	3	12.28	22.97	120.61	3	1.33	8.44

Pile 2

92-08-03	2	2644.18	3	4.51	33.73	270.67	1		9.77
92-08-11	11	2919.19	5	1005.0	63.36	292.78	1		9.97
92-08-23	23	1783.35	6	16.34	27.88	164.42	2	0.79	10.85
92-09-04	35	2301.76	6	131.86	23.93	213.55	2	1.00	10.78
92-09-13	44	1447.59	6	475.52	22.66	103.61	2	1.20	13.97
92-09-26	57	846.05	3	4.15	22.91	74.61	4	2.51	11.34
92-11-05	97	527.11	8	53.05	28.68	44.35	4	6.13	11.89
92-11-19	111	496.70	2	3.04	16.62	38.27	5	5.30	12.98
93-01-12	164	649.81	3	8.21	25.17	72.98	2	0.80	8.90
93-03-13	224	402.07	2	1.45	22.28	53.63	5	5.64	7.50

Pile 3

92-08-02	2	4179.30	3	27.88					
92-08-11	11	4137.69	3	3.54	17.19	265.74	3	61.82	15.57
92-08-23	23	3815.24	3	12.00	37.38	469.42	3	70.87	8.13
92-09-05	35	2749.44	3	8.14	57.25	244.27	3	51.39	11.26
92-09-13	44	1880.56	3	19.92	47.35	195.56	2	35.28	9.62
92-09-28	59	881.42	3	4.07	27.57	84.46	2	1.99	10.44
92-10-18	79	794.69	4	111.72	15.15	76.63	5	11.40	10.37
92-11-19	111	776.34	3	6.47	6.95	85.45	2	44.21	9.09
92-01-14	166	728.50	3	1.64	16.3	77.41	2	39.12	9.41
92-03-13	224	649.61	12	13.10	13.53	98.54	4	11.79	6.59

Pile 4

92-08-03	4	2053.70	1						
92-08-11	12	2786.55	2	4.95	57.86	309.64	1		9.00
92-08-23	24	2483.87	3	7.23	20.92	238.06	3	59.21	10.43
92-09-02	34	2019.64	5	7.29	34.72	231.27	3	16.80	8.73
92-09-13	45	1154.15	5	9.82	20.06	87.28	2	1.99	13.22
92-09-26	58	845.49	3	3.83	9.86	81.65	2	0.00	10.36
92-10-15	77	703.60	8	41.82	4.92	81.15	4	19.39	8.67
92-11-19	112	666.37	3	5.25	2.65	64.33	5	10.70	10.36
93-01-12	165	830.41	3	3.00	-0.04	76.51	4	2.21	10.85

93-03-13	225	793.91	3	5.50	9.99	89.97	6	11.39	8.82

Pile 5

Date	Days	Avg TOC mg/l	n i	S	Avg NH3 mg/l	Avg Org N mg/l	n	S	TOC/ Org N
92-08-02	2	3778.14	3	50.34					
92-08-11	11	3913.80	3	25.11	8.45	416.68	1		9.39
92-08-23	23	3411.28	3	17.62	82.21	316.59	2	0.59	10.78
92-09-04	35	1238.86	2	2.12	9.29	109.38	2	1.39	11.33
92-09-13	44	1846.39	2	0.71	26.89	197.08	1		9.37
92-09-28	59	1518.45	3	9.85	12.39	157.38	2	1.99	9.65
92-10-18	79	1056.51	4	55.94	3.57	125.38	3	6.28	8.43
92-11-19	111	896.36	6	81.37	2.65	87.17	2	1.75	10.28
93-01-14	166	847.07	3	2.35	4.17	94.15	2	5.57	9.00
93-03-13	224	751.98	6	11.02	20.50	83.23	2	0.80	9.03

Pile 6

92-08-03	4	3136.96	3	9.07					
92-08-11	12	4097.17	2	3.54	43.36	419.49	1		9.77
92-08-23	24	2893.69	3	0.58	21.54	313.92	2	1.99	9.22
92-09-02	34	1117.93	3	21.52	18.86	195.11	1		5.73
92-09-13	45	1648.26	3	5.20	13.56	155.13	2	8.36	10.63
92-09-26	58	2260.53	3	3.61	37.45	210.59	4	7.88	10.73
92-10-15	77	1125.69	6	18.49	10.25	93.70	3	0.32	12.01
92-11-19	112	1082.62	3	8.39	2.73	99.47	4	1.89	10.88
93-01-12	165	1168.86	3	6.35	9.05	102.41	3	4.51	11.41
93-03-13	225	996.74	8	32.73	15.66	100.89	4	4.64	9.88

Pile 7

92-08-02	3	3940.59	3	18.04					
92-08-11	12	4255.97	2	5.66	16.89	420.62	1		10.12
92-08-23	24	3644.48	3	14.98	17.46	410.35	2	2.99	8.88
92-09-02	34	1898.47	2	12.02	26.64	167.59	2	0.10	11.33
92-09-13	45	1458.33	3	5.13	5.77	167.24	2	1.20	8.72
92-09-26	58	847.67	3	4.48	5.21	83.48	2	0.20	10.15
92-10-15	77	898.13	5	98.99	0.56	95.24	3	12.48	9.43
92-11-19	112	719.62	6	68.38	4.00	65.32	2	0.16	11.02
93-01-12	165	900.89	3	2.08	6.42	90.09	1		10.00
93-03-13	225	857.24	6	18.28	27.71	99.78	2	0.32	8.59

Pile 8

92-08-02	2	3124.70	3	10.82					
92-08-11	11	1655.06	3	4.24	30.97	149.22	1		11.09
92-08-23	23	2746.05	3	5.03	33.78	164.00	1		16.74
92-09-04	35	2852.98	2	21.92	110.65	336.72	2	2.39	8.47
92-09-13	44	1142.96	2	6.36	6.90	103.61	2	0.00	11.03
92-09-28	59	534.09	3	4.88	10.14	47.58	2	1.19	11.23
92-10-18	79	587.90	5	48.38	6.09	56.68	3	2.65	10.37
92-11-19	111	474.05	3	4.43	6.37	38.63	2	2.39	12.27
93-01-12	164	507.53	3	5.38	12.93	68.50	2	3.07	7.41
93-03-13	224	438.63	6	1.81	9.52	47.52	2	0.64	9.23

Pile R1

Date	Days	Avg TOC mg/l	n i	S	Avg NH3 mg/l	Avg Org N mg/l	n	S	TOC/ Org N
92-08-02	3	3724.30	3	13.22				-	
92-08-11	12	3382.30	3	19.36	40.54	326.59	1		10.36
92-08-23	24	3705.60	3	9.60	47.30	411.05	1		9.01
92-09-05	37	1712.80	3	2.89	49.84	189.20	2	0.40	9.05
92-09-13	45	2725.40	3	8.08	21.54	317.58	2	16.72	8.58
92-09-28	60	1189.00	2	2.12	13.65	134.44	2	10.95	8.84
92-10-20	82	797.30	3	36.41	11.58	99.24	2	6.97	8.03
92-11-19	112	843.70	3	5.63	9.71	84.25		0.30	10.01
93-01-12	165	893.80	3	4.77	15.07	87.9		1.00	10.16
93-03-13	225	716.20	3	7.69	20.84	83.		6.77	8.56
Pile R2									
92-08-02	3	2412.40	3	10.22					
92-08-11	12	4670.20	3	5.65	22.52	568.71	1		8.21
92-08-23	24	2996.40	3	8.12	55.89	269.44	2	1.20	11.12
92-09-05	37	1683.20	3	15.28	46.74	187.22	1		8.99
92-09-13	45	2761.20	3	6.43	24.35	331.24	2	11.35	8.34
92-09-26	60	834.30	3	4.10	19.29	83.06	2	5.98	10.04
92-10-20	82	482.50	3	1.84	8.45	36.46	2	0.20	13.23
92-11-19	112	845.40	3	1.62	12.67	104.03	2	0.20	8.13
93-01-12	165	897.90	3	5.55	8.73	86.29	2	0.20	10.41
93-03-13	225	756.60	3	9.36	23.79	82.84	4	8.51	9.13
Pile L1									
92-08-02	3	3536.28	3	6.35					
92-08-11	12	2760.05	3	17.44	34.21	356.01	2	12.14	7.75
92-08-16	17	3447.48	3	7.78	73.48	373.04	1		9.24
92-08-27	28	3054.08	3	29.82	33.37	297.73	2	1.00	10.26
92-09-05	37	1107.41	3	8.62	16.61	99.67	1		11.11
92-09-13	45	1878.20	3	3.51	34.35	146.68	2	0.00	12.80
92-09-28	60	1239.09	3	6.24	7.04	101.35	2	0.00	12.23
92-10-20	82	688.37	3	3.34	2.90	67.57	2	3.99	10.19
92-11-21	114	703.64	3	1.30	30.41	125.99	2	0.99	5.58
93-01-14	167	710.88	3	3.65	11.41	89.04	2	0.49	7.98
93-03-13	225	571.39	3	7.90	20.13	91.36	3	0.20	6.25
Pile L2									
92-08-02	3	3608.84	2	1.41					
92-08-16	17	2859.74	2	38.18	62.37	292.80	2	0.00	9.77
92-08-27	28	3144.29	3	29.61	10.56	354.88	2	0.20	8.86
92-09-05	37	1825.29	2	1.41	28.15	166.67	1		10.95
92-09-13	45	1968.80	3	9.85	35.05	201.51	2	0.30	9.77
92-09-28	60	745.19	3	3.59	30.13	122.47	2	1.99	6.08
92-10-20	82	695.80	3	8.49	9.86	57.86	2	0.20	12.03
92-11-21	114	857.51	3	1.25	34.98	96.85	2	1.60	8.85
92-01-14	167	569.68	3	7.90	19.78	61.80	2	0.20	9.22

93-03-13	225	646.14	3	6.57	21.68	69.96	2	2.59	9.24

Pile L3

Date	Days	Avg TOC mg/l	ni	S	Avg NH3 mg/l	Avg Org N mg/l	n	S	TOC/ Org N
92-08-02	2	3602.14	2	19.09					
92-08-11	11	4154.76	3	5.86	91.22	470.17	1		8.84
92-08-16	16	3193.99	3	30.62	34.07	309.98	2	0.40	10.30
92-08-27	27	3264.74	3	11.02	24.11	359.53	2	6.77	9.08
92-09-05	36	2591.72	3	10.10	41.53	275.49	2	10.55	9.41
92-09-13	44	2579.81	3	3.21	43.64	247.83	2	0.50	10.41
92-09-28	59	1034.46	3	2.08	9.43	119.66	2	0.40	8.64
92-10-20	81	1491.50	6	180.35	6.33	130.64	2	12.34	11.42
92-11-21	113	1266.63	3	1.00	33.43	153.72	2	0.40	8.24
92-01-14	166	794.65	3	2.80	10.98	95.72	2	0.00	8.30
93-03-13	224	944.36	3	3.19	18.79	113.32	2	0.20	8.33
Pile L4									
92-08-02	2	3735.89	2	9.90	34.07	447.93	2	0.40	8.34
92-08-16	16	3536.17	3	8.50	45.33	434.98	1		8.13
92-08-27	27	3483.75	3	32.15	7.18	378.81	2	0.20	9.20
92-09-05	36	4197.92	3	22.22	184.76	368.82	2	1.99	11.38
92-09-13	44	1851.87	3	3.79	140.07	448.35	2	0.20	4.13
92-09-28	59	1939.16	3	7.81	43.22	227.06	2	0.20	8.54
92-10-20	81	2061.95	2	1.41	8.45	168.45	3	26.43	12.24
92-11-21	113	1752.69	4	20.66	61.19	215.47	3	12.28	8.13
92-01-14	166	1591.12	3	1.15	39.00	152.46	2	3.39	10.44
93-03-13	224	1195.03	3	4.73	33.93	130.92	1		9.13

Appendix D - Temperature and Oxygen Data and Plots

Table D.1 - Pile Temperature and Oxygen Data

Pile 1

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	67.5	
92-08-03	4	63.2	
92-08-05	6	67.6	
92-08-07	8	61.6	
92-08-10	11	58.6	
92-08-11	12	61.9	
92-08-12	13	59.2	
92-08-13	14	65.1	
92-08-14	15	68.3	14.2
92-08-15	16	72.3	
92-08-16	17	66.8	15.4
92-08-17	18	66.5	
92-08-20	21	55.6	17.5
92-08-22	23	52.1	14.4
92-08-25	26	55.9	16.6
92-08-27	28	50.9	
92-08-29	30	54.3	
92-08-31	32	40.9	15.7
92-09-03	35	64.0	14.5
92-09-05	37	61.0	17.5
92-09-07	39	57.2	
92-09-13	45	58.0	20.4
92-09-17	49	55.5	20.0
92-09-20	52	48.5	
92-09-23	55	58.7	12.4
92-09-28	60	61.5	18.5
92-10-05	67	40.5	18.8
92-10-11	73	26.1	19.4
92-10-12	74	27.5	
92-10-13	75	29.0	
92-10-15	77	34.4	
92-10-16	78	41.3	
92-10-18	80	39.5	
92-10-22	84	33.3	
92-10-26	88	28.9	
92-11-01	94	54.0	
92-11-04	97	59.4	18.2
92-11-07	100	57.1	
92-11-11	104	64.5	16.1
92-11-15	108	57.5	
92-11-19	112	54.5	
92-11-22	115	49.5	
92-11-23	116	47.0	
92-12-02	124	43.5	15.0

Pile 2

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	64.1	
92-08-04	4	67.1	
92-08-05	5	68.5	
92-08-06	6	62.0	
92-08-07	7	65.7	
92-08-10	10	62.9	
92-08-11	11	60.2	
92-08-12	12	56.8	
92-08-13	13	62.8	
92-08-14	14	66.6	
92-08-15	15	68.1	
92-08-16	16	64.1	14.0
92-08-17	17	52.6	18.2
92-08-20	20	58.7	
92-08-22	22	50.1	19.4
92-08-25	25	45.2	19.1
92-08-27	27	43.7	
92-08-29	29	37.8	
92-08-31	31	30.3	19.3
92-09-05	36	48.4	20.1
92-09-07	38	57.2	
92-09-13	44	31.1	20.1
92-09-17	48	25.0	20.0
92-09-19	50	52.6	
92-09-20	51	32.3	
92-09-23	54	55.5	16.7
92-09-28	59	54.0	16.7
92-10-05	66	47.5	14.8
92-10-11	72	31.0	20.2
92-10-12	73	28.5	
92-10-13	74	29.5	
92-10-15	76	36.8	
92-10-16	77	36.0	
92-10-18	79	35.1	
92-10-22	84	30.8	
92-10-26	87	32.4	
92-11-01	93	54.0	
92-11-04	96	60.2	
92-11-07	99	53.6	
92-11-11	103	54.1	12.9
92-11-15	107	58.5	
92-11-19	111	54.0	
92-11-22	114	52.0	
92-11-23	115	50.5	13.7

92-12-09	131	40.5	17.3
92-12-17	139	38.0	19.5
92-12-23	146	33.5	20.4
93-01-03	156	25.5	20.6
93-01-10	163	19.0	20.6
93-01-17	170	13.0	20.7
93-01-21	174	16.0	20.7
93-01-28	181	11.5	20.8
93-02-03	187	9.5	20.6
93-02-11	195	5.0	20.9
93-02-18	202	5.8	20.8
93-02-25	209	3.8	20.9
93-03-10	222	4.0	20.9
93-03-18	230	4.0	20.8
93-04-06	249	6.5	
93-04-20	263	8.5	20.7
93-05-11	284	14.0	20.6

92-12-02	123	48 0	13.4
92-12-09	130	46.5	16.2
92-12-17	138	38.5	18.5
92-12-23	144	33.0	20.3
93-01-03	155	24.5	20.6
93-01-10	162	8.8	20.5
93-01-17	169	9.5	20.7
93-01-21	173	14.0	20.9
93-01-28	180	9.5	20.8
93-02-03	186	6.8	20.8
93-02-11	194	2.3	20.7
92-02-18	201	2.5	20.8
92-02-25	208	1.5	20.8
93-03-10	221	5.0	20.9
93-03-18	229	2.3	20.9
93-03-30	241	6.5	20.8
93-04-06	248	7.5	
93-04-20	262	9.3	20.9
93-05-11	283	14.5	20.7

Pile 3

Date	Days	Avg Pile Temp 0 C	Avg Pile % Oxygen
92-08-02	2	64.3	
92-08-04	4	63.5	
92-08-05	5	69.7	
92-08-07	7	59.0	
92-08-10	10	55.4	
92-08-11	11	63.4	
92-08-12	12	55.7	
92-08-13	13	65.9	
92-08-14	14	66.9	
92-08-15	15	68.7	
92-08-16	16	68.8	15.9
92-08-17	17	65.4	17.4
92-08-20	20	64.3	
92-08-22	22	62.6	16.6
92-08-25	25	57.0	18.3
92-08-27	27	50.9	
92-08-29	29	37.7	
92-08-31	31	34.2	15.9
92-09-05	36	64.8	15.4
92-09-09	40	62.3	
92-09-13	44	59.8	18.3
92-09-17	48	46.0	19.6
92-09-19	50	51.5	
92-09-20	51	27.3	
92-09-23	54	47.0	16.5

Pile 4

Date	Days	Avg Pile Temp 0 C	Avg Pile % Oxygen
92-08-01	2	63.0	
92-08-03	4	68.0	
92-08-05	6	67.6	
92-08-07	8	62.7	
92-08-10	11	63.7	
92-08-11	12	66.6	
92-08-12	13	54.2	
92-08-13	14	64.1	
92-08-14	15	67.7	
92-08-15	16	69.2	
92-08-16	17	64.1	15.5
92-08-17	18	67.9	
92-08-20	21	56.3	17.5
92-08-22	23	56.3	17.0
92-08-25	26	56.8	17.2
92-08-29	30	53.2	
92-08-31	32	45.0	13.2
92-09-05	37	63.5	13.7
92-09-07	39	57.9	
92-09-13	45	49.0	17.6
92-09-17	49	50.5	18.0
92-09-19	51	59.0	
92-09-20	52	29.5	
92-09-23	55	48.5	16.0
92-09-28	60	50.8	16.8

92-09-28	59	51.9	17.6
92-10-05	66	37.4	14.7
92-10-11	72	36.4	20.3
92-10-12	73	32.5	
92-10-13	74	29.5	
92-10-15	76	30.0	
92-10-16	77	14.7	
92-10-18	79	21.4	
92-10-22	84	35.0	
92-10-26	87	31.7	
92-11-01	93	54.0	
92-11-04	96	67.6	
92-11-07	99	61.3	
92-11-11	103	67.5	16.2
92-11-15	107	57.0	
92-11-19	111	55.5	
92-11-22	114	56.0	
92-11-23	115	55.0	16.6
92-12-02	123	55.5	16.2
92-12-09	130	53.5	16.9
92-12-17	138	43.0	19.2
92-12-23	144	41.0	20.5
93-01-03	155	37.0	20.6
93-01-10	162	28.5	20.6
93-01-17	169	26.5	20.8
93-01-21	173	16.5	20.9
93-01-28	180	11.8	20.7
93-02-03	186	7.8	20.9
93-02-11	194	5.8	20.6
93-02-18	201	7.0	20.7
93-02-25	208	4.5	20.8
93-03-10	221	6.8	20.3
93-03-18	229	4.0	20.4
93-03-30	241	6.8	20.9
93-04-06	248	7.0	
93-04-20	262	10.8	20.9
93-05-11	283	13.5	20.4

92-10-05	67	47.0	11.7
92-10-11	73	33.0	17.9
92-10-12	74	31.0	
92-10-13	75	29.5	
92-10-15	77	24.0	
92-10-16	78	23.9	
92-10-18	80	26.9	
92-10-22	84	29.8	
92-10-26	88	29.6	
92-11-01	94	54.0	
92-11-04	97	61.3	17.0
92-11-07	100	60.6	
92-11-11	104	56.3	16.1
92-11-15	108	56.0	
92-11-19	112	53.0	
92-11-22	115	47.0	
92-11-23	116	47.0	
92-12-02	124	37.5	16.2
92-12-09	131	35.5	17.7
92-12-17	139	32.5	19.1
92-12-23	146	31.0	20.4
93-01-03	156	26.5	20.7
93-01-10	163	24.0	20.4
93-01-17	170	21.0	20.8
93-01-21	174	9.5	20.9
93-01-28	181	6.8	20.7
93-02-03	187	5.8	20.7
93-02-11	195	7.0	20.8
93-02-18	202	6.0	20.8
93-02-25	209	3.0	20.8
93-03-10	222	6.0	20.9
93-03-18	230	1.5	20.9
93-03-30	242	6.5	20.7
93-04-06	249	7.3	
93-04-20	263	9.0	20.9
93-05-11	284	15.0	20.3

Pile 5

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	64.1	
92-08-04	4	67.1	
92-08-05	5	68.5	
92-08-06	6	62.0	

Pile 6

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	67.5	
92-08-03	4	63.2	
92-08-05	6	67.6	
92-08-07	8	61.6	

92-08-07	7	65.7	
92-08-10	10	62.9	
92-08-11	11	60.2	
92-08-12	12	56.8	
92-08-13	13	62.8	
92-08-14	14	66.6	
92-08-15	15	68.1	
92-08-16	16	64.1	12.5
92-08-17	17	52.6	19.5
92-08-20	20	58.7	
92-08-22	22	50.1	17.0
92-08-25	25	45.2	
92-08-27	27	43.7	
92-08-29	29	37.8	
92-08-31	31	30.3	17.8
92-09-05	36	48.4	17.0
92-09-07	38	57.2	
92-09-13	44	31.1	20.4
92-09-17	48	25.0	20.3
92-09-19	50	52.6	
92-09-20	51	32.3	
92-09-23	54	55.5	15.7
92-09-28	59	54.0	17.4
92-10-05	66	47.5	18.3
92-10-11	72	31.0	19.1
92-10-12	73	28.5	
92-10-13	74	29.5	
92-10-15	76	36.8	
92-10-16	77	36.0	
92-10-18	79	35.1	
92-10-22	84	30.8	
92-10-26	87	32.4	
92-11-01	93	54.0	
92-11-04	96	60.2	
92-11-07	99	53.6	
92-11-11	103	54.1	19.5
92-11-15	107	59.5	
92-11-19	111	46.5	
92-11-22	114	47.0	
92-11-23	115	42.0	17.9
92-12-02	123	52.5	18.1
92-12-09	130	39.0	18.6
92-12-17	138	32.5	19.8
92-12-23	144	25.0	20.6
93-01-03	155	22.5	20.4
93-01-10	162	15.0	20.3
93-01-17	169	10.5	20.5
93-01-21	173	2.5	20.8
93-01-28	180	3.0	20.8
93-02-03	186	4.0	20.9
93-02-11	194	6.5	20.9
93-02-18	201	6.0	20.9
93-02-25	208	3.0	20.8

92-08-10	11	58.6	
92-08-11	12	61.9	
92-08-12	13	59.2	
92-08-13	14	65.1	
92-08-14	15	68.3	
92-08-15	16	72.3	
92-08-16	17	66.8	15.0
92-08-17	18	66.5	
92-08-20	21	55.6	16.7
92-08-22	23	52.1	17.8
92-08-25	26	55.9	17.9
92-08-27	28	50.9	
92-08-29	30	54.3	
92-08-31	32	40.9	17.3
92-09-03	35	64.0	16.5
92-09-05	37	61.0	18.8
92-09-07	39	57.2	
92-09-13	45	58.0	18.4
92-09-17	49	55.5	16.3
92-09-20	52	48.5	
92-09-23	55	58.7	16.0
92-09-28	60	61.5	19.1
92-10-05	67	40.5	16.5
92-10-11	73	26.1	19.2
92-10-12	74	27.5	
92-10-13	75	29.0	
92-10-15	77	34.4	
92-10-16	78	41.3	
92-10-18	80	39.5	
92-10-22	84	33.3	
92-10-26	88	28.9	
92-11-01	94	54.0	
92-11-04	97	59.4	19.0
92-11-07	100	57.1	
92-11-11	104	64.5	19.0
92-11-15	108	51.0	
92-11-19	112	45.5	
92-11-22	115	42.5	
92-11-23	116	46.0	17.5
92-12-02	124	31.5	16.8
92-12-09	131	28.0	18.0
92-12-17	139	19.0	20.2
92-12-23	146	12.0	20.3
93-01-03	156	13.0	20.4
93-01-10	163	5.0	20.5
93-01-17	170	3.5	20.8
93-01-21	174	3.0	20.9
93-01-28	181	1.5	20.9
93-02-03	187	2.0	20.9
93-02-11	195	4.0	20.7
93-02-18	202	2.8	20.8
93-02-25	209	2.5	20.9
93-03-10	222	5.0	20.8

93-03-10	221	4.5	20.7
93-03-18	229	2.5	20.6
93-03-30	241	6.5	20.9
93-04-06	248	7.5	
93-04-20	262	11.3	20.9
93-05-11	283	16.8	20.5

93-03-18	230	3.3	20.9
93-03-30	242	7.5	20.8
93-04-06	249	8.5	
93-04-20	263	11.5	20.7
93-05-11	284	23.0	20.2

Pile 7

Date	Days	Avg Pile Temp °C	Avg Pile % Oxygen
92-07-31	1	67.5	
92-08-01	2	63.0	
92-08-03	4	62.5	
92-08-05	6	68.7	
92-08-07	8	65.0	
92-08-10	11	61.1	
92-08-11	12	67.3	
92-08-12	13	58.5	
92-08-13	14	66.5	
92-08-14	15	69.8	14.6
92-08-15	16	70.6	
92-08-16	17	66.3	14.6
92-08-17	18	63.2	
92-08-20	21	61.3	17.5
92-08-22	23	49.4	15.1
92-08-25	26	48.0	15.9
92-08-27	28	49.8	
92-08-29	30	52.9	
92-08-31	32	40.9	17.0
92-09-06	38	56.9	14.5
92-09-13	45	56.0	17.6
92-09-17	49	60.8	19.9
92-09-19	51	59.2	
92-09-20	52	56.8	
92-09-23	55	62.5	15.8
92-09-28	60	52.5	18.3
92-10-05	67	47.0	17.4
92-10-11	73	53.0	19.4
92-10-12	74	50.5	
92-10-13	75	45.0	
92-10-15	77	50.5	
92-10-16	78	45.2	
92-10-18	80	45.8	
92-10-22	84	52.3	
92-10-26	88	54.3	
92-11-01	94	54.0	
92-11-04	97	57.2	17.5
92-11-07	100	52.6	
92-11-11	104	53.5	20.1

Pile 8

Date	Days	Avg Pile Temp °C	Avg Pile % Oxygen
92-08-02	2	62.8	
92-08-04	4	66.8	
92-08-05	5	70.3	
92-08-07	7	53.5	
92-08-10	10	64.8	
92-08-11	11	65.8	
92-08-12	12	62.3	
92-08-13	13	67.4	
92-08-14	14	63.0	
92-08-15	15	70.0	
92-08-16	16	63.0	14.5
92-08-17	17	62.7	15.0
92-08-20	20	55.5	
92-08-22	22	66.9	17.6
92-08-25	25	56.3	16.1
92-08-27	27	61.0	
92-08-29	29	54.6	
92-08-31	31	40.0	16.7
92-09-05	36	46.2	14.2
92-09-09	40	53.5	
92-09-13	44	67.4	16.7
92-09-17	48	46.2	17.1
92-09-19	50	46.2	
92-09-20	51	30.3	
92-09-23	54	53.9	16.5
92-09-28	59	46.0	16.2
92-10-05	66	44.0	14.1
92-10-11	72	42.5	20.2
92-10-12	73	43.0	
92-10-13	74	29.5	
92-10-15	76	26.0	
92-10-16	77	28.2	
92-10-18	79	41.2	
92-10-22	83	47.8	
92-10-26	87	55.9	
92-11-01	93	54.0	
92-11-04	96	55.6	
92-11-07	99	60.9	
92-11-11	103	62.4	19.6

92-11-15	108	57.0	
92-11-19	112	51.0	
92-11-22	115	50.5	
92-11-23	116	49.0	16.3
92-12-02	124	40.5	15.0
92-12-09	131	38.0	17.6
92-12-17	139	35.5	19.6
92-12-23	146	34.5	20.5
93-01-03	156	33.5	20.6
93-01-10	163	24.5	20.6
93-01-17	170	22.0	20.8
93-01-21	174	18.0	20.8
93-01-28	181	15.8	20.9
93-02-03	187	11.8	20.7
93-02-11	195	7.0	20.7
93-02-18	202	6.8	20.7
93-02-25	209	5.3	20.9
93-03-10	222	6.5	20.9
93-03-18	230	5.5	20.9
93-03-30	242	6.0	20.7
93-04-06	249	8.5	
93-04-20	263	10.3	20.8
93-05-11	284	12.5	20.3

92-11-15	107	61.5	
92-11-19	111	64.0	
92-11-22	114	61.5	
92-11-23	115	56.5	
92-12-02	123	52.5	17.1
92-12-09	130	50.8	18.3
92-12-17	138	48.5	20.3
92-12-23	144	47.5	20.6
93-01-03	155	46.0	20.5
93-01-10	162	39.5	20.5
93-01-17	169	43.0	20.7
93-01-21	173	41.0	20.9
93-01-28	180	30.3	20.8
93-02-03	186	23.5	20.7
93-02-11	194	12.0	20.8
92-02-18	201	9.0	20.7
92-02-25	208	4.8	20.8
93-03-10	221	6.5	20.3
93-03-18	229	6.0	20.0
93-03-30	241	9.0	20.9
93-04-06	248	9.5	
93-04-20	262	10.5	20.8
93-05-11	283	14.0	20.6

Pile R1

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	64.5	
92-08-03	4	67.1	
92-08-05	6	70.0	
92-08-07	8	72.1	
92-08-10	11	68.3	
92-08-11	12	68.5	
92-08-12	13	64.6	
92-08-13	14	67.9	
92-08-14	15	69.2	13.7
92-08-15	16	71.3	
92-08-16	17	68.3	15.0
92-08-17	18	67.3	
92-08-20	21	60.7	16.4
92-08-22	23	69.3	13.5
92-08-25	26	63.8	
92-08-29	30	61.2	
92-08-31	32	63.7	13.1
92-09-03	35	60.0	9.2
92-09-05	37	65.1	12.6
92-09-07	39	63.9	
92-09-13	45	56.4	12.6
92-09-17	49	61.5	17.6

Pile R2

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-01	2	68.5	
92-08-03	4	65.8	
92-08-05	6	70.9	
92-08-07	8	71.9	
92-08-10	11	67.9	
92-08-11	12	68.3	
92-08-12	13	63.0	
92-08-13	14	66.5	
92-08-14	15	69.0	
92-08-15	16	69.7	
92-08-16	17	66.1	15.0
92-08-17	18	68.8	
92-08-20	21	59.1	13.2
92-08-22	23	66.6	12.9
92-08-25	26	64.3	15.2
92-08-29	30	66.9	
92-08-31	32	64.8	11.0
92-09-03	35	59.3	8.4
92-09-05	37	64.9	14.7
92-09-07	39	63.4	
92-09-13	45	58.5	14.5
92-09-17	49	60.0	16.0

92-09-19	51	47.7	
92-09-20	52	42.0	
92-09-23	55	43.0	14.3
92-09-28	60	51.8	18.0
92-10-05	67	44.5	15.1
92-10-11	73	43.1	19.4
92-10-12	74	35.5	
92-10-13	75	29.5	
92-10-15	77	36.8	
92-10-16	78	16.2	
92-10-18	80	17.0	
92-10-22	84	22.0	
92-10-26	88	24.8	
92-11-01	94	54.0	
92-11-04	97	54.1	17.6
92-11-07	100	52.9	
92-11-11	104	57.0	18.9
92-11-15	108	61.5	
92-11-19	112	45.5	
92-11-22	115	42.0	
92-11-23	116	46.5	
92-12-02	124	40.0	20.4
92-12-09	131	35.0	20.4
92-12-17	139	28.0	20.6
92-12-23	146	24.5	20.2
93-01-03	156	22.0	20.5
93-01-10	163	16.0	20.4
93-01-17	170	11.0	20.4
93-01-21	174	5.5	20.9
93-01-28	181	4.0	20.9
93-02-03	187	3.0	20.7
93-02-11	195	4.3	20.6
93-02-18	202	4.0	20.9
93-02-25	209	2.5	20.8
93-03-10	222	1.5	20.8
93-03-18	230	1.5	20.9
93-03-30	242	6.8	20.9
93-04-06	249	7.0	
93-04-20	263	7.0	20.8
93-05-11	284	10.5	20.7

92-09-19	51	60.5	
92-09-20	52	42.0	
92-09-23	55	46.5	14.4
92-09-28	60	48.2	17.6
92-10-04	66	54.1	
92-10-05	67	41.7	15.5
92-10-11	73	34.0	19.1
92-10-12	74	32.0	
92-10-13	75	29.5	
92-10-15	77	23.6	
92-10-16	78	24.0	
92-10-18	80	21.8	
92-10-22	84	23.3	
92-10-26	88	32.1	
92-11-01	94	54.0	
92-11-07	100	53.0	
92-11-11	104	58.8	20.1
92-11-15	108	51.0	
92-11-19	112	44.0	
92-11-23	116	51.0	
92-12-02	124	44.0	18.8
92-12-09	131	41.0	19.5
92-12-17	139	29.5	19.8
92-12-23	146	24.0	19.9
93-01-03	156	22.8	20.6
93-01-10	163	14.8	20.5
93-01-17	170	11.5	20.6
93-01-21	174	8.5	20.9
93-01-28	181	7.3	20.7
93-02-03	187	7.0	20.8
93-02-11	195	8.5	20.9
93-02-18	202	6.8	20.7
93-02-25	209	4.5	20.9
93-03-10	222	4.8	20.8
93-03-18	230	1.3	20.9
93-03-30	242	7.0	20.9
93-04-06	249	7.8	
93-04-20	263	9.3	20.9
93-05-11	284	15.0	20.6

Pile L1

Date	Days	Avg Pile Temp ^0C	Avg Pile % Oxygen
92-08-02	3	65.0	
92-08-05	6	70.5	
92-08-06	7	69.2	
92-08-10	11	70.0	
92-08-11	12	69.3	

Pile L2

Date	Days	Avg Pile Temp ^0C	Avg Pile % Oxygen
92-08-02	3	66.2	
92-08-05	6	68.8	
92-08-06	7	67.3	
92-08-07	8	59.7	
92-08-10	11	67.1	

92-06-12	13	65.5	
92-08-13	14	64.4	
92-08-14	15	67.3	
92-08-15	16	69.8	
92-08-16	17	65.6	15.5
92-08-17	18	66.4	
92-08-20	21	58.4	14.1
92-08-22	23	66.6	15.0
92-08-25	26	64.3	16.1
92-08-27	28	64.6	
92-08-29	30	66.9	
92-08-31	32	64.0	13.0
92-09-05	37	59.8	14.1
92-09-07	39	55.6	
92-09-13	45	61.6	14.5
92-09-17	49	43.5	19.4
92-09-19	51	45.9	
92-09-20	52	42.0	
92-09-23	55	42.0	15.5
92-09-28	60	41.5	17.7
92-10-05	67	34.5	17.8
92-10-11	73	29.0	20.1
92-10-12	74	42.5	
92-10-13	75	28.0	
92-10-15	77	25.0	
92-10-16	78	27.1	
92-10-18	80	25.3	
92-10-22	84	19.8	
92-10-26	88	30.5	
92-11-01	94	52.8	
92-11-04	97	54.2	
92-11-07	100	60.5	
92-11-11	104	54.5	17.3
92-11-15	108	56.0	
92-11-19	112	51.3	
92-11-22	115	46.0	
92-11-23	116	52.5	
92-12-02	124	55.0	18.2
92-12-09	131	54.0	19.0
92-12-17	139	44.0	20.5
92-12-23	146	40.5	20.5
93-01-03	156	38.0	20.7
93-01-10	163	29.5	20.6
93-01-17	170	24.0	20.9
93-01-21	174	22.5	20.8
93-01-28	181	17.3	20.8
93-02-03	187	12.0	20.8
93-02-11	195	5.8	20.7
93-02-18	202	5.5	20.7
93-02-25	209	1.3	20.8
93-03-10	222	2.8	20.8
93-03-18	230	2.0	20.8
93-03-30	242	7.0	20.9

92-08-11	12	69.6	
92-08-12	13	62.8	
92-08-13	14	62.2	
92-08-14	15	62.9	
92-08-15	16	53.5	
92-08-16	17	38.1	15.6
92-08-17	18	53.7	
92-08-20	21	38.1	16.8
92-08-22	23	49.7	15.7
92-08-25	26	42.2	16.8
92-08-27	28	34.9	
92-08-29	30	40.2	
92-08-31	32	59.5	11.1
92-09-05	37	53.8	
92-09-07	39	51.4	
92-09-13	45	53.2	19.9
92-09-17	49	38.0	17.9
92-09-19	51	46.9	
92-09-20	52	34.3	
92-09-23	55	40.1	14.8
92-09-28	60	47.8	16.5
92-10-05	67	41.3	14.1
92-10-11	73	38.7	18.5
92-10-12	74	42.5	
92-10-13	75	41.5	
92-10-14	76	36.9	
92-10-16	78	43.0	
92-10-18	80	45.8	
92-10-22	84	34.3	
92-10-26	88	49.3	
92-11-01	94	64.1	
92-11-04	97	56.5	
92-11-07	100	63.2	
92-11-11	104	64.5	17.7
92-11-15	108	64.5	
92-11-19	112	56.0	
92-11-22	115	49.0	
92-11-23	116	51.5	
92-12-02	124	47.0	16.4
92-12-09	131	45.3	18.0
92-12-17	139	35.5	20.4
92-12-23	146	29.5	20.5
93-01-03	156	22.5	20.5
93-01-10	163	17.8	20.5
93-01-17	170	12.5	20.6
93-01-21	174	12.5	20.7
93-01-28	181	8.3	20.8
93-02-03	187	5.0	20.8
93-02-11	195	3.8	20.8
93-02-18	202	2.5	20.8
93-02-25	209	2.5	20.9
93-03-10	222	4.5	20.7
93-03-18	230	2.5	20.8

93-04-06	249	8.0	
93-04-20	263	9.0	20.8
93-05-11	284	13.0	20.8

93-03-30	242	6.8	20.9
93-04-06	249	7.5	
93-04-20	263	9.0	20.8
93-05-11	284	12.0	20.7

Pile L3

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	62.4	
92-08-04	4	66.5	
92-08-05	5	70.2	
92-08-06	6	67.3	
92-08-07	7	67.0	
92-08-10	10	66.8	
92-08-11	11	65.5	
92-08-12	12	62.2	
92-08-13	13	62.1	
92-08-14	14	65.4	
92-08-15	15	69.9	
92-08-16	16	62.6	15.8
92-08-17	17	65.6	16.7
92-08-20	20	64.1	19.6
92-08-22	22	65.1	16.2
92-08-25	25	65.7	
92-08-27	27	63.2	
92-08-29	29	67.1	
92-08-31	31	64.1	15.4
92-09-05	36	64.4	13.1
92-09-07	38	57.0	
92-09-13	44	60.5	14.7
92-09-17	48	53.0	12.6
92-09-19	50	51.5	
92-09-20	51	50.0	
92-09-23	54	36.1	17.2
92-09-28	59	41.2	16.0
92-10-05	66	35.4	15.0
92-10-11	72	37.0	11.7
92-10-12	73	32.0	
92-10-13	74	33.0	
92-10-14	75	29.1	
92-10-16	77	30.3	
92-10-18	79	45.0	
92-10-22	83	37.3	
92-10-26	87	53.7	
92-11-01	96	55.0	
92-11-04	93	70.6	
92-11-07	99	56.4	
92-11-11	103	64.3	20.0
92-11-15	107	55.5	

Pile L4

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-02	2	60.4	
92-08-05	5	69.0	
92-08-07	7	67.0	
92-08-10	10	66.0	
92-08-11	11	65.5	
92-08-12	12	63.7	
92-08-13	13	63.6	
92-08-14	14	63.8	
92-08-15	15	69.7	
92-08-16	16	66.2	15.0
92-08-17	17	61.5	15.9
92-08-20	20	61.9	19.6
92-08-22	22	61.8	16.0
92-08-25	25	63.4	
92-08-27	27	59.8	
92-08-29	29	60.0	14.3
92-09-05	36	58.8	16.2
92-09-07	38	51.5	
92-09-13	44	56.1	19.6
92-09-17	48	38.5	17.6
92-09-19	50	49.0	
92-09-20	51	31.1	
92-09-23	54	48.0	15.5
92-09-28	59	51.0	18.2
92-10-05	66	49.5	13.3
92-10-11	72	48.0	17.9
92-10-12	73	35.5	
92-10-13	74	41.5	
92-10-14	75	32.7	
92-10-16	77	40.8	
92-10-18	79	43.3	
92-10-22	83	41.3	
92-10-26	87	56.1	
92-11-01	93	61.6	
92-11-04	96	60.9	
92-11-07	99	62.6	
92-11-11	103	61.3	20.1
92-11-15	107	52.0	
92-11-19	111	47.0	
92-11-22	114	43.0	
92-11-23	115	39.0	16.5

92-11-19	111	47.0	
92-11-22	114	49.5	
92-11-23	115	49.5	
92-12-02	123	53.5	20.3
92-12-09	130	52.0	20.2
92-12-17	138	37.0	20.4
92-12-23	144	30.5	20.3
93-01-03	155	28.0	20.4
93-01-10	162	24.5	20.6
93-01-17	169	18.0	20.8
93-01-21	173	8.0	20.7
93-01-28	180	5.5	20.8
93-02-03	186	3.8	20.7
93-02-11	194	5.3	20.8
92-02-18	201	3.5	20.9
92-02-25	208	2.8	20.7
93-03-10	221	6.0	20.7
93-03-18	229	5.0	20.7
93-03-30	241	7.0	20.9
93-04-06	248	8.0	
93-04-20	262	12.0	20.8
93-05-11	283	14.0	20.2

92-12-02	123	46.0	16.1
92-12-09	130	42.0	17.5
92-12-17	138	29.5	17.9
92-12-23	144	19.0	17.0
93-01-03	155	15.5	19.2
93-01-10	162	9.0	20.6
93-01-17	169	5.0	20.8
93-01-21	173	5.0	20.9
93-01-28	180	3.5	20.9
93-02-03	186	2.3	20.9
93-02-11	194	2.5	20.6
92-02-18	201	1.3	20.8
92-02-25	208	2.0	20.8
93-03-10	221	5.0	20.9
93-03-18	229	2.8	20.6
93-03-30	241	7.5	20.9
93-04-06	248	7.3	
93-04-20	262	14.8	20.8
93-05-11	283	16.5	20.2

Pile C1

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-05	2	64.1	
92-08-07	4	58.7	
92-08-10	7	56.6	
92-08-11	8	55.6	
92-08-12	9	55.6	
92-08-15	12	65.3	
92-08-17	14	56.3	19.9
92-08-20	17	38.1	
92-08-22	19	49.8	
92-08-29	26	62.0	
92-08-31	28	63.0	16.3
92-09-03	31	61.6	8.8
92-09-06	34	69.4	
92-09-13	41	67.9	20.0
92-09-17	45	57.5	16.0
92-09-19	47	57.0	
92-09-20	48	52.8	
92-09-23	52	57.5	11.2
92-09-28	57	57.5	15.8
92-10-05	63	59.0	18.0
92-10-11	69	40.0	18.4
92-10-13	71	39.5	
92-10-16	74	51.5	

Pile C2

Date	Days	Avg Pile Temp ^{0}C	Avg Pile % Oxygen
92-08-05	2	66.0	
92-08-07	4	67.7	
92-08-10	7	66.4	
92-08-11	8	64.8	
92-08-12	9	63.8	
92-08-15	12	68.3	
92-08-17	14	61.3	20.1
92-08-20	17	55.6	
92-08-22	19	54.6	
92-08-29	26	61.0	
92-08-31	28	65.0	
92-09-03	31	61.6	9.1
92-09-06	34	67.8	
92-09-13	41	67.7	19.1
92-09-17	45	53.0	15.9
92-09-19	47	58.5	
92-09-20	48	59.0	
92-09-23	52	53.5	11.3
92-09-28	57	58.5	12.6
92-10-05	63	58.5	13.0
92-10-11	69	50.0	19.3
92-10-13	71	42.5	
92-10-16	74	45.5	

92-10-18	76	54.0		92-10-18	76	65.3	
92-10-22	80	53.0		92-10-22	80	51.0	
92-10-26	87	52.0		92-10-26	87	56.5	
92-11-01	90	57.5		92-11-01	90	58.5	
92-11-04	93	48.8	17.1	92-11-04	93	51.2	17.8
92-11-07	96	50.8		92-11-07	96	53.2	
92-11-11	100	43.9	18.9	92-11-11	100	42.3	18.5
92-11-15	104	43.5		92-11-15	104	45.0	
92-11-19	108	24.0		92-11-19	108	27.5	
92-11-23	112	41.5	20.3	92-11-23	112	40.5	18.1
92-12-02	120	24.0	20.5	92-12-02	120	27.5	20.5
92-12-09	127	20.5	20.4	92-12-09	127	23.5	20.5
92-12-17	135	17.0	20.4	92-12-17	135	20.5	20.6
92-12-23	141	14.0	20.3	92-12-23	141	19.5	20.3
93-01-03	152	10.5	20.5	93-01-03	152	14.5	20.5
93-01-10	159	8.0	20.5	93-01-10	159	9.3	20.5
93-01-17	166	7.0	20.6	93-01-17	166	10.0	20.7
93-01-21	170	5.0	20.9	93-01-21	170	6.5	20.7
93-01-28	177	3.3	20.8	93-01-28	177	3.5	20.8
93-02-03	183	2.5	20.9	93-02-03	183	4.8	20.7
93-02-11	191	3.0	20.8	93-02-11	191	4.5	20.7
92-02-18	198	2.0	20.8	92-02-18	198	2.5	20.9
92-02-25	205	1.8	20.6	92-02-25	205	2.5	20.8
93-03-10	218	6.6	20.9	93-03-10	218	7.0	20.8
93-03-18	226	3.0	20.7	93-03-18	226	3.5	20.7
93-03-30	238	6.0	20.9	93-03-30	238	6.5	20.9
93-04-06	244	13.5		93-04-06	244	11.5	
93-04-20	259	32.5	17.8	93-04-20	259	27.5	17.0
93-05-11	280	31.5	16.4	93-05-11	280	24.5	18.1

D.2 Temperature and Oxygen Plots

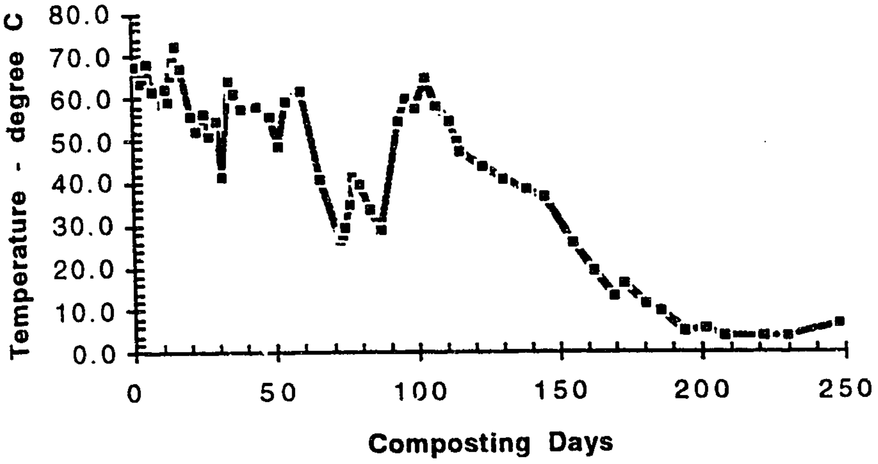


Figure D.1 Pile Temperature vs Composting Days - Pile 1
Med C:N ratio, Low M.C.

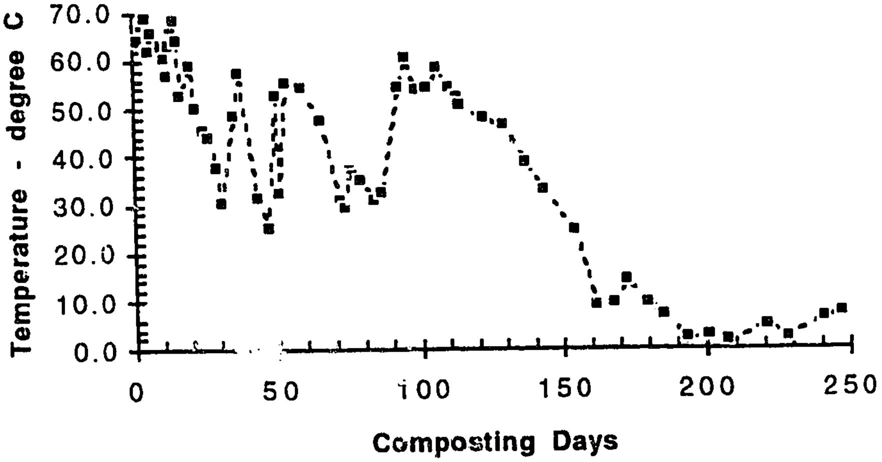


Figure D.2 Pile Temperature vs Composting Days - Pile 2
Hi C:N , Low M.C.

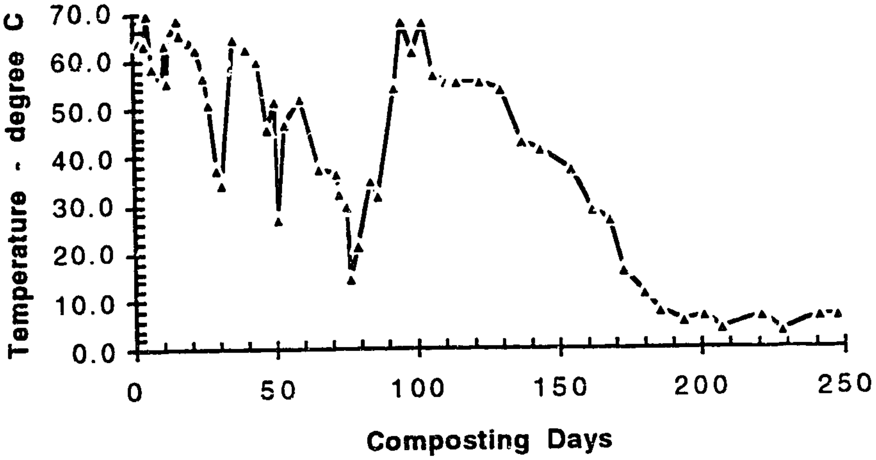


Figure D.3 Pile Temperature vs Composting Days - Pile 3
Med C:N, Hi M.C.

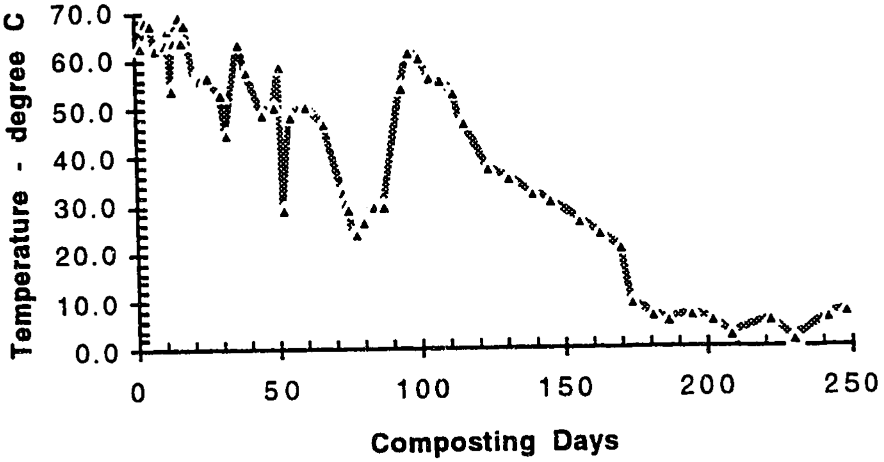


Figure D.4 Pile Temperature vs Composting Days - Pile 4
Hi C:N,Hi M.C.

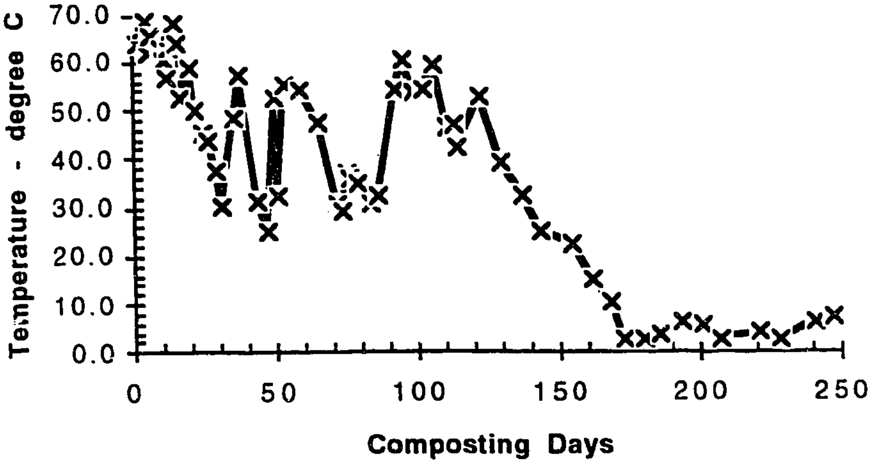


Figure D.5 Pile Temperature vs Composting Days - Pile 5 Med C:N, Hi M.C.

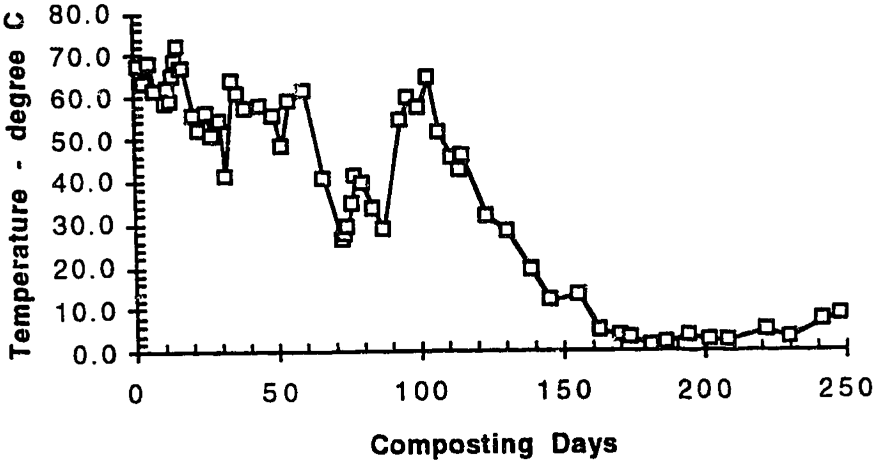


Figure D.6 Pile Temperature vs Composting Days - Pile 6 Hi C:N, Low M.C.

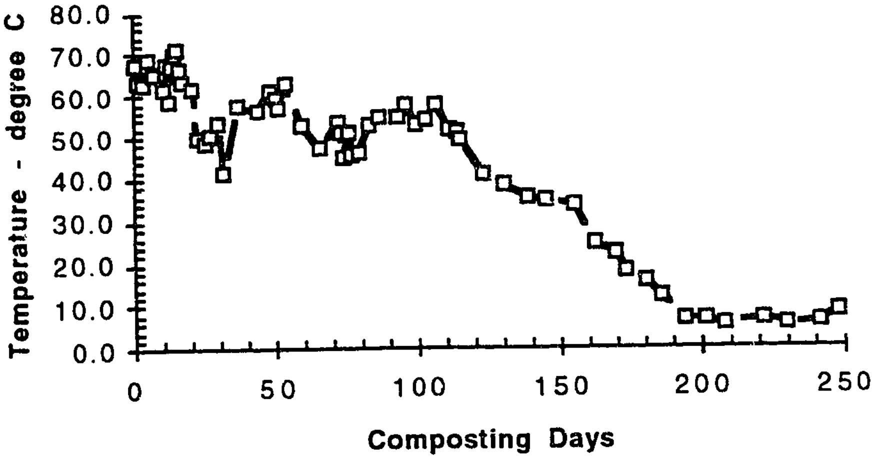


Figure D.7 Pile Temperature vs Composting Days - Pile 7
Med C:N, Hi M.C.

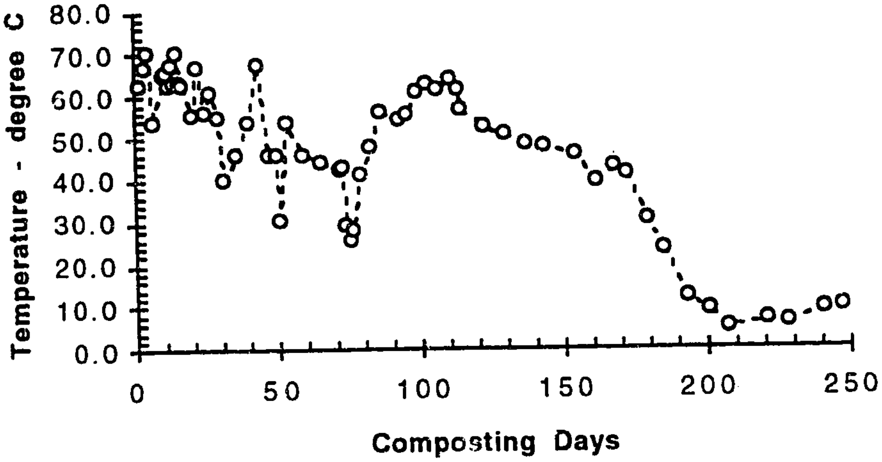


Figure D.8 Pile Temperature vs Composting Days - Pile 8
Hi C:N, Hi M.C.

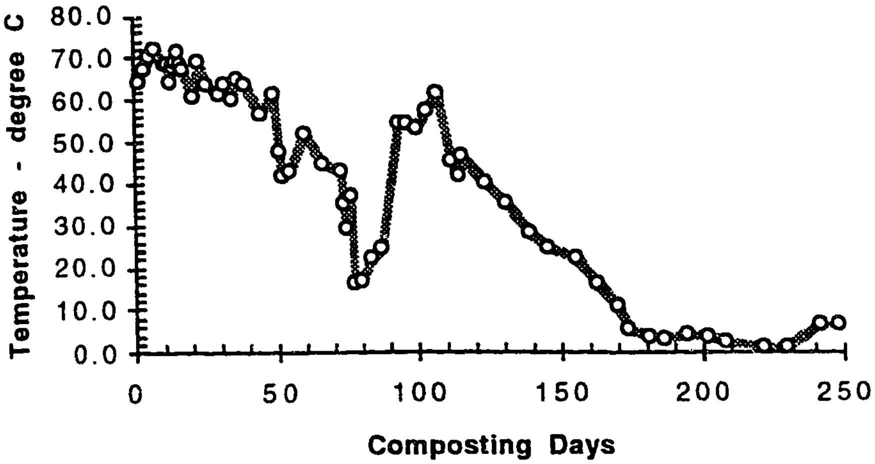


Figure D.9 Pile Temperature vs Composting Days - Pile R1 Med C:N, Hi M.C.

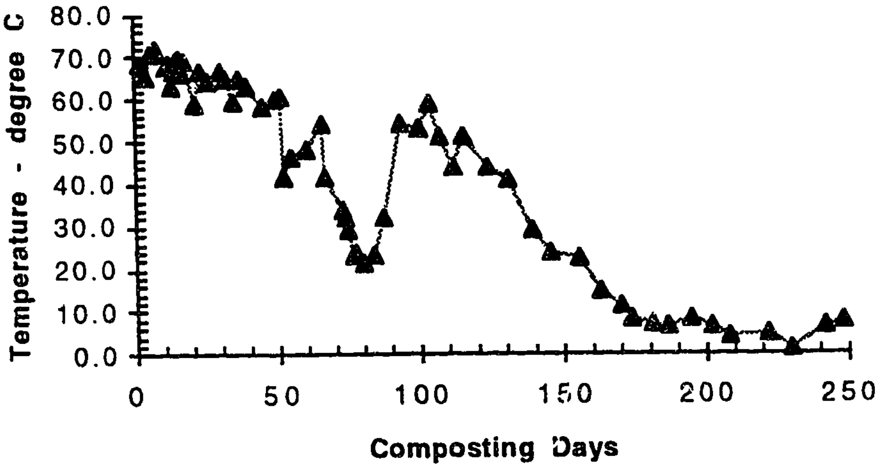


Figure D.10 Pile Temperature vs Composting Days - Pile R2 Med C:N, Hi M.C.

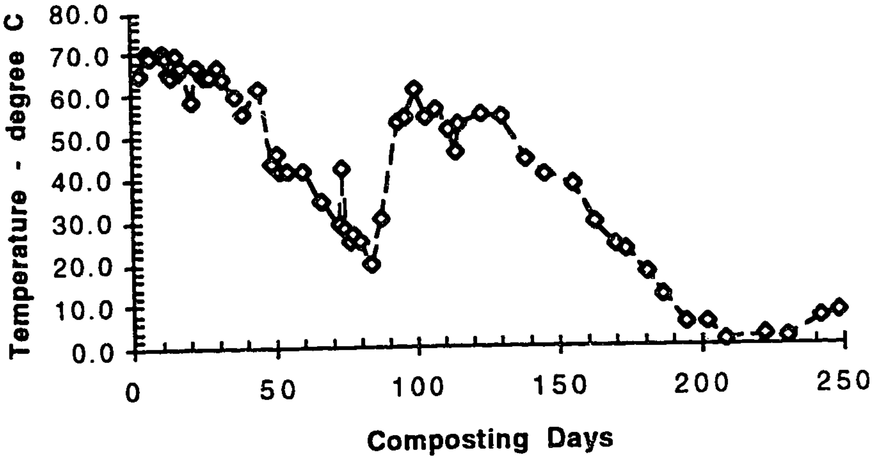


Figure D.11 Pile Temperature vs Composting Days - Pile L1 Low C:N, Hi M.C.

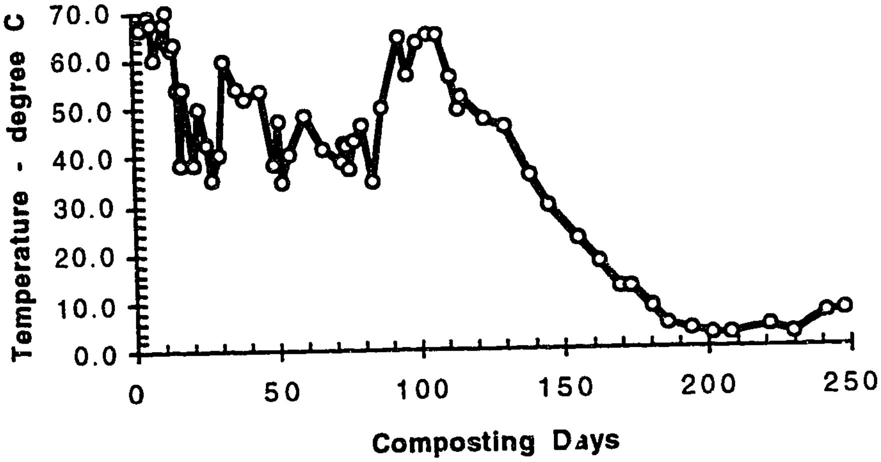


Figure D.12 Pile Temperature vs Composting Days - Pile L2 Low C:N, Low M.C.

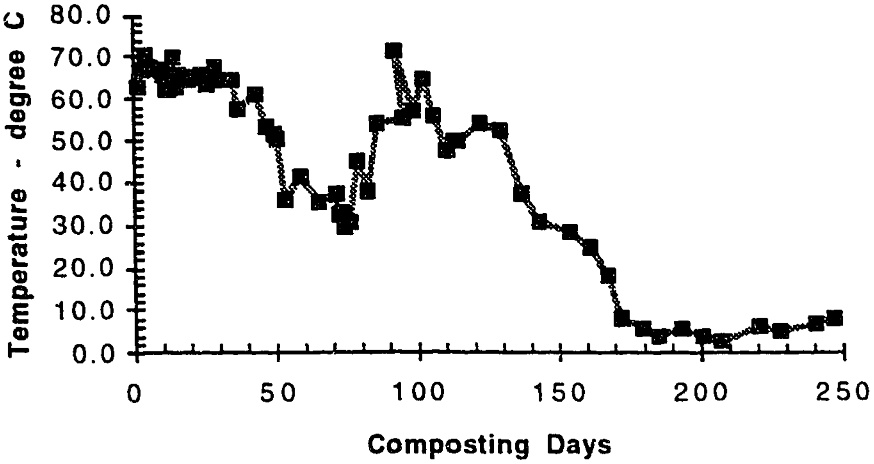


Figure D.13 Pile Temperature' vs Composting Days - Pile L3 Low C:N, Hi M.C.

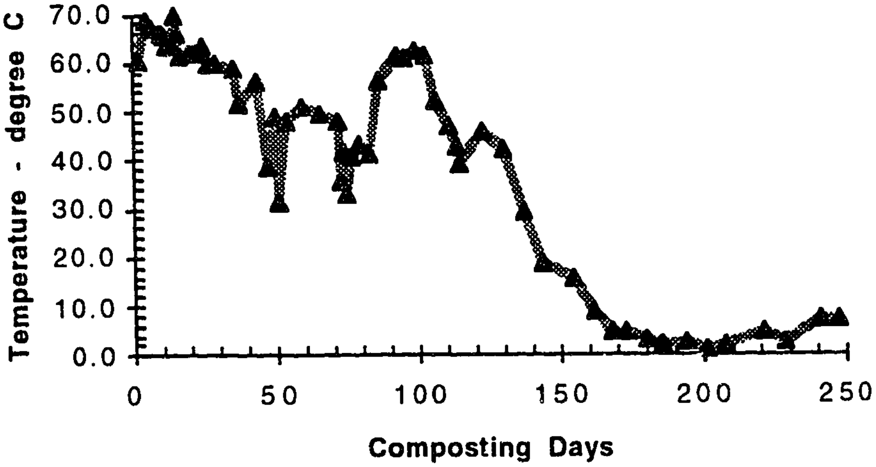


Figure D.14 Pile Temperature vs Composting Days - Pile L4 Low C:N, Low M.C.

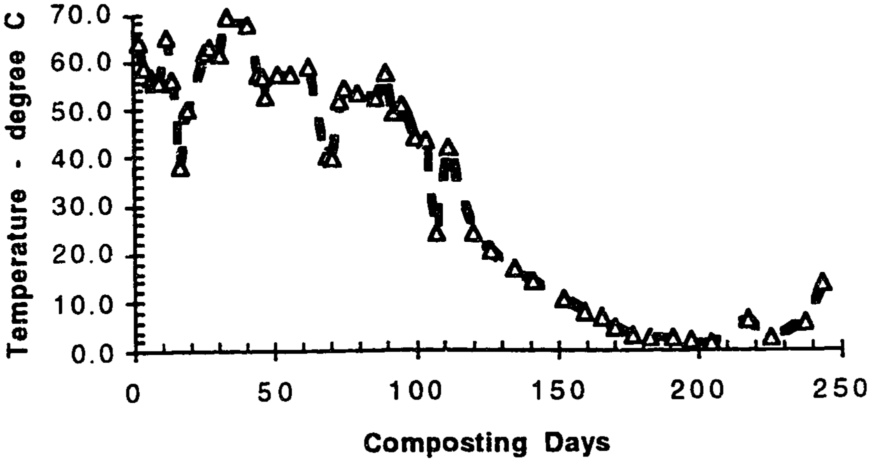


Figure D.15 Pile Temperature vs Composting Days - Pile C1 Control Pile

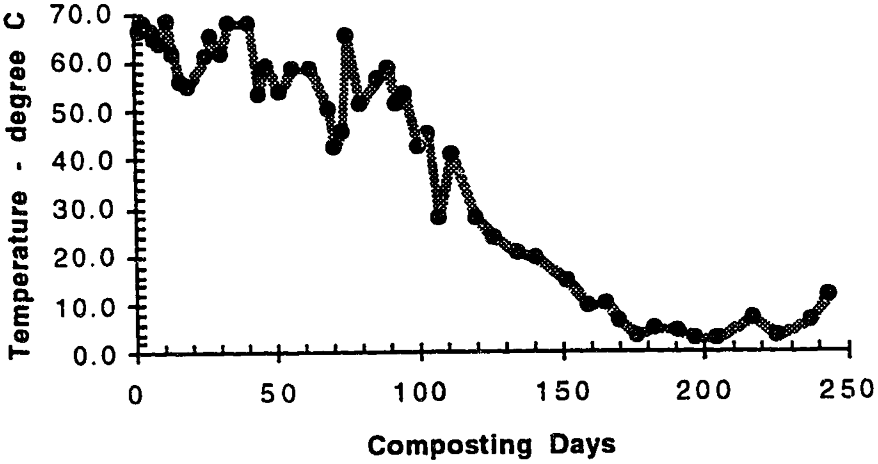


Figure D.16 Pile Temperature vs Composting Days - Pile C1 Control Pile

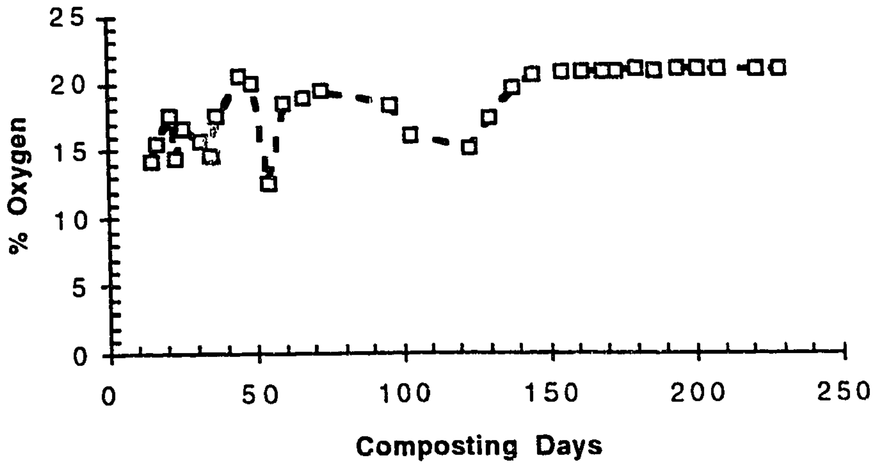


Figure D.17 Pile % Oxygen vs Composting Days - Pile 1
Med C:N, Low M.C.

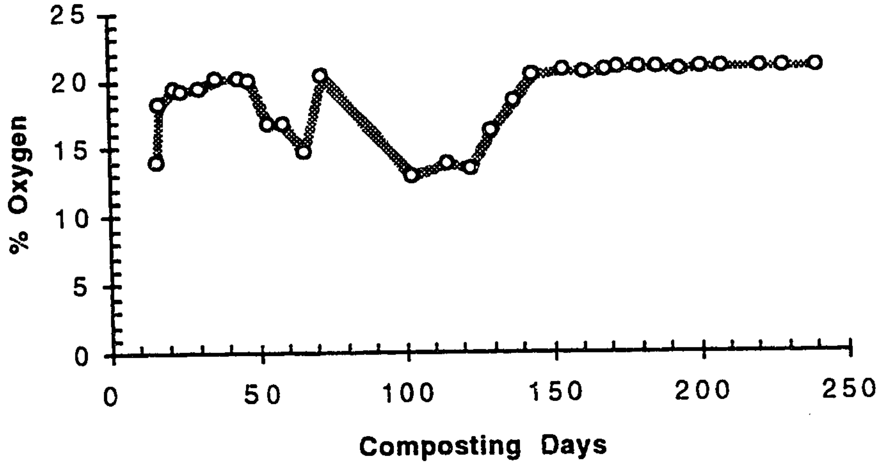


Figure D.18 Pile % Oxygen vs Composting Days - Pile 2
Hi C:N, Low M.C.

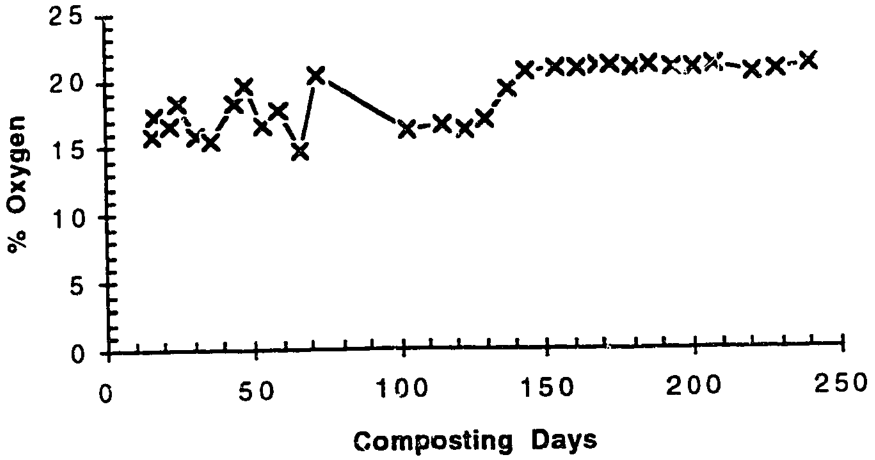


Figure D.19 Pile % Oxygen vs Composting Days - Pile 3 Med C:N, Hi M.C.

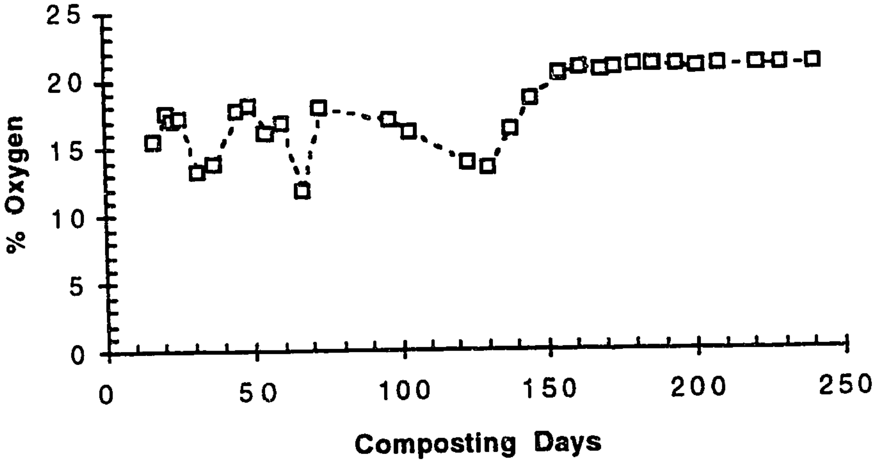


Figure D.20 Pile % Oxygen vs Composting Days - Pile 4 Hi C:N, Hi M.C.

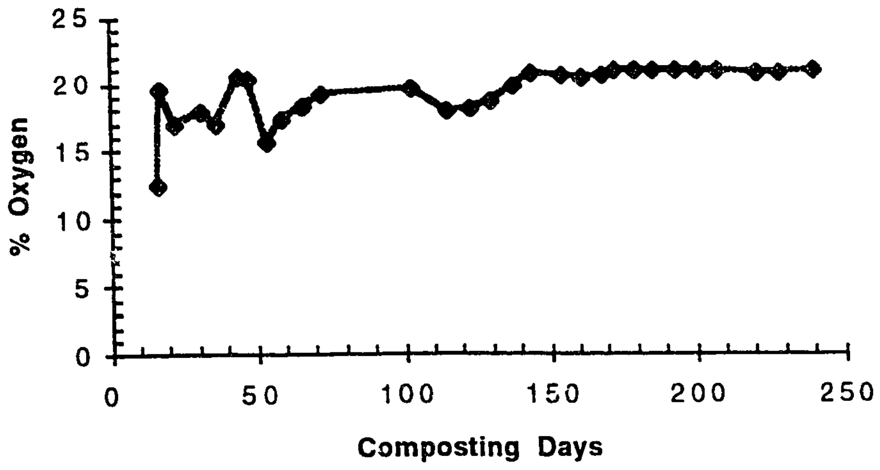


Figure D.21 Pile % Oxygen vs Composting Days - Pile 5 Med C:N, Low M.C.

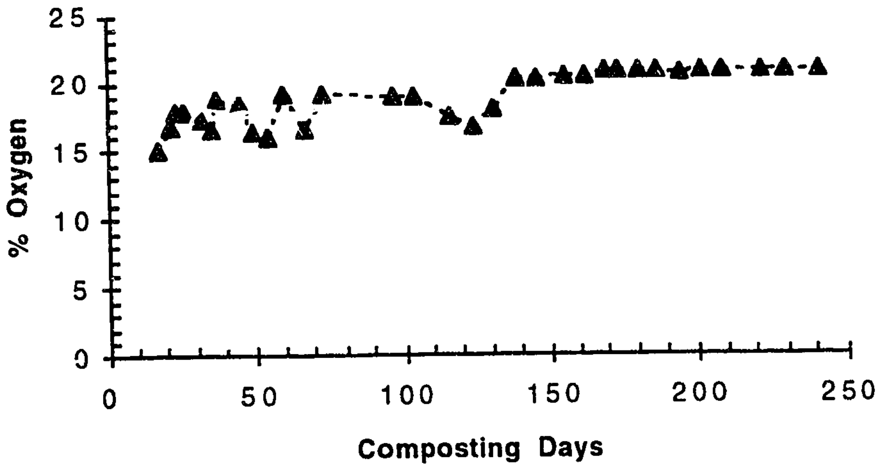


Figure D.22 Pile % Oxygen vs Composting Days - Pile 6 Hi C:N, Low M.C.

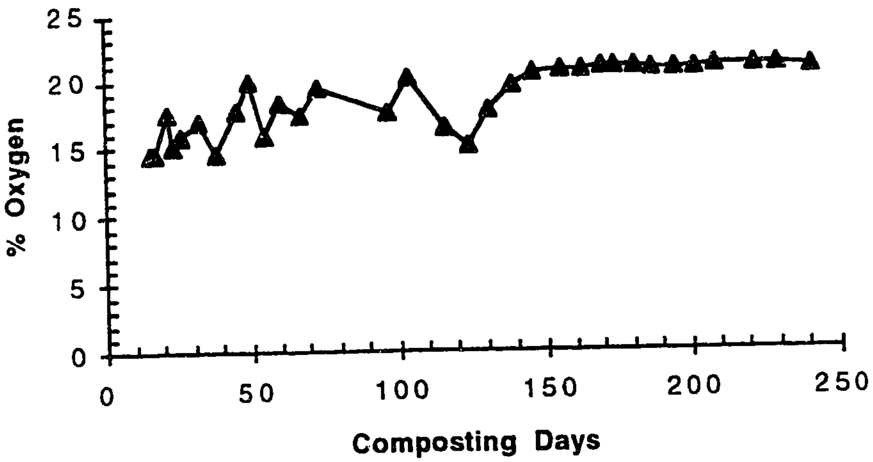


Figure D.23 Pile % Oxygen vs Composting Days - Pile 7 Med C:N, Low M.C.

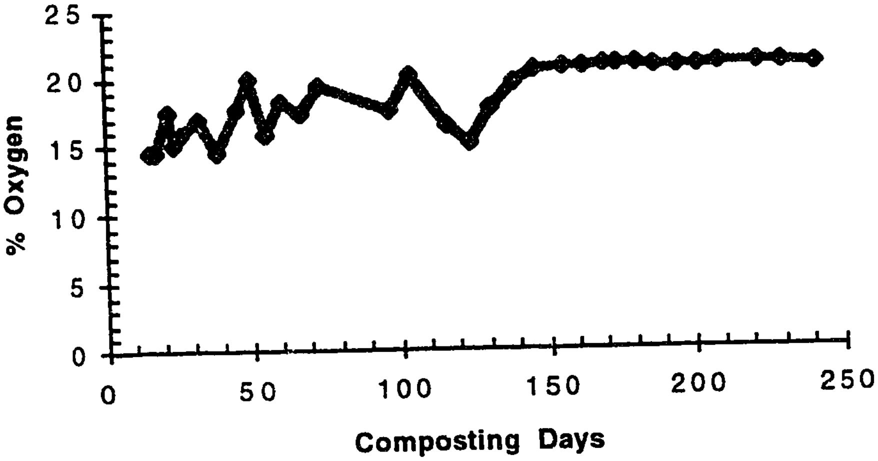


Figure D.24 Pile % Oxygen vs Composting Days - Pile 8 Hi C:N, Hi M.C.

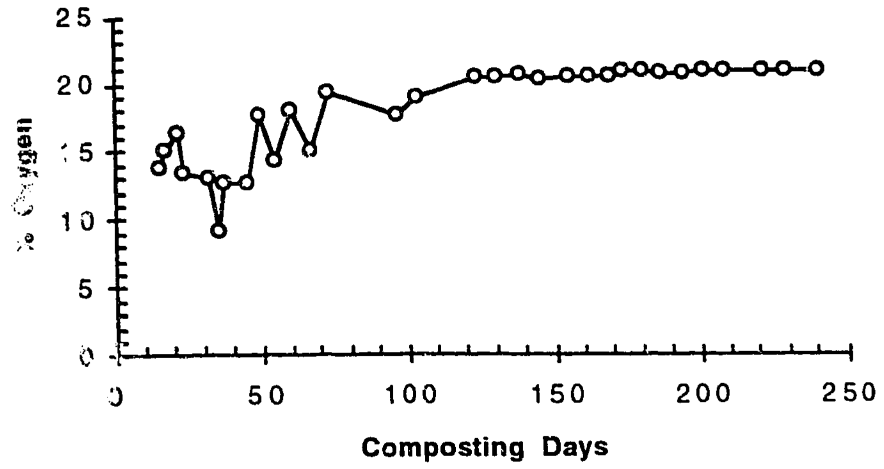


Figure D.25 Pile % Oxygen vs Composting Days - Pile R1 Med C:N, Hi M.C

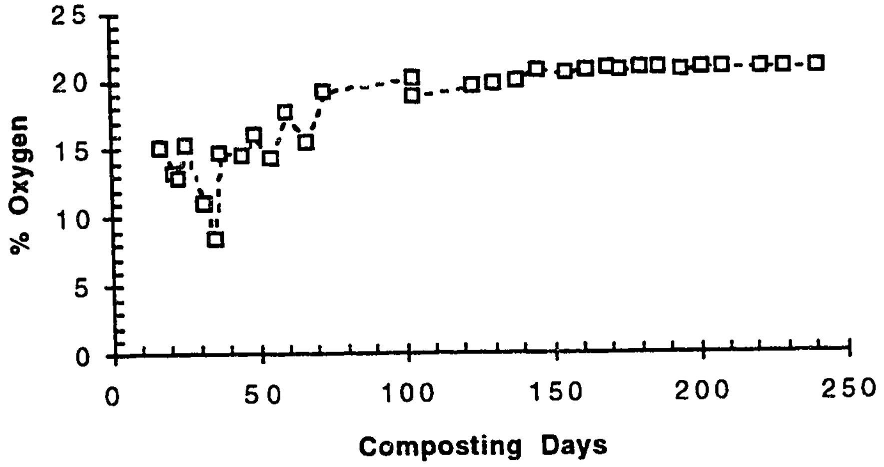


Figure D.26 Pile % Oxygen vs Composting Days - Pile R2 Med C:N, Hi M.C

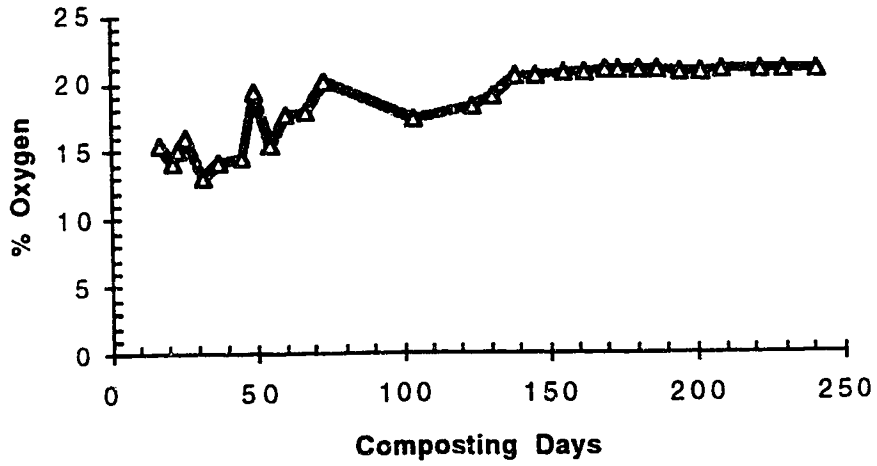


Figure D.27 Pile % Oxygen vs Composting Days - Pile L1
Low C:N, Hi M.C.

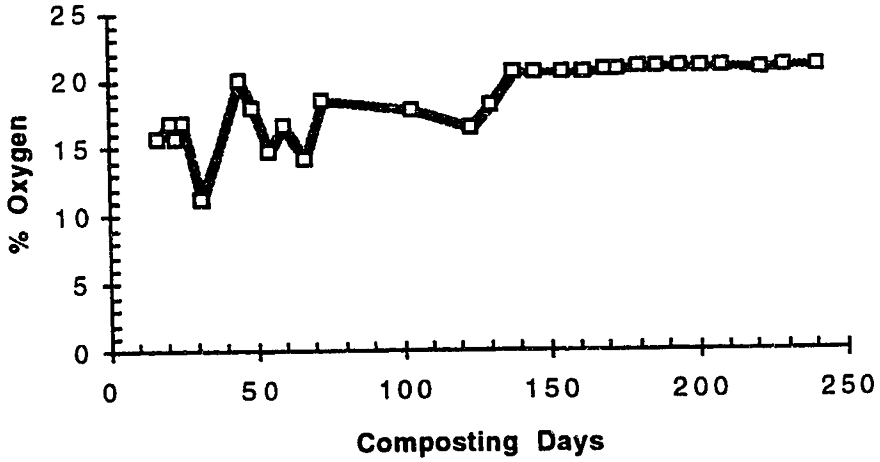


Figure D.28 Pile % Oxygen vs Composting Days - Pile L2
Low C:N, Low M.C.

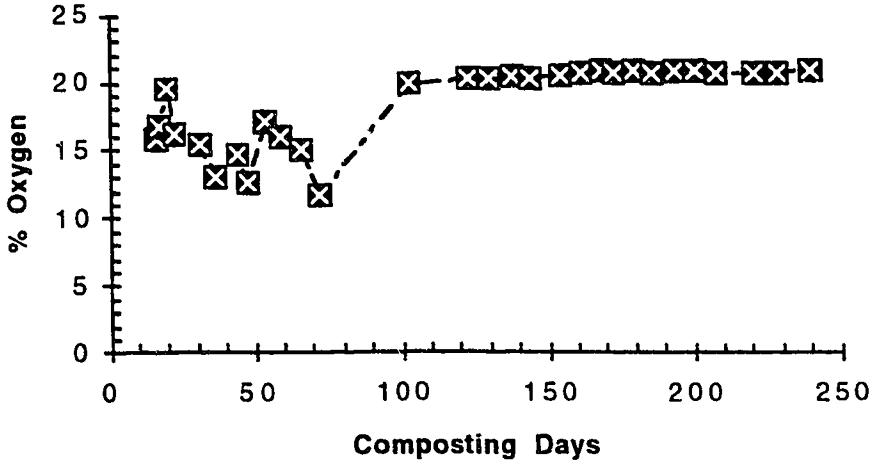


Figure D.29 Pile % Oxygen vs Composting Days - Pile L3 Low C:N, Hi M.C.

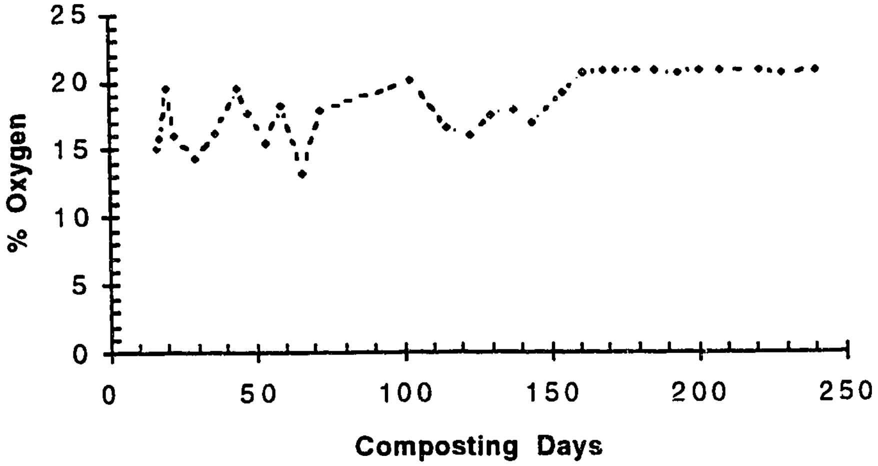


Figure D.30 Pile % Oxygen vs Composting Days - Pile L4 Low C:N, Low M.C.

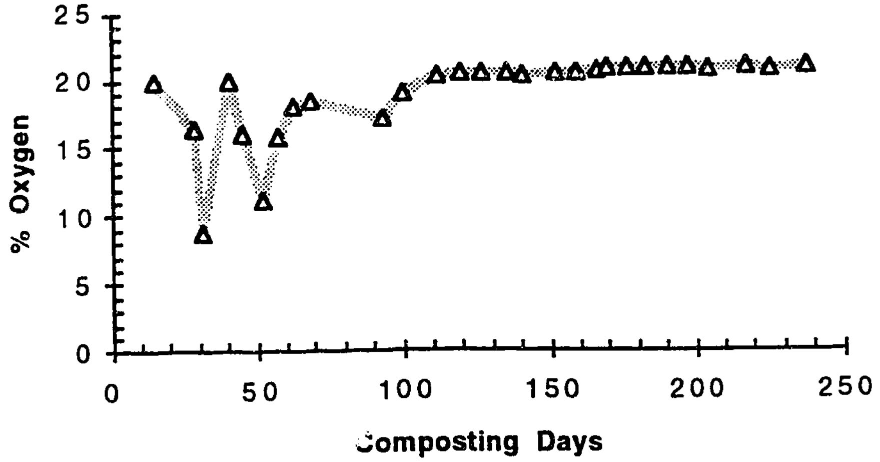


Figure D.31 Pile % Oxygen vs Composting Days - Pile C1 Control Pile

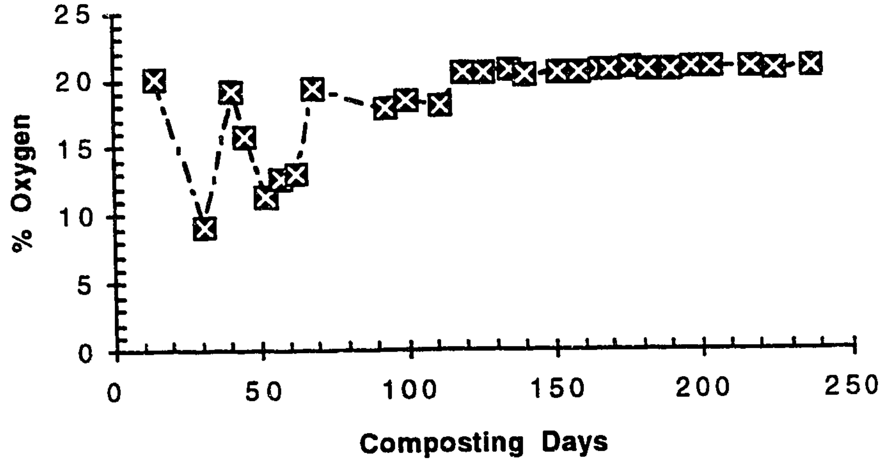


Figure D.32 Pile % Oxygen vs Composting Days - Pile C2 Control Pile

Appendix E - Factorial Results Summary

Table E.1 - Factorial Results Summary

Case 1 Botched Factorial Design Matrix
Full Period Y= % Decrease in TOC (Water extracts)

			Variables						
Pile	**C**	**1**	**2**	**3**	**1 2**	**1 3**	**2 3**	**1 2 3**	**Y**
L2	1	-1	-0.89	-1	0.89	1	0.89	-0.89	-82.1
2	1	1	-0.63	-1	-0.63	-1	0.63	0.63	-84.8
L1	1	-1	0.83	-1	-0.83	1	-0.83	0.83	-83.8
4	1	1	0.76	-1	0.76	-1	-0.76	-0.76	-61.3
L4	1	-1	-0.94	1	0.94	-1	-0.94	0.94	-68.0
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	-68.2
L3	1	-1	0.71	1	-0.71	-1	0.71	-0.71	-73.8
8	1	1	0.64	1	0.64	1	0.64	0.64	-86.0
R1	1	0	0.81	1	0	0	0.81	0	-80.9
R2	1	0	0.73	1	0	0	0.73	0	-80.8
7	1	0	0.77	1	0	0	0.77	0	-78.3
1	1	0	-1.01	-1	0	0	1.01	0	-81.5
3	1	0	0.71	-1	0	0	-0.71	0	-84.5
5	1	0	-0.96	1	0	0	-0.96	0	-80.1

Results

Effects	**Est Value**	**ß**	**(- or +)**	**9 5 % C I**	
0	-156.28	-78.14	3.93	-82.07	-74.21
1	0.99	0.49	5.16	-4.66	5.65
2	-0.27	-0.13	4.87	-5.00	4.73
3	3.24	1.62	3.93	-2.31	5.55
1 2	4.46	2.23	6.53	-4.30	8.76
1 3	-8.20	-4.10	5.16	-9.26	1.06
2 3	-9.14	-4.57	4.87	-9.44	0.29
1 2 3	-12.16	-6.08	6.53	-12.61	0.45

95 %, 2 sided, df=14-8=6
t=2.45

Source	**SS**	**df**	**ms**
Total	86232.11	14	6159.44
Model	86021.70	8	10752.71
Residual	210.41	6	35.07
Pure Error	6.42	2	3.21
Lack of Fit	203.99	4	51.00
Ftable	19.3	F,4,2, % 5	
F calc	31.8		

Avg Y replicates -80.8

Half Normal Plot

i	**Est Effect**	**Abs Value**	**% Pi**
1	2	0.27	7.14
2	1	0.99	21.43
3	3	3.24	35.71
4	1 2	4.46	50.00
5	1 3	8.20	64.29
6	2 3	9.14	78.57
7	1 2 3	12.16	92.86

Variable	
1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

Case 2 Botched Factorial Design Matrix
Full Period Y= % Increase in Dry Bulk Densities

			Variables						
Pile	**Constant**	**1**	**2**	**3**	**1 2**	**1 3**	**2 3**	**1 2 3**	**Y**
L2	1	-1	-0.89	-1	0.89	1	0.89	-0.89	56.9
2	1	1	-0.63	-1	-0.63	-1	0.63	0.63	55.8
L1	1	-1	0.83	-1	-0.83	1	-0.83	0.83	68.3
4	1	1	0.76	-1	0.76	-1	-0.76	-0.76	62.6
L4	1	-1	-0.94	1	0.94	-1	-0.94	0.94	59.9
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	63.4
L3	1	-1	0.71	1	-0.71	-1	0.71	-0.71	60.7
8	1	1	0.64	1	0.64	1	0.64	0.64	34.4
R1	1	0	0.81	1	0	0	0.81	0	49.9
R2	1	0	0.73	1	0	0	0.73	0	48.2
7	1	0	0.77	1	0	0	0.77	0	47.6
1	1	0	-1.01	-1	0	0	1.01	0	49.5
3	1	0	0.71	-1	0	0	-0.71	0	46.4
5	1	0	-0.96	1	0	0	-0.96	0	71.3

Results

Effects	**Est Value**	**ß**	**(- or +)**	**95%CI**		***Source***	**SS**	**df**	**ms**
0	112.23	56.12	4.89	51.23	61.00	Total	44176.23	14	3155.45
1	-8.82	-4.41	6.41	-10.82	2.00	Model	43851.44	8	5481.43
2	-6.57	-3.28	6.05	-9.33	2.76	Residual	324.79	6	54.13
3	-1.27	-0.64	4.89	-5.52	4.25	Pure Error	2.97	2	1.48
1 2	-10.70	-5.35	8.12	-13.47	2.76	Lack of Fit	321.82	4	80.46
1 3	-5.11	-2.56	6.41	-8.96	3.85	Ftable	19.3	F,4,2, % 5	
2 3	-13.77	-6.88	6.05	-12.93	-0.84	F calc	10.9		
1 2 3	-8.70	-4.35	8.12	-12.47	3.77				
						Avg Y replicates	48.8		

95 %, 2 sided, df=14-8=6
t=2.45

Half Normal Plot

i	**Effect**	**Abs Value**	**% Pi**
1	3	1.27	7.14
2	1 3	5.11	21.43
3	2	6.57	35.71
4	123	8.70	50.00
5	1	8.82	64.29
6	1 2	10.70	78.57
7	2 3	13.77	92.86

Variable

1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

Case 3 Botched Factorial Design Matrix
Active Period Y= % Decrease in TOC (Water extracts)

			Variables						
Pile	**Constant**	**1**	**2**	**3**	**1 2**	**1 3**	**2 3**	**1 2 3**	**Y**
L2	1	-1	-0.89	-1	0.89	1	0.89	-0.89	-80.1
2	1	1	-0.63	-1	-0.63	-1	0.63	0.63	-81.2
L1	1	-1	0.83	-1	-0.83	1	-0.83	0.83	-76.2
4	1	1	0.76	-1	0.76	-1	-0.76	-0.76	-67.6
L4	1	-1	-0.94	1	0.94	-1	-0.94	0.94	-53.1
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	-65.5
L3	1	-1	0.71	1	-0.71	-1	0.71	-0.71	-64.8
8	1	1	0.64	1	0.64	1	0.64	0.64	-84.8
R1	1	0	0.81	1	0	0	0.81	0	-76.5
R2	1	0	0.73	1	0	0	0.73	0	-65.0
7	1	0	0.77	1	0	0	0.77	0	-78.3
1	1	0	-1.01	-1	0	0	1.01	0	-80.2
3	1	0	0.71	-1	0	0	-0.71	0	-81.4
5	1	0	-0.96	1	0	0	-0.96	0	-76.3

Results

Effects	**Est Value**	**ß**	**(- or +)**	**9 5 % C I**	
0	-147.72	-73.86	5.17	-79.03	-68.69
1	-6.80	-3.40	6.78	-10.18	3.38
2	-1.69	-0.84	6.40	-7.24	5.55
3	7.78	3.89	5.17	-1.28	9.06
1 2	0.92	0.46	8.58	-8.13	9.04
1 3	-10.08	-5.04	6.78	-11.82	1.74
2 3	-8.99	-4.50	6.40	-10.89	1.90
1 2 3	-5.80	-2.90	8.58	-11.48	5.69

Source	**SS**	**df**	**ms**
Total	76973.42	14	5498.10
Model	76610.01	8	9576.25
Residual	363.41	6	60.57
Pure Error	163.09	2	81.55
Lack of Fit	200.32	4	50.08
Ftable	19.3	F,4,2, % 5	
F calc	1.2		

Avg Y -68.8
replicates

95 %, 2 sided, df=14-8=6
t=2.45

Half Normal Plot

i	**Effect**	**Abs Value**	**% Pi**
1	12	0.92	7.14
2	2	1.69	21.43
3	123	5.80	35.71
4	1	6.80	50.00
5	3	7.78	64.29
6	23	8.99	78.57
7	13	10.08	92.86

Variable	
1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

Case 4 Botched Factorial Design Matrix
Active Period Y= % Increase in Dry Bulk Density

		Variables							
Pile	**Constant**	**1**	**2**	**3**	**1 2**	**1 3**	**2 3**	**1 2 3**	**Y**
L2	1	-1	-0.89	-1	0.89	1	0.89	-0.89	56.1
2	1	1	-0.63	-1	-0.63	-1	0.63	0.63	56.7
L1	1	-1	0.83	-1	-0.83	1	-0.83	0.83	63.1
4	1	1	0.76	-1	0.76	-1	-0.76	-0.76	59.5
L4	1	-1	-0.94	1	0.94	-1	-0.94	0.94	55.4
6	1	1	-0.90	1	-0.90	1	-0.90	-0.90	53.2
L3	1	-1	0.71	1	-0.71	-1	0.71	-0.71	53.0
8	1	1	0.64	1	0.64	1	0.64	0.64	30.9
R1	1	0	0.81	1	0	0	0.81	0	45.8
R2	1	0	0.73	1	0	0	0.73	0	39.9
7	1	0	0.77	1	0	0	0.77	0	41.0
1	1	0	-1.01	-1	0	0	1.01	0	39.6
3	1	0	0.71	-1	0	0	-0.71	0	46.7
5	1	0	-0.96	1	0	0	-0.96	0	70.3

Results

Effects	**Est Value**	**ß**	**(- or +)**	**9 5 % CI**	
0	103.60	51.80	6.01	45.79	57.81
1	-7.92	-3.96	7.88	-11.84	3.92
2	-6.23	-3.11	7.43	-10.55	4.32
3	-3.99	-2.00	6.01	-8.00	4.01
1 2	-7.02	-3.51	9.98	-13.48	6.47
1 3	-6.02	-3.01	7.88	-10.89	4.87
2 3	-15.01	-7.51	7.43	-14.94	-0.07
1 2 3	-6.30	-3.15	9.98	-13.13	6.82

95 %, 2 sided, df=14-8=6
t=2.45

Source	**SS**	**df**	**ms**
Total	37608.96	14	2686.35
Model	37118.15	8	4639.77
Residual	490.81	6	81.80
Pure Error	20.09	2	10.04
Lack of Fit	470.72	4	117.68
Ftable	19.3	F,4,2, %	5
F calc	23.4		
Avg Y replicates	41.9		

Half Normal Plot

i	**Effect**	**Abs Value**	**% Pi**
1	3	3.99	7.14
2	1 3	6.02	21.43
3	2	6.23	35.71
4	123	6.30	50.00
5	1 2	7.02	64.29
6	1	7.92	78.57
7	2 3	15.01	92.86

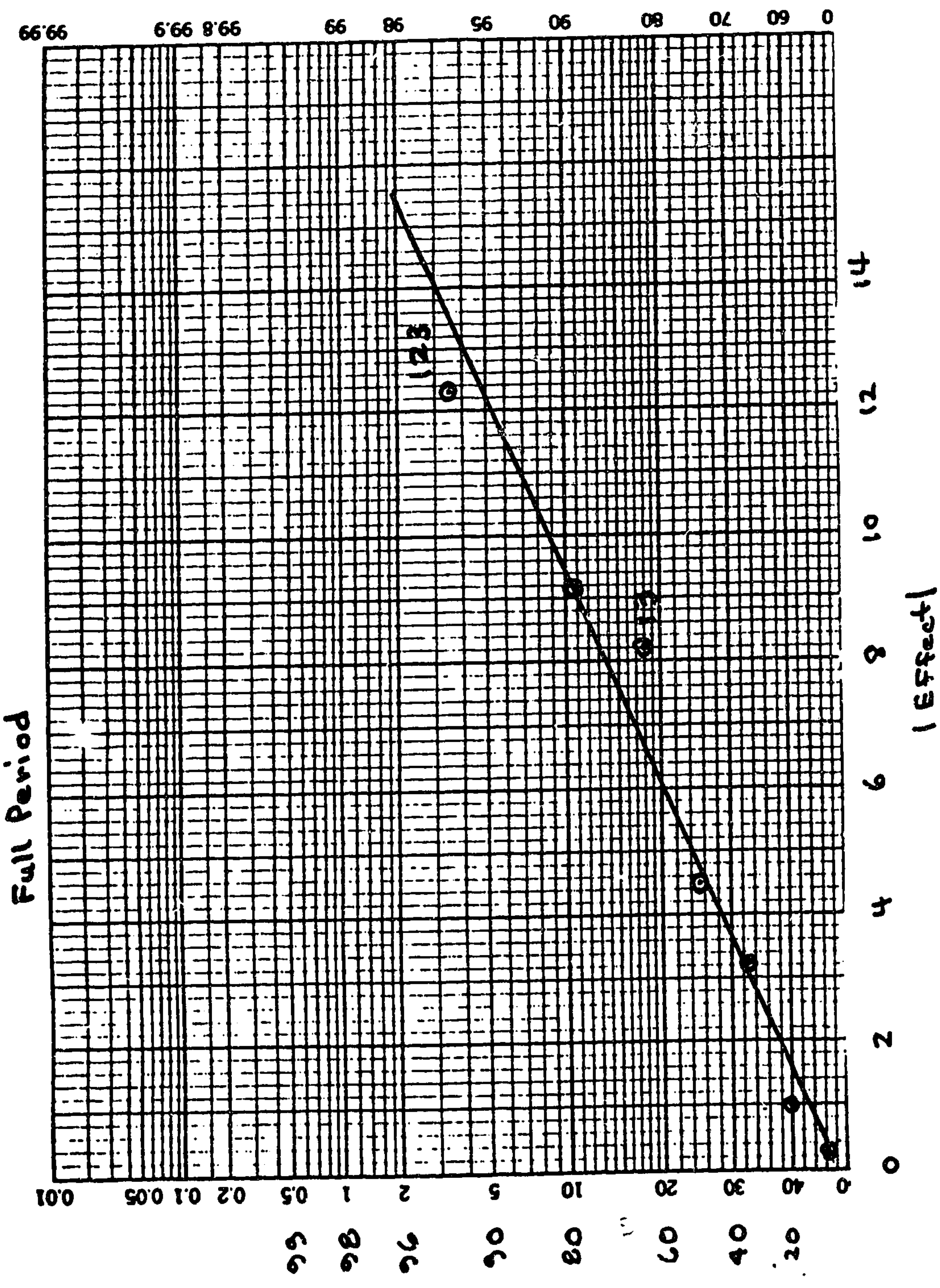
Variable	
1	C:N ratio
2	Moisture Content
3	Porosity Adjustment
C	Constant

Abs value= absolute value of Effects

E.1 Half Normal Plot
TOC
Full Period

$P_i = (i - 1/2)/n$

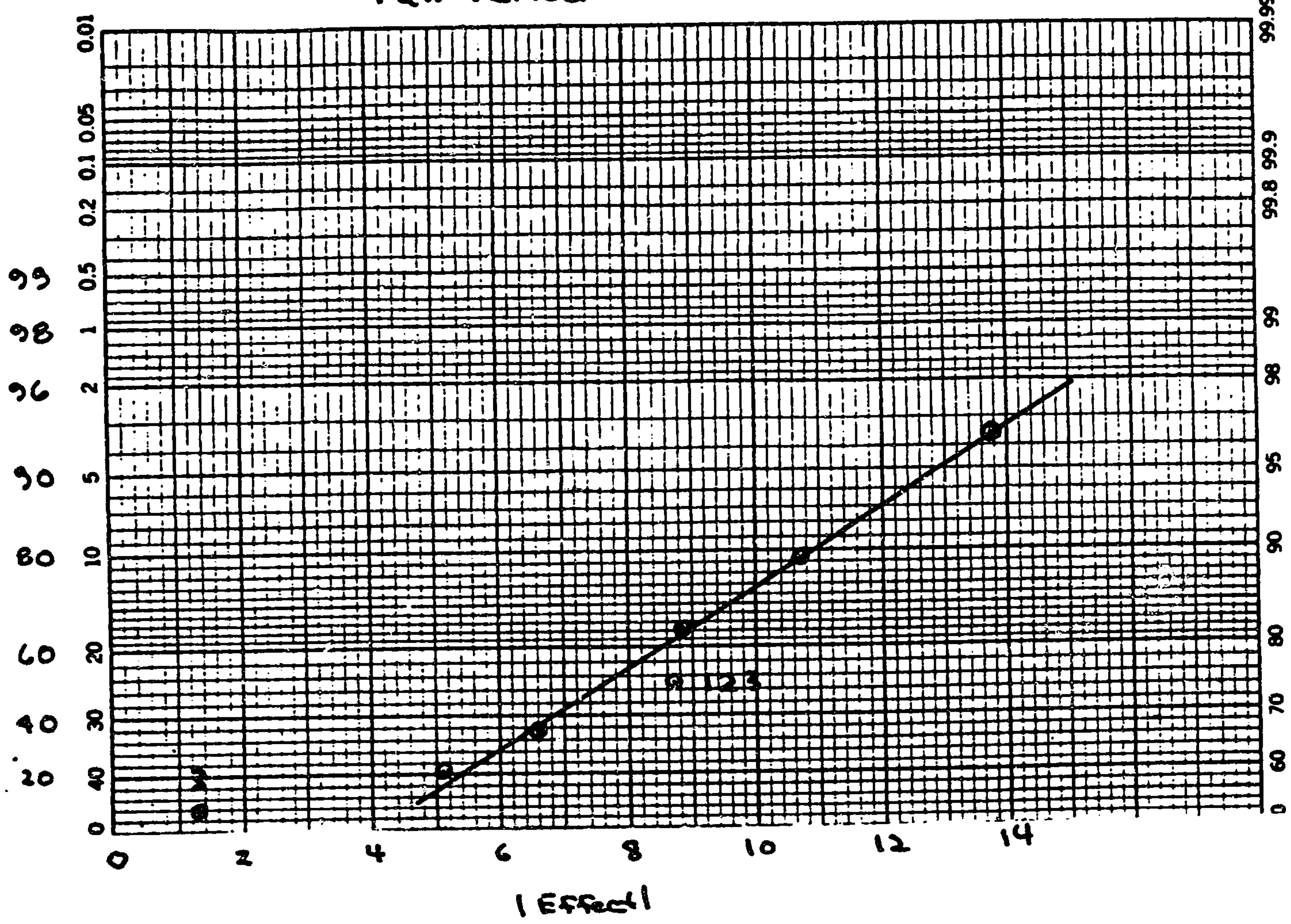
$P' = 2P - 100$



E.2 Half Normal Plot
DBD
Full Period

$P_i = (i - 1/2)/n$

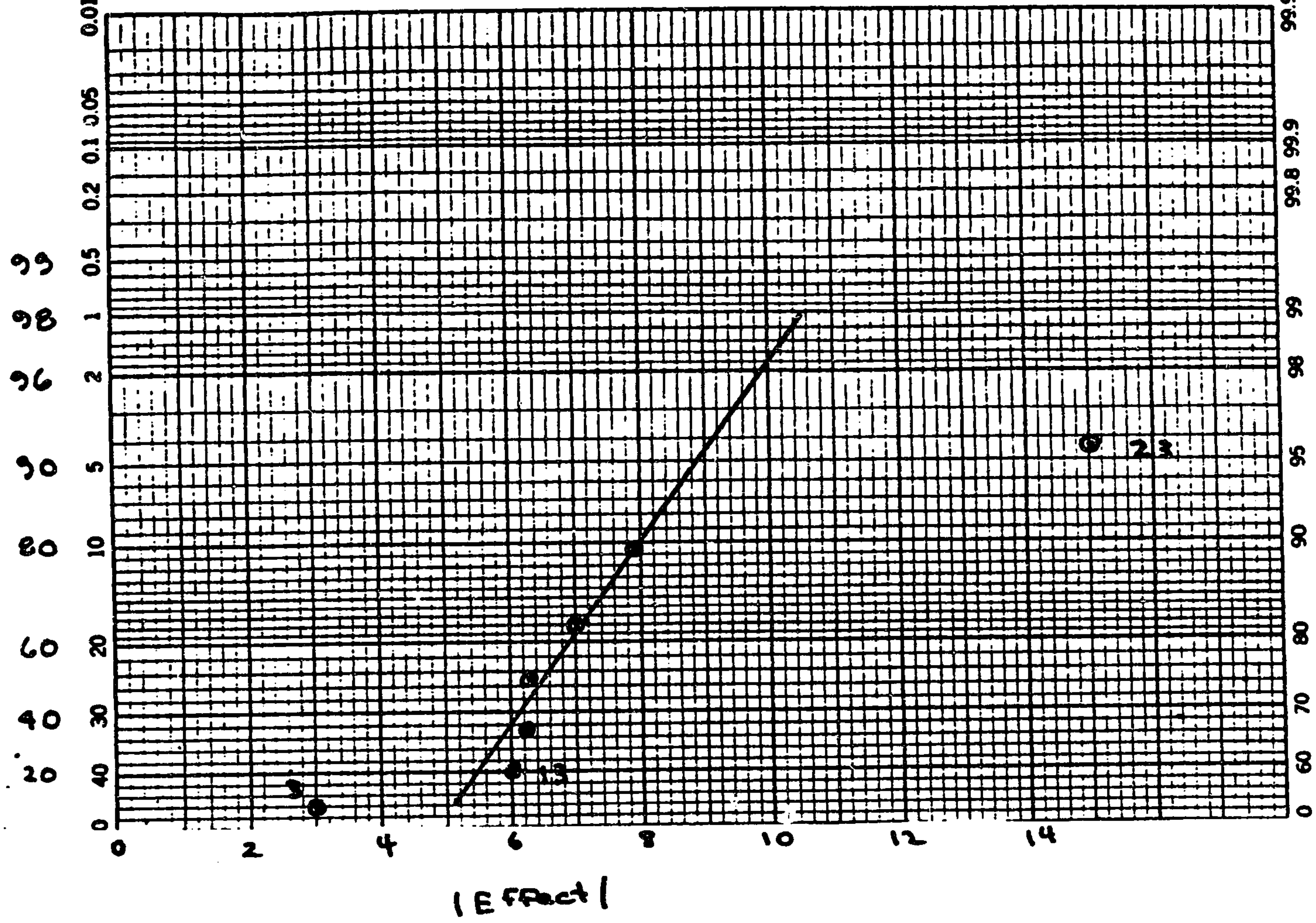
$P' = 2P - 100$



E.4 Half Normal Plot
OBD
Active Period

$P_i = (i - 1/2)/n$

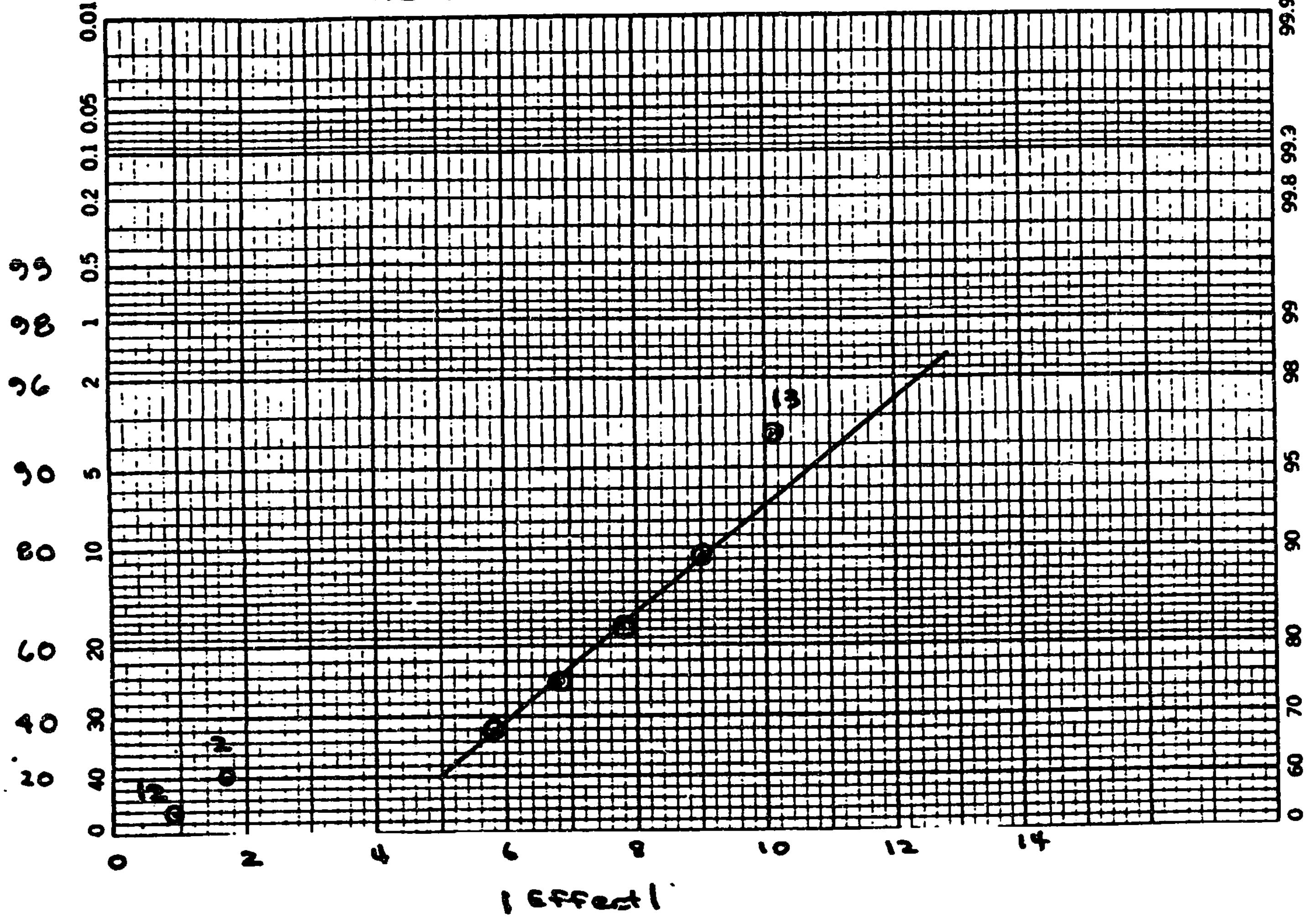
$P' = 2P - 100$



E.3 Half Normal Plot
TOC
Active Period

$P_i = (i - 1/2)/n$

$P' = 2P - 100$



Appendix F - Decomposition Models Summary

Table F.1 - ANOVA Results - Decomposition Models

ANOVA Results - Decomposition Models

% C data		**Model**	
	0 Order	1st Order	2nd Order
Avg R^2 Value	**0.70**	**0.77**	**0.78**

Source of variation	sum of squares	degrees of freedom	mean square	F Ratio	F Prob
Between Groups	0.0456	2	0.0228	3.471	0.0423
Within Groups	0.2158	33	0.0065		
Total	0.2614	35			

Reject Ho: that Means are equal

There is no difference between individual group average R^2 squared values using the Student-Newman-Keuls Test with a 5% significance level.

TOC data		**Model**	
	0 Order	1st Order	2nd Order
Avg R^2 Value	**0.68**	**0.74**	**0.76**

Source of variation	sum of squares	degrees of freedom	mean square	F Ratio	F Prob
Between Groups	0.0416	2	0.0208	9.0278	0.0007
Within Groups	0.0760	33	0.0023		
Total	0.1176	35			

Reject Ho: that Means are equal

There is a difference between the average R^2 value of the 0 order and 1st order and 0 order and 2nd order using the the Student-Newman-Keuls Test with a 5% significance level.

Table F.2 - Comparison of Pile 1st Order Decomposition Rates

% C data

Reference Pile	Piles Significantly Different than Reference Pile	Significant t value
2	L1	0.04886
5	8	0.04713
8	5	0.04713
	L1	0.01369
	L3	0.04098
	L4	0.04098
L1	2	0.04886
	8	0.01369
	L2	0.01588
L2	L1	0.01588
	L3	0.02174
	L4	0.04723
L3	8	0.01873
	L2	0.02174
L4	8	0.04098
	L2	0.04723

Table F.3 - Comparison of Pile TOC 1st Order Decomposition Rates

TOC data

Reference Pile	Piles Significantly Different than Reference Pile	Significant t value
3	L4	0.02503
7	L4	0.04347
8	L4	0.02927
L4	3	0.02503
	7	0.04347
	8	0.02927