Compost Science & Utilization, (2005), Vol. 13, No. 2, 90-97

Composting Residuals From a Strawboard Manufacturing Facility

Scott Chapman[1] and Daryl McCartney[2]
1. *Department of Civil Engineering, University of Manitoba, Winnipeg, Manitoba, Canada*
2. *Department of Civil and Environmental Engineering, University of Alberta, Edmonton, Alberta, Canada*

The purpose of this research was to investigate the compostability of waste residuals from a strawboard manufacturing facility. Phase 1 used bench-scale reactors to compost various recipes using three feedstock materials (straw, process unders, and livestock lagoon sludge) at different moisture levels for a nine-week period. Water addition and the addition of unders to the compost mixture increased degradability. The livestock lagoon waste did not significantly improve degradability. Phase 2 focused on the straw feedstock, investigating the effects of straw particle size using four unshredded:shredded straw ratios (by volume): 100:0; 67:33; 33:67; and 0:100. The recipes were composted in 140 L rigid plastic containers for a period of 180 days at a moisture content of 70% (wet basis). Volatile solids (VS) and lignocellulose degradation was greatest for recipes containing both shredded and unshredded straw, with the recipe containing 67% shredded straw performing the best (35% VS removal). Pure unshredded and shredded straw had VS reductions of 29% and 26%, respectively. Total volume reductions ranged from 80 to 90%. Hemicellulose was completely degraded for all recipes by day 95. By day 180 cellulose content had decreased from 3.75 to 0.75 g/g ash for all four recipes. By day 180, lignin degradation was greatest for recipes containing both shredded and unshredded straw (reduction from 1.0 to 0.4 g/g ash) while lignin content decreased from 1.0 to 0.6 g/g ash for the other recipes. It was concluded that recipes containing a mixture of shredded and unshredded straw provided better composting conditions.

Introduction

Dow BioProducts Ltd. operates a strawboard manufacturing facility located near Elie, Manitoba. Each year approximately 6,000 wet tonnes (wt) of straw become too wet for use as feedstock (i.e. >25% moisture content). To date there is approximately 60,000 wt of unusable straw stored at the facility in 1m x 1m x 2m rectangular bales. The manufacturing process also produces, on average, 5,000 wt/year of fine process residuals (unders). This investigation was undertaken to determine the technical feasibility of composting these waste materials.

Straws vary greatly in their chemical composition according to variety and age. The approximate chemical composition of straw is 36% cellulose, 25% hemicellulose, and 18% lignin (Rykens 1977). The remaining portions are composed of salts, insoluble ash (silica) and various other organic compounds. Because lignin is the most recalcitrant component of the plant cell wall, the higher the proportion of lignin the lower the bioavailability of the substrate. The effect of lignin on the bioavailability of outer cell wall components is thought to be largely a physical restriction with lignin molecules reducing the surface area available to enzymatic penetration and activity (Haug 1993). Eiland *et al.* (2001) evaluated the composting of *Miscanthus* straw and liquid pig manure in both open box and closed reactor systems and found no lignin degradation. Other researchers observed the degradation of hemicellulose and cellulose in straw composting (Epstein 1997; Eklind 1998), however, the effects of particle size reduction on the composting of a high carbon material such as straw have not been reported.

The goal of the research was to assess how particle size impacts straw composting, particularly composting rate, degree of degradation, and volume reduction. The specific research objectives were to:

- Quantify the effects from the addition of water and/or nitrogen.
- Evaluate the effects of particle size on the rate of straw degradation and volume reduction.

Materials And Methods

The experimental program was completed in two phases. Phase 1 was a preliminary investigation aimed at comparing the impact of: 1) water addition; 2) unders addition; and 3) nitrogen addition in the form of livestock lagoon sludge. The results of Phase 1 were used to select a recipe for Phase 2. Phase 2 used four unshredded:shredded straw ratios (by volume): 100:0; 67:33; 33:67; and 0:100.

Material

The straw was obtained from the Dow BioProducts stack yard and is mainly AC Barrie wheat straw, a predominant variety of wheat farmed in the 50 to 80 km feedstock collection radius of the strawboard manufacturing facility. Straw used for Phase 1 was randomly sampled from 1998 stock and was shredded to a maximum particle size of approximately 10 cm using a 3 horse power chipper/shredder, (Crary Bearcat Model 530, West Fargo, North Dakota). Straw used for Phase 2 was randomly sampled from 1997 and 2000 stock. The shredded straw was obtained from a 460 horsepower tub grinder (Haybuster Model H1100E, Jamestown, North Dakota). The process unders used in Phase 1 were obtained from the Dow BioProducts strawboard manufacturing facility. The unders are removed from the strawboard manufacturing process at the wet screens (0.3 x 0.2 mm slots) just before the dryers. Process unders were not included in Phase 2 of the experiment since process improvements at the strawboard manufacturing plant led to the elimination of the unders from the waste stream. The livestock lagoon sludge was obtained from James Valley Colony, a Hutterite farming colony. The lagoon received waste from fifty-five diary cows, 14,000 laying hens, and 600 farrow-to-finish hogs. The physical-chemical properties of the feedstock materials are presented in Table 1. Initial lignin, cellulose, and hemicellulose percentages of the straw used in Phase 2 were 11.4, 42.5, and 19.6, respectively. Characteristic particle sizes of the unshredded and shredded straw are shown in Table 2. The particle size such that 10% of the particles are smaller than that size is denoted by D_{10}. D_{30} and D_{60} are defined similarly. The coefficient of uniformity (C_U) indicates the range of particle sizes in the material (i.e. the higher the value of C_U the larger the range of particle sizes).

Composting Set-Up

The bench-scale composting period for Phase 1 was 63 days. Seven different recipes were investigated in duplicate resulting in a total of 14 reactors. The recipe descriptions are shown in Table 3. Recipes 2A to 2E were based on the projected long-term waste generation at the strawboard manufacturing facility (6,000 wet tonnes straw/year, 5,000 wet tonnes process unders/year). The various recipes were selected to answer the three specific questions shown in Table 4. Plastic, 3.8 litre pails with loose fitting lids were placed

TABLE 1.
Feedstock and initial bench-scale recipe material characteristics (Phases 1 and 2)

Materials	%MC (db)	%TKN (db)	%OC (db)	C:N (wt:wt)
Phase 1				
Straw	57 (16.6)	1.43 (0.22)	45.3 (2.2)	28.5
Unders	18	1.48	45.6	31.0
Lagoon Mixture	93 (0.2)	23.5 (13.8)	13.9 (1.5)	0.6
Phase 1				
Recipe 1A	57	1.43 (0.22)	45.7 (0.1)	32.0
Recipe 1B	70	1.43 (0.22)	44.3 (0.6)	31.0
Recipe 2A	40	1.29 (0.13)	44.8 (0.2)	34.7
Recipe 2B	55	1.29 (0.13)	44.5 (0.1)	34.5
Recipe 2C	62.5	1.29 (0.13)	44.8 (0.3)	34.7
Recipe 2D	70	1.29 (0.13)	45.1 (0.4)	35.0
Recipe 2E	62.5	1.55 (0.18)	44.6 (0.0)	28.8
Phase 2				
All recipes	70	0.76 (0.06)	48.9 (0.8)	64.2

Note: values shown are mean values (standard deviations in parentheses).

TABLE 2.
Initial particle size analysis of phase 2 material

Recipe (unshredded:shredded)	D_{10} (mm)	D_{30} (mm)	D_{60} (mm)	C_U (D_{60}/D_{30})
100:0	1.5	3.6	8.0	5.3
67:33	1.1	2.0	4.7	4.3
33:67	1.1	2.3	4.1	3.7
0:100	0.9	1.8	3.2	3.6

Note: x% of particles smaller that D (mm).

TABLE 3.
Phase 1 recipe descriptions

	Feedstock (% of wet weight)				
Reactor	Straw	Unders	Lagoon Mixture	Water	Initial MC (%)
1A	100	NA	NA	NA	57
1B	70	NA	NA	30	70
2A	55	45	NA	NA	40
2B	41	34	NA	25	55
2C	34	28	NA	38	62.5
2D	27	22	NA	51	70
2E	32	25	43	NA	62.5

(NA = not added)

TABLE 4.
Phase 1 recipes used for comparisons

Research Questions	Recipes Used for Comparison
Impact of water addition	1A and 1B; 2A to 2D
Impact of under addition	1A and 2B; 1B and 2D
Impact of additional N source	2C and 2E

in an environmental chamber maintained at 55°C. The reactors were mixed and readjusted to target moisture contents twice each week. Depending on the recipe used, the initial amount of dry material in each reactor ranged from 80 to 150 g.

The Phase 2 experimental run lasted 180 days. This time frame was selected to represent a six-month composting season on the Canadian Prairies. The four recipes (in duplicate) were composted in 140 L plastic containers (Schaefer System International Limited, Compostainer Model, Brampton, Ontario, Canada). Three oxygen/temperature sampling ports, (1 cm diameter) located 10, 35, and 50 cm above the bottom of the container, were drilled into two sides of each container. The containers were placed in an environmental chamber where the average temperature and relative humidity for the duration of the experiment was 42.6°C and 41.7% respectively. Passive aeration (no forced aeration) was used. The contents of each reactor were removed each week for mixing, sampling, and moisture adjustments. The moisture content was maintained at 70% (wet basis). Loads were placed on top of the reactor contents to simulate stress fields at a 2.5 m depth within a windrow compost pile. The loads needed were calculated by first running a series of tests on each recipe to determine the wet bulk density in a 1.5 m diameter cylindrical container (Wizbicki 2002), with added loads of 3, 6, and 10 kPa. Using the equations found in McCartney and Chen (2001) a plot of compost pile depth versus free airspace (FAS) was prepared and loads were selected that resulted in an FAS of ≥30% for each recipe. The loads used from days 0 to 119 were 2.70, 3.54, 5.41, and 6.88 kPa (38.70, 50.75, 77.55, and 98.62 kg) for the 100:0, 67:33, 33:67, and 0:100 recipes, respectively. The loads were removed on day 119. The initial mass of straw used in each recipe was 15.3, 19.8, 29.9, and 31.7 kg for the 100:0, 67:33, 33:67, and 0:100 recipes, respectively.

Sampling

Initial samples were taken for both phases of the experiment. During Phase 1 the weight of the reactor contents and MC were determined twice per week. Phase 2 employed a weekly sampling protocol in which the contents of each reactor were spread out on a tarp and ten approximately equal random samples of 50 g each were taken to form a composite sample. Quartering techniques were then used to obtain a 50 g sample for analysis. The cumulative amounts of sample removed from each reactor throughout the entire composting period ranged from 4.5 to 9.1% of the initial dry weight. Temperature and oxygen measurements were taken using the three oxygen/temperature sampling ports. Reported values are an average of measurements taken from the three sampling ports for each reactor. Temperature measurements were taken daily from day 2 to day 56 only, at which time the temperature profile for each compost reactor was similar to that of the environmental chamber. To ensure oxygen was not limiting the reactions, it was originally intended to report on oxygen levels during the first 21 days, however, the oxygen data for the first 12 days was removed from the data set due to a malfunctioning oxygen probe. Pore space oxygen measurements were reported for a one-week period from day 13 to day 20.

Physical and Chemical Analyses

In Phase 1 of the experiment, MC was measured using an infra-red moisture balance (CSC Scientific Company, Inc., Fairfax, Virginia) with a 125-watt infrared lamp (McCartney and Tingley 1998). The 5 g samples used for moisture determination were returned to the reactor. Total solids (TS), volatile solids (VS), and fixed solids (FS) were determined using standard methods 2540 B and E (APHA 1995). The organic carbon (OC) content was calculated using equation 1:

$$OC = (1-FS)/1.8 \text{ (Haug 1993, Liao } et\ al. \text{ 1995)} \quad (1)$$

where OC and FS are based on the dry weight fraction. Total kjeldahl nitrogen (TKN) analysis was determined using the method of McGill & Figueiredo (1993). The C:N ratio was calculated using the OC and TKN values. For Phase 1, mass balances were conducted to determine VS reduction and N loss. Phase 2 fibre analysis was based on separate determinations of neutral detergent fibres (NDF), acid detergent fibres (ADF) and lignin. ADF (Komarek *et al.* 1993) and NDF (Komarek *et al.* 1994) were analyzed using the ANKOM Fibre Analyser #F200 (Fairport, New York). The NDF fraction, that material which is not solubilized by neutral detergent, is an estimate of total fibre content (lignin, cellulose, hemicellulose), while the ADF fraction, that material which is not solubilized by acid detergent, contains cellulose and lignin. Lignin was determined on the remaining material after ADF analysis and further treatment with

72% sulphuric acid (van Soest 1963). Results from NDF, ADF and lignin determinations were used to estimate contents of hemicellulose (NDF - ADF) and cellulose (ADF – lignin). Bulk density was determined using the procedures in method 07.01-A proposed by USCC (1997), with the exception that the vessel used had a diameter of 25cm and a height of 57cm. Particle density was determined using the water pycnometer method (Klute *et al.* 1986) with the exception that a 1 litre volumetric flask was substituted for the pyconometer in order to accommodate larger sample volumes. Details on FAS calculations can be found in Eftoda and McCartney (2002). Particle size analysis was completed using the ASTM standard method D 422-63 (ASTM 1990). Hand sieving was used with sieve screen sizes of 37.5, 19.0, 9.5, 4.75, 2.36, 1.18, 0.6, 0.3, and 0.15 mm (1.5, 0.75, 0.375, 0.187, 0.091, 0.0465, 0.0236, 0.0118, 0.00591 inches). Temperature and oxygen measurements were made using an oxygen-temperature probe (Demista Instruments Model No. OT-21, Mt. Prospect, Illinois).

Results And Discussion

Phase 1

A summary of the observations for the Phase 1 recipes is presented in Table 5. An increase in moisture content resulted in a greater VS reduction in the recipes consisting of only straw (1A & 1B). A similar trend was seen for the recipes using straw and unders: an increased VS reduction with increasing MC where VS reduction reached a maximum of 71.3% for recipe 2D. Figure 1 more clearly indicates the strong positive linear trend (R^2=0.9983) associated with MC for recipes 2A, 2B, 2C, and 2D. Using Figure 1, comparisons between recipes 1A and 2B and recipes 1B & 2D showed an increased VS reduction with the addition of unders to the compost mixture. The increased VS reduction, an indication of increased degradability, was likely due to better degradability of the unders material. Since decomposition occurs on particle surfaces, the smaller particle size of the unders increases the surface area available and therefore improves degradability.

TABLE 5.
A summary of observations for the Phase 1 recipes

Recipe	VS Reduction (%)	N Loss (%)	% Weight Reduction (dry basis)	Final C:N Ratio
1A	45.8	17.0	39.3	20.9
1B	58.2	8.5	48.9	14.2
2A	46.9	17.1	38.9	22.2
2B	58.7	18.8	48.7	17.6
2C	65.9	23.4	55.4	15.5
2D	71.3	18.6	58.8	12.3
2E	69.9	32.4	57.9	12.8

Note: characteristics shown are averages of duplicate reactors for each recipe.

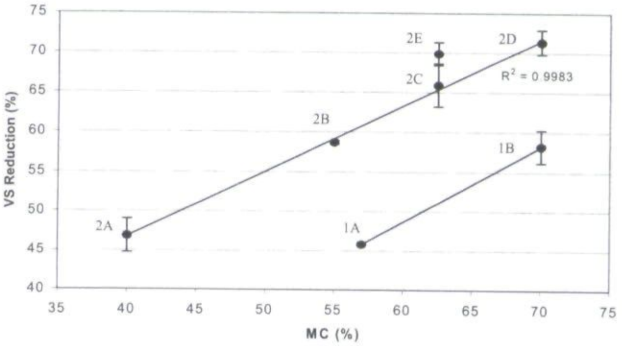

FIGURE 1. VS reduction versus moisture content for Phase 1 recipes (averages of duplicate reactors). Note: error bars represent ± one standard deviation of recipe duplicates.

It was also possible to assess the potential advantages of adding an inexpensive nitrogen source (livestock lagoon sludge) by analyzing VS reduction. Recipes 2C and 2E were compared to make this assessment. The initial N contents and C:N ratios are shown in Table 1. Figure 1 indicates that the added N in Recipe 2E did not result in a statistically significant advantage over Recipe 2C with respect to VS reduction. The starting recipe characteristics shown in Table 1 indicate a high N content of the straw material which resulted in a marginal difference in the initial C:N ratio of the two recipes. This probably reduced the expected advantages of the nitrogen addition.

Assuming the dry weight loss was due to VS losses, the VS removal profiles for the Phase 1 test period were calculated (data not presented). For recipes 1A and 1B, similar VS removals occurred in the first 20 days. Recipe 1B, with a higher MC, showed a greater overall reduction for the remainder of the experiment, resulting in higher VS removals (Table 5). This trend was similar for recipes 2A to 2D.

The N loss for each of the compost recipes is shown in Table 5. Comparison of recipes 1A & 1B (varying only in MC) indicated a smaller N loss for the recipe with a higher MC (recipe 1B). This comparison seems to agree well with theory, i.e. the higher moisture content in recipe 1B would act as a sink for the nitrogen, preventing volatilization losses. No statistical significance was noted between the straw-only recipes and the straw/unders recipes. No trend was observed between N loss and MC in the straw/unders recipes (recipes 2A through 2D).

Phase 2

Temperature monitoring for each compost reactor continued until day 56, at which point the temperature profile was similar to that within the environmental chamber. The average temperature within the environmental chamber was 42.6°C. Temperature maxima were reached on day 4 for all recipes and gradually decreased throughout the monitoring period. Average temperatures for the 100:0, 67:33, 33:67, and 0:100 recipes were 46.5°C, 48.9°C, 50.0°C, and 48.3°C from day 0 to 56, respectively. The 33:67 recipe exhibited the highest temperatures throughout the monitoring period. This could be attributed to a higher level of microbial activity (heat generation) and/or less heat loss as compared to the other recipes. A trend of decreasing oxygen levels with decreasing particle size was observed. Average oxygen levels (%) from days 13 to 20 were 17.5, 12.9, 10.0, and 8.9 for recipes 100:0, 67:33, 33:67, and 0:100, respectively. During the monitoring, all recipes exhibited pore space oxygen levels well above the minimum oxygen concentration of 5% suggested by Rynk *et al.* (1992).

Summaries of the Phase 2 material characteristics are presented in Tables 1 and 6. Bulk density of the material is an important design parameter. An analysis of the initial and final dry bulk densities indicated the recipe with the largest initial particle size (100:0) attained the largest increase in dry bulk density (10.9 times the initial) while recipes 67:33, 33:67, and 0:100 achieved increases of 10.4, 8.1, and 3.9 times their initial dry bulk density, respectively. The highest densities were observed in the recipes containing a mixture of shredded and unshredded material. Weight reduction also followed this trend with the exception that the 33:67 recipe showed a greater weight reduction than the 67:33 recipe. The initial and final C:N ratios were similar for the recipes.

The volume reductions for each recipe are shown in Figure 2. It should be noted that the results shown are an average of duplicate reactors for each recipe and do not take into account the amounts of material withdrawn for weekly sampling purposes. Also, the loads used to simulate a 2.5 m depth in a windrow compost pile were removed on day 119 of the experiment resulting in a slight fluffing of the compost material represented by a mild peak in Figure 2. Volume reductions of ≥50% were observed by day 50 for all recipes. The 67:33 and 33:67 recipes showed similar rates of volume reduction before stabilizing at approximately 10% of their initial volumes indicating the recipes with mixtures of unshredded and shredded straw were more conducive to rapid volume reduction. The 100:1 recipe did not exhibit the same rates of volume reduction as the 67:33 and 33:67 recipes, but also finished at approximately 10% of its initial volume. The 0:100 recipe showed the least amount of volume reduction (81%) perhaps owing to the smaller initial particle size. The differences in volume reduction could have important implications in the design of a full-scale straw composting operation.

TABLE 6.
Final compost characteristics of the Phase 2 treatments

Recipe (unshredded: shredded)	Dry Bulk Density (kg/m^3) Initial	Dry Bulk Density (kg/m^3) Final	Initial FAS (%)	% Weight Reduction (dry basis)	C:N Ratio Initial	C:N Ratio Final
100:0	20.1	219.5	87	77.5	64.2	13.5
67:33	31.4	327.0	79	73.6	64.2	11.1
33:67	49.1	399.5	68	74.3	64.2	9.4
0:100	58.0	225.7	62	67.3	64.2	10.7

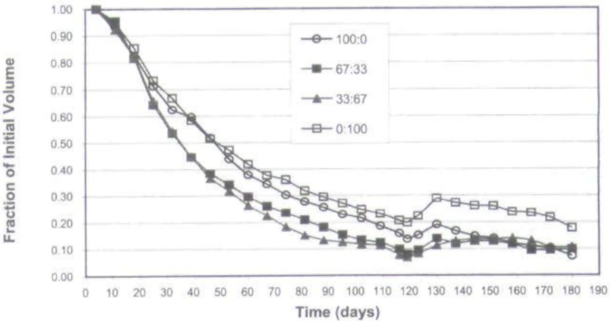

FIGURE 2. Volume reductions for Phase 2 recipes (averages of duplicate reactors).

Volatile Solids Reduction

A plot of volatile solids (%VS) for each recipe throughout the duration of the experiment is shown in Figure 3. Volatile solids (VS) decrease was most significant and rapid for the 33:67 recipe, which decreased from 88% to a final value of 58%. The 100:0, 67:33, and 0:100 recipes showed final VS values of 63, 61, and 65%,

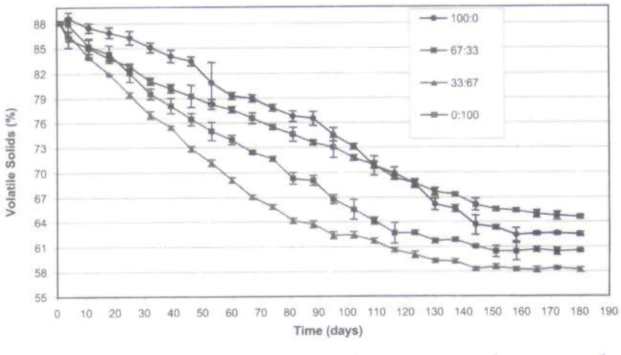

FIGURE 3. Volatile solids (%VS) for Phase 2 recipes (averages of duplicate reactors). Note: error bars represent ± one standard deviation of recipe duplicates.

respectively. VS decreases slowed significantly in all reactors after approximately 140 days. Total VS removals (mass balance basis) ranged from 25 to 35%. Eiland *et al.* (2001) evaluated the composting of *Miscanthus* straw and liquid pig manure in both open box and closed reactor systems. VS in the box system decreased from 75% to 68%. In the reactor system, VS decreased from 78% to 65%. VS slowed significantly at approximately day 120 in both systems. The total VS reductions in the Eiland *et al.* (2001) experiment ranged from 7 to 13%, much lower than the 25 to 35% observed in this experiment. Moisture content in systems in the Eiland *et al.* (2001) experiment were as low as 53% in the box system with final moisture contents of 80% for both systems. Also, temperatures in that experiment varied from 16°C to maxima of 65 to 70°C. The conditions in the present experiment may have been better suited for straw composting. Temperature was stable within the 40 to 50°C range (ideal for thermophilic fungi) and moisture content was controlled at 70% (±5%).

VS degradation in the 100:0 recipe may have been slowed by the larger initial particle size. The smaller particle sizes (and pore spaces) in the 0:100 recipe, coupled with a high moisture content of 70%, may have produced oxygen constraints which limited oxygen transport (McCauley and Shell 1956; Miller 1991; Hamelers 1992; Tseng *et al.* 1995; Richard 1996) and reduced the rate of decomposition (Richard *et al.* 1999). Pore space oxygen measurements from day 13 to day 20 seem to indicate, however, that oxygen levels were adequate (>5%). Some other factor not identified during the experiment may have contributed to this observation.

Fibre Degradation

The degradation of straw fibres (hemicellulose, cellulose, and lignin) during composting is shown in Figures 4, 5, and 6. As the homogeneity of the composting material increased (due to decreasing particle size) over the composting period, the within recipe variability decreased with time, as indicated by the error bars presented in Figures 4 to 6. Generally, fibre degradation was most rapid and complete for the compost recipes containing mixtures of unshredded and shredded straw. The 33:67 recipe performed the best, followed closely by the 67:33 recipe. Recipes containing pure unshredded (100:0) or shredded (0:100) straw showed the slowest rates of degradation.

Hemicellulose decreased from 1.72 g g^{-1} ash to zero by day 90 for the 67:33, 33:67, and 0:100 recipes and by day 110 for the 100:0 recipe. While hemicellulose was eliminated in this experiment, Eiland *et al.* (2001) observed that hemicellulose content only decreased to 6% of the initial hemicellulose content at the end of the composting period (190 days in the box system, 150 days in the closed reactor). In the experiment by Eiland *et al.* (2001), cellulose reached stable levels at day 50. Cellulose final levels of 36% and 30% of initial cellulose levels were determined for the box and reactor systems, respectively. As stated previously in the discussion of VS reduction, the conditions in the present experiment may have been better suited for straw composting. The stabilization of cellulose was most rapidly achieved by

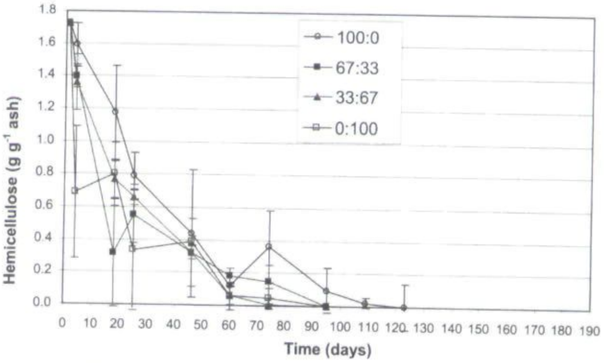

FIGURE 4. Hemicellulose degradation during Phase 2 composting (average of duplicate reactors). Note: error bars represent ± one standard deviation of recipe duplicates.

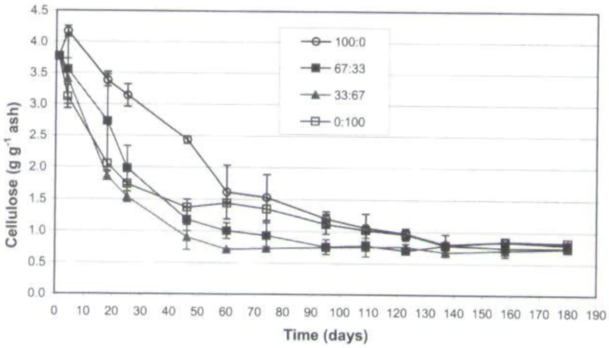

FIGURE 5. Cellulose degradation during Phase 2 composting (average of duplicate reactors). Note: error bars represent ± one standard deviation of recipe duplicates.

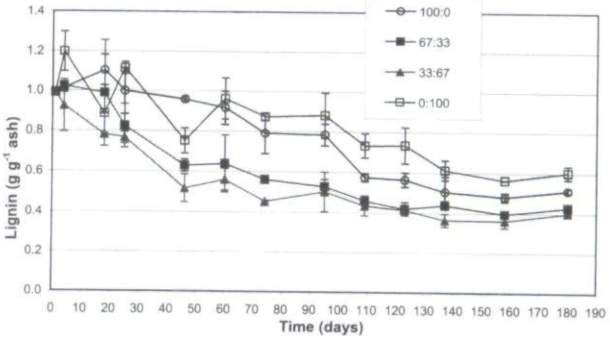

FIGURE 6. Lignin degradation during Phase 2 composting (average of duplicate reactors). Note: error bars represent ± one standard deviation of recipe duplicates.

the 33:67 recipe (day 60), followed by the 67:33 recipe (day 95), and the 100:0 and 0:100 recipes (day 137). By day 137, cellulose content had decreased from 3.75 to 0.75 g g^{-1} ash for all recipes, representing a loss of 80%.

Additionally, work reported by Epstein (1997) determined that after 153 days of composting, straw had lost approximately 33% of the hemicellulose and 50% of the cellulose initially present. No change in cellulose levels was observed before day 24 and the most rapid degradation occurred from day 24 to day 90. Results from the present experiment show that rapid degradation of hemicellulose and cellulose began early in the composting period (by day 4) and continued until approximately day 60.

Eklind (1998) evaluated the degradation of the fibre fraction as half-life times (50% degradation). In that evaluation, straw composting exhibited half-life times for hemicellulose and cellulose of 29 and 26 days, respectively. Eiland *et al.* (2001) observed half-life times for hemicellulose and cellulose of 21 and 100 days, respectively. Results for this study were similar to the straw-only composting in Eklind's (1998) experiment with half-life times for hemicellulose of approximately 20 days for all recipes, and cellulose half-life times of 50 days for the 100:0 recipe and 25 days for all the other recipes.

Epstein (1997) reported on the biochemical changes that occur during the composting of wheat straw. Cellulose and hemicellulose, constituting 45.32% and 35.69% of the initial dry weight, decreased to 13.27% and 16.98% of the original dry weight in 60 days. Also, the straw had lost 50% of its initial dry weight after 60 days of composting, essentially representing the loss of hemicellulose and cellulose. In the present study, cellulose and hemicellulose decreased from 42.47% and 19.65% of the initial dry weight to 22 to 30% and 0.5 to 5%, respectively after 60 days. All recipes had lost 50% of the initial dry weight by the 90th day of composting. After 180 days, cellulose had decreased to 30% of the initial dry weight while hemicellulose had been completely degraded.

The microbial enzymes catalyzing degradation of hemicellulose and cellulose are repressed by the presence of low-molecular weight carbon sources that are more easily metabolized than hemicellulose and cellulose (Madigan *et al.* 2000). This explanation supports the results obtained by Eiland *et al.* (2001) where, while composting straw with liquid pig manure, the metabolism of readily available carbon creating high metabolic rates resulted in a period of high temperature where hemicellulose and cellulose degradation was delayed. However, hemicellulose and cellulose degradation is noticed earlier for this experiment (day 4), indicating a lack of more easily degraded carbon.

The degradation of lignin was slower and less complete than hemicellulose and cellulose degradation in this experiment (Figure 6). Lignin content decreased from 1.0 to 0.4 g g^{-1} ash for the 67:33 and 33:67 recipes, 0.5 g g^{-1} ash for the 100:0 recipe, and 0.6 g g^{-1} ash for the 0:100 recipe. Lignin levels were approximately stable by day 140. In the work done by Eiland *et al.* (2001), no degradation of lignin was observed. It was hypothesized that this was caused by the presence of nitrogen in the final stage of the composting period, because lignin-degrading enzymes are induced by nitrogen limitation. The initial C:N ratios were 25 and 16 for the box and reactor systems, respectively. The initial C:N ratio in this study was 64.2, perhaps creating more ideal nitrogen-limiting conditions for lignin degradation.

One of the important implications of this research is the potential for decreased operating costs. While the experimental data showed that shredding will increase degradation rates, it is not necessary to shred all the material. A facility may achieve similar or even superior composting performance by only shredding half of the material before composting, resulting in significant cost savings. Further full-scale work should be completed to confirm the bench-scale work.

Summary and Conclusions

Phase 1 of the research was a preliminary investigation that employed small bench-scale compost reactors containing various recipes using the three feedstock materials (straw, process unders, and a livestock lagoon sludge) at different moisture levels in an attempt to gain an understanding of composting effectiveness and to aid in the selection of several recipes that could be used for larger-scale laboratory testing. The recipe variations used formed the basis for comparing the impacts of: 1) water addition; 2) unders addition; and 3) nitrogen addition in the form of a lagoon mixture. The Phase 1 small bench-scale results for this project indicated:

1) The VS reduction (indicating degradability) was greater for the compost recipes containing unders suggesting the possibility that unders are more easily biodegraded.

2) A clear trend emerged indicating that VS reduction was aided by an increase in moisture content for the straw and straw/unders recipes.

3) The advantages of adding a nitrogen source were limited when considering VS reduction. The N addition also resulted in a greater loss of N throughout the experiment. No trend emerged with respect to N loss with increasing moisture content for the straw/unders recipes.

Phase 2 was a larger-scale investigation focused on the composting of four recipes of varying straw particle sizes. The objectives for this phase were to investigate the effects of particle size on compost degradation and volume reduction and to monitor the rate and degree of degradation over a typical Canadian Prairie summer composting period (180 days) to estimate the degradability of straw. Based on the analysis of the observed data the following conclusions were made:

1) Degradation of volatile solids and lignocelluloses was most rapid and complete for recipes containing both shredded and unshredded straw, with the recipe containing 67% shredded straw and 33% unshredded straw performing the best.

2) Volume reduction reached approximately 90% for recipes containing either unshredded straw only or a mixture of unshredded and shredded straw.

3) Data suggests potential cost savings at full-scale facilities. While shredding will increase degradation rates, it is not necessary to shred all the material. Further full-scale work should be completed to confirm the bench-scale work.

Acknowledgements

Funding for this project was provided by the Waste Reduction and Pollution Prevention (WRAPP) fund from Manitoba Conservation. Straw was supplied by Dow BioProducts Ltd.

References

APHA. 1995. *Standard methods for the examination of water and wastewater, 19th Ed.* American Public Health Association. American Wastewater Association. Waste Environment Federation.

ASTM. 1990. Standard test method for particle-size analysis. D 422-63. Annual Book of ASTM Standards. Volume 04.08 Soil and Rock. ASTM. Philadelphia, Pennsylvania.

Eftoda, G. and D. McCartney. 2002. Correlating bench-scale FAS tests to full-scale windrow composting performance. *Proceedings of 2002 International Symposium on Composting and Compost Utilization*. Columbus, Ohio.

Eiland, F., M. Leth, M. Klamer, A.-M. Lind, H.E.K. Jensen and J.J.L. Iversen. 2001. C and N turnover and lignocellulose degradation during composting of *miscanthus* straw and liquid pig manure. *Compost Science and Utilization*, 9:186-196.

Eklind, Y. 1998. Carbon and nitrogen turnover during composting and quality of the compost product. PhD. Thesis. Agraria 93, Swedish University of Agricultural Sciences. Uppsala, Sweden.

Epstein, E. 1997. *The science of composting*. Technomic Publishing Co., Lancaster, Pennsylvania.

Hamelers, H.V.M. 1992. A theoretical model of composting kinetics. *In*: H.A.J. Hoitink and H. Keener (eds.). *Science and Engineering of Composting*. Columbus, Ohi, Renaissance Publications, pp. 36-58.

Haug, R.T. 1993. The practical handbook of compost engineering. Lewis Publishers. CRC Press, Inc., Boca Raton, Florida.

Klute, A. *et al.* 1986. Methods of soil analysis. American Society of Agronometry, Inc., Soil Science Society of America Inc., Madison, Wisconsin.

Komarek, A.R., J.B. Robertson and P.J. van Soest. 1993. A comparison of methods for determining ADF using the filter bag technique versus conventional filtration. *Proceedings of the National Conference on Forage Quality, Evaluation and Utilization*. Journal of Dairy Science, 77(suppl. 1).

Komarek, A.R., J.B. Robertson and P.J. van Soest. 1994. Comparison of the filter bag technique to conventional filtration in the van Soest NDF analysis of 21 feeds. *Proceedings of the National Conference on Forage Quality*. Evaluation and Utilization. Abstracts, p. 78, University of Nebraska, Lincoln, Nebraska.

Liao, P.H., A.T. Vizcarra, A. Chen and K.V. Lo. 1995. A comparison of different bulking agents for the composting of fish offal. *Compost Science and Utilization*, 3:80-86.

Madigan, M.T., J.M. Martinko and J. Parker. 2000. *In:* Brock, *Biology of Microorganisms*, Prentice Hall. New Jersey. pp. 227-228.

McCartney, D. and H. Chen. 2001. Using a biocell to measure effect of compressive settlement on free air space and microbial activity in windrow composting. *Compost Science and Utilization*, 9:285-302.

McCartney, D. and J. Tingley. 1998. Development of a rapid moisture content method for compost materials. *Compost Science and Utilization*, 6:3:14-25.

McCauley, R.F. and B.J. Shell. 1956. Laboratory and operational experiences in composting. *Proceedings of the 11th Industrial Waste Conference*, Purdue Univ. Eng. Bull. Series No. 91, pp. 436-453.

McGill, W.B. and C.T. Figueiredo. 1993. Total Nitrogen Method 22.2. *In: Soil sampling and methods of analysis*. Ed. M.R. Carter. Lewis Publishers, Boca Raton, Florida.

Miller, F.C. 1991. Biodegradation of solid wastes by composting. In: A.M. Martin (ed.). Biological Degradation of Wastes. Elsevier Applied Science, London, pp. 1-31.

Richard, T.L., L.P. Walker and J.M. Gossett. 1999. The effects of oxygen on solid-state biodegradation kinetics. *Proceedings of the Inst. of Biological Engineering* 2: A10-A30. IBE Publications, Athens, Georgia.

Richard, T.L. 1996. Oxygen transport [Online], Available: http://www.cfe.cornell.edu/compost/oxygen/oxygen.transport.html. [March 5 2002].

Rykens, B.A. 1977. Some possible uses of straw. Report on Straw Utilization Conference, Feb. 24-25, 1977, Oxford, England, UK.

Rynk, R. 1992. *On farm composting handbook.* NRA#S-54. Northeast Regional Agricultural Engineering Service, Ithaca, New York.

Tseng, D.Y., J.J. Chalmers, O.H. Tuovinen and H.A.J. Hoitink. 1995. Characterization of a bench-scale system for studying the biodegradation of organic solid wastes. *Biotechnol. Progr.*, 11:443-451.

USCC. 1997. Test methods for the examination of composting and compost. 1st Ed. The U.S. Composting Council.

Van Soest, P.J. 1963. Use of detergents in the analysis of fibrous feeds. Journal of Association of Official Analytical Chemists, 46:825-835.

Wizbicki, R. 2002. Effect of biocell diameter on the measurement of physical behavior of wood chips. Department of Civil Engineering Undergraduate Thesis. University of Manitoba. Winnipeg, Manitoba, Canada.