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BIOREMEDIATION OF A PCB-CONTAMINATED SOIL VIA COMPOSTING

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ABSTRACT

Polychlorinated biphenyls (PCBs) were widely used in the past and now contaminate many industrial and natural areas. In this study, a PCB-contaminated soil from a former paper mill was mixed with a yard trimmings amendment and composted in field scale piles to determine the effect of soil to amendment ratio on PCB degradation. Temperature, oxygen concentrations, and a number of other environmental parameters that influence microbial activity during composting were monitored. The PCBs in contaminated soil had a concentration of 16 ±1 mg/kg dw and an average of 4 chlorines per biphenyl. The soil was composted with five levels of yard trimmings amendment (14% to 82% by weight) in pilot scale compost piles (25 m^3) turned once per month. Results showed up to a 40% loss of PCBs with amendment levels of 60% and 82%. Congener specific PCB analysis indicated that less chlorinated PCB congeners (1-3 chlorines per biphenyl) were preferentially degraded. Bench-scale studies indicated that less than 1% of the PCBs in the contaminated soil were volatilized from composts during incubation with forced aeration at 55° C. In conclusion, PCB loss observed during the composting of the PCB-contaminated soil appeared to be largely due to biodegradation and not volatilization. Effective bioremediation of aged PCB-contaminated soils may require coupling of composting with additional remediation technologies to reduce levels of PCB congeners with greater than 4 chlorines.

KEYWORDS: composting, polychlorinated biphenyls, Aroclor, PCB, biodegradation, volatilization, paper mill sludge.

INTRODUCTION

PCBs (polychlorinated biphenyls) are a group of hazardous environmental pollutants classified as carcinogens by the US-EPA (Davila et al., 1993). Due to their widespread use and the lack of regulations governing their disposal in the past, PCBs now contaminate many industrial and natural areas. They are of great concern because of their environmental persistence in both terrestrial and aquatic environments. Although now banned in most areas, PCBs were used in the past as heat transfer fluids, dielectric fluids, flame retardants, solvent extenders, and ink carriers (De-voogt et al., 1984; Abramowitz, 1990; Davila et al., 1993). Commercial PCBs occur as complex mixtures containing over 100 different PCB congeners with varying degrees of chlorine substitutions on the biphenyl ring. For example, commercial PCB mixtures Aroclors 1242, 1254, and 1260 contain 42, 54, and 60% by weight chlorine. From 1957-1971, more than 20 million kilograms of a technical PCB mixture (Aroclor 1242) was used in the US in carbonless copy paper that contained approximately 26% PCBs by weight (de Voogt et al., 1984). PCBs were also used in newspaper as an ink carrier during this period.

Efficient microbial degradation of PCBs requires diverse metabolic activities due to the high number of congeners. In addition, degradation of PCBs has been shown to occur primarily via co-metabolism in that the microorganisms responsible for PCB transformation are unable to grow on PCBs as a sole carbon source (Abramowitz, 1990; Boyle et al., 1992) and require a co-substrate for microbial growth and degradation activity. Composting is one way to provide both a highly diverse microbial community with a range of metabolic capabilities and co-substrate(s) for PCB metabolism.

Composting offers an inexpensive and effective way to bioremediate contaminated soils (Williams and Keehan, 1993; Doyle et al., 1986; Funk et al., 1993). During composting, organic matter is rapidly degraded by a diverse community of microorganisms under predominantly aerobic conditions (Peters et al., 2000; Beffa et al., 1995; Michel et al., 2001; Michel et al., 1993). From 40 to 70% of the original organic matter present in composts is converted to carbon dioxide and water while the rest is transformed into humus (Michel et al., 1993). The substrates used in composting (such as grass, leaves, manure and other organic residues) are inexpensive and widely available. Compost addition to soils increases soil fertility and could be used to restore land in contaminated areas. Composting also offers the advantages of high temperatures which facilitate high rates of organic matter degradation, mass transfer and contaminant solubility, and changing physical/chemical microenvironments which support diverse organisms and metabolic activities (Beffa et al., 1995; Peters et al., 2000; Michel et al., 2001). Typically, costs for compost bioremediation range from \$50 to \$140 per ton (Cole, 1998). By comparison, a PCB-contaminated site remediation project utilizing a hazardous waste landfill was reported to cost approximately \$212 per ton (Pepper, 1995) and incineration costs for contaminated soils can be as high as \$550 per ton (Cole, 1998). Thus composting represents a potentially low cost and efficient management technology to reduce the concentration of PCBs in contaminated soils.

Snell (1982) reported that as much as 75% of a lower chlorinated PCB mixture (Aroclor 1221) added at a concentration of 500 mg/kg disappeared after 30 days of composting. More recently, Hogan et al. (1989), reported 83% disappearance of Aroclor 1232 (11 mg/kg) and 1.6% volatilization after 35 days of composting at 50° C. Lazzari et al. (1999) reported that the concentration of PCBs in a biosolids/wood waste compost increased from 53 ±2 ppb to 73 ±4 ppb on a dry weight basis after 90 days of composting, representing a PCB loss of approximately 9-15% when accounting for the 34-38% overall dry matter loss. However, there have been no studies to date on PCB degradation in contaminated soils (> 1000 ppb) during field scale composting. The objective of this project was to evaluate the field scale bioremediation of a PCB-contaminated soil with a yard trimmings composting amendment that is inexpensive and widely available. Laboratory scale composting experiments were also conducted using PCB-contaminated soil spiked with Aroclors (commercial PCB mixtures such as 1248) to determine the potential volatility of PCBs during composting.

MATERIALS AND METHODS

The site used for this project was a former paper-mill that produced boxboard and carton boxes. It is a 97 acre parcel that consists of seven lagoons (now dry), a drainage ditch network, a cinder disposal area, and two lagoon sludge disposal areas one of which was called the Southwest fill area. PCBs are ubiquitous at the site and have been detected in drainage ditch sediments, all seven lagoons, and both fill areas. The highest levels of PCBs (~290 ppm) were detected in the Southwest fill area and for this reason it was selected as the site for this study.

The congener profile of the PCBs in the contaminated soils (Figure 1) were most similar to Aroclor 1248 (although some highly chlorinated congeners found in Aroclor 1260 were also present). One of the feed stocks used at this mill was recycled paper possibly including PCB containing carbonless copy paper and/or newspaper and this likely was the source of the PCB-contamination in paper sludge soil at the site. In addition, the ubiquity of the PCBs support the idea that the PCB-contamination was not the result of an isolated spill, but was associated with paper processing.

Experimental Design

Excavated PCB-contaminated soil was composted in field scale compost piles to determine the effect of soil to amendment ratio on PCB degradation. A work pad (100’ by 150’) was constructed to accommodate seven experimental compost piles, two feed stock piles and to facilitate maneuvering heavy equipment such as excavators, trucks and shredders. An impermeable layer of 3mm plastic formed the floor of the pad and a drainage pipe conveyed leachate from the pad directly into an already PCB-contaminated lagoon. A slab of PCB-contaminated soil 15’ x 60’ x 5’ (167 yd^3) was excavated from the Southwest Fill Area and placed on the work pad. This excavated soil was mixed and used for all field and laboratory scale experiments.

Compost piles containing approximately 25 yd^3 of material were constructed with surface to volume ratios of 1.5-1.9 m^2/m^3, equivalent to those normally found in large scale windrows turned with a commercial straddle type windrow turner (Michel et al., 1996). The piles consisted of various mixtures of the excavated PCB-contaminated soil and a yard trimmings amendment. To assure adequate mixing, a mechanical shredder (Willibald MZA 3250) was used to prepare the compost mixes. Various amounts of contaminated soil and yard trimmings were measured by volume, fed into the shredder simultaneously to obtain a uniform mix, and formed into piles for composting. The percent weight of amendment and soil in each pile was calculated based on the measured bulk density of the feed stocks (Table 1).

Each month the experimental piles were remixed and turned with a front-end loader. To turn and mix the piles, they were broken down, mixed and reformed twice. This process was designed to simulate large scale windrow construction and turning wherein feed stocks are laid out in adjacent rows, then mixed, formed into continuous windrows, and turned using a dedicated windrow turner which has both a mixing and shredding action.

Temperatures were measured using an analog compost thermometer with a four foot probe at 1.5 and 3 foot depths in four locations of each pile on a weekly or biweekly basis to monitor the status of the composting process. Oxygen concentrations in the compost piles were monitored with a polaragraphic oxygen electrode at 1.5 and 3-foot depths at two locations in each pile.

To demonstrate a true reduction in PCB concentration as a result of remediation in heterogeneous materials such as compost, a large number of samples are required for analysis. Eight composite samples (~5 kg) were collected from each pile at different locations to compensate for sample variance. Samples were taken immediately after pile turning to assure that they were well mixed and representative. Samples were transported to Michigan State University (MSU) for the measurement of PCB concentrations as described below, and to the MSU soil testing laboratory for the measurement of organic matter content, ash content, moisture content, pH, bulk density, total nitrogen and carbon, C:N ratio and other parameters necessary for the overall monitoring of the composting process, as described by Michel et al. (1996). The concentrations of total K, Ca, Mg, P and trace elements were determined by plant tissue analysis using plasma emission spectroscopy according to the method of Jones (1977). Seed germination and growth trials were done by Woods End Research Lab (Mt. Vernon, Maine).

Non-polar, acid extractable, and ash fractions of the PCB contaminated soil, the yard trimmings amendment, and a finished compost were determined by proximate carbon analysis (Crohn and Bishop, 1999; Michel et al., 1993) using 50 gm samples.

PCB analysis

PCBs in compost and other samples were analyzed by capillary gas chromatography (Quensen et al., 1990). Compost sub samples (20 g) were transferred to cellulose thimbles, spiked with a surrogate (initially 246-246-CB, later tribromobenzene), and Soxhlet extracted overnight (~20 h) with hexane:acetone (1:1, vol:vol). Following extraction, the solvent volume (initially ~125 ml) was reduced to ~20 ml on a rotary evaporator. The solvent extract was then transferred to a separatory funnel for the first part of the sample cleanup procedure. The sample was then dried and ashed so that PCB concentration could be determined on a per gram ash and per gram dry weight basis.

Chromatographic analysis was performed using Hewlett Packard GC Chemstation (Rev A.04.02) with an HP-5890 GC, HP-7673A auto sampler, 15 m HP-5 capillary column (0.32 mm ID and 0.25 µm film thickness) and electron capture detector. Two microliter samples were injected into the GC using the split injection technique. The split ratio was approximately 10:1, the inlet temperature was 200°C, and the detector temperature was 325°C. The oven program was 140°C for 1 min, ramped 2°C/min to 230°C, then 30°C to 300°C and held for 15 minutes. The high temperature and long hold time were required to allow interfering compounds to elute from the column prior to the next injection. Quantification was performed using a 3 level calibration table and standards consisting of a mixture of Aroclors 1242 and 1260 fortified with the surrogates; 2-CB, 3-CB, 4-CB, 2-2-CB, and 26-CB (Quensen, 1990).

To determine the extent of PCB degradation, the samples were compared based on the amount of PCBs per gram dry weight (ppm) as well as the amount of PCBs per gram of ash (PCB/g ash). This was necessary because during composting up to 50% of the dry weight may be lost as CO_2 potentially leading to a misleading increase in the concentration of PCBs when measured as PCB/g dry weight as observed by Lazzari et al. (1999). Ash, on the other hand, remains relatively constant during composting. So, by comparing the initial amount of PCB/g ash, to the final amount of PCB/g ash in each pile, the actual loss of PCBs due to composting could be determined.

Lab Experiments

To determine the extent of PCB volatilization during composting, experiments were conducted using 4 liter lab-scale composter reactors with flow restrictors that allowed precise control of the air flow rate (Michel et al., 1995). The air was pre-humidified at the composting temperature to minimize compost drying and maintain optimal moisture conditions. The exit gas from the composters flowed through florisil and/or polyurethane foam plugs to trap volatilized PCBs (Chiarenzelli et al., 1997; Michel et al., 1996), and then through a KOH solution to trap evolved CO_2. The temperature of the system was controlled at 37° or 55° C to simulate conditions found during large scale windrow composting. The trapped PCBs were Soxhlet extracted using hexane:acetone 9:1, and quantified as described above.

RESULTS AND DISCUSSION

Properties of the PCB-contaminated soil

The properties of the excavated soil and starting compost mixes are presented in Table 1. The soil (Pile F, Table 1) had a moderate C:N ratio of 40, a moisture content of 62%, an acidic pH of 4.8 and a bulk density of 875 kg/m^3. The organic matter content of the soil was 40%, nearly half of which consisted of an acid extractable fraction (Figure 2) that are consistent with cellulose and hemicellulose components of a paper mill sludge. The soil contained a high weight percent of organic ($MeCl_2$) extractable material relative to the yard trimmings amendment and composted yard trimmings (Figure 2). Approximately 5% by weight of the soil was organic solvent extractable, compared to less than 0.5% of the soil and compost indicating relatively high levels of non-polar organics other than PCBs in the soil (Figure 2). The total PCB concentration of this soil ranged from 10 to 30 ppm with an average (S.E.) of 16 ± 1 mg/kg dry weight.

Selection of Composting Amendments

For large-scale bioremediation via composting, a readily available, inexpensive, and compostable amendment is required. The amendment must make up for nutritional and physical deficits of the contaminated soil. For example, the amendment should provide readily degradable carbon to fuel co-metabolism of the pollutants by the microbes, nitrogen for the growth of microbial biomass, and physical structure to allow airflow and increase porosity of the soil (Rynk et al., 1991). The target C:N ratio for the piles was 30:1, with a moisture content of 55%. Large amounts of inexpensive and compostable yard trimmings are readily available in Michigan and other states and these complement the properties of the contaminated soil. The yard trimmings used in this study contained a mixture of leaves, fresh grass, and brush at a 2:1:1 volume ratio.

The properties of the yard trimmings amendment used for the first set of field experiments are presented in Table 1 (Pile G). The yard trimmings had a somewhat lower organic matter content as compared to yard trimmings collected in a previous study (Michel et al. 1996). However the low moisture content, and low bulk density of the yard trimmings provided porosity and drying for the wet, dense, contaminated soil.

Effect of yard trimmings amendment level on PCB degradation during composting

Seven compost piles were constructed to determine the effects of soil to amendment ratio on PCB degradation. The piles consisted of mixtures of the excavated PCB-contaminated soil, and yard trimmings amendment at levels of 14%, 27%, 39%, 60%, and 82%. These were called piles A, B, C, D, and E respectively (Table 1). One pile with 100% contaminated soil (Pile F) and one with 100% yard trimmings (Pile G) were also constructed as controls.

The addition of yard trimmings to contaminated soil led to the development of elevated temperatures indicating active composting (Figure 3A). The maximum temperature in Pile A, which contained only 14% yard trimmings, was 45° C. Temperatures in Piles receiving 60% and 82% yard trimmings (Piles D and E) reached 60° C. By contrast, un-amended PCB-contaminated soil (Pile F) did not generate temperatures significantly above ambient levels. The highest temperature of 70° C was observed in the pile containing only yard trimmings (Pile G, Figure 3A).

Since composting is largely an aerobic process, efficient air movement through the compost piles is required to maintain sufficient oxygen levels for aerobic microorganisms and to prevent the development of anaerobic conditions and odor generation during composting (Michel et al., 1996; Rynk, 1992). Our data indicated that a substantial amount of the interstitial oxygen was depleted during composting (Figure 3B), but that the interstitial gas within the experimental piles was not completely depleted of oxygen and remained aerobic during composting as evidenced by oxygen concentrations above 2% (Figure 3B).

The levels of total PCBs and individual PCB congeners were determined on days 0, 70, 119, and 370 days of composting. After 370 days, up to 40% total PCB loss was observed (Pile E) although considerable sample variation was seen (Figure 4). Much of the decrease in PCB concentration occurred during the first 70 days of composting (Figure 4). The percent PCB degradation was linearly correlated (r^2=0.75) to the amount of amendment added to the soil (Figure 5). As compared to the level of PCBs in the contaminated soil (16 mg/kg dry weight) PCB levels fell to below 3 (mg/kg dry weight) in the final compost (Pile E). Part of this decrease is attributable to loss during composting while the remainder is due to dilution of the contaminated soil with the yard trimmings amendment.

Less chlorinated congeners (1-3 chlorines per biphenyl) appeared to be preferentially degraded during composting while more highly chlorinated congeners (>4 chlorines per biphenyl) were less degradable (Table 2). In Pile D the concentration of PCBs with 1 to 3 chlorine substitutions dropped from 4.6 ±0.6 mg/kg ash to 1.1 ±0.1 mg/kg ash representing a loss of 72%. No significant loss of congeners with more than 3 chlorine substitutions was observed in any of the piles (Table 2). These findings are consistent with previous studies of bacterial PCB degradation showing that under aerobic conditions, highly chlorinated PCB congeners are recalcitrant (Boyle, et al., 1992; Abramowitz, 1990).

Since compost would ultimately be used to restore topsoil at the site, tests were conducted to compare the ability of the un-amended and uncomposted PCB-contaminated soil, composted PCB-contaminated soil, and compost alone to support plant germination and growth. Samples were tested with a seven-day seedling trial to measure the phytotoxicity of a selection of the composted PCB-contaminated soil samples. The results indicated that all of the samples supported excellent seed germination of both Wheat and Cress relative to an optimized soil test media (Table 3). However, the samples varied in the amount of plant growth they supported. Nine out of ten composted contaminated soil samples supported fair to good plant growth while the uncomposted PCB-contaminated soil alone exhibited poor plant growth (Table 3). Additionally, it was observed that in field scale piles the excavated soil supported almost no plant growth over a three-year period while prolific plant growth was observed after only a few months on a compost pile constructed from PCB-contaminated soil and yard trimmings. It should be pointed out that the poor plant growth may have been due to factors other than PCBs such as the high Zn and acidic conditions observed in the contaminated soil (Table 1). Nevertheless, these results indicate that in addition to reducing PCB levels, composting improved the ability of the contaminated soil to support plant growth. Since plants channel nutrients to roots and the soil via root exudates, planting in composted PCB-contaminated soils could potentially provide nutrients for soil PCB degrading microorganisms on a long-term basis. Therefore composting, followed by phytoremediation, may be a strategy worth further research to improve the extent of degradation of PCBs in contaminated soils.

Volatilization of PCBs during composting

The extent of PCB loss due to volatilization is an important factor to consider when evaluating composting as a bioremediation option. The elevated temperatures generated during composting, and the convection of air through compost piles, could potentially increase the extent of PCB volatilization from contaminated soils. Numerous studies have implicated atmospheric volatilization as one of the fates of environmental PCBs (Chiarenzelli, et al., 1997). Hogan et al. (1989), reported that 1.6% of a low chlorinated Aroclor mixture (Aroclor 1232) was volatilized after 35 days of composting at 50° C; however, the extent of volatilization of higher chlorinated mixtures such as Aroclor 1248, 1254 and 1260 from composts has not previously been determined. Measurement of PCB volatilization during field scale composting is technically difficult. Therefore, laboratory scale experiments were conducted to estimate the extent of PCB volatilization during the composting of the PCB-contaminated soil at composting temperatures for periods similar to those found in the field scale piles (Figure 3A). Results indicated that less than 1% of the PCBs present in the soil were volatilized during lab scale composting at temperatures of 55 C for up to 50 days with forced aeration at a rate much greater than that occurring in the naturally ventilated piles (data not shown).

CONCLUSIONS AND PERSPECTIVES

This study represents the first field scale demonstration of the degradation of PCBs in a contaminated soil during composting. Up to a 40% loss of total PCBs was observed during field scale composting of the PCB-contaminated soils. Congeners with up to 3 chlorines were preferentially degraded during composting. Little or no loss of higher chlorinated congeners (>4 chlorines per biphenyl) was observed.

Since extensive degradation of lower chlorinated PCBs (1-3 chlorines) occurs during composting under aerobic conditions, to effectively bioremediate the PCB-contaminated soil, composting would have to be coupled with additional remediation technologies capable of reducing PCB congeners with greater than 4 chlorines. For example, prior anaerobic treatment could yield a PCB mixture with less chlorinated congeners (Quensen et al., 1990) and this may be more amenable to bioremediation by composting. PCB dechlorination is known to occur under anaerobic conditions, however the biphenyl ring is not degraded to a significant extent and lower chlorinated congeners accumulate. Therefore, anaerobic treatment followed by composting may be an approach that deserves further study.

Results indicated that a considerable amount of plant growth occurs on composted PCB-contaminated soil while no growth was observed on PCB-contaminated soil alone. Plant growth channels nutrients from the plant roots into the soil and provides a nutrient source for soil microorganisms on a continuous basis. Composting, followed by phytoremediation, may be another useful strategy for improving the extent of degradation of PCBs on a long-term basis.

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Table 1. Initial properties of compost piles made from yard trimmings and PCB-contaminated soil[a].

	Pile						
	F	**G**	**A**	**B**	**C**	**D**	**E**
Contaminated Soil (%)	100	0	86	73	61	40	18
Yard Trimmings (%)	0	100	14	27	39	60	82
Bulk Density (kg/m^3)	875	440	630	540	590	480	430
PCB (mg/kg dw)[b]	16.3 ±0.8	0.0 ±0.0	14.3 ±0.4	14.7 ±0.3	12.7 ±0.4	8.9 ±0.1	6.8 ±0.1
Moisture%	61.9 ±1.5	34.4 ±2.0	52.3 ±1.5	48.1 ±0.3	44.3 ±0.8	37.0 ±1.1	32.7 ±1.3
OM%	40.5 ±2.2	32.1 ±2.2	35.7 ±3.0	33.6 ±0.5	33.0 ±0.3	31.2 ±0.8	35.0 ±0.6
pH	4.81 ±0.07	8.18 ±0.15	6.80 ±0.08	7.35 ±0.09	7.65 ±0.13	7.74 ±0.04	7.90 ±0.03
Carbon (%)	25.4 ±1.8	18.7 ±1.1	21.9 ±0.5	21.0 ±0.4	20.3 ±0.5	16.9 ±0.4	17.8 ±0.5
Nitrogen (%)	0.66 ±0.04	0.78 ±0.06	0.74 ±0.03	0.71 ±0.01	0.85 ±0.12	0.85 ±0.03	0.94 ±0.03
Nitrate (ppm)	1.0 ±16.1	68.6 ±0.6	7.7 ±1.0	39.1 ±27.4	26.1 ±4.6	51.9 ±11.7	64.2 ±14.8
C/N ratio	39.8 ±2.6	24.5 ±2.1	29.8 ±1.3	29.8 ±0.6	26.4 ±2.3	19.9 ±0.5	18.8 ±0.7
Phosphorus (%)	0.07 ±0.04	0.17 ±0.01	0.11 ±0.01	0.12 ±0.01	0.17 ±0.04	0.14 ±0.01	0.14 ±0.01
Potassium (%)	0.05±0.07	0.62 ±0.01	0.14 ±0.01	0.22 ±0.01	0.39 ±0.09	0.44 ±0.03	0.51 ±0.03
Calcium (%)	0.09 ±0.27	1.29 ±0.06	0.62 ±0.03	0.91 ±0.06	1.64 ±0.25	2.25 ±0.23	2.56 ±0.33
Magnesium (%)	0.05 ±0.05	0.25 ±0.03	0.22 ±0.02	0.27 ±0.03	0.60 ±0.13	0.83 ±0.17	0.67 ±0.18
Sodium (%)	0.05 ±0.01	0.08 ±0.00	0.08 ±0.01	0.07 ±0.01	0.07 ±0.01	0.09 ±0.01	0.08 ±0.01
Boron (ppm)	4.7 ±0.9	21.6 ±0.5	9.6 ±0.5	15.2 ±0.6	15.4 ±1.5	17.8 ±0.8	21.4 ±0.7
Zinc (ppm)	1476 ±13	114 ±567	403 ±21	325 ±9	319 ±21	261 ±7	231 ±12
Manganese (ppm)	9 ±25	201 ±1	48 ±2	88 ±6	117 ±8	195 ±17	200 ±13
Copper (ppm)	17 ±4	37 ±1	22 ±1	27 ±1	25 ±1	34 ±2	39 ±2
Iron (ppm)	572 ±264	3344 ±76	1102 ±41	1327 ±77	1983 ±157	2689 ±158	3019 ±197
Aluminum (ppm)	5816 ±110	1673 ±993	7671 ±307	6510 ±173	6076 ±645	5426 ±225	4190 ±205

a-values are averages for eight samples ± one standard deviation on a dry weight basis except where indicated.
b-values are averages for eight samples ± standard error on a dry weight basis.

Table 2. Degradation of PCB congeners with different degrees of chlorine substitution during composting of PCB-contaminated soil amended with yard trimmings[a].

Pile[b]	Compost Amendment (dw %)	Day	Number of chlorines in PCB congeners and PCB concentration (mg/kg ash)		
			1 to 3 Cl/ PCB	4 to 5 Cl/PCB	6 to 8 Cl/PCB
F	0.00	0	7.3 ±0.8	14.0 ±1.7	6.0 ±2.3
		370	5.2 ±0.8	18.3 ±2.9	5.6 ±1.9
A	0.14	0	7.1 ±0.7	11.7 ±1.1	3.4 ±0.8
		370	3.0 ±0.2	13.2 ±0.9	4.7 ±0.8
B	0.27	0	7.1 ±0.5	11.6 ±1.5	3.4 ±0.4
		370	2.9 ±0.5	11.4 ±1.6	3.2 ±0.6
C	0.39	0	5.3 ±0.7	10.9 ±2.0	2.7 ±0.5
		370	2.4 ±0.3	8.3 ±0.6	2.6 ±0.3
D	0.60	0	4.6 ±0.6	6.3 ±0.7	2.0 ±0.2
		370	1.1 ±0.1	7.5 ±0.9	2.0 ±0.2
E	0.82	0	3.5 ±0.5	4.7 ±0.8	2.2 ±0.8
		370	1.0 ±0.2	3.8 ±0.5	1.5 ±0.2

a- Values are means of nine measurements **±** standard error reported on an ash basis.

b- See Table 1 for the composition of each Pile. Pile F is a control pile with no amendment added.

Table 3. Germination and seven day seedling growth trial[a] using PCB-contaminated soil composted with yard trimmings.

	Germination[b] (% of control)		Weight per plant[c] (% of control)	
Sample	Wheat	Cress	Wheat	Cress
Compost on Day 370[d]	93	100	82	87
Contaminated soil (1)	98	88	79	62
Contaminated soil (2)	98	88	54	65
Pile C on day 370	93	94	67	78
Pile D on day 119	98	98	71	80
Pile E on day 370	98	93	68	86
Pile E on day 700	98	90	74	74
Pile K on day 90	90	94	59	74

a-Values represent percent of an optimized growth medium control (Pro-Mix).
b-Values greater than 85 are considered not phytotoxic.
c- Phytotoxicity classification values; **>90 Excellent, 80-90 Good, 64-80 Fair, <65 Poor**.
d-Pile G day 370 as given in Table 1.

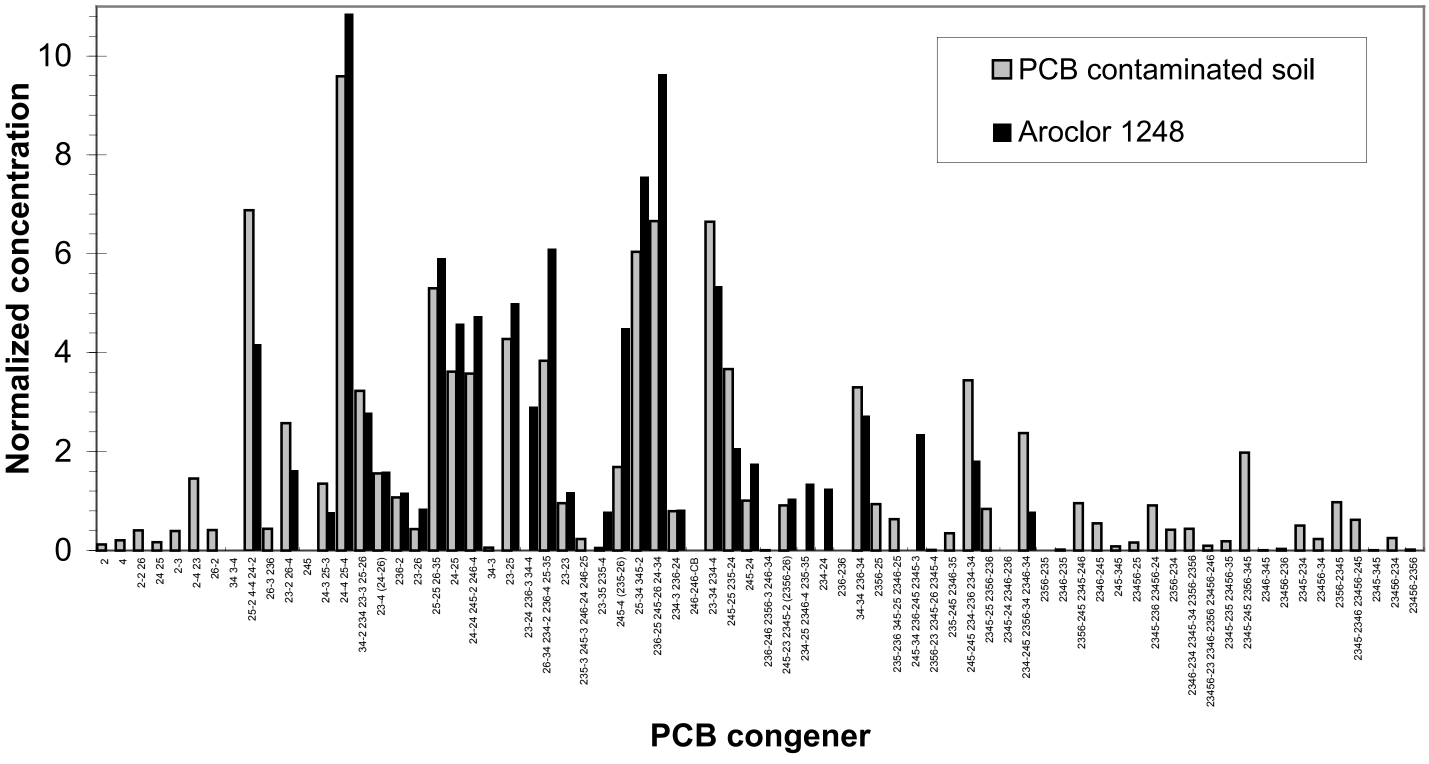

Figure 1. Comparison of PCB congener profiles in a PCB-contaminated soil with that of commercial Aroclor 1248.

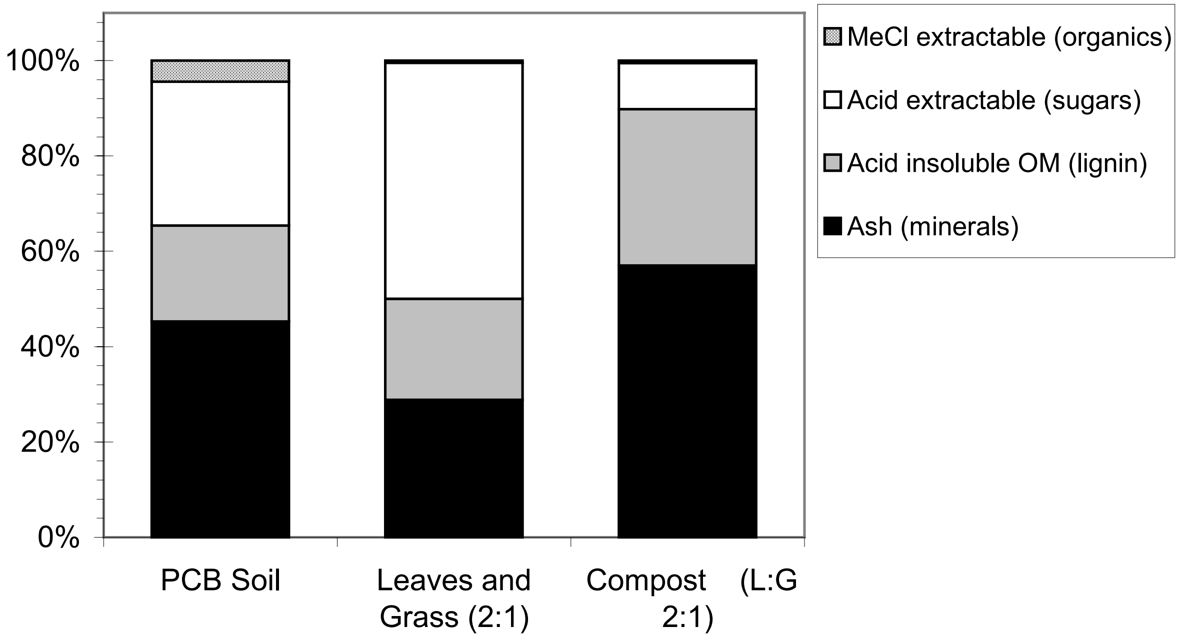

Figure 2. Proximate carbon analysis of a PCB contaminated soil, a yard trimmings amendment and a finished yard trimmings compost.

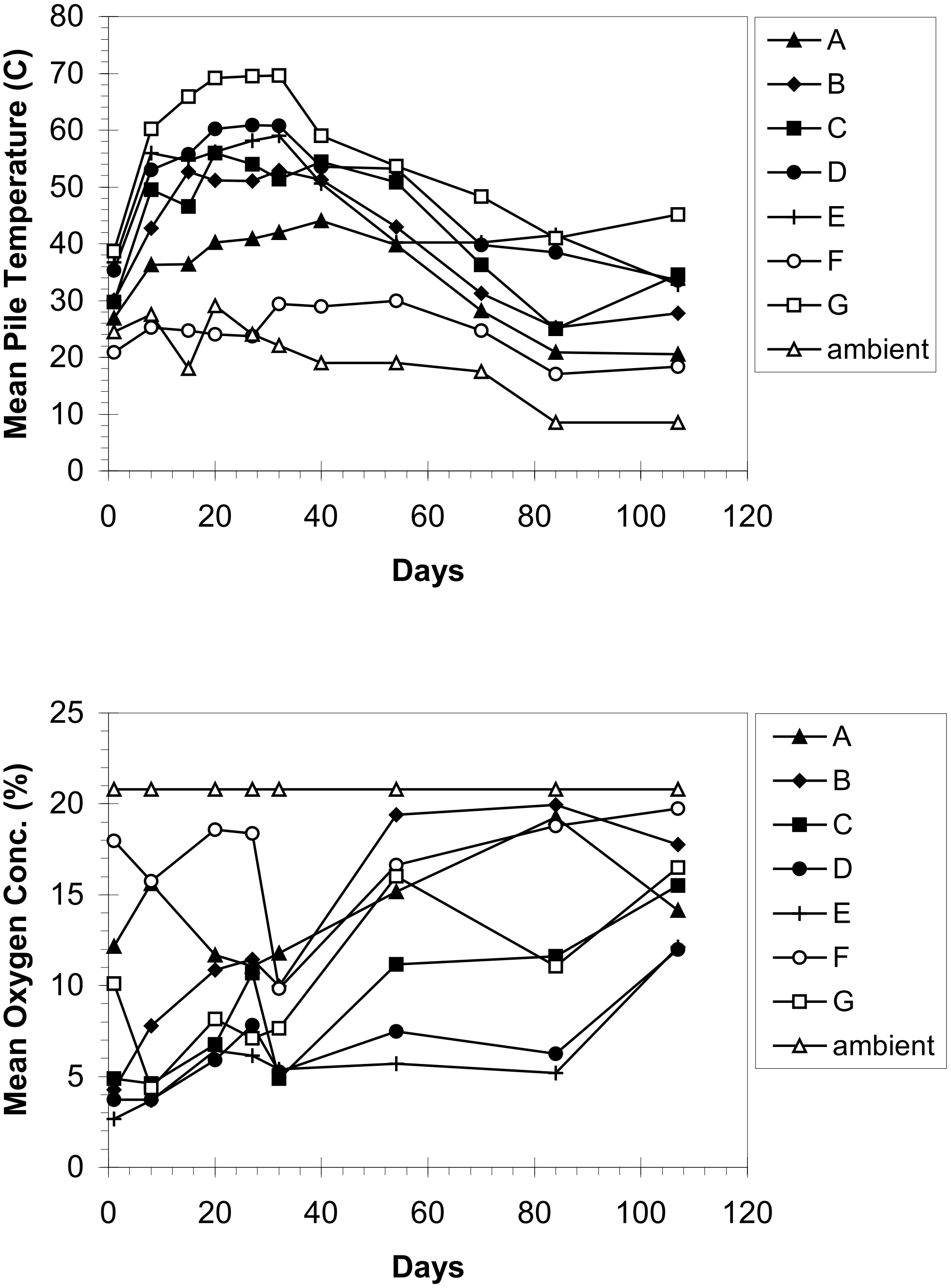

Figure 3. **A.** Mean pile temperature during the composting of mixtures of yard trimmings and PCB-contaminated soils. Each value represents the mean of 8 different measurements. **B.** Mean pile oxygen concentrations during the composting of mixtures of yard trimmings and PCB-contaminated soils. Each value represents the mean of six measurements. Ambient oxygen concentrations are plotted for comparison. See Table 1 for a description of piles A-G.

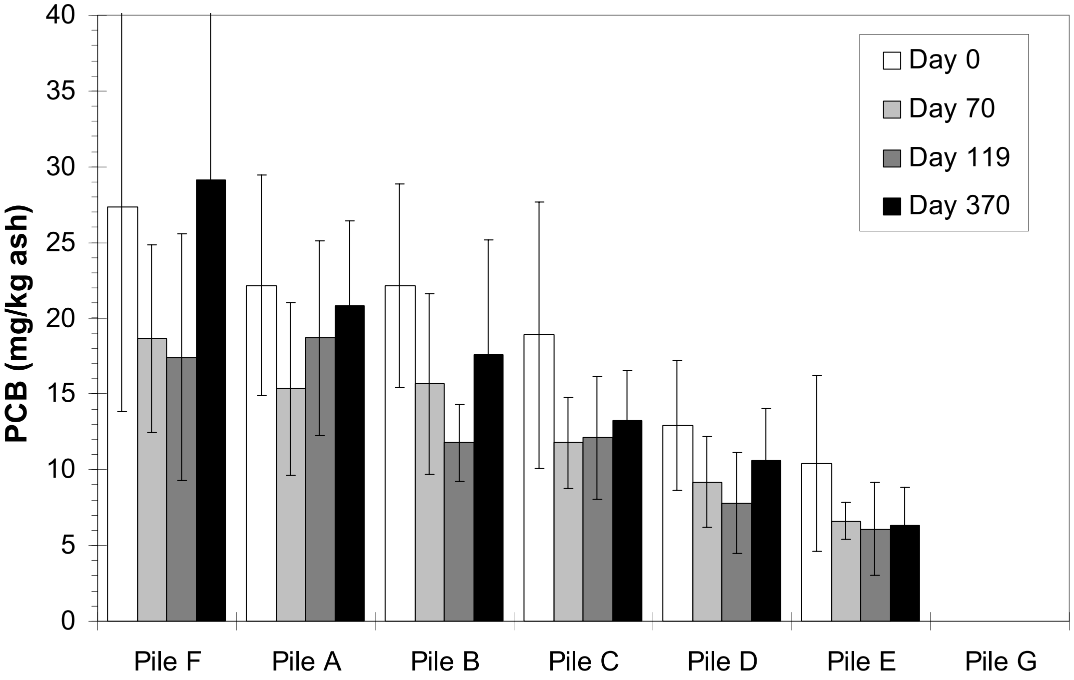

Figure 4. Average PCB concentrations in pilot scale compost piles A to G from day 0 to 370 (see Table 1 for descriptions). Values are averages for eight samples. Error bars represent one standard deviation. Values are in units of mg/kg ash.

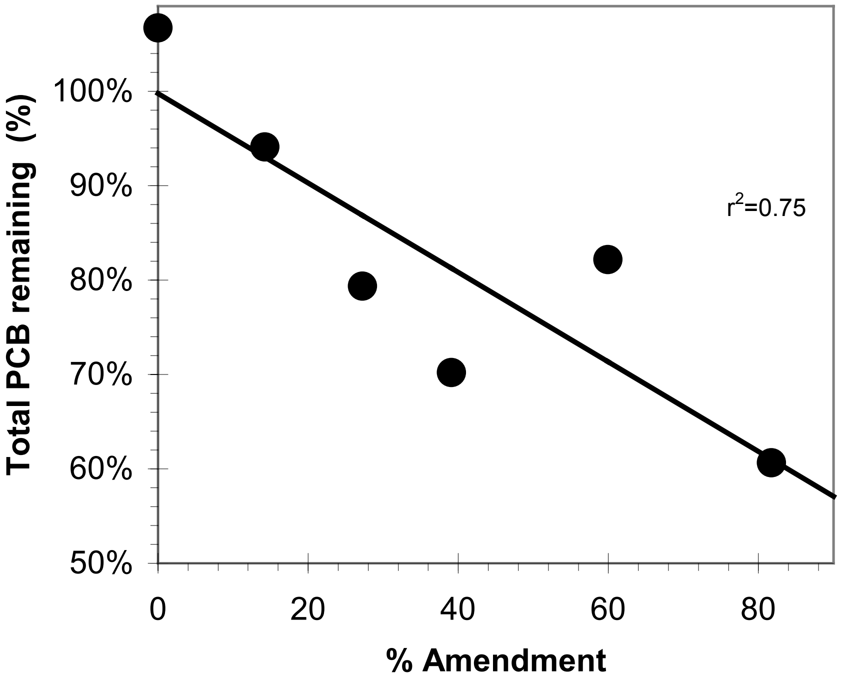

Figure 5. Effect of amendment level on the extent of PCB loss during composting of a PCB-contaminated soil. Soil was amended with yard trimmings as shown on the x-axis.