United States
Environmental Protection
Agency

Solid Waste
and Emergency Response
(5306W)

EPA530-R-98-008
April 1998

An Analysis of Composting As an Environmental Remediation Technology

Printed on paper that contains at least 20 percent postconsumer fiber.

Chapter 1

Introduction

The composting process is currently viewed primarily as a waste management method to stabilize organic waste, such as manure, yard trimmings, municipal biosolids, and organic urban wastes. The stabilized end-product (compost) is widely used as a soil amendment to improve soil structure, provide plant nutrients, and facilitate the revegetation of disturbed or eroded soil (Cole, 1994; Cole, 1995; Harmsen, 1994; McNabb, 1994). The information and data presented in this document were compiled and analyzed by Michael A. Cole, Ph.D.

Within the past few years, laboratory-, greenhouse-, and pilot-scale research has indicated that the composting process and the use of mature compost also provide an inexpensive and technologically straightforward solution for managing hazardous industrial waste streams (solid, air, or liquid) and for remediating soil contaminated with toxic organic compounds (such as solvents and pesticides) and inorganic compounds (such as toxic metals). For example, a large number of hydrocarbons, which are common industrial contaminants found in soil and exhaust gas, degrade rapidly during the composting process or in other compost-based processes. Furthermore, the addition of mature compost to contaminated soil accelerates plant and microbial degradation of organic contaminants and improves plant growth and establishment in toxic soils. When mature compost is added to contaminated soils, remediation costs are quite modest in comparison to conventionally used methods. Mature compost also controls several plant diseases without the use of synthetic fungicides or fumigants.

This report summarizes the available information on the use of compost for managing hazardous waste streams (as well as other applications) and indicates possible areas for future investigations. Attention to cross-media transfer of contaminants during implementation of various bioremediation technologies presented in this report is recommended. A recent publication by the U.S. Environmental Protection Agency (EPA), entitled *Best Management Practices (BMPs) for Soil Treatment Technologies* (EPA530-R-97-007, May 1997), could be consulted to address the cross-media transfer concerns.

The Composting Process

Composting is a managed system that uses microbial activity to degrade raw organic materials, such as yard trimmings, so that the end-product is relatively stable, reduced in quantity (when compared to the initial amount of waste), and free from offensive odors. Composting can be done on a large or small scale, with the management requirements and intensity increasing dramatically as system size increases. In its simplest form, compostable material is arranged in long rows (windrows) and turned periodically to ensure good mixing (Figure 1). This process can handle large quantities of input, such as yard trimmings of up to 100,000 cubic yards per year, on only a few acres of land.

Raw materials that tend to be very odorous during composting, such as municipal waste sludge (biosolids), can be processed in more elaborate systems and in a confined facility where odorous air can be treated. These systems use rotating drums, trenches, or enclosed tunnels for initial processing, followed by a covered curing period (Figures 2, 3, and 4). In addition, the Beltsville Agricultural Research Center in Beltsville, Maryland, developed a composting system of intermediate complexity, between open-air windrows and the sophisticated systems shown in Figures 2 to 4 (Parr, 1978; Willson, 1980; U.S. EPA, 1985). The Beltsville system has several desirable features, and its generic design is adaptable to suit specific purposes. As shown in Figure 5, air is drawn through the compostable material and scrubbed of odorous compounds in a soil filter. Mature compost can be substituted for the soil filter. A compost filter has several advantages over a soil filter, including a higher adsorptive capacity for volatile organic compounds (VOCs) and better air permeability properties. Compost filters are currently used in Europe at composting plants to eliminate nearly all volatile emissions.

All composting methods share similar characteristic features and processes. Initially high microbial activity and heat production cause temperatures within the compostable material to rise rapidly into the thermophilic range (50 ^{o}C and higher). This temperature range is maintained by periodic turning or the use of controlled air flow (Viel, 1987). After the rapidly degradable components are consumed, temperatures gradually fall during the "curing" stage (Figure 6). At the end of this stage, the material is no longer self-heating, and the finished compost is ready for use. Substantial changes occur in microbial populations and species abundance during the various temperature stages (Gupta, 1987). Mesophilic bacteria and fungi are dominant in the initial warming period, thermophilic bacteria (especially actinomycetes) during the high temperature phase, and mesophilic bacteria and fungi during the curing phase

(Finstein, 1975). The resulting compost has a high microbial diversity (Beffa, 1996 and Persson, 1995), with microbial populations much higher than fertile, productive soils (Table 1) and many times higher than in highly disturbed or contaminated soils. Therefore, compost bioremediation takes far less time than natural attenuation of toxic materials (land farming). Microbial populations in soil (both fertile and contaminated) substantially vary from season to season. In most cases, the addition of compost greatly increases microbial populations and activity (Table 2). Since the microbes are the primary agents for degradation of organic contaminants in soil (Alexander, 1994), increasing microbial density can accelerate degradation of the contaminants (Cole, 1994). In soil systems, microbial composition is greatly modified by organic input composition (Martin, 1992 and Struwe, 1986); the same degree of variation can be expected in composting systems. The impact of initial feedstock composition on microorganism development in compost needs to be further studied.

Table 1

Microbial Populations in Soil and Mature Yard Trimmings Compost

Material	**Bacteria** (millions per gram dry weight)	**Fungi** (thousands per gram dry weight)
Fertile soil[a]	6 to 46	9 to 46
Recently reclaimed soil after surface mining[b]	19 to 170	8 to 97
Pesticide-contaminated mix of silt and clay[c]	19	6
Mature compost[d]	417	155

[a] Cole, 1976 (for reclaimed soil)
[b] Cole, unpublished data
[c] Cole, 1994
[d] Cole, 1994

Dramatic changes in chemical composition occur during the composting process. Most starting materials for composting are plant-derived residues and contain carbon in the form of polysaccharides (cellulose and hemicellulose), lignin, and tannin. The end-product has a low polysaccharide content, most of which is microbial cell wall and extracellular gums (Macauley,

1993), with about 25 percent of the initial carbon content present in the form of highly stabilized humic substances (Chen, 1993). Organic matter content ranges from 30 to 50 percent of dry weight, with the remainder being minerals. The combination of high organic content and a variety of minerals makes compost an excellent adsorbent for both organic and inorganic chemicals.

The practical aspects of using the composting process or mature compost to manage hazardous industrial waste streams are described in the sources cited above. Additional information can be found in the documents cited in the Bibliography on page 105.

Table 2[a, b]

Dehydrogenase Activity in Uncontaminated Soil or Pesticide-Contaminated Soil With or Without Mature Yard Trimmings Compost

Percentage of Contaminated Soil	Matrix	Not Planted	Planted
100	Contaminated soil	16[c]	18[c]
50	Contaminated soil and	25	32
25	Uncontaminated soil	25	59
0	Uncontaminated soil	40	68
50	Contaminated soil and	336	370
25	Compost	613	575
0	Compost	1,464	1,299

[a] This table shows the high dehydrogenase enzyme activity as a measure of microbial activity in contaminated soil.
[b] After preparing the mixtures and transferring them into flower pots, the pots were incubated in a greenhouse for 6 weeks. Planted treatments had four corn plants per pot, while unplanted treatments had no plants.
[c] Units are µmoles product formed per 24 hours per gram of soil, with higher values indicating greater microbial activity.

Figure 1

Windrows of Leaves at a Community Yard Trimmings Composting Site

Height and width of windrows are determined primarily by the size of the turning equipment.

Figure 2

Aerated Rotating Drum Composting System at Aufschafenburg, Germany

The drum temperature and oxygen content are monitored continuously, and air addition and mixing are done as needed to maintain conditions within designated ranges.

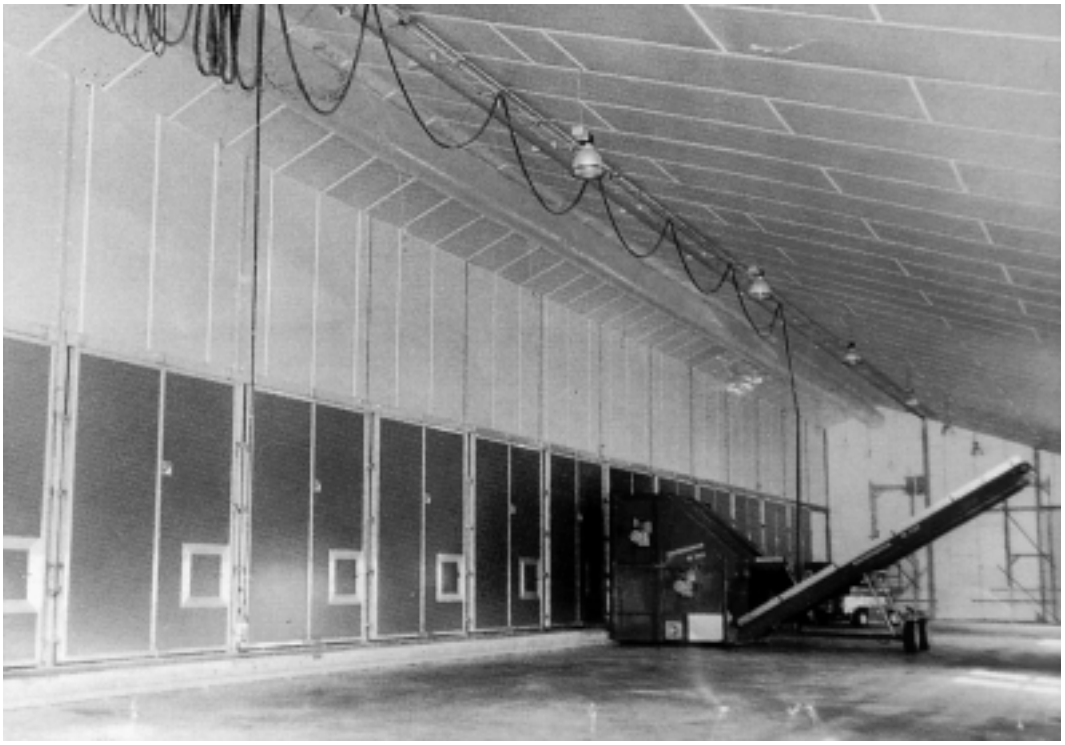
Figure 3

Trench Composting System at Saint Cloud, Minnesota

Air and temperature control is provided by subfloor vents and large blowers. Material is turned daily and water is automatically added as necessary.

Figure 4

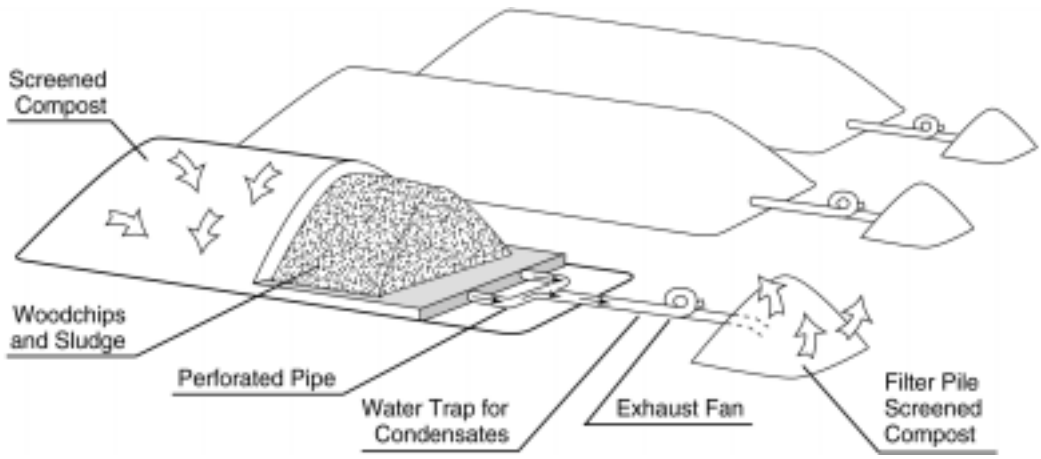
Tunnel Composting System Used in Europe



Exit air is treated in a compost biofilter, and temperature and oxygen content of the air are monitored.

Figure 5

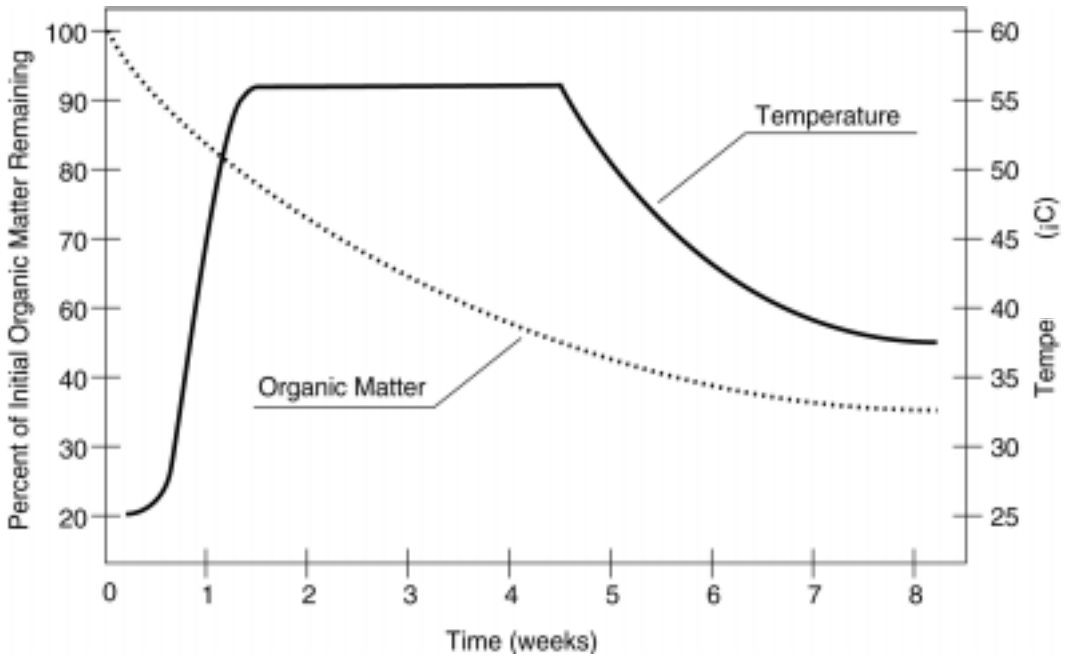
Design of the Beltsville Aerated Pile Composting System



Air is drawn through the composting mass and odorous volatile compounds are removed in a soil biofilter (Willson, 1980).

Figure 6

Temperature Profile and Loss of Initial Organic Material During Composting



The time scale for the entire cycle would range from about 8 weeks to 6 months, depending on the composition of the source material and management intensity. Temperature is measured in degrees Celsius.

References

Alexander, M. *Biodegradation and Bioremediation*. San Diego: Academic Press, 1994.

Beffa, T., M. Blanc, L. Marilley, J.L. Fischer, P.F. Lyon, and M. Aragno. "Taxonomic and Metabolic Microbial Diversity During Composting." In *The Science of Composting*, by M. de Bertoldi, P. Bert, and P. Tiziano, 149-161. London: Blackie Academic and Professional, 1996.

Chen, Y. and Y. Inbar. "Chemical and Spectroscopic Analyses of Organic Matter Transformations During Composting in Relation to Compost Maturity." In *Science and Engineering of Composting*, by H.A.J. Hoitink and H.M. Keener, 551-600. Worthington, OH: Renaissance Publications, 1993.

Cole, M.A. "Effect of Long-term Atrazine Application on Soil Microbial Activity." *Weed Science* 24 (1976): 473-476.

Cole, M.A., X. Liu, and L. Zhang. "Plant and Microbial Establishment in Pesticide-Contaminated Soils Amended With Compost." In *Bioremediation Through Rhizosphere Technology*, edited by T.A. Anderson and J.R. Coats, 210-222. Washington, DC: American Chemical Society, 1994.

Cole, M.A., X. Liu, and L. Zhang. "Effect of Compost Addition on Pesticide Degradation in Planted Soils. In *Bioremediation of Recalcitrant Organics*, edited by R.E. Hinchee, D.B. Anderson, and R.E. Hoeppel, 183-190. Columbus, OH: Battelle Press, 1995.

Finstein, M.S. and M.L. Morris. "Microbiology of Municipal Solid Waste Composting." *Advances in Applied Microbiology* 19 (1975): 113-151.

Gupta, V.K., M.P.S. Bakshi, and P.N. Langar. "Microbiological Changes During Natural Fermentation of Urea-wheat Straw." *Biological Wastes* 21 (1987): 291-299.

Harmsen, J., H.J. Velthorst, and I.P.A.M. Bennehey. "Cleaning of Residual Concentrations With an Extensive Form of Landfarming." In *Applied Biotechnology for Site Remediation*, edited by R.E. Hinchee, D.B. Anderson, F.B. Metting, Jr., and G.D. Sayles, 84-91. Boca Raton, FL: Lewis Publishers, 1994.

Macauley, B.J., B. Stone, K. Iiyama, E.R. Harper, and F.C. Miller. "Compost Research Runs "Hot" and "Cold" at La Trobe University." *Compost Science and Utilization* 1 (1993): 6-12.

Martin, T.L., D.A. Anderson, and R. Goates. "Influence of the Chemical Composition of Organic Matter on the Development of Mold Flora in Soil. *Soil Science* 54 (1992): 297-302.

McNabb, D.H., R.L. Johnson, and I. Guo. "Aggregation of Oil- and Brine-contaminated Soil to Enhance Bioremediation. In *Hydrocarbon Bioremediation*, by R.E. Hinchee, B.C. Allenman, R.E. Hoeppel, and R.N. Miller, 296-302. Boca Raton, FL: Lewis Publishers, 1994.

Parr, J.F., E. Epstein, and G.B. Willson. "Composting Sewage Sludge for Land Application." *Agriculture and Environment* 4 (1978): 123-137.

Persson, A., M. Quednau, and S. Ahrne. "Composting Oily Sludges: Characterizing Microflora Using Randomly Amplified Polymorphic DNA." In *Monitoring and Verification of Bioremediation*, by R.E. Hinchee, G.S. Douglas, and S.K. Ong, 147-155. Columbus, OH: Battelle Press, 1995.

Struwe, S. and A. Kjøller. "Changes in Population Structure During Decomposition." In *Microbial Communities in Soil*, edited by V. Jensen, A. Kjøller, and L.H. Sørensen, 149-162. London: Elsevier Applied Science Publishers, 1986.

U.S. EPA. *Composting of Municipal Wastewater Sludges*. EPA625-4-85-014. Washington, DC, 1985.

Viel, M., D. Sayag, A. Peyre, and L. André. "Optimization of In-vessel Co-composting Through Heat Recovery." *Biological Wastes* 20 (1987): 167-185.

Willson, G.B., J.F. Parr, E. Epstein, P.B. Marsch, R.L. Chaney, D. Colacicco, W.D. Burge, L.J. Sikora, C.F. Tester, and S. Hornick. *Manual for Composting Sewage Sludge by the Beltsville Aerated-Pile Method*. EPA600-8-80-022. Washington, DC, 1980.

Chapter 2

Remediation of Soils Contaminated With Toxic Organic Compounds

Introduction

Owners of property contaminated with toxic chemicals are required under federal and state regulations to decontaminate the site or remove contaminated soil to a safe disposal facility, such as a hazardous or special waste landfill. Decontamination or removal of soil is costly, as shown by the values in Figure 7. These high cleanup costs may exceed the value of the property and dramatically decrease the willingness of the property owner to initiate remediation. Therefore, inexpensive, effective remedial methods could encourage the cleanup of the nearly 1,300 locations on the National Priorities List (NPL or "Superfund"). Thousands of smaller sites that might pose a threat to adjacent populations also await cleanup. For example, approximately 75,000 to 100,000 leaking below-ground petroleum storage tanks exist in this country (Brown, 1985). In the United States alone, there are about 37,000 candidate sites for Superfund, 80,000 sites covered under the Resource Conservation and Recovery Act (RCRA), 1.5 million leaking underground tanks storing a wide variety of materials, and 25,000 Department of Defense sites in need of remediation (Glass, 1995).

The sale of contaminated property is difficult at best. Many owners abandon their contaminated property rather than try to sell or decontaminate it. These abandoned sites, or brownfields, represent lost opportunities for productive reuse. Long-term use of property for military operations also results in contamination (most often with organic solvents, petroleum hydrocarbons, and explosives). As in the private sector, cost can be a critical barrier to military site remediation. The remediation costs for NPL and RCRA sites alone may reach $750 billion, an amount equal to the current U.S. military budget for about 15 years (Wilson, 1994). The cost estimate for remediation of sites in the European Union is between $300 and $400 billion. At these costs, it is unlikely that more than a small fraction of the most critical sites will ever be remediated.

One possible solution to these problems is use of remedial methods that are significantly less expensive than those commonly used, such as removal of contaminated soil. On average, bioremediation is among the lowest cost methods for detoxification of soils contaminated with organic compounds (Figure 7), and composting is intermediate in cost among the

bioremediation technologies (Figure 8). When comparing the total budget for cleanup of a large site, the savings associated with the use of bioremediation vs. chemical- or physical-based technologies give bioremediation an overwhelming monetary advantage (Table 3).

Table 3

Total Project Costs for Various Remedial Options

Remedial Technology	Total Project Costs[a]
Vacuum extraction	$2.5 million
Compost-based	**$3.6 million**
Solidification	$7.3 million
Thermal desorption	$11.4 million
Offsite landfill	$10.8 million
Onsite incineration	$18.9 million

[a] Costs are based on a 1-acre site, 20 feet deep (about 32,000 cubic yards). Values are an average for a variety of biodegradable contaminants such as fuels, lubricants, and polynuclear aromatic hydrocarbons.

Applications of Composting or Compost Addition Methodologies

A wide range of common environmental contaminants degrade rapidly in compost, as summarized in Table 4 and Figure 9. Of the compounds shown in Figure 9, the explosives 2,4,6 trinitrotoluene (TNT) and Royal Demolition Explosives (RDX) are the most widely studied, in experiments ranging from bench (laboratory) scale to large pilot studies. Most of the experiments focused on the composting process, with typical results shown in Figure 10. One study found that up to 30 percent contaminated soil by volume could be mixed with compostable materials and still achieve thermophilic conditions (Brinton, 1994). Another study found that the inclusion of 40 percent contaminated soil in a composting mix resulted in subthermophilic temperatures and reduced degradation of explosives (Williams, 1991). Both of these studies indicate that a mixture of 30 percent contaminated soil with 70 percent initial compost feedstock provides the best results. Volume loss of feedstock is typically about 50 percent of initial, so the final, decontaminated mix has about twice the volume of contaminated soil.

Table 4

Contaminants That Degrade in Compost or During the Composting Process

General Class of Contaminant	Examples
Petroleum hydrocarbons (TPH)	Gasoline, diesel fuel, jet fuel, oil, and grease
Polynuclear aromatic hydrocarbons (PAH)	Wood preservatives, coal gasification wastes, refinery wastes
Pesticides	Insecticides and herbicides
Explosives	TNT, RDX, nitrocellulose

If contaminants degrade completely, disposal of the extra volume should not be a problem. If contaminant degradation is incomplete, however, a substantially larger volume of contaminated material will need to be further treated or disposed of. This problem can be avoided by following a gradualistic approach from bench-scale to pilot-scale to full-scale projects, to ensure that reliable degradation of contaminants can be achieved (Saber, 1995 and U.S. EPA, 1989). One difficulty with this approach, when using the composting process, is that laboratory-scale composting units may not provide results similar in either extent or time scale to results obtained in large-scale composting. For example, one study found relatively poor degradation of the explosive TNT in laboratory reactors (Kaplan, 1982), whereas other studies indicate good degradation of TNT in pilot-scale studies. Based on this example, even partial degradation under laboratory test conditions might be justification for conducting larger scale pilot studies. Increasing the total volume of material is less of a problem when mature compost is added to contaminated soil, since a mixture of 40 percent (by weight) compost and 60 percent contaminated soil provided good degradation of several pesticides (Liu, 1996).

A common complaint about solid-phase bioremediation methods is that they are too slow. For example, commonly used procedures for bioremediation of petroleum-contaminated soils require several months to a year to achieve cleanup, a time scale that may be in excess of established deadlines or the owner's patience. A recent study compared the time required to degrade a mixture of volatile organic solvents, polynuclear aromatic hydrocarbons (PAH), and phenanthrene in a solid-phase system (biopile) and in a slurry-phase reactor. Biopile treatment time was 94 days and degraded 99 percent of initial volatiles, 91 percent of PAH, and 87

percent of phenanthrene. In contrast, a 10-day treatment in a slurry-phase reactor degraded 99 percent of initial volatiles, 63 percent of PAH, and 58 percent of phenanthrene. In this case, the biopile took substantially longer but resulted in greater contaminant degradation and was achieved at a lower cost than the slurry-phase reactor. Extended time periods increase cost, since the site must be monitored and operated for an extended period. Using the composting process or adding mature compost to biopile-type operations, however, may dramatically decrease cleanup time, as shown in the following examples.

One recent study examined the degradation of the herbicide dicamba during the composting process (Dooley, 1995). Successful remediation was achieved in only 52 days, as shown in Figure 11. Typical degradation rates for dicamba in soil, without the compost, are 1 to 2 mg/kg/month (Goring, 1975). Hence, treatment time for a high concentration of dicamba, without using composting, would have been 1 year or more.

In another study, a mixture of soil contaminated with mineral oil and grease (35 percent v/v) was composted with maple leaves (20 percent v/v), alfalfa (35 percent v/v), and other ingredients. Highly weathered hydrocarbon mixtures, such as those present in the soil studied, are often resistant to biodegradation. After an initial period of rapid degradation, degradation of the residual material ceased (Figure 12). During the landfarming phase of the study, only 30 percent of the contaminants degraded after 180 days. In contrast, a 50 percent degradation rate was achieved by composting in 105 days (73 percent degradation was reached in 287 days). An 85 percent degradation rate was achieved by composting oily sludges containing hydrocarbon mixes in the lubricating oil and diesel oil molecular weight range (Persson, 1995). Decomposed horse manure was used to maintain mesophilic (25 ^{o}C to 35 ^{o}C) composting conditions.

Two recent studies documented the effects of mature compost on hydrocarbon degradation in soil-compost mixes in laboratory reactors (Stegmann, 1991 and Hupe, 1996). The best results were achieved by mixing mature, 6-month-old compost with TPH-contaminated soil. The studies found degradation rates of about 375 mg TPH/kg/day, values much higher than those reported for in situ biodegradation—40 mg/kg/day (Atlas, 1991). TPH-contaminated soils frequently contain 5,000 to 20,000 mg TPH/kg. Based on the rates shown in Figure 13, these materials could be remediated, using compost, in only 2 weeks to 2 months, in contrast to the 6 months or more required for typical landfarming operations. Mass balance studies (Table 5) indicated that during a 21-day treatment period, substantial mineralization and bound residue

formation occurred. The chemical nature of the bound residue was not determined. This material could be either strongly sorbed hydrocarbon or partially degraded hydrocarbon that was coupled to humic materials in the compost. A field-scale study (Bartusiak, 1984) achieved oil degradation rates of about 110 mg/kg/day with a steel mill sludge containing primarily relatively high molecular weight—and therefore, relatively slowly degraded—hydrocarbons (Westlake, 1974).

Table 5

Mass Balance for Carbon From Petroleum Hydrocarbons During Incubation of a Soil-Compost Mixture

Fraction	Percentage of Initial-C in Fraction
Extractable TPH	8
Volatilized	4
Converted to CO_2	59
Not accounted for (bound residue)	24
Microbial biomass	4

Source: Hupe, 1996.

Degradation of various aromatic compounds has been studied in composting systems, including chlorophenols, pesticides, and PAH. The degradation of 2-chloro- and 2,4-dichlorophenol during composting results in a rapid loss of parent compounds, as shown in Figure 14 (Benoit, 1995). Mass balance studies indicate that complete mineralization (formation of carbon dioxide) was relatively limited, with most of the carbon going into a bound residue fraction (Figure 15). The bound residues might be the result of oxidative coupling of the chlorophenols, or their metabolites, to humic materials in the compost. Similar behavior of chlorophenols has been reported in soil (Stott, 1983). A similar study yielded a 90 percent degradation rate, in 5 days, for easily degraded naphthalene and 1- and 2-methylnaphthalene during composting of wood preservative-contaminated soil, as well as 80 percent degradation for slowly degraded PAHs, such as chrysene and pyrene, in 15 days (Civilini, 1996a).

In addition to the direct use of composting or mature compost to accelerate contaminant degradation, microorganisms also can be isolated from compost for both basic biochemical studies and as inoculants in remediation projects (Civilini, 1996a; Civilini, 1996b; Castaldi, 1995).

The high temperatures achieved during composting also accelerate the relatively slow chemical reactions in soil, where temperatures are only 15 ^{o}C to 30 ^{o}C in most temperate climates. By comparison, typical temperatures during composting are 50 ^{o}C or higher. Humic materials can catalyze degradation of atrazine (Li, 1972) and other compounds (Stevenson, 1994). Since the humic content of mature compost can be as high as 30 percent by weight, whereas typical soils contain less than 5 percent, compost provides a much higher concentration of reactive material than is found in soil.

Composting of contaminated materials can be done on a field scale using simple designs, such as those shown in Figures 16 and 17. The designs are mechanically simple, are inexpensive, and provide full containment of materials while preventing washing away by rain. If volatile compounds are being processed, air flow can be set to draw air into the pile and pass it through a biofilter to remove the volatiles. In this case, the complexity is in the biological component, not the physical components, and the only moving parts are the microbes and the ventilation system. The result is likely to be an effective, fast-acting, and inexpensive remediation system. Guidelines for successful operation of these systems are provided in the references for Chapter 1.

No remedial technology is appropriate for all contaminants and situations. Guidelines for the best use of composting or addition of mature compost for remediation include:

- Contaminants less than 20 feet deep
- Contaminants that are biodegradable and/or strongly adsorbed to the compost
- Soil that is toxic to plants and microbes

Use of the composting process or addition of mature compost is not likely to be successful for polychlorinated biphenyls (PCB) because the biodegradability of the more highly chlorinated congeners is poor. For example, one study found that only the congeners with two or three chlorines were degraded during composting (Michel, 1997). Similarly, another study found that benzo(a)pyrene, a 5-ring polynuclear aromatic compound of poor biodegradability, was not degraded during bench-scale production of municipal solid waste (MSW) compost (Overcash,

1993). These authors also found that the PCB 2,2',4,4'-tetrachlorobiphenyl (added at the beginning of the composting process) was present in the finished compost (i.e., it was not degraded during the process).

Before composting can be widely accepted as a remedial technology, several issues need to be resolved. First, substantial anecdotal evidence indicates that the degradation rate of specific contaminants is affected by the materials being composted. For example, 16 percent mineralization was found for ^{14}C-labeled pentachlorophenol during 60 days of incubation with laboratory-produced compost or spent mushroom substrate (a form of compost created from the material that remains after commercial production of edible mushrooms, *Agaricus bisporus*). Thirty percent mineralization occurred, however, in mushroom medium of a lesser degree of stabilization (Semple, 1995).

Second, a relatively low extent of mineralization of aromatic compounds occurs in compost, and, in some cases, water-extractable metabolites form. In some studies, potentially toxic intermediates formed during laboratory composting of explosives (Kaplan, 1982). One recent study reported a 98 percent transformation of TNT during composting, but the material retained about 12 percent of its original mutagenicity, and the aqueous leachate still had about 10 percent of its toxicity to an aquatic invertebrate, as shown in Figure 18 (Griest, 1993). When properly handled, however, field-level composting of explosives can reduce contaminants to undetectable levels with an extremely low occurrence of toxic intermediates, as was recently accomplished at the Umatilla Army Depot (Emery, 1996).

The other critical issue is whether the lack of full degradation and formation of nonextractable metabolites is a satisfactory endpoint of remediation. The behavior of aromatic compounds in compost is similar to the behavior of hydroxylated or amino aromatic compounds in soils, where partial degradation occurs, followed by covalent coupling of the metabolite to humic substances, as shown in Figure 19 (Bertin, 1991; Calderbank, 1989; Richnow, 1994; Haider, 1994; Sjoblad, 1981). Hydroxylated metabolites form during the degradation of nearly all aromatic compounds (Kelley, 1993). In some cases, coupling of chlorinated phenols to humic materials is accompanied by dehalogenation (Dec, 1994). This process, referred to as formation of bound residues, results in the long-term immobilization of metabolites but not their complete destruction. The bound residues typically are very slowly degraded (Wolf, 1976 and Völkel, 1994). Bound residues are defined by the International Union of Pure and Applied Chemistry (IUPAC) as "chemical species originating from pesticides, used according to good

agricultural practice, that are unextracted by methods which do not significantly change the chemical nature of these residues" (Völkel, 1994). In practice, loss of extractability by organic solvents is suggestive of bound residue formation (Haider, 1994). The process is not simply adsorption (Piccolo, 1994), since sorbed low-molecular weight metabolites often remain solvent-extractable. Bound residue formation results from the synthesis of relatively labile bonds, such as ester groups, creating relatively low long-term stability.

On the other hand, formation of ether linkages between humic materials and metabolites results in relatively long-term stabilization of the metabolite in a form of low bioavailability. If the metabolite is actually incorporated into the core structure of the humic acid (Stevenson, 1994), the residence time of the metabolite-derived carbon will be decades to centuries. Substantial amounts of ^{14}C derived from ^{14}C-labelled 2,4-dichlorophenoxyacetic acid (2,4-D) are incorporated into humic and fulvic acids during composting of yard trimmings containing 2,4-D (Michel, 1995).

During a recent bioremediation project, Bioremediation Service, Inc., successfully bioremediated 14,000 tons of TNT, RDX, HMX, and other nitroaromatic compound-contaminated soils at the Umatilla Army Depot. A specific recipe of organic amendments was selected to balance the C:N ratio, structure, moisture, and porosity and to optimize explosive degradation. At project end, over 75 percent of all samples indicated that the explosives had been degraded to below detection by EPA SW-846 Method 8330. What remained was a humus-rich soil, with no toxic intermediates, that has been shown to be a value-added soil additive (Emery, 1996).

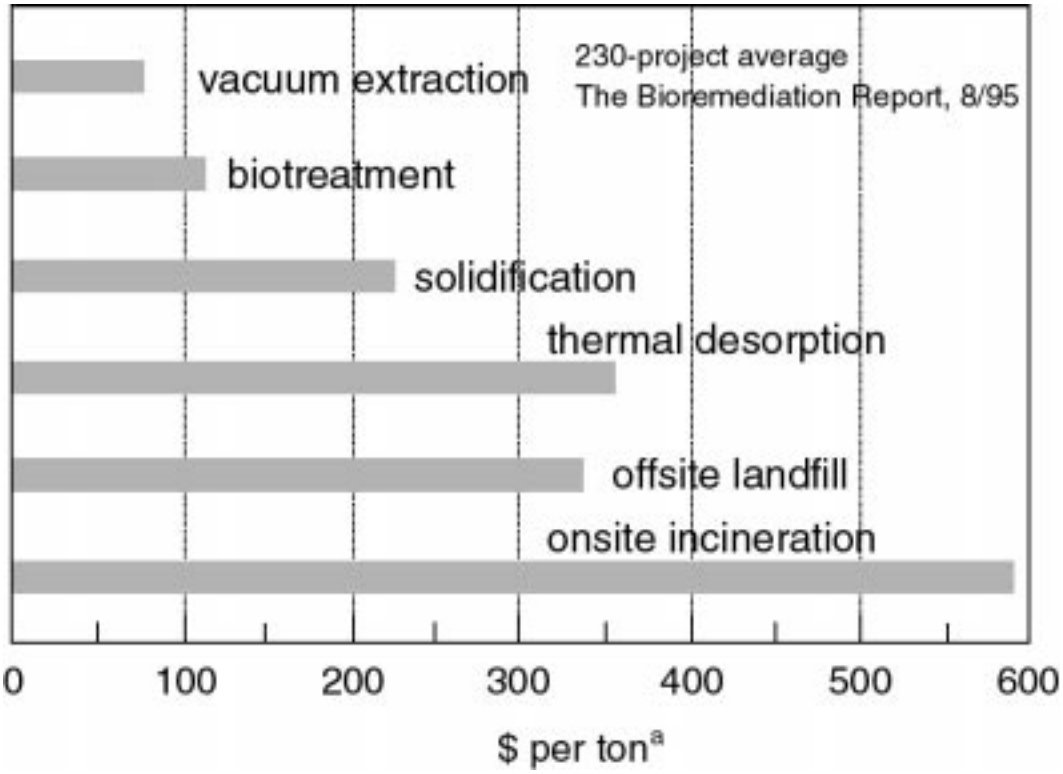
A number of studies on xenobiotic degradation in compost were conducted by measuring the loss of only the parent compound, but these studies did not adequately measure volatilization or adsorption of compounds to vessel components, such as plastics. At thermophilic temperatures, volatilization losses can be significant. One study found that nearly 50 percent of added chlordane is volatilized, but only about 5 percent is converted to bound residues; the balance is recovered as parent compound (Petruska, 1985). Another study reported 17 percent volatilization, 45 percent adsorption to vessel materials, and 25 percent biodegradation of ^{14}C-naphthalene in laboratory reactors (Silviera, 1995). If the study detailed only the loss of naphthalene, 87 percent of the naphthalene would have been apparently degraded.

A third issue that requires resolution is the fact that the outcome of remediation experiments may vary depending on the scale of the experiment. For example, bench-scale results may not transfer well in terms of degradation rate to pilot-scale or field-scale experiments. In several

cases, better results are obtained in larger scale experiments when compared to very small-scale laboratory experiments. Part of the difficulty in this case is probably the result of the inability to generate typical and authentic composting conditions in small laboratory containers. For pilot-scale composting studies, a volume of at least 10 to 20 cubic meters of material is required to achieve the typical thermal profiles seen in large windrows. Hence, the results from a pilot study of only a cubic meter may not transfer to a larger system.

Figure 7

Comparative Costs of Remedial Options for Soils or Hazardous Wastes

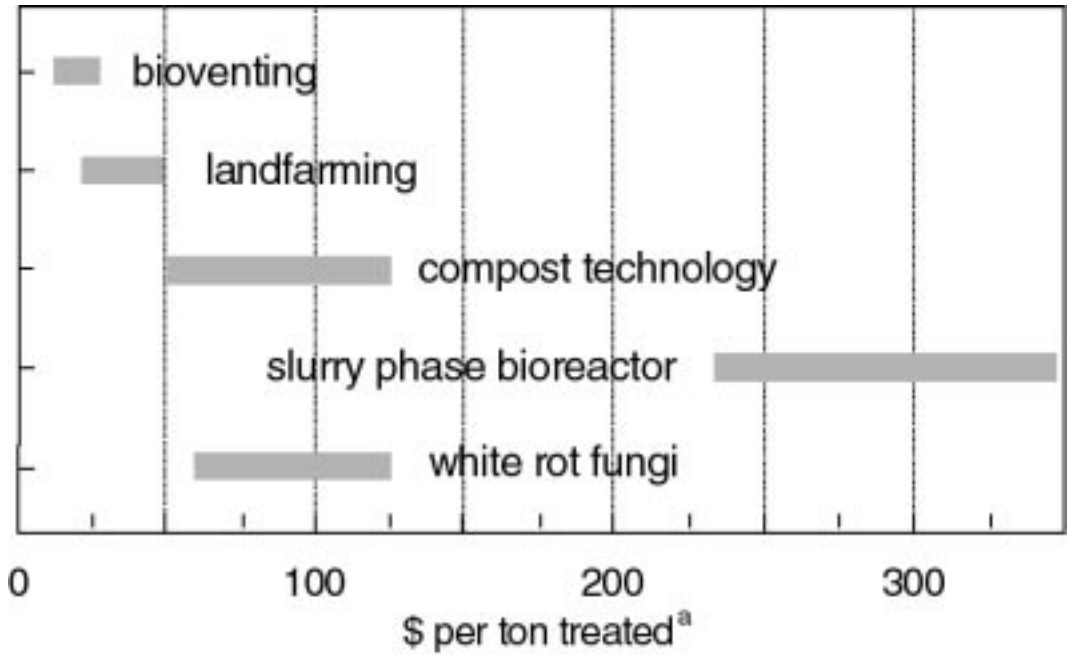


[a] Values are an average for a variety of biodegradable contaminants such as fuels, lubricants, and PAH.

Data obtained from The Bioremediation Report, August 1995.

Figure 8

Comparative Costs of Bioremediation Options for Soils or Hazardous Wastes



[a] Values are an average for a variety of biodegradable contaminants such as fuels, lubricants, and PAH.

Figure 9

Structures of Organic Compounds That Have Been Shown to Degrade During Composting or in Soil Amended With Mature Compost

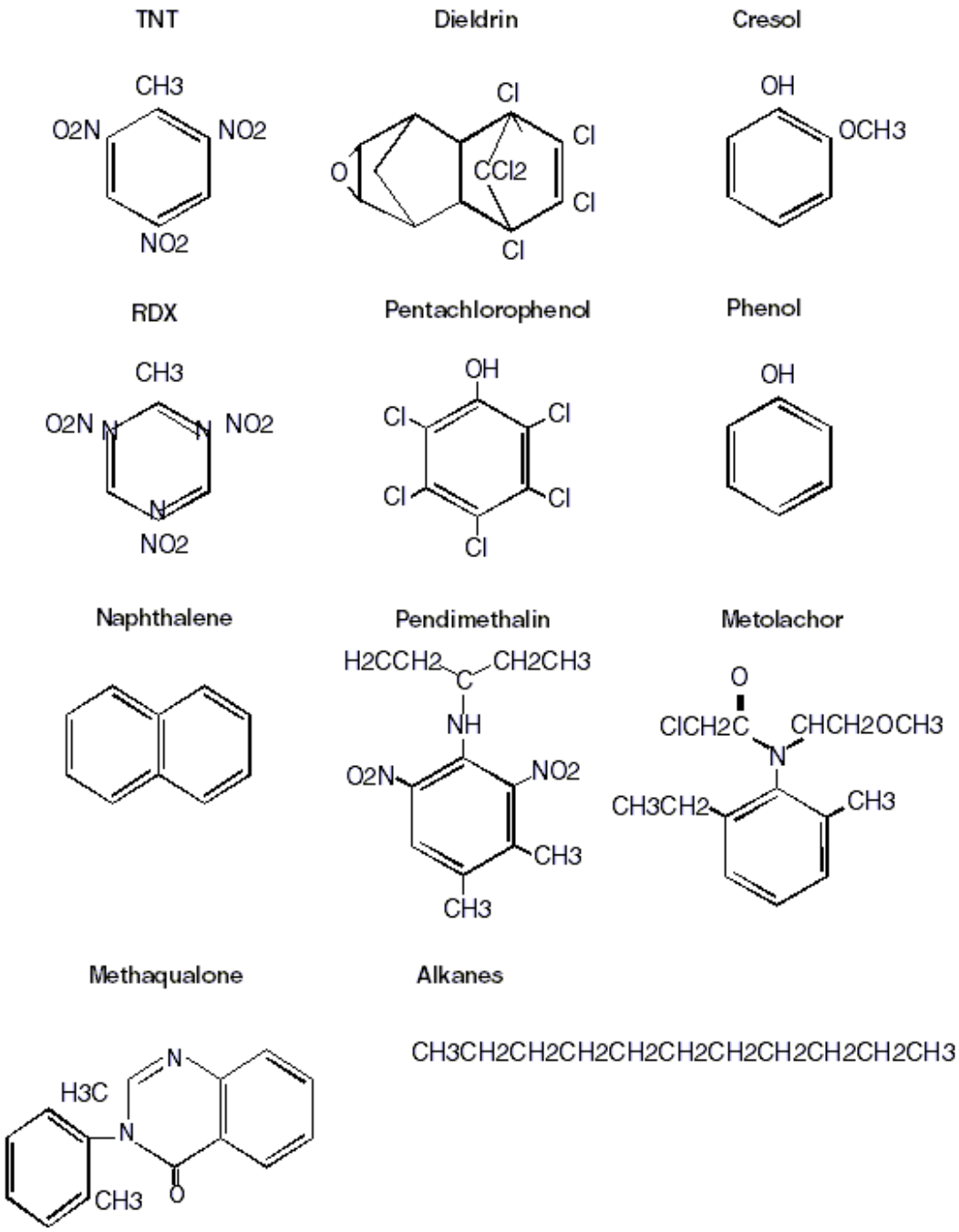
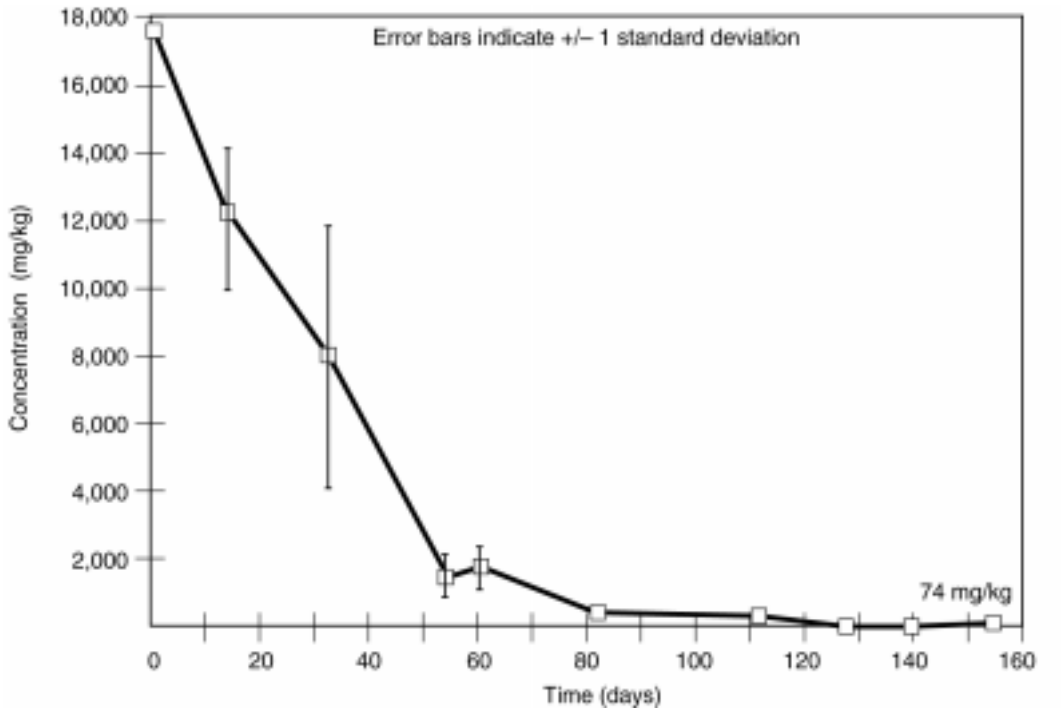


Figure 10

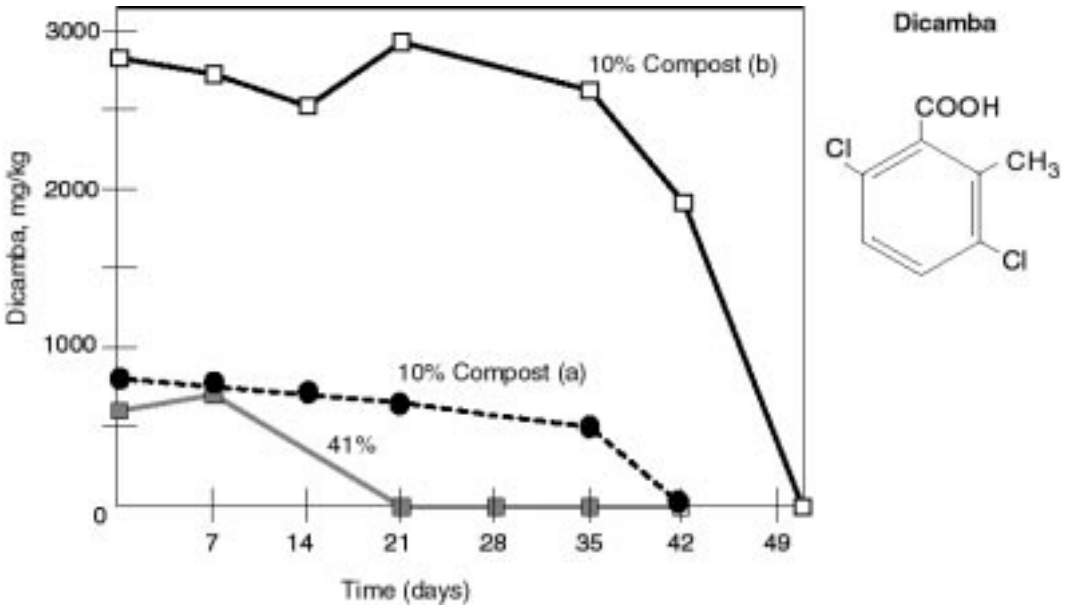
Degradation of the Explosive TNT During Composting



Source: Williams, 1993

Figure 11

Degradation of the Herbicide Dicamba During Composting



[a] A mixture of 10% compost with a waste containing a low concentration of dicamba.
[b] A mixture of 10% compost with a waste containing a high concentration of dicamba.

Source: Dooley, 1995

Figure 12

Degradation of Mineral Oil and Grease During Composting

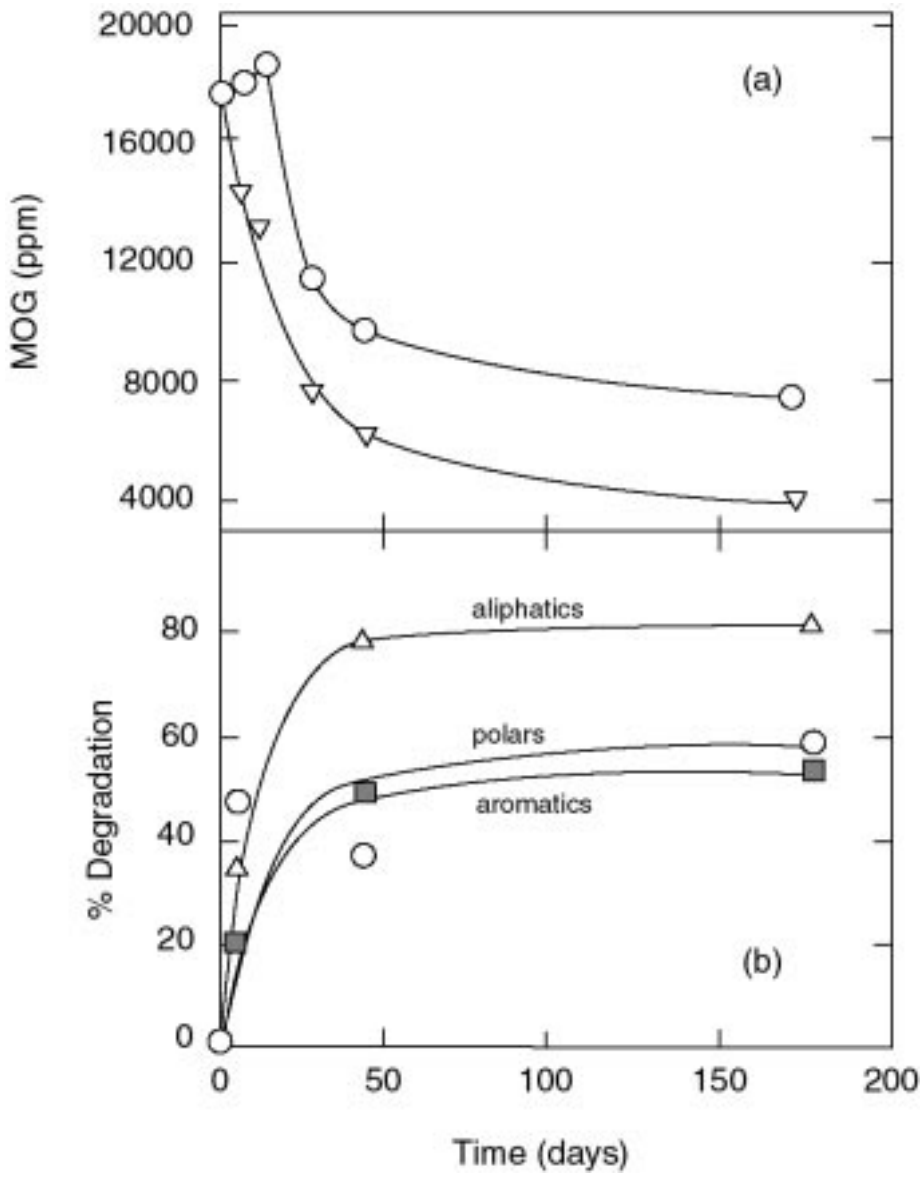
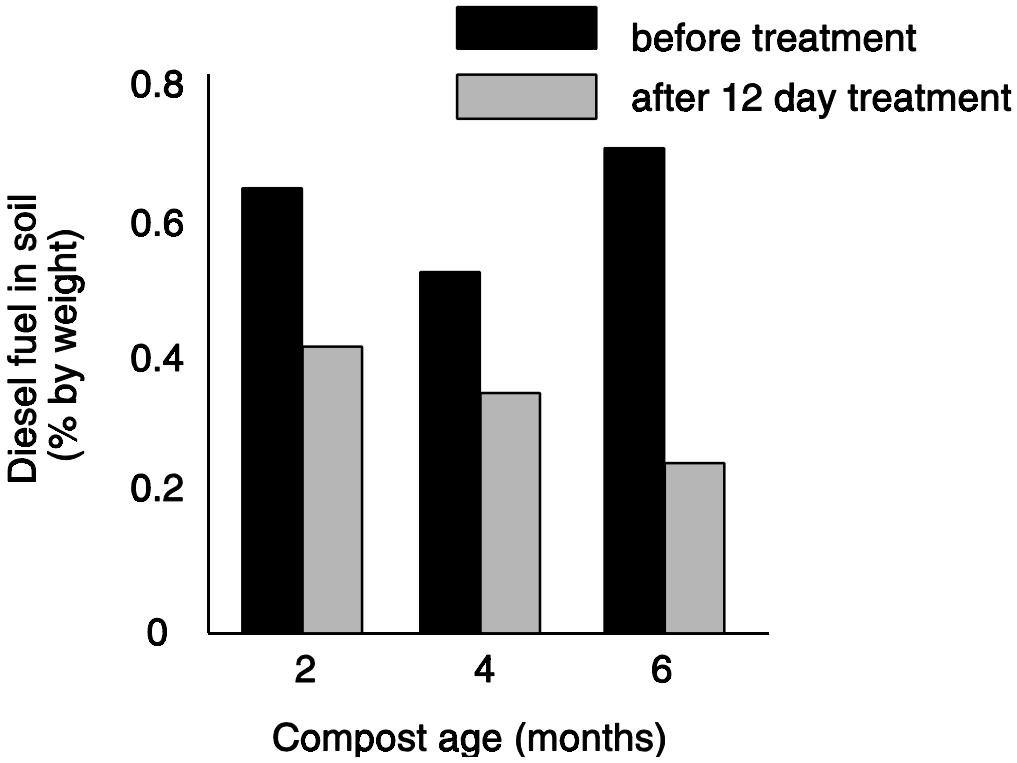


Figure A: Degradation of mineral oil and grease (all components).
Figure B: Degradation of specific components.
Circles: Degradation of aliphatic polar components.

Source: Beaudin, 1996

Figure 13

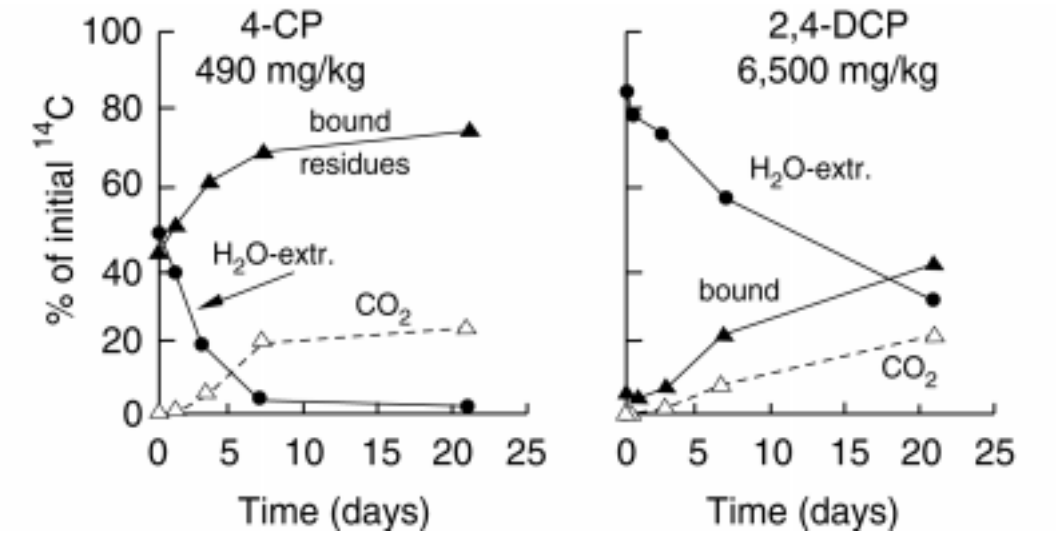
Degradation of Petroleum Hydrocarbons in Compost-Amended Soil



Source: Stegmann, 1991

Figure 14

Degradation of 2-Chlorophenol (2-CP) and 2,4-Dichlorophenol (2,4-DCP) During Composting

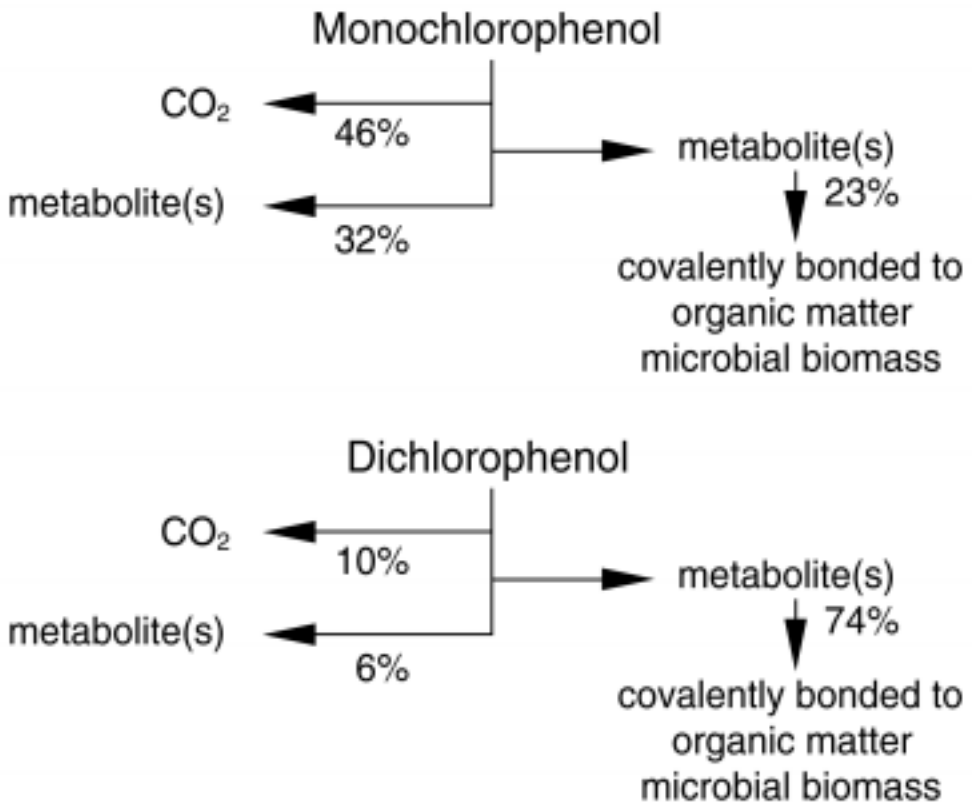


"Bound residues" are compounds that are unextractable by water and/or methanol.

Source: Benoit, 1995

Figure 15

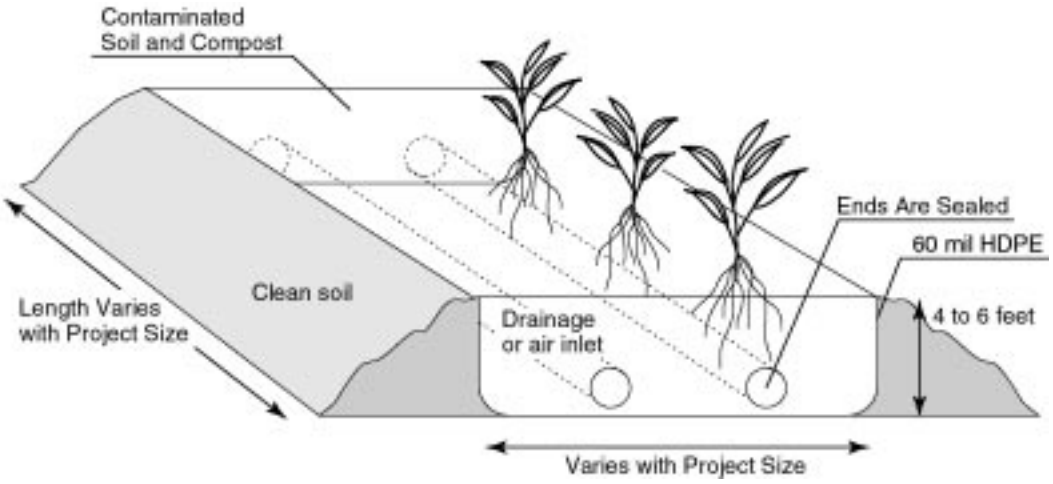
Distribution of ^{14}C Derived From 2-CP and 2,4-DCP After Composting



Source: Benoit, 1995

Figure 16

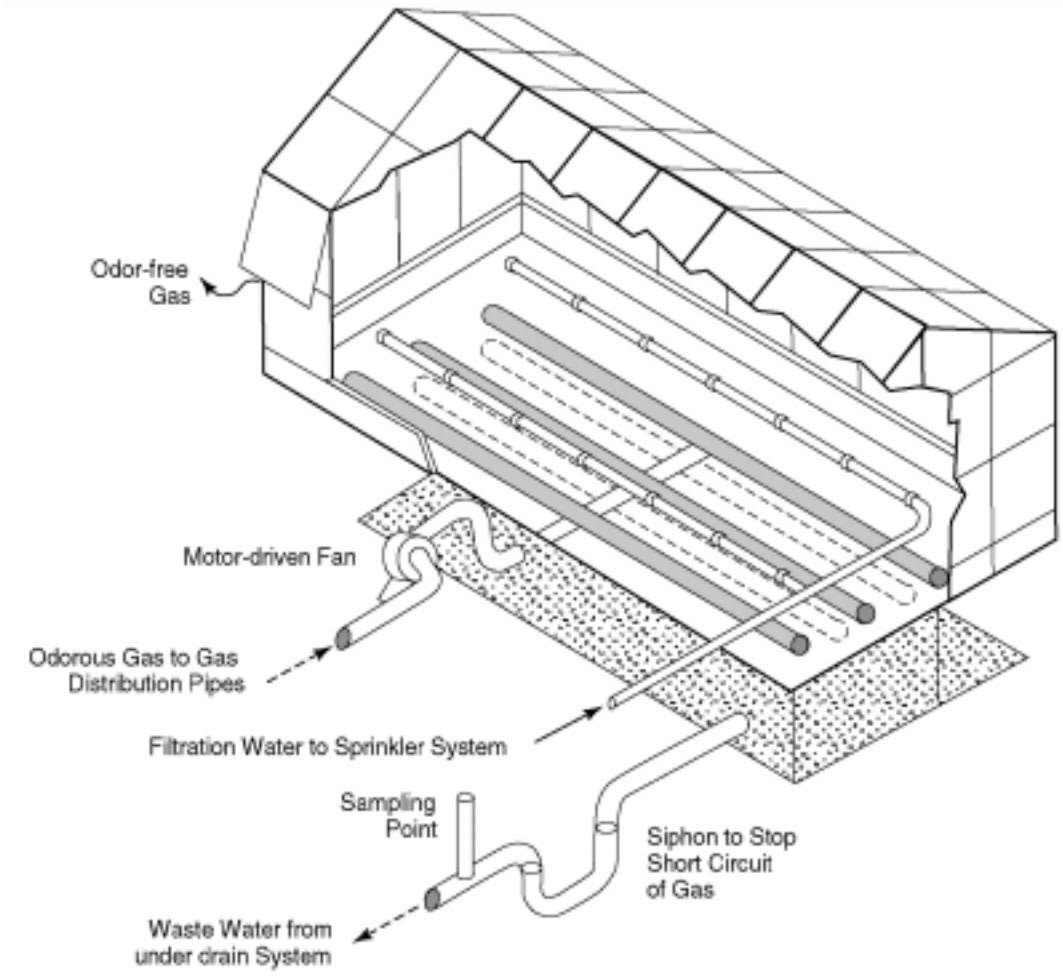
A Simple Contained System for Composting of Hazardous Waste or Treatment of Mixtures of Compost and Contaminated Soil



Source: Cole, unpublished

Figure 17

Enclosed Biofilter Design for Capture of Volatiles Produced During Composting of Contaminated Soil

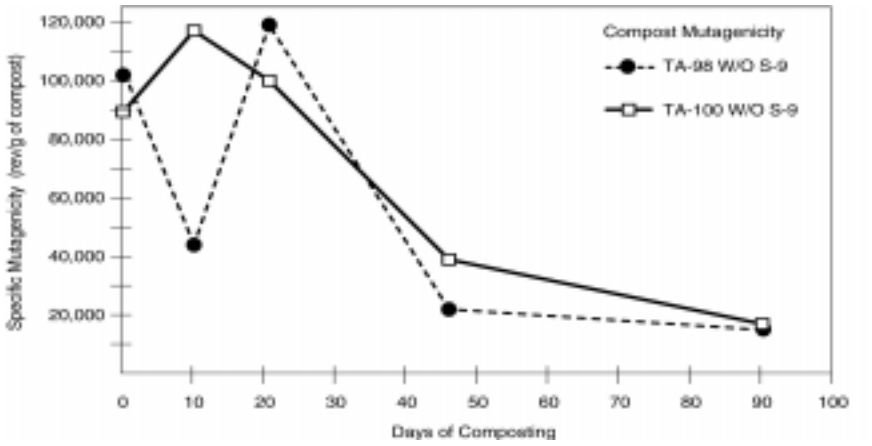


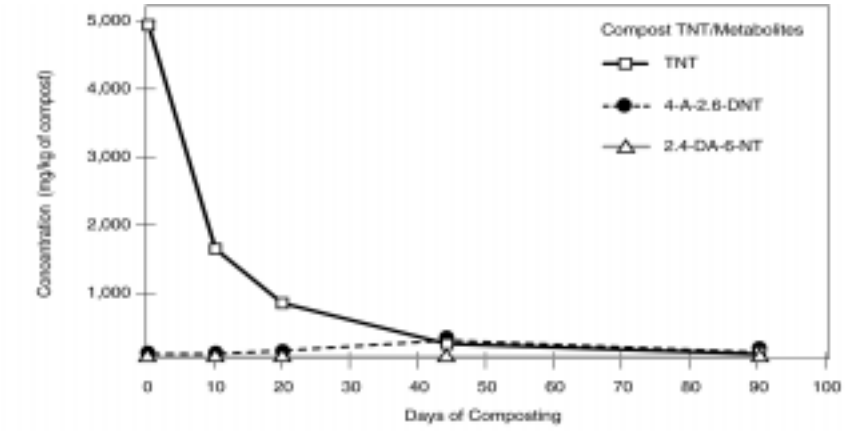
Note: Soil warmth could be maintained by heat from input gas. Gas distribution pipes are buried.

Source: Carlson, 1996

Figure 18

Reduction in Total TNT Content, Leachable TNT, Toxicity, and Mutagenicity of Explosives-Contaminated Soil During In-Vessel Composting

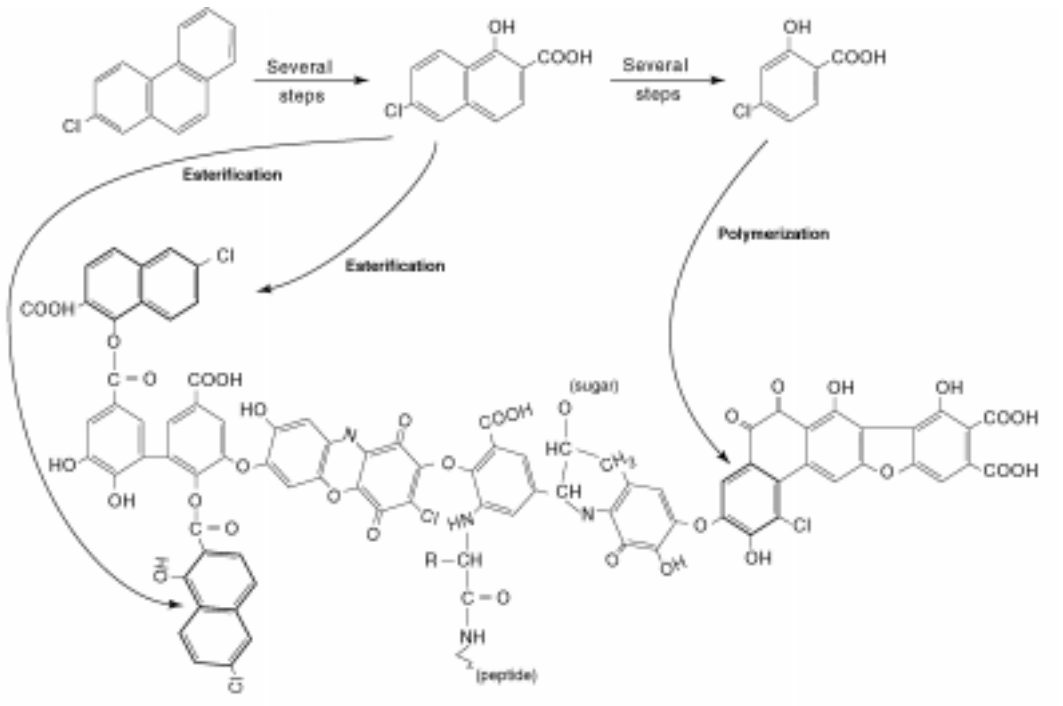




Source: Griest, 1993

Figure 19

Possible Mechanism for Formation of Bound Residues During Composting of Soil Containing Aromatic Contaminants



Source: Humic acid structures (Stevenson, 1994), reactions (Richnow, 1994)

References

Atlas, R.M. "Bioremediation of Fossil Fuel Contaminated Soils." In *In Situ Bioreclamation*, by R.E. Hinchee and R.F. Olfenbuttel, 15. Boston: Butterworth-Heinemann, 1991.

Bartusiak, R.D. "Microbial Destruction of Industrial Solid Waste. In *Solid and Liquid Wastes: Management Methods and Socioeconomic Considerations,* edited by S.K. Majumdar and E.W. Miller, 93-103. Easton, PA: The Pennsylvania Academy of Science, 1984.

Beaudin, N., R.F. Caron, R. Legros, J. Ramsey, L. Lawlor, and B. Ramsay. "Cocomposting of Weathered Hydrocarbon-contaminated Soil." *Compost Science and Utilization* 4 (1996): 37-45.

Benoit, P. and E. Barriuso. "Effect of Straw Composting on the Degradation and Stabilization of Chlorophenols in Soil." *Compost Science and Utilization* 3(3) (1995): 31-37.

Bertin, G. M., F. Andreux, and J.M. Portal. "Contribution to the Study of Nonextractable Pesticide Residues in Soils: Incorporation of Atrazine in Model Humic Acids Prepared From Catechol." In *Diversity of Environmental Biogeochemistry*, edited by J. Berthelin, 105-110. Amsterdam: Elsevier, 1991.

Brinton, W.F., E. Evans, and M.L. Droffner. *Amendment Selection and Process Monitoring for Contaminated Soil Composting: Final Report*. ENAEC-TS-CR-8109. U.S. Army Environmental Center, 1994.

Brown, R.A., Norris, R.D., and G.R. Bruaker. "Aquifer Restoration With Enhanced Bioreclamation." *Pollution Engineering* 17 (1985): 25-28.

Calderbank, A. "The Occurrence and Significance of Bound Pesticide Residues in Soil." *Reviews of Environmental Contamination and Toxicology* 108 (1989): 71-103.

Castaldi, F.J., K.J.Bombaugh, and B. McFarland. "Thermophilic Slurry-phase Treatment of Petroleum Hydrocarbon Waste Sludges." In *Microbial Processes for Bioremediation*, by R.E. Hinchee, F.J. Brockman, and C.M. Vogel, 231-250. Columbus, OH: Battelle Press, 1995.

Civilini, M.C., M. de Bertoldi, and N. Sebastianutto. "Composting and Selected Microorganisms for Bioremediation of Contaminated Materials." In *The Science of Composting*, by M. de Bertoldi, P. Bert, and P. Tiziano, 913-923. London: Blackie Academic and Professional, 1996a.

Civilini, M.C. and N. Sebastianutto. "Degradation of Naphthalene by Microorganisms Isolated From Compost." In *The Science of Composting*, by M. de Bertoldi, P. Bert, and P. Tiziano, 870-883. London: Blackie Academic and Professional, 1996b.

Dec, J. and J.M. Bollag. "Dehalogenation of Chlorinated Phenols During Binding to Humus." In *Bioremediation Through Rhizosphere Technology*, edited by T.A. Anderson and J.R. Coats, 102-111. Washington, DC: American Chemical Society, 1994.

Dooley, M.A., K. Taylor, and B. Allen. "Composting of Herbicide-contaminated Soil." In *Bioremediation of Recalcitrant Organics*, edited by R.E. Hinchee, D.B. Anderson, and R.E. Hoeppel, 199-207. Columbus, OH: Battelle Press, 1995.

Emery, D.D. and P.C. Faessler. *First Production-level Bioremediation of Explosives-contaminated Soil in the U.S.* Portland, OR: Bioremediation Service, Inc., 1996.

Glass, D.J., T. Raphael, R. Valo, and J. van Eyk. "International Activities in Bioremediation: Growing Markets and Opportunities." In *Applied Bioremediation of Petroleum Hydrocarbons*, edited by R.E. Hinchee, J.A. Kittel, and H.J. Reisinger, 11-33. Columbus, OH: Battelle Press, 1995.

Goring, C.A.I., D.A. Laskowski, J.W. Hamaker, and R.W. Meikle. "Principles of Pesticide Degradation in Soil." In *Environmental Dynamics of Pesticides*, edited by R. Haque and V.H. Freed, 135-172. New York, NY: Plenum Press, 1975.

Griest, W.H., A.J. Stewart, R.L. Tyndall, J.E. Caton, C.H. Ho, K.S. Ironside, W.M. Caldwell, and E. Tan. "Chemical and Toxicological Testing of Composted Explosives-contaminated Soil." *Environmental Toxicology and Chemistry* 12 (1993): 1105-1116.

Haider, K., M. Spiteller, A. Wais, and M. Fild. "Interaction of Humic Substances With Xenobiotics—An Analytical Approach to 'Bound' Organic Residues. In *Humic Substances in the Global Environment and Implications on Human Health,* edited by N. Senesi and T.M. Miano, 1071-1073. Amsterdam: Elsevier, 1994.

Hupe, K., J.C. Luth, J. Heerenklage, and R. Stegmann. "Enhancement of the Biological Degradation of Contaminated Soils by Compost Addition." In *The Science of Composting,* by M. de Bertoldi, P. Bert, and P. Tiziano, 913-923. London: Blackie Academic and Professional, 1996.

Kaplan, D.L. and A.M. Kaplan. "Thermophilic Biotransformations of 2,4,6-trinitrotoluene Under Simulated Composting Conditions. *Applied and Environmental Microbiology* 44 (1982): 757-760.

Kelley, I., J.P. Freeman, F.E. Evans, and C.E. Cerniglia. "Identification of Metabolites From the Degradation of Fluoranthene by Mycobacterium sp. Strain PYR-1." *Applied and Environmental Microbiology* 59 (1993): 800-806.

Li, G.C. and G.T. Felbeck, Jr. "Atrazine Hydrolysis as Catalyzed by Humic Acids." *Soil Science* 114 (1972): 201-209.

Liu, X. and M.A. Cole. "Minimum Effective Compost Addition for Remediation of Pesticide-contaminated Soil." In *The Science of Composting*, by M. de Bertoldi, P. Bert, and P. Tiziano, 903-912. London: Blackie Academic and Professional, 1996.

Michel, Jr., F.C. Oral presentation at Conference on Emerging Technologies in Hazardous Waste Management IX, September 1997.

Michel, Jr., F.C., C.A. Reddy, and L.J. Forney. "Microbial Degradation and Humification of the Lawn Care Pesticide 2,4-dichlorophenoxyacetic Acid During the Composting of Yard Trimmings." *Applied and Environmental Microbiology* 61 (1995): 2566-2571.

Overcash, M.R., Y. Li, and J. Koerwer. "Plant Response to Specific Organics in Compost-amended Soil." In *Proceedings of The Composting Council's Fourth National Conference,* 1-3. Arlington, VA: The Composting Council, 1993.

Persson, A., M. Quednau, and S. Ahrne. "Composting Oily Sludges: Characterizing Microflora Using Randomly Amplified Polymorphic DNA." In *Monitoring and Verification of Bioremediation*, by R.E. Hinchee, G.S. Douglas, and S.K. Ong, 147-155. Columbus, OH: Battelle Press, 1995.

Petruska, J.A., D.E. Mullins, R.W. Young, and E.R. Collins, Jr. "A Benchtop System for Evaluation of Pesticide Disposal by Composting." *Nuclear and Chemical Waste Management* 5 (1985): 177-182.

Piccolo, A. "Interactions Between Organic Pollutants and Humic Substances in the Environment." In *Humic Substances in the Global Environment and Implications on Human Health,* edited by N. Senesi and T.M. Miano, 961-979. Amsterdam: Elsevier, 1994.

Richnow, H.H., C. Reidt, R. Seifert, and W. Michaelis. "Chemical Cross-linking of Xenobiotic and Mineral Oil Constituents to Humic Substances Derived From Polluted Environments." In *Humic Substances in the Global Environment and Implications on Human Health,* edited by N. Senesi and T.M. Miano, 1043-1048. Amsterdam: Elsevier, 1994.

Saber, D.L. "Hierarchy of Treatability Studies for Assured Bioremediation Performance." In *Monitoring and Verification of Bioremediation*, by R.E. Hinchee, G.S. Doglas, and S.K. Ong, 157-163. Columbus, OH: Battelle Press, 1995.

Semple, K.T. and T.R. Fermor. "Composting Systems for the Bioremediation of Chlorophenol-contaminated Land." In *Bioremediation of Recalcitrant Organics*, edited by R.E. Hinchee, D.B. Anderson, and R.E. Hoeppel, 93-100. Columbus, OH: Battelle Press, 1995.

Silviera, A.E. and R.B. Ganho. "Composting Wastes Contaminated With Naphthalene." *Compost Science and Utilization* 3(4) (1995): 78-81.

Sjoblad, R.J. and J.M. Bollag. "Oxidative Coupling of Aromatic Compounds by Enzymes From Soil Microorganisms." In *Soil Biochemistry: Volume 5*, edited by E.A. Paul and J.N. Ladd, 113-152. New York, NY: Marcel Dekker, Inc., 1981.

Stegmann, R., S. Lotter, and J. Heerenklage. "Biological Treatment of Oil-contaminated Soils in Bioreactors." In *On-Site Bioreclamation*, edited by R.E. Hinchee and R.F. Olfenbuttel, 188-208. Boston: Butterworth-Heinemann, 1991.

Stevenson, F.J. *Humus Chemistry*. New York, NY: John Wiley & Sons, 1994.

Stott, D.E., J.P. Martin, D.D. Focht, and K. Haider. "Biodegradation, Stabilization in Humus, and Incorporation Into Soil Biomass of 2,4-D and Chlorocatechol Carbons." *Soil Science Society of America Journal* 47 (1983): 66-70.

U.S. EPA. *Guide for Conducting Treatability Studies Under CERCLA*. EPA540-2-89-058. Washington, DC, 1989.

Völkel, W., T. Choné, M. Mansour, I. Scheunert, and F. Andreux. "MnO_2-induced Addition of 3,4-dichloroaniline to Catechol Rings: A Model for the Formation of Pesticide Bound Residues in Humus." In *Humic Substances in the Global Environment and Implications on Human Health,* edited by N. Senesi and T.M. Miano, 1201-1206. Amsterdam: Elsevier, 1994.

Westlake, D.W.S., A. Jobson, R. Phillippe, and F.D. Cook. "Biodegradability and Crude Oil Composition." *Canadian Journal of Microbiology* 20 (1974): 915-928.

Williams, R.T., and K.R. Keehan. "Hazardous and Industrial Waste Composting." *Science and Engineering of Composting.* Worthington, OH: Renaissance Publishers (1993): 363-382.

Williams, R.T. and P.J. Marks. *Optimization of Composting of Explosives Contaminated Soil: Final Report.* CETHA-TS-CR-91053. Washington, DC: U.S. Army Corps of Engineers, 1991.

Wilson, D.J. and A.N. Clarke. *Hazardous Waste Site Soil Remediation*, 5. New York, NY: Marcel Dekker, Inc., 1994.

Wolf, D.C. and J. P. Martin. "Decomposition of Fungal Mycelia and Humic-type Polymers Containing Carbon-14 From Ring and Side-chain Labeled 2,4-D and Chlorpropham." *Soil Sci. Soc. Am. J.* 40 (1976): 700-704.

Chapter 3

Compost-Based Biofilters for Treatment of Contaminated Air and Wastewater Streams

Introduction

Federal regulations such as the Clean Air Act and RCRA require the treatment of industrial (and other) wastewater and air streams to prevent the release of toxic or harmful chemicals into the environment. Granular activated carbon (GAC) is widely used for this purpose and as a polishing step in wastewater treatment; however, it is expensive and not very effective under conditions of high air humidity or with liquid wastestreams. GAC's maintenance costs and time requirements can be high. In addition, when toxic materials are trapped in GAC, it may require disposal as a hazardous waste. GAC's high cost and maintenance requirements sparked the search for low-maintenance, relatively inexpensive substitutes. Cost considerations are particularly acute for livestock operations, which can be very odorous, making them difficult to site far enough from towns and expanding suburban populations to avoid odor problems (Nielsen, 1986 and Nielsen, 1988).

Biofilter technologies are an effective alternative to GAC treatment in several applications. A biofilter is a porous, solid matrix containing attached microorganisms. When contaminated air or water passes through the filter, the contaminants are transferred from the air or water into the aqueous phase of the filter or into biomass or filter materials. The compounds can then be adsorbed and/or degraded by the microbial biofilm, as shown in Figure 20 (Apel, 1993; Saberiyan, 1994; Standefer, 1993). Sand and gravel biofilters have been used to treat wastewater for decades (Andersson, 1994 and Tschui, 1994). These filters can be very effective, removing up to 99 percent of organic compounds and significantly reducing other odorous or harmful constituents, such as hydrogen sulfide. Several problems are commonly encountered with these sand and gravel systems, including a tendency for the bed to pack down, thereby reducing the flow rate unless pressure is increased. In addition, channelization of flow can occur, and the biofilm can destabilize. Difficulties such as packing are easily solved by using a dimensionally stable bed material (sand, gravel, or activated carbon). These materials are not very satisfactory as biomass supports, however, and sloughing of biomass with resultant loss of performance is common. Sand and gravel also have low adsorptive

capacities, so the only adsorptive material in these systems is the microbial biomass itself. Using compost as the filter medium—particularly for air streams—provides high porosity, high adsorptive capacity for organic and inorganic compounds, good moisture retention, and the ability to support high degradation rates (Devinny, 1994). Compost biofilters have the further advantage of relatively long lifespans: 1 to 1.5 years of satisfactory performance before bed materials need to be changed (Leson, 1991; Conrad, 1995; Ottengraf, 1983). In contrast, GAC filters might need to be changed more frequently, often daily or monthly, depending on the pollutant content of the incoming air or water stream.

Commercial-scale compost biofilters have been used in Europe for the past 20 years to treat exhaust gases from composting plants (Bohn, 1975 and Haug, 1993). The number of VOCs removed is substantial, and removal efficiencies are generally high, as shown in Table 6 (Williams, 1993). Compost biofilters also can be used to treat odorous air from wastewater facilities, biosolids composting plants, and industrial facilities (Carlson, 1966; Bohn, 1975; Finn, 1997; Leson, 1991; Segall, 1995). The effluent gases from biosolids and MSW composting facilities are a complex mixture of terpenes, organic solvents (Eitzer, 1993), and biological products, such as short chain organic acids, amines, and aldehydes (Wilber, 1990 and Miller, 1993). Volatiles content at these facilities is in the range of 20 to 150 mg VOC/m^3 of air (Kissel, 1992), and odor intensity is high (Bidlingmaier, 1996). The ability of compost biofilters to remove such a wide range of compounds at relatively high concentrations indicates these filters are likely to be effective in a wide range of situations, from wastewater treatment plants to odor-generating food processing plants (Leson, 1991). Since the VOC spectrum of manures (Kreis, 1978) is similar to that of composting biosolids or MSW, biofilters are likely to be successful for removing odorous compounds from air exiting animal confinement facilities.

In contrast to compost-based bioremediation (Chapter 2), where there is substantial published literature and relatively limited practical demonstration, the published literature on compost biofilters is very sparse, with most of the available information being anecdotal or not referenced. Most successful biofilters are developed empirically, rather than on a substantial base of fundamental research. One inventor, for example, tried 30 different mixes for a compost matrix before finding one that was satisfactory (Conrad, 1995). Technological innovations frequently follow the increased availability of basic knowledge; in the case of compost biofilters, there is ample opportunity for improved designs, enhanced performance, and improved reliability.

Table 6

Volatiles Removal Efficiencies of Full-Scale Compost Biofilters

Compost Source	Volatiles Removed	Inlet Air Content	Exit Air Content	Percentage Removed
MSW compost	Ethanol Diacetyl Limonene Acetoin Total organic-C	391 mg C/m^3 16 16 64 557	not detected not detected 5 mg C/m^3 not detected 40	> 99 > 99 69 > 99 93
MSW compost	Total C	230 mg C/m^3	8	97
MSW compost	Odorous organics[a]	2,400 odor units	70 odor units	97
Biosolids compost	H_2S[b]	not given	not given	> 99.8
MSW compost	Total C	45 mg C/m^3	4 mg C/m^3	94

Adapted from van der Hoek, 1985.
[a] Volatile odorous compounds include a range of short-chain organic acids, aldehydes, dimethylsulfide, dimethyldisulfide, and dimethyltrisulfide.
[b] Removal of H_2S is probably a combination of chemical precipitation of sulfide as iron sulfide and microbial oxidation of sulfide to odorless and nonvolatile sulfate iron.

Compost biofilters are 83 to 99 percent effective at removing hydrogen sulfide gas and several simple aromatic compounds, as shown in Table 7 (Ergas, 1995). In a recent study, two biofilters were run in parallel, with substantial differences in performance between the two filters. The filters were also relatively effective in removing chlorinated aliphatic solvents and other volatiles (Figure 21), except for trichloromethane and tetrachloroethylene.

In another study, laboratory-scale compost biofilters were shown to be effective degraders of trichloroethylene (TCE), but only if the inlet air was supplemented with methane or propane (Watwood, 1995). Methane or propane addition was necessary because TCE-degrading organisms do not grow with TCE as the sole carbon and energy source (Lu, 1995). The requirement for a cosubstrate may also explain the relatively poor performance of the filters tested in similar studies (Ergas, 1995). The percentage of TCE removed was quite high in most cases, but there were substantial differences in performance among different compost types.

The specific cosubstrate (methane or propane) used also had a large effect on performance (Figure 22). Initial removal of TCE from the air phase appeared to be primarily by adsorption and/or transfer into micropores within the compost, since actual degradation of a single application of TCE required 10 to 20 days. Overall removal efficiency was 99.2 percent when inlet air contained 5,000 µg/L of TCE.

Table 7

Removal Efficiencies of a Compost Biofilter for Hydrogen Sulfide, Benzene, Toluene, and Xylene Isomers

Analyte	Inlet Concentration (µg/L)	Biofilter 1, Outlet Concentration	Percentage Removed	Biofilter 2, Outlet Concentration	Percentage Removed
Hydrogen sulfide	19,900	20	99.9	200	99.7
Benzene	900	68	95	210	83
Toluene	1,060	75	97	180	88
m- and p-xylene	260	27	93	61	88
o-xylene	95	17	91	25	88

Adapted from Ergas, 1995.

Field-scale use of compost biofilters to remove odorous compounds and methane from landfill gas during landfill mining also has been studied (Göschl, 1995). The performance of the filters was impressive. Shock loads of 3 to 9 percent v/v methane were introduced at irregular intervals, but the filters effectively removed the methane rapidly, as shown in Figure 23. Most of the methane removal resulted from very rapid microbial degradation, since methane is neither very water-soluble nor easily adsorbed to the organic fraction of the filter. The increased carbon dioxide content and decreased oxygen content of exit air shortly after a pulse of methane is also consistent with the rapid biodegradation of the gas. This treatment method provides a simple, effective way to improve air quality, especially because methane is now regarded as an undesirable atmospheric gas because of its contribution to the greenhouse effect and smog formation.

Compost biofilters are also effective at removing the VOCs generated during the recycling of spray cans (Conrad, 1995). VOCs are released when the cans are punctured. The gas is passed through a multistage compost biofilter, where 99 percent of the solvents and propellants are removed. Typical recommendations for maximum VOC concentrations for biofilters are about 5,000 mg/L of air, above which the solvents can inhibit microbial activity in the compost (Leson, 1991). With a multistage system, VOC inputs of around 25,000 mg/L can be processed effectively, a result that demonstrates clearly that substantial improvements can be made in relation to current biofilter performance.

The majority of compost biofilters are used to treat air streams, but there are indications that compost is also a suitable material for the treatment of contaminated water. A good example is a commercial stormwater filter (Conrad, 1995 and Stewart, 1994) that proved effective at removing oil, grease, and toxic metals found in stormwater runoff.

Regardless of the specific filter material being used, all biofilters have certain operational requirements that, if neglected, lead to performance losses. A successful compost biofilter has the following characteristics (Leson, 1991; Ottengraf, 1986; Haug, 1993; Williams, 1993; Ernst, 1987; Toffey, 1997):

- High porosity and water-holding capacity are required. Substantial differences exist among composts and between compost and peat (Figure 24A). The MSW compost shown in Figure 24 is not satisfactory as a filter medium because of its low total porosity and rapid loss of air-filled pore space as moisture content is increased. This material develops a high back pressure when moist, which greatly increases pump requirements (Figure 24B).

- Performance improves with increased time in service. This benefit results from the selection of microorganisms tolerant to shock loads and other organisms with a high growth rate (Figure 25).

- Additional nutrients are required. Although composts typically have 1 to 2 percent w/w nitrogen, most of that nitrogen is not rapidly bioavailable. As a result, systems handling high organic loads are likely to be nitrogen-deficient, unless a soluble form such as ammonium or nitrate is added. A relevant study demonstrated that the performance of a biofilter treating hexane vapors was improved dramatically by the addition of nitrogen (Morgenroth, 1996).

Without a nitrogen supplement, an 80 centimeter column removed only 40 to 70 percent of the incoming hexane, but a 60 centimeter column, supplied with nitrogen, removed 90 to 100 percent of the incoming hexane.

- Moisture content must remain between 50 to 70 percent to ensure high microbial activity. High moisture content also increases the capture of water-soluble VOCs when compared to a drier filter. For most applications, humidification of incoming air is required. In some situations, humidification of air entering the bottom of the filter must be combined with the addition of liquid water to the top of the filter, in order to maintain proper moisture conditions.

- Operating temperatures must remain between 20 ^{o}C and 35 ^{o}C. Below 20 ^{o}C, microbial activity is relatively low, and the organisms' ability to degrade contaminants is reduced. Above 35 ^{o}C, many mesophilic organisms display decreased activity. The temperature requirement imposes a limit on temperature of the incoming air. If air temperature is too high, filter efficiency will be affected, and the filter will be subject to excess water loss.

- Residence time of the gas phase going through the filter should be at least 30 seconds. With shorter residence times, inadequate capture and degradation of input VOCs are likely. As a consequence of this requirement, filters are more effective when treating low-velocity and/or low-volume air streams.

- Typical depth of the filter bed should be 1 meter. Shorter depths provide poor performance, except at very low flow rates. Filter beds greater than 1 meter in depth have a tendency to compact, thereby increasing air pressure requirements.

- The system must be designed to ensure uniform air distribution upon entering the filter, and the filter medium must be dimensionally stable so that crack formation and channeling of airflow does not occur. Channeling decreases residence time and the percentage of the filter that is active, drastically reducing filter performance.

Figure 20

Mechanisms for Contaminant Removal From Wastestreams During Passage Through Biofilters

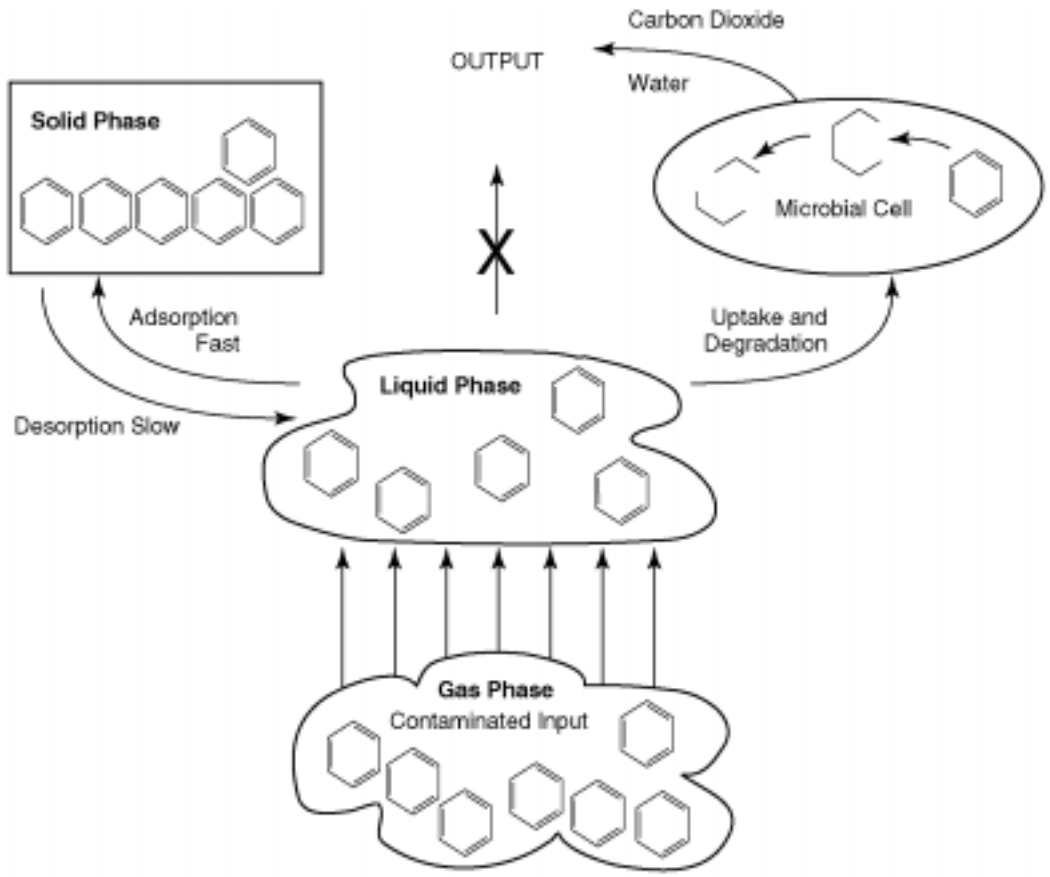
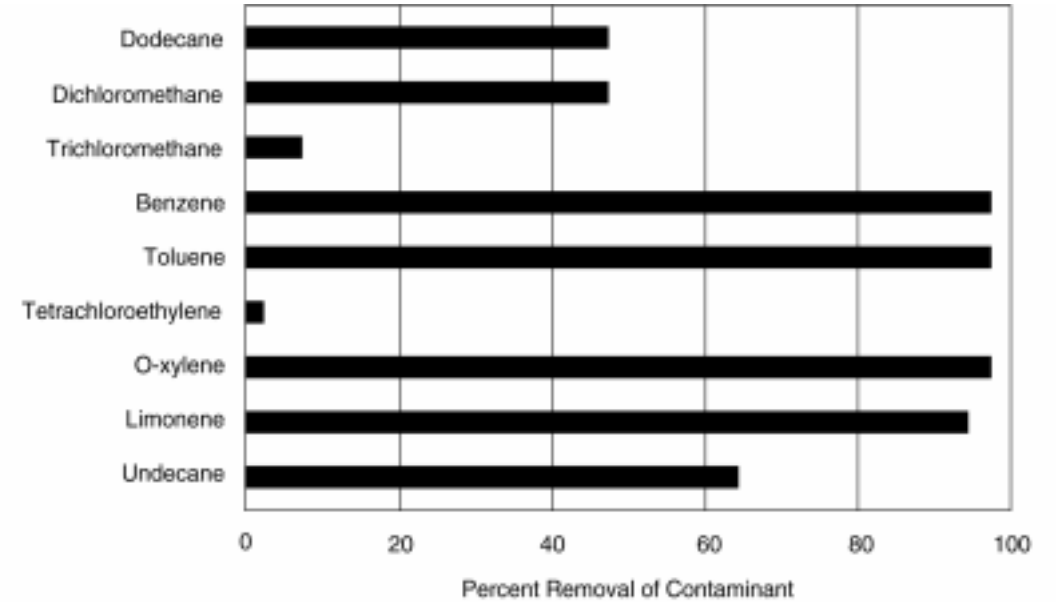


Figure 21

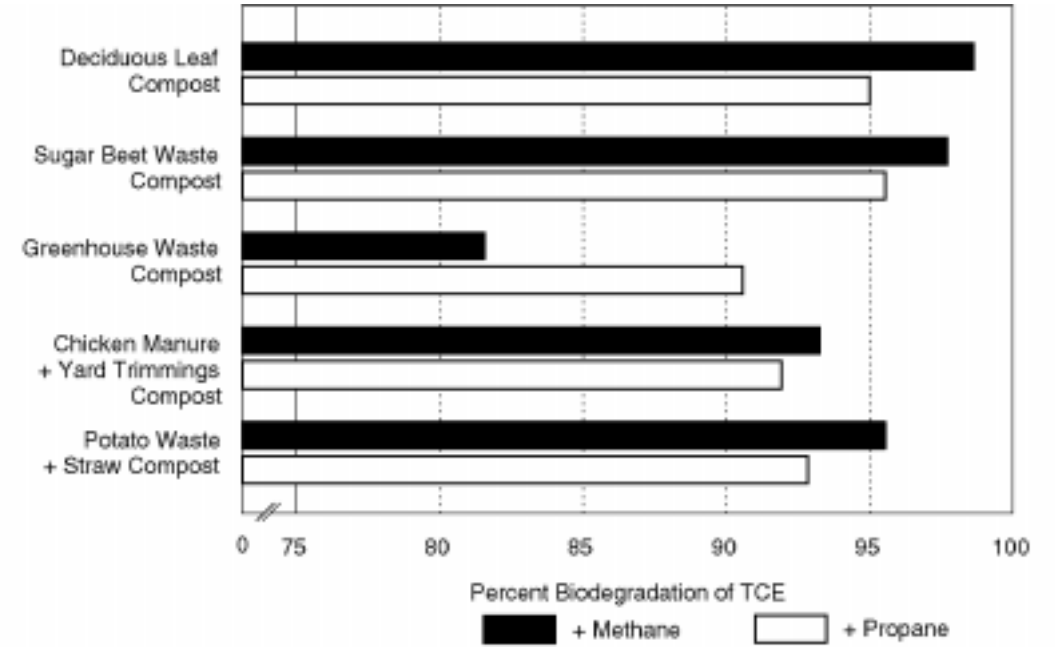
Removal Efficiency of Compost Biofilters for Synthetic Volatile Organic Compounds



Source: Ergas, 1995 (Figure 5)

Figure 22

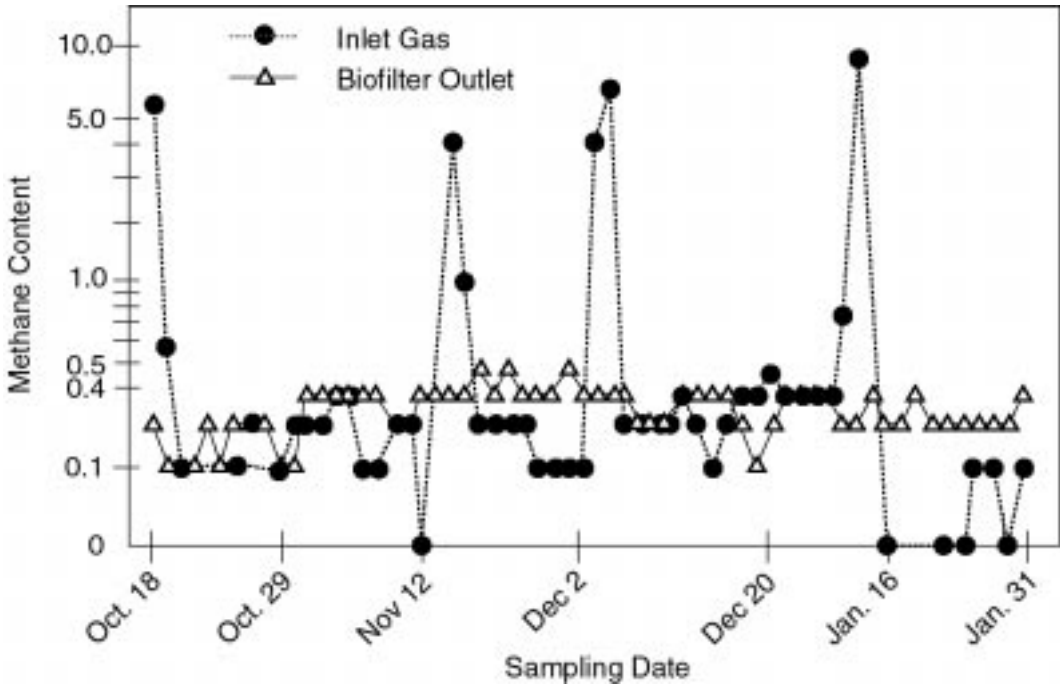
Percentage Degradation of Trichloroethylene During Passage Through Biofilters Made From Different Kinds of Compost



Source: Watwood, 1995 (Figure 4A)

Figure 23

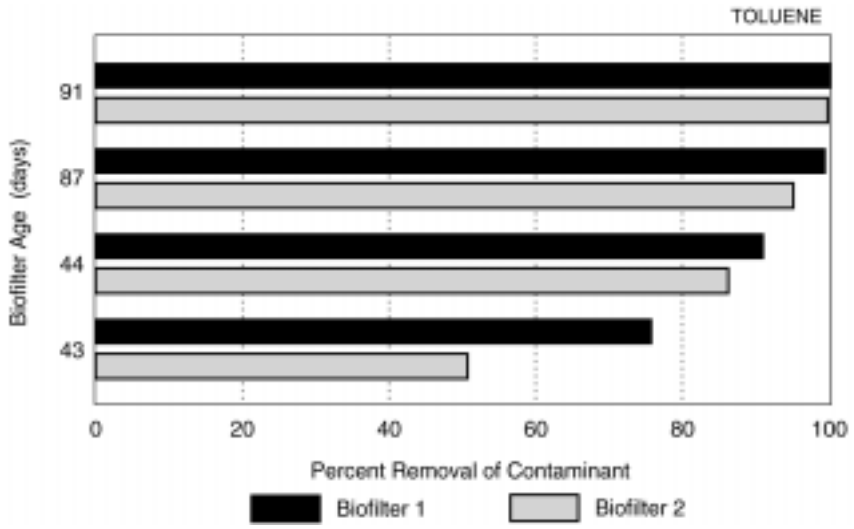
Removal of Methane From Landfill Gas During Mining Operations

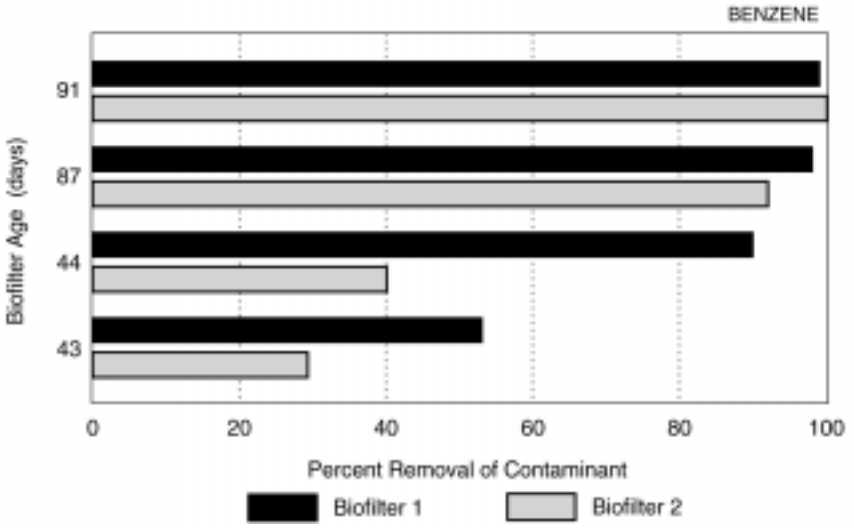


Source: Göschl, 1995 (Figure 2)

Figure 24

Improved Removal Efficiency of a Compost Biofilter With Increasing Time in Operation

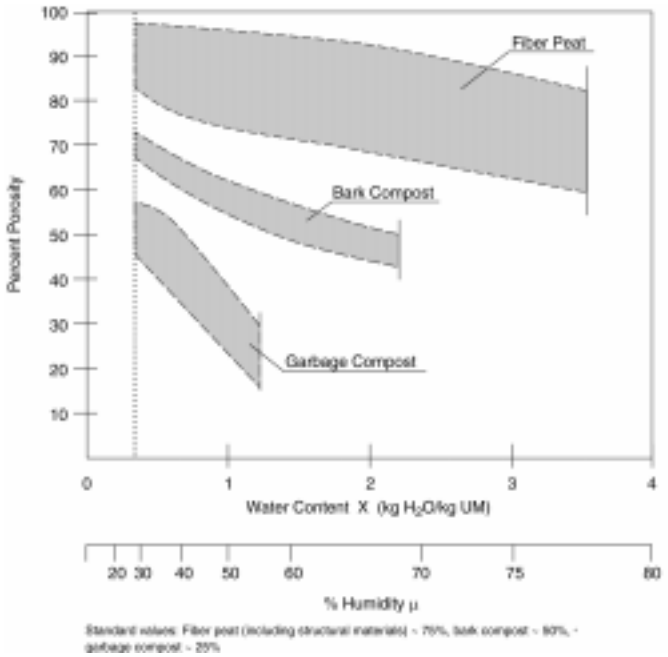


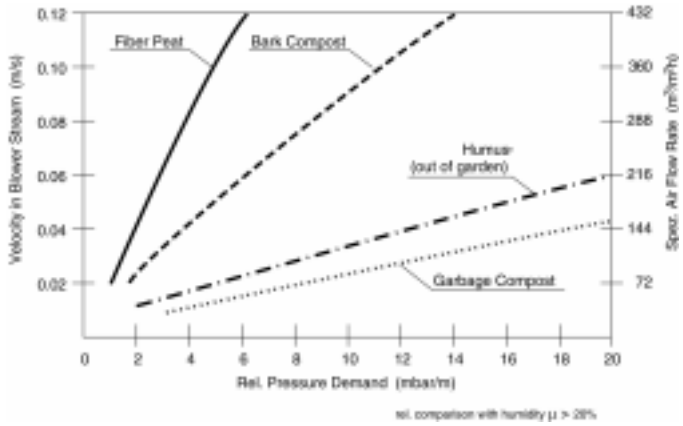


Source: Ergas, 1995 (Table 3)

Figure 25

Porosity of Several Filter Media as a Function of Water Content and Power Requirements of Various Materials





Source: Zeisig, 1988 (Figures 1 and 2)

References

Andersson, B., H. Aspegren, D.S. Parker, and M.P. Lutz. "High Rate Nitrifying Trickling Filters." *Water Science and Technology* 29(10-11) (1994): 47-52.

Apel, W.A., P.R. Dugan, M.B. Wiebe, E.G. Johnson, J.M. Wolfram, and R.D. Rogers. "Bioprocessing of Environmentally Significant Gases and Vapors With Gas-phase Bioreactors: Methane, Trichloroethylene, and Xylene." In *Emerging Technologies in Hazardous Waste Management III*, edited by D.W. Tedder and F.G. Pohland, 411-428. Washington, DC: American Chemical Society, 1993.

Bidlingmaier, W. "Odour Emissions From Composting Plants." In *The Science of Composting*, edited by M. de Bertoldi, P. Bert, and P. Tiziano, 71-79. London: Blackie Academic and Professional, 1996.

Bohn, H.L. "Soil and Compost Filters of Malodorant Gases." *Journal of the Air Pollution Control Association* 25 (1975): 953-955.

Carlson, D.A. and C.P. Leiser. "Soil Beds for the Control of Sewage Odors." *Journal of the Water Pollution Control Association* 38 (1966): 829-840.

Conrad, P. "Commercial Applications for Compost Biofilters." *BioCycle* 36 (October 1995): 57-60.

Devinny, J.S., V.F. Medina, and D.S. Hodge. "Biofiltration for Treatment of Gasoline Vapors." In *Hydrocarbon Bioremediation*, by R.E. Hinchee, B.C. Alleman, R.E. Hoeppel, and R.N. Miller, 12-19. Boca Raton, FL: Lewis Publishers, 1994.

Eitzer, B.D. "Survey of Volatile Organic Chemical Emissions From Waste Composting Facilities." In *The Composting Council's Fourth Annual Conference Research Symposium*, 9-11. Arlington, VA: The Composting Council, 1993.

Ergas, S.J., E.D. Schroeder, D.P.Y. Chang, and R.L. Morton. "Control of Volatile Organic Compound Emissions Using a Compost Biofilter." *Water Environment Research* 67 (1995): 816-821.

Ernst, A.A. and D. Ritner. "New Ways for Design, Construction, and Operation of Compost Filters for Special Purposes." In *Compost: Production, Quality, and Use*, edited by M. de Bertoldi, 440-452. New York, NY: Elsevier Applied Science, 1987.

Finn, L. and R. Spencer. "Managing Biofilters for Consistent Odor and VOC Treatment." *BioCycle* 38 (January 1997): 40-44.

Göschl, R. "Odor Stabilization in Waste Disposal Sites." In *In Situ Aeration: Air Sparging, Bioventing, and Related Remediation Processes,* edited by R.E. Hinchee, R.N. Miller, and P.C. Johnson, 289-295. Columbus, OH: Battelle Press, 1995.

Haug, R.T. "Biofiltration." In *The Practical Handbook of Compost Engineering*, 586-600. Boca Raton, FL: Lewis Publishers, 1993.

Kissel, J.C., C.L. Henry, and R.B. Harrison. *Biomass and Bioenergy* 3(3-4) (1992): 181.

Kreis, R.D. *Control of Animal Production Odors: The State-of-the-Art*. EPA600-2-78-083. Washington, DC, 1978.

Leson, G. and A.M. Winer. "Biofiltration: An Innovative Air Pollution Control Technology for VOC Emissions." *Journal of the Air and Waste Management Association* 41 (1991): 1045-1054.

Lu, C.J., C.Y. Chang, and C.M. Lee. "Aerobic Biodegradation of Trichloroethylene by Microorganisms That Degrade Aromatic Compounds." In *Bioremediation of Chlorinated Solvents*, edited by R.E. Hinchee, A. Leeson, and L. Semprini, 1-7. Columbus, OH: Battelle Press, 1995.

Miller, F.C. "Minimizing Odor Generation." In *Science and Engineering of Composting*, edited by H.A. J. Hoitink and H.M. Keener, 219-241. Worthington, OH: Renaissance Publications, 1993.

Morgenroth, E., E.D. Shroeder, D.P.Y. Chang, and K.M. Scow. "Nutrient Limitation in a Compost Biofilter Degrading Hexane." *Journal of the Air and Waste Management Association* 46 (1996): 300-308.

Nielsen, V.C., J.H. Voorburg, and P. L'Hermite. *Odour Prevention and Control of Organic Sludge and Livestock Farming*. London: Elsevier Applied Science Publishers, 1986.

Nielsen, V.C., J.H. Voorburg, and P. L'Hermite. *Volatile Emissions from Livestock Farming and Sewage Operations*. London: Elsevier Applied Science Publishers, 1988.

Ottengraf, S.P.P. "Exhaust Gas Purification." *Biotechnology, Volume 8*, 427-452. Weinheim, Germany: VCH Verlagsgesellschen, 1986.

Ottengraf, S.P.P. and A.H.C. van den Oever. "Kinetics of Organic Compound Removal From Waste Gases With a Biological Filter." *Biotechnology and Bioengineering* 25 (1983): 3089-3102.

Saberiyan, A.G., M.A. Wilson, E.O. Roe, J.S. Andrilenas, C.T. Esler, G.H. Kise, and P.E. Reith. "Removal of Gasoline Volatile Organic Compounds via Air Biofiltration: A Technique for Treating Secondary Air Emissions From Vapor-extraction and Air-stripping Systems." In *Hydrocarbon Bioremediation*, by R.E. Hinchee, B.C. Alleman, R.E. Hoeppel, and R.N. Miller, 1-11. Boca Raton, FL: Lewis Publishers, 1994.

Segall, L. "Biosolids Composting Facility Opts for In-vessel System." *BioCycle* 36 (1995): 39-43.

Standefer, S. and C. van Lith. "Biofilters Minimize VOC Emissions." *Environmental Protection* (March 1993): 48-58.

Stewart, W. Compost Stormwater Filter Engineering System. Environmental Excellence Award and Innovator of the Year Award. Association of Washington State Business, 1994.

Toffey, W.E. "Biofiltration—Black Box or Biofilm?" *BioCycle* 38 (June 1997): 58-63.

Tschui, M., M. Boller, W. Gujer, J. Eugster, C. Mader, and C. Stengel. *Water Science and Technology* 29(10-11) (1994): 53-60.

van der Hoek, K.W. and J. Oosthoek. "Composting: Odour Emission and Odour Control by Biofiltration." In *Composting of Agricultural and Other Wastes*, edited by J.K.R. Gasser, 271-281. London: Elsevier Applied Science Publishers, 1985.

Watwood, M.E. and S. Sukesan. "Biodegradation of Trichloroethylene in Finished Compost Materials." *Compost Science and Utilization* 3 (1995): 6-19.

Wilber, C. and C. Murray. "Odor Source Evaluation." *BioCycle* (March 1990): 68-72.

Williams, T.O. and F.C. Miller. "Composting Facility Odor Control Using Biofilters." In *Science and Engineering of Composting*, edited by H.A. Hoitink and H.M. Keener, 262-281. Worthington, OH: Renaissance Publications, 1993.

Zeisig, H.D. "Experiences With the Use of Biofilters to Remove Odours From Piggeries and Hen Houses." In *Volatile Emissions From Livestock Farming and Sewage Operations*, edited by V.C. Nielsen, J.H. Voorburg, and P. L'Hermite, 209-216. London: Elsevier Applied Science, 1988.

Chapter 4

Potential for Reclamation of Mine Spoils and Brownfields With Compost

Mineral extraction operations and industrial activities can leave a substantial legacy of environmental problems in their wake. EPA estimates there are approximately 300,000 abandoned mine sites in the United States. In addition to being unattractive, these sites can present a significant environmental hazard from the leaching of acid and toxic metals into groundwater, as well as erosional transport of hazardous constituents and spoil materials into surface waters. Natural revegetation is often prevented in these areas because of low pH, phytotoxic concentrations of metals, poor physical structure for plant growth, and slopes too steep for plant establishment. Even if plants can be established, growth is often so poor that an economically viable crop, such as hay or pasturage, cannot be generated (Fitzgerald, 1979). There is no way, therefore, to recover rehabilitation expenses. Depending on the extent of rehabilitation, costs to reclaim mine spoils can range from $1,000 to $5,000 per acre, values which fall in the range of valuable farmland.

In older urban industrial areas, substantial land exists where industries failed and the properties were abandoned. In some cases, these properties, or brownfields, could be redeveloped or converted to parks if not for their extensive contamination and/or very poor soil conditions. There are approximately 200,000 to 650,000 brownfields in the United States (Airst, 1996 and Carey, 1996). Using current cleanup technologies, the cost to remediate these sites would far exceed the value of the properties (Carey, 1996). Since remediation expenses exceed the value of the property, there is no economically feasible way to recover these costs. In light of the expenses involved, both mine spoils and brownfields remain unrestored and relatively worthless, in spite of EPA efforts to accelerate the reuse process (Slutzky, 1995 and Cichon, 1997). This chapter describes some straightforward and relatively inexpensive alternative options for remediating these sites using compost to improve soil conditions, reduce erosion, enhance plant establishment, and immobilize toxic metals.

Mine spoils and brownfields share a number of problems, including:

- Soil compaction or poor physical structure. This results in poor or no plant development and contributes to offsite contamination via soil that erodes from the barren site. Eroded soil transfers contaminated material into surface water and onto adjacent property. The transfer of pyrite-containing spoil from mine sites results in water acidification. If the contaminated material is porous, the lack of plant cover results in a transfer of soluble contaminants into groundwater sources. If plants are present, however, they intercept some of the contaminants and thereby limit transfer to ground water. Thus, for a variety of reasons, revegetation of these sites is a significant first step in limiting ongoing environmental damage.

- The presence of pyrite. Pyrite minerals are very common associates of ore-bearing minerals. When exposed to air and water, pyrite is converted to soluble iron and sulfuric acid, resulting in soil acidification and acid drainage. Few, if any, plants will grow in acidified soil. If plants can be established in this soil, they will compete for water with the microorganisms that cause acidification and diminish acid formation.

Metals are an important component of industrial activity, but many of these metals are highly toxic to humans, animals, and plants. The most common metals in this category are lead, copper, zinc, cadmium, and mercury. Metal contamination of industrial sites and abandoned mine spoils is common. Transfer of solid toxic metals by wind and water erosion and by leaching of water-soluble metals is a serious threat to surface and ground waters.

A vast amount of literature exists that strongly indicates that waste organic materials can alleviate all or many of the problems described above. Part of this literature was used as the basis for the Clean Water Act Section 503 regulations governing the safe use of biosolids and biosolids compost (Ryan, 1993). The value of organic materials in improving the structure and water infiltration of compacted or sandy soils and in enhancing plant establishment is well known among agriculturalists (Steffen, 1979; Sabrah, 1995; Rodale, 1945).

Biosolids (also known as municipal sewage sludge) were used to enhance plant growth on mine spoils in the eastern United States (Figure 26) and on spent oil shale in the western United States (Figure 27). Plants did not absorb the potentially toxic metals in the biosolids, nor were the metals accumulated by pheasants or swine (Hinesly, 1979) that were fed grain grown in sludge-amended soils. In addition, the metal content of wild birds who nested in biosolids-

treated mine spoils was not increased, with a few exceptions (Gaffney, 1979). The toxic metals remain in a low-bioavailability form for at least 20 years after biosolids application (Chaney, 1994). Taken together, these results indicate that organic-rich materials, such as compost, are likely to be a useful remediation aid to assist revegetation and to immobilize toxic metals in mine spoils and brownfields.

When compared to the large amount of information available on the use of compost for bioremediation of soils contaminated with organic compounds, very little literature is available on soil reclamation using compost to enhance plant growth and to immobilize toxic metals in soil. Because of similarities in composition between compost and the products formed by degradation of waste materials in soil (Almendros, 1991), however, the existing literature suggests compost may be a useful material for remediation activities. Compost has a number of advantages over commonly used organic wastes:

- Compost is rich in humic materials, which have residence times in soil of decades to centuries. Because of this long residence time, improvement in soil structure will be relatively persistent. In contrast, raw wastes added to soil quickly lose their organic matter and degrade within a few years. The beneficial effects, encountered soon after applying raw wastes, quickly decrease. Failure of revegetation efforts is a common problem with raw wastes, usually occurring 2 or 3 years after planting. Use of persistent organic matter, such as compost, may be a solution to this problem.

- Improving the structure of compacted soil may require up to 20 percent by weight of organic materials. If raw wastes are used, this high rate of application may provide excess nutrients, such as nitrogen, that pose a pollution problem and promote anaerobic soil conditions under which plants will not thrive. In contrast, nutrient release from composted materials is quite slow (Tyson, 1993); therefore, high application rates can be used without producing a nutrient excess. Spent mushroom substrate (a type of compost) has been used for soil reclamation. An application rate of 175 tons per acre supplied adequate, but not excessive, nutrient levels. When applied at 175 tons per acre, revegetation was achieved on slopes averaging 25 percent (Rupert, 1995).

- Compost is more effective for revegetation of steep slopes than raw waste materials or biosolids. Dried biosolids cannot be used to revegetate slopes greater than 12 percent, because the material washes away (Kerr, 1979). In contrast, spent mushroom substrate can successfully revegetate slopes up to 25 percent when it is incorporated into soil (Rupert, 1995). In addition, slopes up to 42 percent have been successfully revegetated with 3-inch-thick surface applications of yard trimmings compost (Ettlin, 1993). A mature compost tends to be self-adhesive and forms a flexible, noneroding blanket when applied to the soil surface. It also provides a good growth medium for plant establishment, because the organic matter is stabilized and releases nutrients slowly. In contrast, most raw wastes and uncomposted biosolids have a granular character making them erosion-prone. When used at high application rates, raw wastes and biosolids can actually prevent, rather than enhance, plant growth.

- Spent mushroom substrate has been used as a filter medium to treat acid mine drainage (Stark, 1994). Under relatively low flow conditions, the pH of incoming mine drainage was increased from 4.0 to 6.5 after passage through the filter. Soluble manganese and iron also decreased. These results indicate that compost, when added to acidified soils, increases pH into a range satisfactory for plant growth, reduces the content of water-soluble metal ions, and maintains these improved conditions over time.

A 25-ton-per-acre application of MSW compost to surface mine spoils resulted in a decrease in bulk density from 1.74 g/cm^3 to 1.49 g/cm^3 (Fenton, 1955). Since plant roots have difficulty penetrating soil with bulk densities over 1.5 g/cm^3 (Russell, 1973), the compost addition brought bulk density into a satisfactory range for plant development. Hydraulic conductivity was increased 42-fold with compost treatment, resulting in less runoff and more water penetration into the soil. The combination of plant establishment and increased water infiltration dramatically reduced soil erosion. Synthetic polymers are frequently used for erosion suppression, but the benefits on soil properties are small when compared to compost. For example, application of water-soluble formulations of polyacrylamide are effective at reducing erosion but increase infiltration only slightly (Trout, 1995). Overall, polymers are less effective than compost, because they do not improve conditions for plant root growth, even though they help reduce erosion.

In one interesting experiment, biosolids and straw compost were applied to colliery spoils; grass establishment did not occur unless compost was added, as shown in Figure 28 (Atkinson, 1992). In addition, the productivity of the grass was highly correlated with the amount of compost added (Figure 29). In contrast, compost did not influence the growth of trees planted in the same material. Composted biosolids were used to successfully revegetate surface-mined land in the eastern United States (Griebel, 1979). The compost was very effective in promoting plant growth (Figure 30) and increased soil pH from a pretreatment value of 2.9 to 5.0.

The results in Figure 30 are a striking example of the beneficial effects of compost on initial plant establishment, but a recent project indicates that using compost for revegetation has many benefits (Pinamonti, 1996). The results in Figure 31 indicate that compost has three benefits when used for revegetation projects: (1) early plant establishment is greater when compost is added, (2) at all time periods, the percentage of plant cover is higher with compost, and (3) long-term persistence of the initial vegetation is enhanced in comparison to areas without compost.

Accumulation of sodium in soils near oil wells is a common phenomenon. In order to prime the wells, brine is often pumped into them and released. The sodium interacts with the soil and increases bulk density. The high salinity prevents plant growth. If the sodium is not removed, the soil remains barren. Application of MSW compost and gypsum (calcium sulfate) to saline- and alkaline-contaminated soil in Israel increased oat yields from 180 kg/ha in untreated plots to 5,560 kg/ha in treated plots. Chloride content decreased from 11,080 kg Cl/ha in untreated plots to 4,120 kg Cl/ha in treated plots. Depth of root penetration was greater in treated plots as well (Avnimelech, 1992).

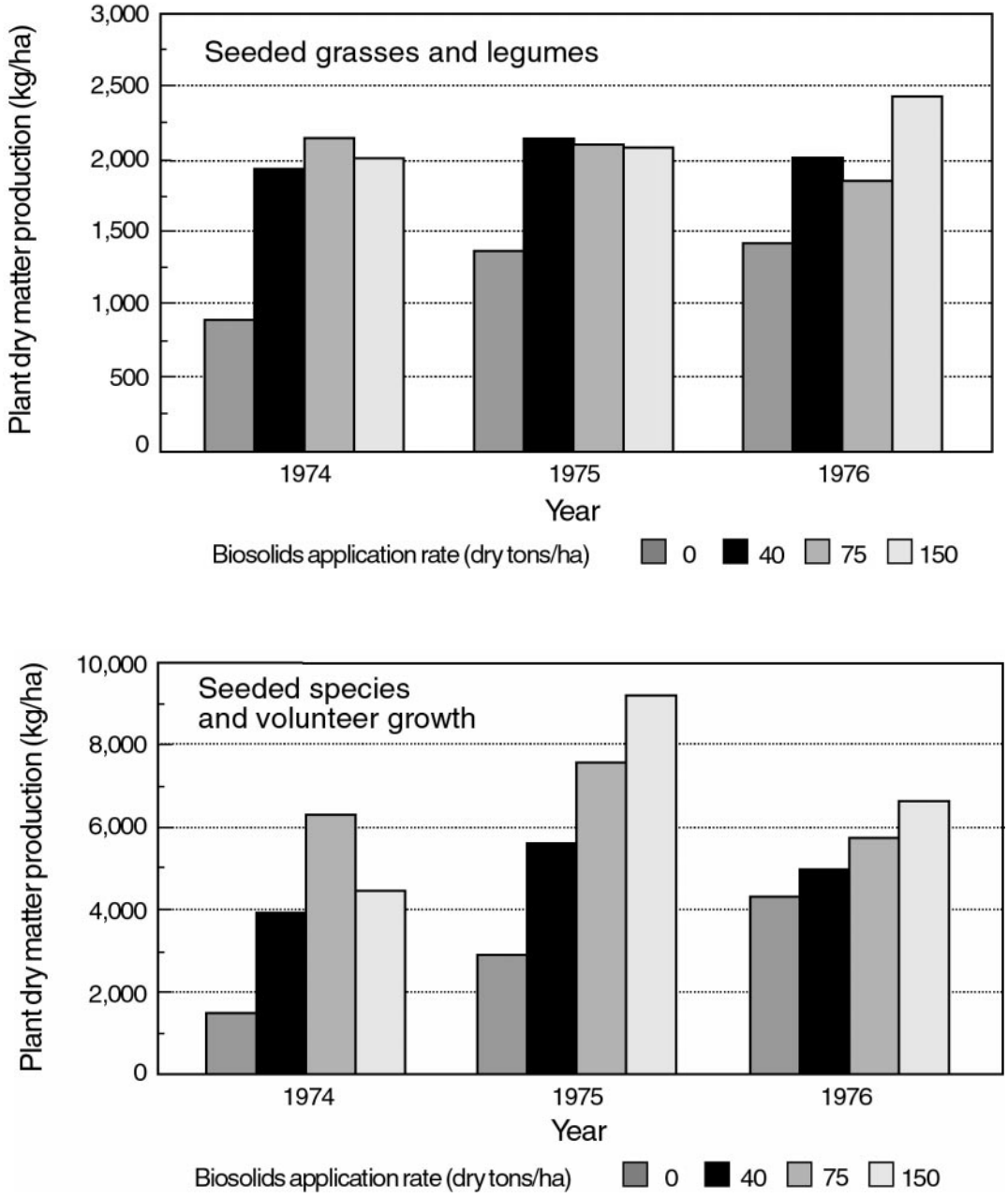
If soils are contaminated with toxic metals, the only available options for remediation are removal of the soil and burial in a suitable landfill, chemical immobilization, or use of chemical extractants to remove the metals from soil (Bolton, 1995 and Smith, 1995). All of these options are expensive and impractical for the large volumes of material present at abandoned mine sites. Several researchers have suggested investigating alternatives to remediation of large metal-contaminated sites, such as immobilization—the conversion of the metal to a form of low bioavailability by combining it with hydroxyapatite (Ma, 1994 and Xu, 1994)—or by reaction with organic (humic) and inorganic components of compost (Schnitzer, 1977). Modest declines in water-extractable cadmium, zinc, and nickel, but not copper, occur during the composting of

sewage sludge (García, 1995). This decline is attributed to adsorption of the metals by the humic materials in the compost. If compost of low metal contamination is mixed with metal-contaminated soil, the same reaction is expected to occur, thereby reducing mobility of the metal. A recent study examined the uptake of toxic metals using soil amended with 25 percent by weight (equivalent to about 125 tons per acre) of biosolids compost containing 8 mg/kg cadmium, 323 mg/kg copper, 56 mg/kg nickel, 151 mg/kg lead, 3.6 mg/kg selenium, 219 mg/kg chromium, and 831 mg/kg zinc (Warman, 1995). Swiss chard, a metal-accumulating plant species, was used. There were no increases in plant tissue content of zinc, cadmium, copper, nickel, chromium, or lead when compared to plants grown in soil without compost. Tissue levels of selenium, however, were elevated. The lack of metal uptake by the plants is a good indication that compost strongly binds metals and prevents their uptake. The same results can be expected if compost is added to metal-contaminated soil, thereby preventing transfer of metals from soil into food chains. Based on the results of this and similar studies, use of compost to decrease metal availability in contaminated soils might be a viable alternative to soil removal or chemical extraction. At the present time, however, this treatment is not included at most composting facilities as an acceptable method for metal remediation (Smith, 1995).

There is a growing interest in the idea that contamination standards should be risk-based, rather than simply concentration-based (Chaney, 1994; National Research Council, 1994; Hoddinott, 1992). In a risk-based appraisal, removal of toxic metals from soil may be unnecessary, if the environmental mobility and bioavailability can be reduced sufficiently. Application of the risk principle to mine sites and brownfields may be an excellent solution to two very large-scale contamination problems. Because of the potential financial savings and social and environmental values of remediating these sites, research to establish feasibility of this concept should be strongly considered.

Figure 26

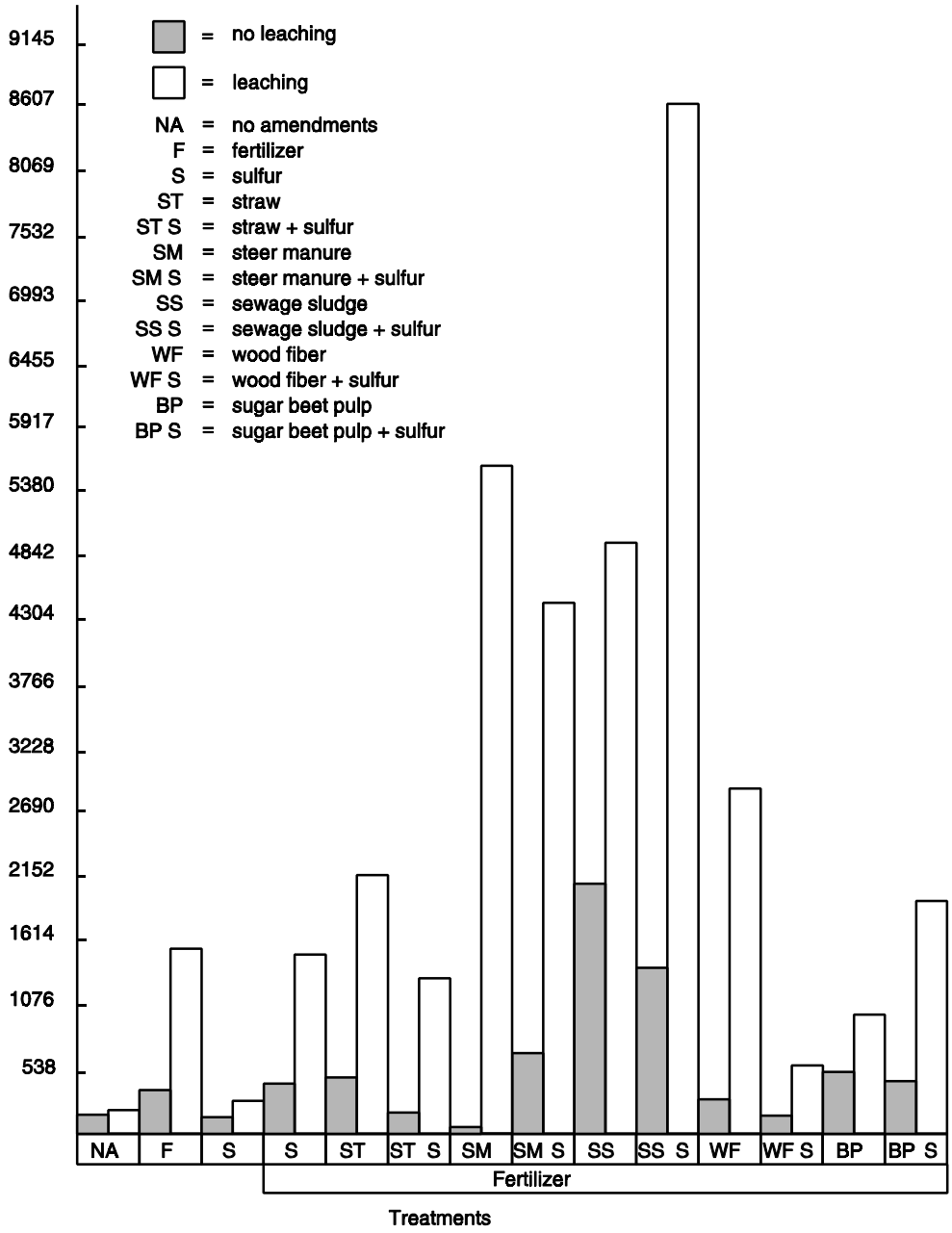
Plant Growth in Mine Spoils With or Without Biosolids Addition



Source: Kerr, 1979

Figure 27

Biomass Production by Wheatgrass in Oil Shale With or Without Organic Amendments

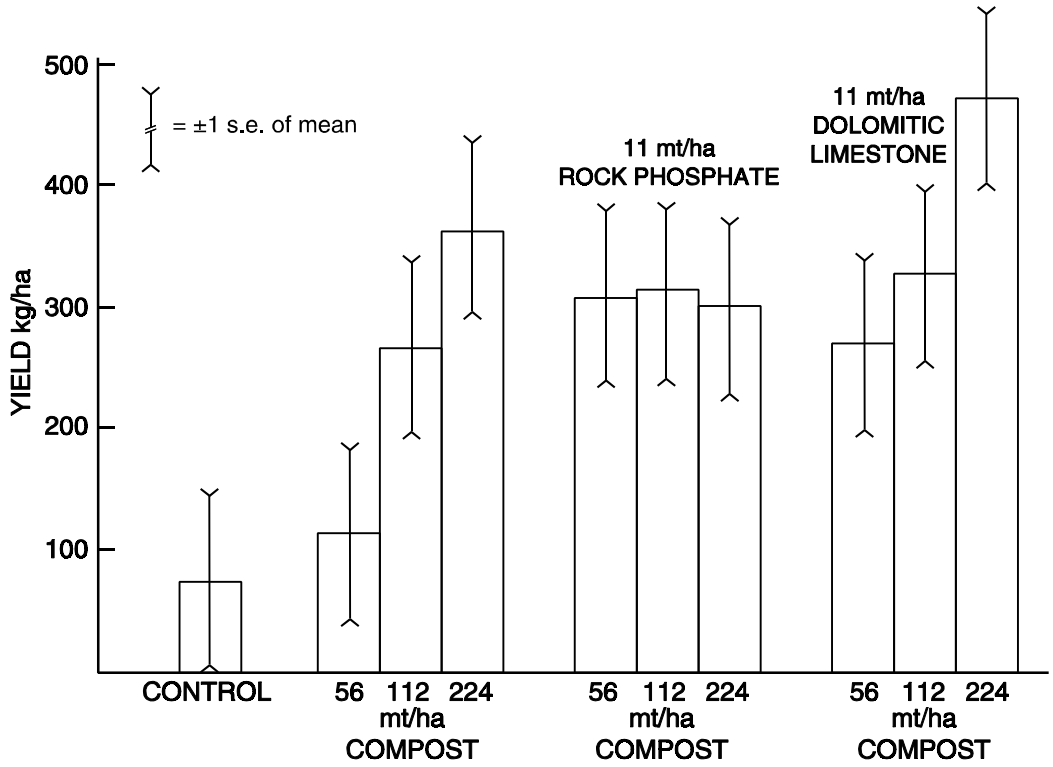


Note the especially large beneficial effect of sewage sludge (SS treatments).

Source: Williams, 1979

Figure 28

Biomass Production by Tall Fescue and Birdsfoot Trefoil in Acid Strip Mine Spoil as Affected by Addition of Biosolids Compost

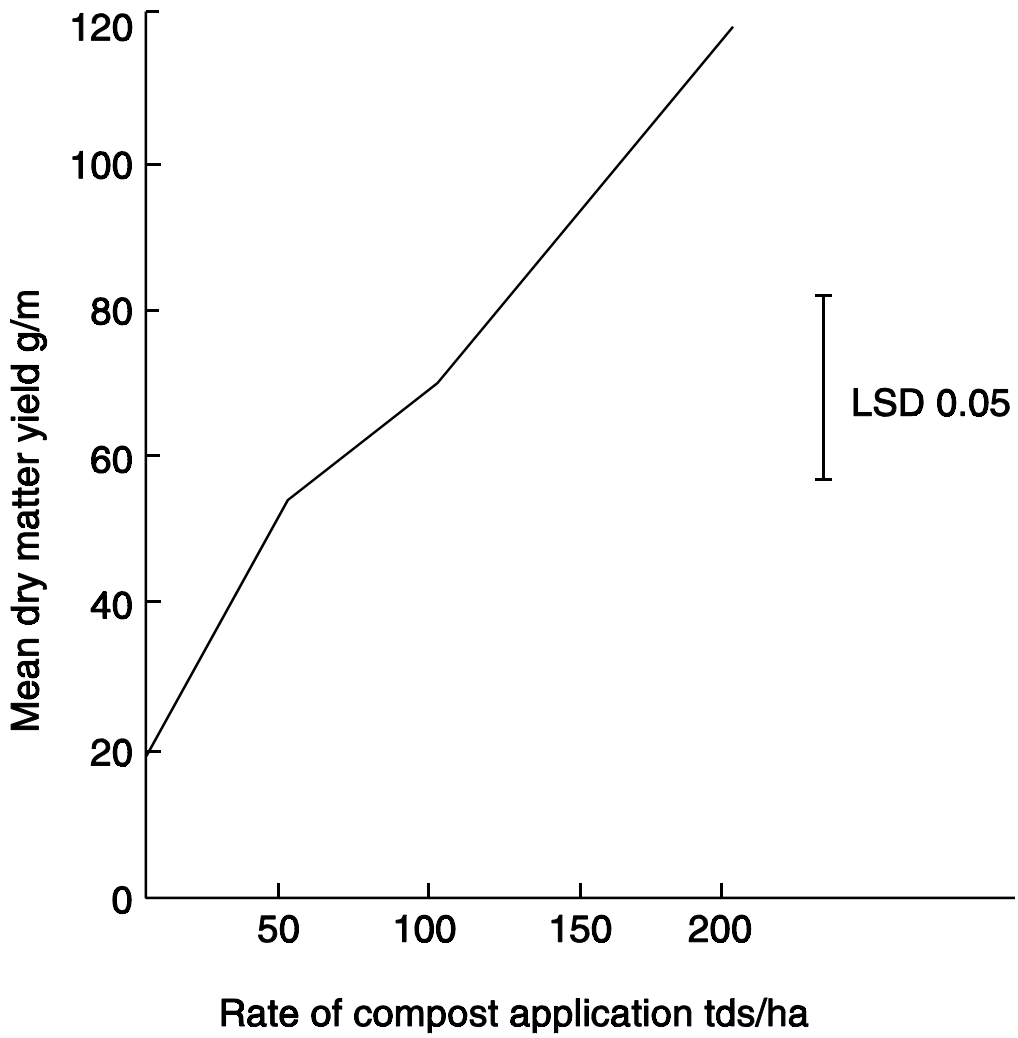


kg/ha=kilograms per hectare
mt/ha=metric tons per hectare

Source: Griebel, 1979

Figure 29

Effect of Compost Addition Rate on Grass Production in Colliery Spoil Material



g/m=grams per square meter
tds/ha=tons dry solids per hectare
LSD=least significant difference

Source: Atkinson, 1992

Figure 30

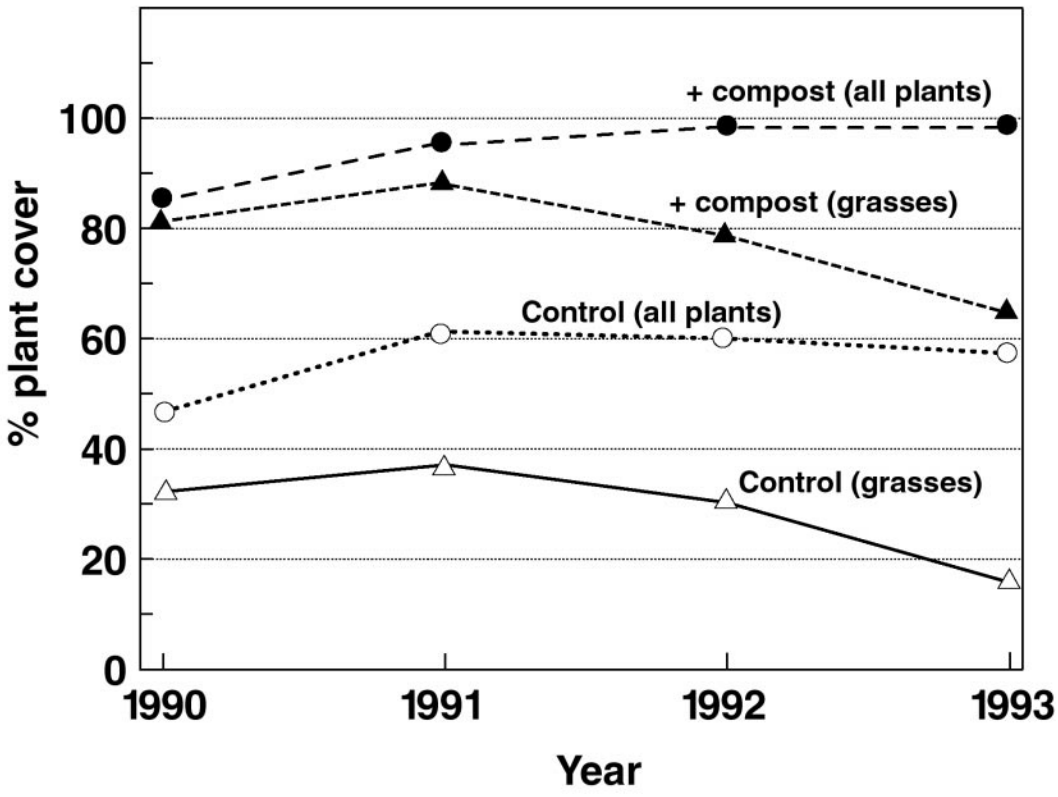
Plant Establishment With or Without Compost Addition

Revegetation occurred only in plots to which compost was added.

Source: Atkinson, 1992

Figure 31

Enhanced Revegetation of Ski Tracks by Addition of 125 Tons of Compost Per Hectare



References

Airst, R.L. "Turning Brownfields to Greenbacks." *Environmental Protection* (November 1996): 28-29, 35.

Almendros, G., R. Frund, F.J. Gonzalez-Vila, K.M. Haider, H. Knicker, and H.D. Ludemann. "Analysis of ^{13}C and ^{15}N CPMAS NMR-spectra of Soil Organic Matter and Composts." *FEBS Letters* 282 (1991): 119-121.

Atkinson, S.L., J.M. Lopez-Real, and G.P. Buckley. "Evaluation of Composted Sewage Sludge-straw for the Reclamation of Derelict Land: The Reclamation of Colliery Spoil." *Acta Horticulturae* 302 (1992): 237-248.

Avnimelech, Y., M. Kochva, Y. Yotal, and D. Shkedy. "The Use of Compost as a Soil Amendment." *Acta Horticulturae* 302 (1992): 217-236.

Bolton Jr., H. and Y.A. Gorby. "An Overview of the Bioremediation of Inorganic Contaminants." In *Bioremediation of Inorganics*, edited by R.E. Hinchee, J.L. Means, and D.R. Burris, 1-16. Columbus, OH: Battelle Press, 1995.

Carey, J. "Urban Fields of Dreams." *Business Week* (May 1996): 80-86.

Chaney, R.L. and J.A. Ryan. *Risk Based Standards for Arsenic, Lead, and Cadmium on Urban Soils*. Frankfurt, Germany: DECHEMA, 1994.

Cichon, E. "Changing the Focus of Brownfields Cleanups." *Pollution Engineering* 29 (April 1997): 48-50.

Ettlin, L., and B. Stewart. "Yard Debris Compost for Erosion Control." *BioCycle* 34 (December 1993): 46-47.

Fenton, G.K. "Temporal Variation of Soil Hydraulic Properties on Municipal Solid Waste Amended Mine Soils." *Transactions of the American Society of Agricultural Engineers* 38 (1955): 775-782.

Fitzgerald, P.R. "Recovery and Utilization of Strip-mined Land by Application of Anaerobically Digested Sludge and Livestock Grazing." In *Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land*, edited by W.E. Sopper and S.N. Kerr, 498-506. University Park, PA: The Pennsylvania State University Press, 1979.

Gaffney, G.R. and R. Ellertson. "Ion Uptake of Redwinged Blackbirds Nesting on Sludge-treated Soils." In *Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land*, edited by W.E. Sopper and S.N. Kerr, 507-515. University Park, PA: The Pennsylvania State University Press, 1979.

García, C., J.L. Moreno, T. Hernández, F. Costa, and A. Polo. . "Effect of Composting on Sewage Sludges Contaminated With Heavy Metals." *Bioresource Technology* 53 (1995): 13-19.

Griebel, G.E., W.H. Armiger, J.F. Parr, D.W. Steck, and J.A. Adam. "Use of Composted Sewage Sludge in Revegetation of Surface-mined Areas." In *Utilization of Sewage Effluent and Sludge on Forest and Disturbed Land,* edited by W.E. Sopper and S.N. Kerr, 293-305. University Park, PA: Pennsylvania State University Press, 1979.

Hinesly, T.D., L.G. Hansen, E.L. Ziegler, and G.L. Barrett. "Effects of Feeding Corn Grain Produced on Sludge-amended Soil to Pheasants and Swine." In *Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land*, edited by W.E. Sopper and S.N. Kerr, 481-495. University Park, PA: The Pennsylvania State University Press, 1979.

Hoddinott, K.B. (ed.). *Superfund Risk Assessment in Soil Contamination Studies*. Philadelphia, PA: American Society for Testing and Materials, 1992.

Kerr, S.N., W.E. Sopper, and B. R. Edgerton. "Reclaiming Anthracite Refuse Banks With Heat-dried Sewage Sludge." In *Utilization of Sewage Effluent and Sludge on Forest and Disturbed Land*, edited by W.E. Sopper and S.N. Kerr, 333-351. University Park, PA: The Pennsylvania State University Press, 1979.

Ma, O.Y., T.J. Logan, and S.J. Traina. "Effects of NO_3^-, Cl^-, F^-, SO_4^{2-}, and CO_3^{2-} on Pb^{2+} Immobilization by Hydroxyapatite." *Environmental Science and Technology* 28 (1994): 408-418.

National Research Council. *Ranking Hazardous-Wastes Sites for Remedial Action*, 294. Washington, DC: Academy Press, 1994.

Pinamonti, F. and G. Zorzi. "Experiences of Compost Use in Agriculture and in Land Reclamation Projects." In *The Science of Composting*, edited by M. de Bertoldi, P. Bert, and P. Tiziano, 517-527. London: Blackie Academic and Professional, 1996.

Rodale, J.I. "Chapter 9: Advantages of Compost Farming." In *Pay Dirt,* 83-92. New York: The Devin-Adair Company, 1945.

Rupert, D.R. "Use of Spent Mushroom Substrate in Stabilizing Disturbed and Commercial Sites." *Compost Science and Utilization* 3(1) (1995): 80-83.

Russell, E.J. *Soil Conditions and Plant Growth, 10th Edition*, 530. London: Longman Group Limited, 1973.

Ryan, J.A. and R.L. Chaney. "Regulation of Municipal Sewage Sludge Under the Clean Water Act Section 503: A Model for Exposure and Risk Assessment for MSW-compost." In *Science and Engineering of Composting*, by H.A.J. Hoitink and H.M. Keener, 422-450. Worthington, OH: Renaissance Publications, 1993.

Sabrah, R.E.A., H.M.A. Magid, S.I. Abdel-Aal, and R.K. Rabie. "Optimizing Physical Properties of a Sandy Soil for Higher Productivity Using Town Refuse Compost in Saudi Arabia." *Journal of Arid Environments* 29 (1995): 253-262.

Schnitzer, M. and H. Kodama. "Reactions of Minerals With Soil Humic Substances." In *Minerals in the Soil Environment*, 741-770. Madison, WI: Soil Science of America, 1977.

Slutzky, D., and L. Jacobson. "EPA's Brownfields Initiatives." *Mortgage Banking* 55 (July 1995): 91-93.

Smith, L.A. and J.M. Houthoofd. "Considerations in Deciding to Treat Contaminated Soils in Situ." In *Bioremediation of Inorganics*, edited by R.E. Hinchee, J.L. Means, and D.R. Burris, 149-164. Columbus, OH: Battelle Press, 1995.

Stark, L.R., W.R. Wenerick, F.M. Williams, S.E. Stevens, Jr., and P.J. Wuest. "Restoring the Capacity of Spent Mushroom Compost to Treat Coal Mine Drainage by Reducing the Inflow Rate: A Microcosm Experiment." *Water, Air, and Soil Pollution* 75 (1994): 405-420.

Steffen, R. "The Value of Composted Organic Matter in Building Soil Fertility." *Compost Science and Land Utilization* 20 (September/October 1979): 34-37.

Trout, T.J., R.E. Sojka, and R.D. Lentz. "Polyacrylamide Effect on Furrow Erosion and Infiltration." *Transactions of the American Society of Agricultural Engineers* 38 (1995): 761-766.

Tyson, S.C. and M.L. Cabrera. "Nitrogen Mineralization in Soils Amended With Composted and Uncomposted Poultry Litter." *Communications in Soil Science and Plant Analysis* 24 (1993): 2361-2374.

Warman, P.R., T. Muizelaar, and W.C. Termeer. "Bioavailability of As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, Se, and Zn From Biosolids Amended Compost." *Compost Science and Utilization* 3(4) (1995): 40-50.

Williams, B.D. and P.E. Packer. "Sewage Sludge and Other Organic Materials as Amendments for Revegetation of Spent Oil Shale." In *Utilization of Municipal Sewage Effluent and Sludge on Forest and Disturbed Land*, 353-358. University Park, PA: Pennsylvania State University Press, 1979.

Xu, Y., F.W. Schwartz, and S.J. Traina. "Sorption of Zn^{2+} and Cd^{2+} on Hydroxyapatite Surfaces." *Environmental Science and Technology* 28 (1994): 1472-1480.

Chapter 5

Suppression of Plant Diseases and Pests by Compost

Plants are susceptible to damage or death as a result of attack on their seeds, stems, leaves, and root systems from a wide range of disease-causing microorganisms, insects, and nematodes (microscopic worms). Farmers and horticulturists suffer billions of dollars in losses as a result of this damage. For the past 40 to 50 years, synthetic pesticides have been used to control these problems. The use of many of these common pesticides—particularly soil fumigants that are effective controls for fungi and nematodes—has been prohibited or severely restricted during the past 20 years (Quarles, 1995). Increasingly stringent standards designed to protect agricultural workers from pesticide exposure also have been developed. These restrictions on pesticide use have sparked substantial interest in using natural biological processes to control pests and pathogens.

Biological control is the use of one biological species to reduce populations of a different species. Successful and commercialized examples include ladybugs to depress aphid populations, parasitic wasps to reduce moth populations, use of the bacterium *Bacillus thuringenensis* to kill mosquito and moth larvae, and introduction of fungi, such as *Trichoderma*, to suppress fungal-caused plant diseases. In all of these cases, the idea is not to completely destroy the pathogen or pest, but rather to reduce the damage below economically significant values. The development and commercialization of specific biocontrol agents is a lengthy and expensive process. Many biocontrol products are legally classified as pesticides and are subject to the same regulatory requirements as synthetic pesticides (Segall, 1995). New product registration is often costly and time-consuming (Deacon, 1993). There also has been a fair amount of concern about the unexpected negative impacts of releasing biocontrol agents outside their natural range (Howarth, 1991; Longworth, 1987; Pimentel, 1980). These issues have generated interest in finding naturally occurring materials, with pest-controlling properties, that do not require formal registration. In conjunction with the use of these products, major changes in overall crop production and soil management systems also might be necessary (Hoy, 1992).

Among the available candidates for natural products with pest and disease control potential, the composting process and compost have been relatively widely studied. It is well established

that the thermophilic conditions and intense microbial competition during composting kill or inactivate nearly all the microorganisms that cause plant, animal, or human disease (Farrell, 1993; Bollen, 1996; Avgelis, 1992). One exception to this is the Tobacco Mosaic Virus, which may survive composting (Hoitink, 1976a). After disease-infested crop residues are composted, the material is no longer infectious and can be safely applied to farm fields without contributing to disease problems. In contrast, uncomposted residues can serve as an inoculum for infection of subsequent crops. The composting process has proven effective at destroying plant pathogenic nematodes, bacteria, viruses, and fungi (Bollen, 1996; Lopez-Real, 1985; Bollen, 1985).

Mature compost, in many cases, also contains natural organic chemicals and beneficial microorganisms that kill or suppress disease-causing microorganisms. Several mechanisms of action for this phenomenon have been proposed (Hoitink, 1986a; Hoitink, 1986b; Hoitink, 1991a; Hoitink, 1993), including interspecific competition for nutrients, production of chemicals with antimicrobial activity, production of enzymes that destroy the cell walls of pathogens, and changes in the environmental conditions of the soil, which inhibit pathogen growth.

Among the various compostable materials, wood bark has been the most widely studied as a growth medium for potted plants and for its disease-suppressive properties. The original intentions for using wood bark were to find a beneficial use for this abundant and inexpensive waste material and to reduce the consumption of peat, a relatively expensive and nonrenewable natural product. Since some barks contain phytotoxic compounds (Self, 1978), composting became a routine practice for reducing phytotoxicity. Early observations indicated that the composted bark also reduced disease severity in potted plants (Gerrettson-Cornell, 1976; Hoitink, 1975; Hoitink, 1976a and 1976b; Hoitink, 1977; Hoitink, 1980; Malek, 1975). Today, the use of composted bark as a fungicide is widely accepted (Hoitink, 1993). This allows growers to reduce their reliance on chemical fungicides (Daft, 1979) and to decrease operating costs and worker hazards associated with chemical fungicide applications.

Figures 32 and 33 show the effectiveness of composted bark potting mixes on decreasing the severity of root rot in greenhouse-grown poinsettias. Figure 34 illustrates the superior ability of two composts to suppress plant damage in potting media inoculated with high levels of the root pathogen *Fusarium oxysporum*. In both situations, the composted materials provided much better disease reduction results than did peat.

Disease suppression following compost application also has been demonstrated under field conditions. Compost has been shown to increase the stand density of alfalfa in fields where yields have been declining, presumably because of increased disease pressure (Logsdon, 1993). Compost also can significantly decrease the severity of gummy stem blight and damping off diseases in squash, as well as suppress rootknot nematodes and Rhizoctonia root rot (Logsdon, 1993). Some composts have been found to suppress dollar spot disease in putting greens as shown in Figure 35 (Nelson, 1991). There are several remarkable features regarding this discovery, including:

- Large differences in the effectiveness of different composts. One municipal sewage sludge compost was moderately effective, while another was completely ineffective.

- Large variations in suppressiveness at different sampling times during the same year, especially when compared to fungicide treatments.

- Very large between-year performance of some composts, but not others. The varied effectiveness of the composts is similar to behavior of other biocontrol products (Deacon, 1993).

One of the most critical limitations to increased use of biocontrol products, with a few exceptions, is the inability of these products to control diseases with the same consistency as synthetic chemicals. The lack of consistent performance is probably the result of complex interactions between environmental conditions that modify plant susceptibility to a pathogen and/or change the relative infective potential of the pathogen (Burdon, 1992; Dickman, 1992; Couch, 1960). The suppressive activity of a biocontrol agent also will vary under different environmental conditions (Baker, 1982; Mandelbaum, 1990). Plants that are stressed by lack of moisture and/or elevated temperatures, or whose root systems have been damaged by nematode or insect attack, are more vulnerable to disease. In general, fungal activity is regulated by substrate and nutrient availability, water content of the medium, oxygen and carbon dioxide levels, and the presence of other organisms that compete for materials required by the fungus. Depending upon which combination of these conditions is present at a given time, disease incidence can vary greatly, as shown in Figure 35. Conditions were so favorable

to pathogen development for the October 18, 1990, sample date, for example, that even chemical treatment was only partially effective. In such conditions, the ability of a single biocontrol agent to consistently suppress diseases is limited. A possible solution to this problem may come from the use of antagonistic fungi and actinomycetes from composted pine bark and sand mixtures (Hardy, 1995). About 80 percent of these fungi and actinomycetes are disease-suppressive when inoculated into sterilized compost. Compost containing a mixture of suppressive organisms also is expected to contain pathogen growth under a wide range of conditions, as shown in the hypothetical case illustrated in Figure 36. In this case, consistent suppression of the pathogen by either *Trichoderma*, *Bacillus*, or a mixture of the two cannot occur, because the activity range of the pathogen falls outside the range of either organism or a combination of them. In contrast, at least one member of the much more diverse group of antagonists found in compost will be active under any of the conditions where the pathogen is active. Thus, a likely consequence of increased antagonist diversity is improved biocontrol under the wide-ranging conditions encountered in the field.

Some composts also can modify bacterial populations in the plant rhizosphere (the root–soil interface) and increase the abundance of bacteria that are antagonists of various root-pathogenic fungi, as shown in Figure 37. In laboratory situations, however, fungi isolated from compost suppressed spore germination in the highly beneficial mycorrhizal fungus *Glomus mosseae* (Calvet, 1992). Some composts contain microorganisms that suppress pathogenic fungi in soil and on the plant root system, whereas other composts may actually have deleterious effects on root microorganisms.

In addition to controlling fungal pathogens, compost also can modify the severity of nematode damage (Roy, 1976). One study examined the effects of MSW compost on populations of rootknot nematode and plant growth in pot and field studies (Marull, 1997). In pot studies, the addition of 33 percent by weight of compost significantly increased plant growth and significantly decreased nematode populations in the mixes. Sixty-six percent compost, however, did not stimulate plant growth or decrease nematode populations any better than the 33 percent treatment. The lack of growth stimulation at 66 percent compost was probably the result of inhibition of plant growth at high rates of compost addition (see Iannotti, 1994, for example). The effects of municipal waste compost on nematode populations are detailed in Table 8.

Table 8

Effects of MSW Compost on Populations of the Root-Parasitic Nematode *Meloidogyne Javanica* and on the Incidence of Root Galls in a Field Study

Treatment	Nematode Numbers per 250 cm^3 Soil		Nematodes per g Root		Root Gall Severity	
	Non-fumigated	Fumigated	Non-fumigated	Fumigated	Non-fumigated	Fumigated
Control	4380	7460	17,000	13,450	90	91
+ compost	1410[a]	1100[a]	8,010[a]	7,760[a]	80	73

[a] Indicates a significant decrease as a result of compost application.
Source: Marull, 1997 (Table 6)

Compost's ability to suppress soil-borne pathogens is well documented; however, a few reports indicate compost extracts (or "teas") also have disease-reducing properties against foliar pathogens. Extracts of spent mushroom substrate, cattle manure, and sheep manure compost proved ineffective at controlling apple scab in orchards (Yohalem, 1994). Results with control of red pine seedling blight were more encouraging, with extracts of spent mushroom substrate from three different sources providing significant reductions in disease severity (Figure 38). There are often substantial differences in the effectiveness of extracts from different sources (Nelson, 1991). At the present time, producing compost extracts is not a well-developed technology. Individuals devise various procedures for preparing the extracts, with substantial differences in the procedures among different workers. Many variables exist in the production of such materials, including the type and age of compost used and the incubation and extraction procedures employed. While these extracts may have pathogen-suppressing activity in some cases, it is not clear if that activity is due to chemicals in the extracts or to the microorganisms whose growth is favored during extract preparation. This topic is likely to be a fruitful area for future research.

The specific mechanisms for disease suppression by compost have not been clearly identified. Understanding of the mechanisms behind compost's suppression of pathogens is complicated by the fact that raw plant materials, which are composted, might contain organic compounds with antipathogen properties (Qasem, 1995). In some cases, these organic

compounds are destroyed by the time compost is mature. It is not always certain, however, that the composts used for disease suppression studies are mature. A further complication is the ability of some uncomposted waste materials to affect populations of plant pathogenic fungi and pests, such as nematodes (Bridge, 1996), and for some composts to have no greater disease-suppressive properties than the raw materials from which they are made (Figure 39) (Asirifi, 1994). If an immature compost is used, some of its pathogen-suppressive activity may be due to the raw input components rather than compost constituents. As a result, the mechanism of pathogen suppression may vary in compost from lot to lot, in some cases as the result of chemical control and in other cases of biocontrol. Based on some of the references cited in Chapter 1, the relative abundance of different microbial species varies with compost age and composition of input; therefore, biotic composition of different composts is probably also a variable feature among the work of different researchers. Some composts also contain VOCs with pathogen-suppressive activity (Tavoularis, 1995).

The use of compost for disease suppression involves a remarkably complicated set of interactions among various microorganisms, chemical constituents of composted materials, and plant tissues. It is evident that, in certain situations and with particular specialized growth media, such as container mixes that include bark, compost is an effective substitute for synthetic chemicals in the control of pathogens. Since there is a very reduced availability of synthetic fungicides and a decreased willingness to use them, further research on compost-based disease control is highly desirable. Several studies indicate that compost is an excellent source of disease-suppressive bacteria and fungi, and, therefore, it is likely to be a fruitful source of biological materials for biotechnological applications. Since chemicals in compost also can affect pathogens, compost may be a useful source of natural products with biocontrol activity.

Figure 32

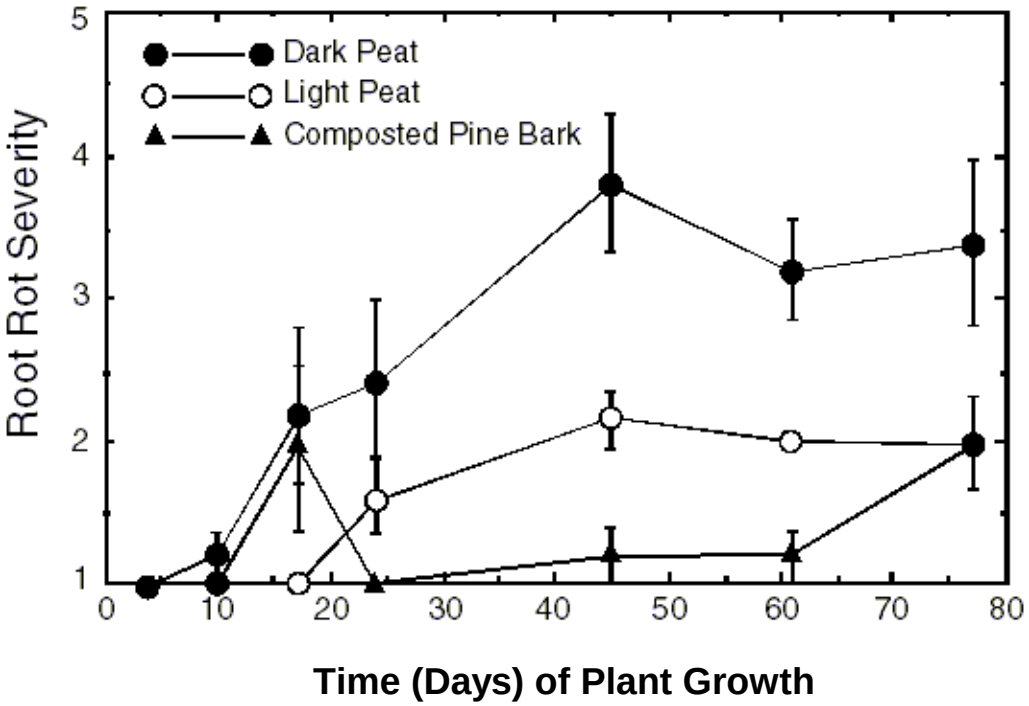
Root Systems of Poinsettia Plants

Plants were grown in mixes containing peat without disease-suppressive properties (top row), disease-suppressive peat (middle row), or disease-suppressive composted pine bark (bottom row). Light-colored roots are healthy, while dark-colored roots are diseased.

Source: Hoitink, 1991a and 1991b

Figure 33

Severity of Root Rot of Poinsettia Plants

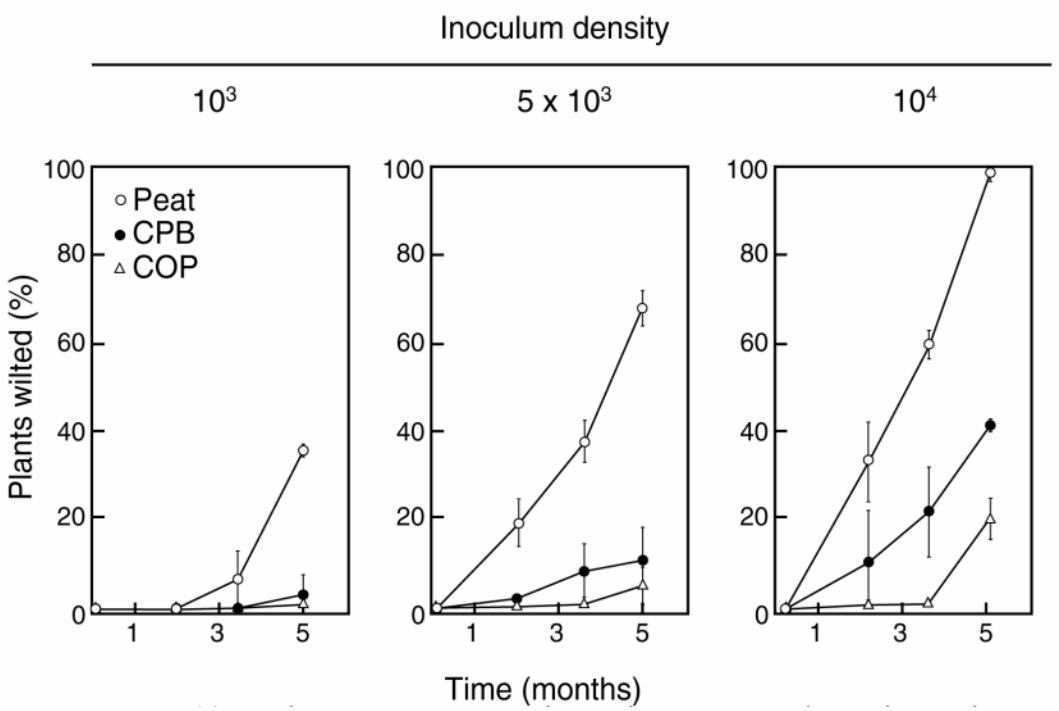


Plants were grown in mixes containing peat without disease-suppressive properties, disease-suppressive peat, or disease-suppressive composted bark. Root rot severity ranges from 1 to 5, with 5 being the most severe.

Source: Boehm, 1992

Figure 34

Disease Severity (Percentage of Wilted Carnation Plants) When Grown in Mixes Containing Peat and Sand (Peat), Composted Bark and Sand (CPB), or Composted Olive Pumice* and Sand (COP)

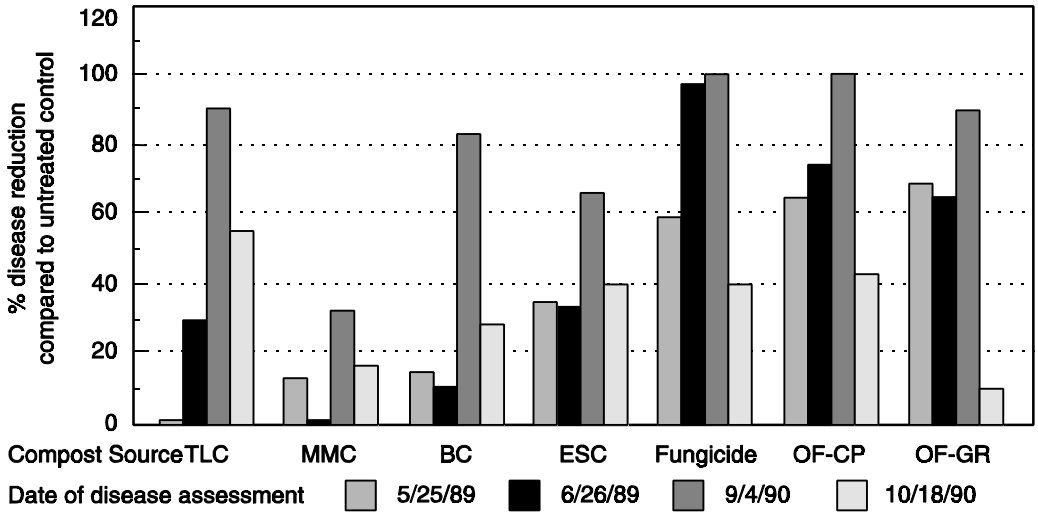


*Olive pumice is the waste generated during the processing of olives for oil.

Source: Pera, 1989

Figure 35

Relative Disease-Suppressing Ability of Composts and Fertilizers Against the Turfgrass Disease Dollar Spot

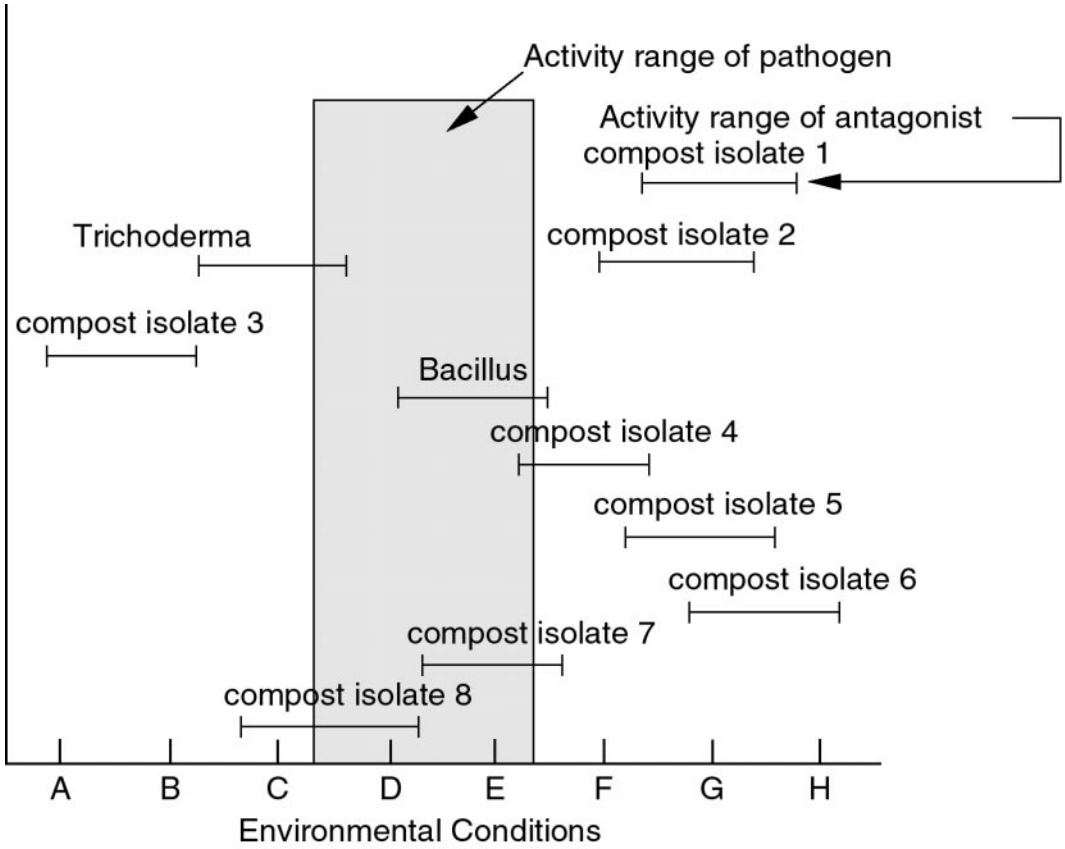


Abbreviations: TLC=turkey litter compost, MMC=manure compost, BC=brewery waste compost, ESC=Endicott sludge compost, fungicide=propiconazole, OF-CP=an organic (not composted) fertilizer, and OF-GR=another organic (not composted) fertilizer.

Source: Nelson, 1991 (Table 3)

Figure 36

A Hypothetical Case to Illustrate the Value of a Diverse Disease-Suppressive Population in Comparison to Single Antagonists or a Mixture of Two Antagonists

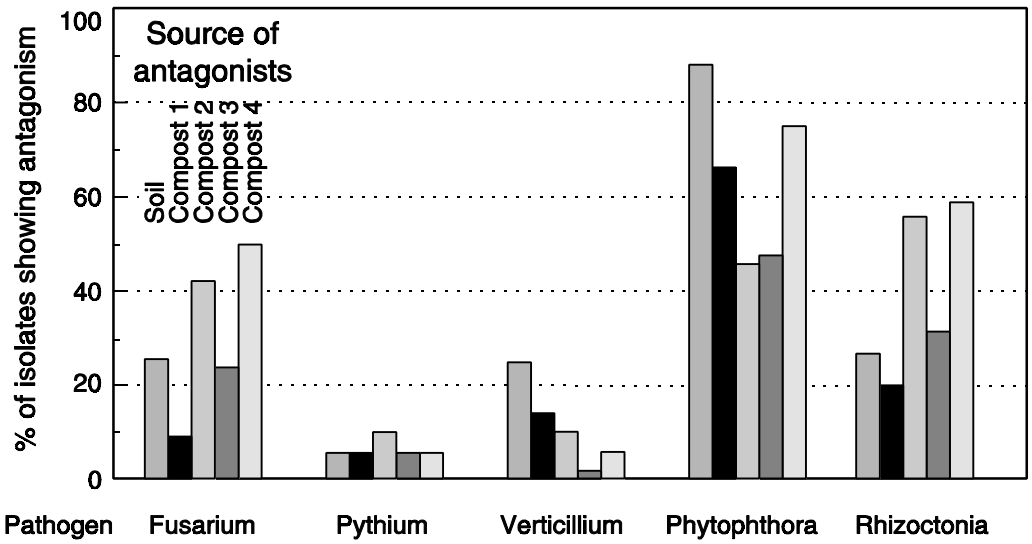


An "environmental condition" is a particular combination of moisture content, substrate and nutrient availability, and oxygen and carbon dioxide content that favors or reduces activity of an organism.

Source: Cole, unpublished

Figure 37

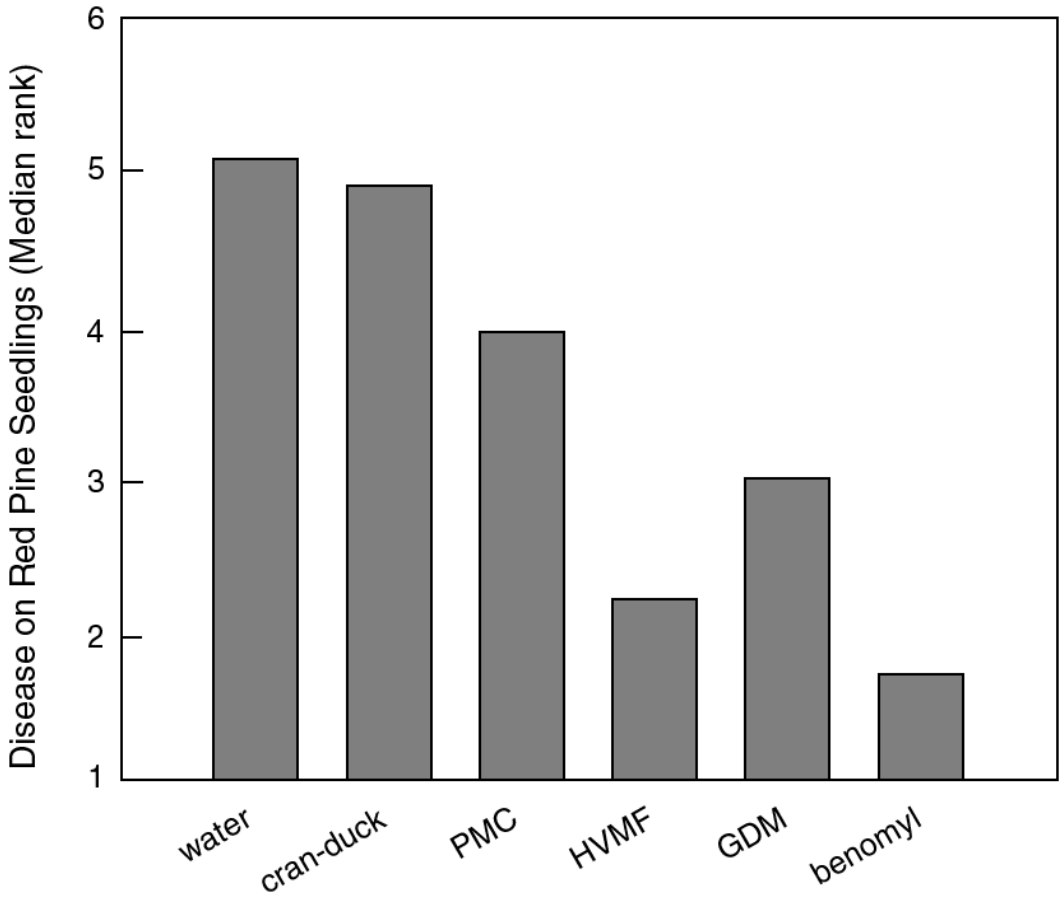
Incidence of Bacteria With Suppressive Activity Toward Fungal Pathogens on Plant Root Systems Growing in Soil or Compost



Source: Alvarez, 1995 (Table 4)

Figure 38

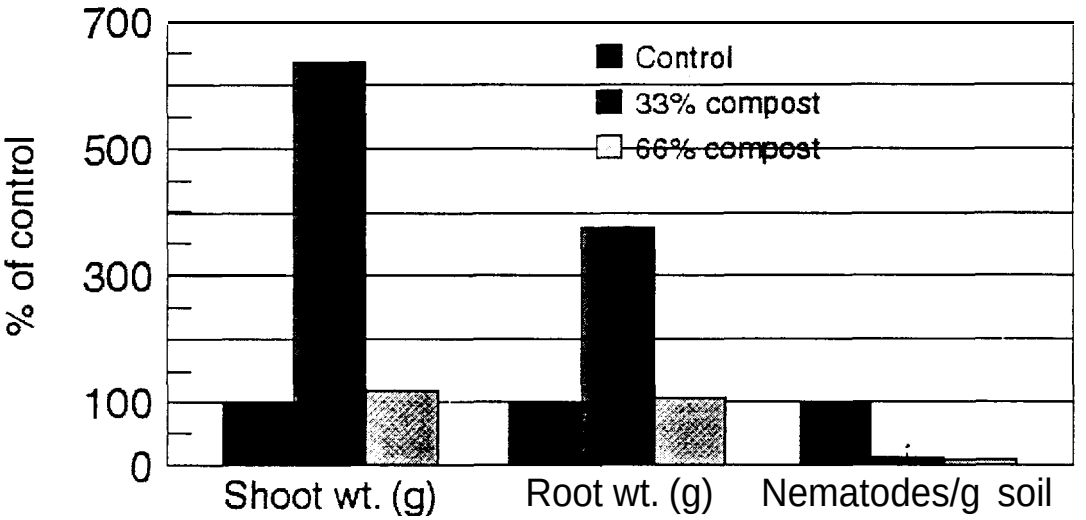
Influence of Extracts of Spent Mushroom Substrate (PMC, HVMF, and GDM) and a Compost Prepared From Cranberry Waste and Duck Manure on Disease Severity of Red Pine Blight



Source: Yohalem, 1994 (Figure 5)

Figure 39

Effects of MSW Compost on Green Pepper Growth and Populations of the Root-Parasitic Nematode *Meloidogyne Javanica* in a Pot Study



Source: Marull, 1997 (Table 2)

References

Alvarez, B., S. Gagné, and H. Antoun. "Effect of Compost on Rhizosphere Microflora of the Tomato and on the Incidence of Plant Growth-promoting Rhizobacteria." *Applied and Environmental Microbiology* 61 (1995): 194-199.

Asirifi, K.N., W.C. Morgan, and D.G. Parbery. "Suppression of Sclerotinia Soft Rot of Lettuce With Organic Soil Amendments." *Australian Journal of Experimental Agriculture* 34 (1994): 131-136.

Avgelis, A.D. and V.I. Manios. "Elimination of Cucumber Green Mottle Mosaic Tobamovirus by Composting Infected Cucumber Residues." *Acta Horticulturae* 302 (1992): 311-314.

Baker, K.F. and R.J. Cook. *Biological Control of Plant Pathogens*, 176. St. Paul, MN: The American Phytopathological Society, 1982.

Bollen, G.J. "The Fate of Plant Pathogens During Composting of Crop Residues." In *Composting of Agricultural and Other Wastes*, edited by J.K.R. Gasser, 282-290. London: Elsevier Applied Science Publishers, 1985.

Bollen, G.J. and D. Volker. "Phytohygienic Aspects of Composting." In *The Science of Composting*, edited by M. de Bertoldi, P. Bert, and P. Tiziano, 233-246. London: Blackie Academic and Professional, 1996.

Bridge, J. "Nematode Management in Sustainable and Subsistence Agriculture." *Annual Review of Phytopathology* 34 (1996): 201-225.

Burdon, J.J. "The Growth and Regulation of Pathogenic Fungal Populations." In *The Fungal Community*, edited by G.C. Carroll and D.T. Wicklow, 173-181. New York, NY: Marcel Dekker, Inc., 1992.

Calvet, C., J.M. Barea, and J. Pera. "In Vitro Interactions Between the Vesicular-arbuscular Mycorrhizal Fungus *Glomus mosseae* and Some Saprophytic Fungi Isolated From Organic Substrates." *Soil Biology and Biochemistry* 24 (1992): 775-780.

Couch, H.B. and J.R. Bloom. "Influence of Environment on Diseases of Turfgrasses. I. Effect of Nutrition, pH, and Soil Moisture on Sclerotinia Dollar Spot." *Phytopathology* 50 (1960): 761-763.

Daft, G.C., H.A. Poole, and H.A.J. Hoitink. "Composted Hardwood Bark: A Substitute for Steam Sterilization and Fungicide Drenches for Control of Poinsettia Crown and Root Rot." *HortScience* 14 (1979): 185-187.

Deacon, J.W. and L.A. Berry. "Biocontrol of Soil-borne Plant Pathogens: Concepts and Their Application." *Pesticide Science* 37 (1993): 417-426.

Dickman, A. "Plant Pathogens and Long-term Ecosystem Changes." In *The Fungal Community*, edited by G.C. Carroll and D.T. Wicklow, 499-520. New York, NY: Marcel Dekker, Inc., 1992.

Farrell, J.B. "Fecal Pathogen Control During Composting." In *Science and Engineering of Composting*, edited by H.A.J. Hoitink and H.M. Keener, 282-300. Worthington, OH: Renaissance Publications, 1993.

Gerrettson-Cornell, L., F.R. Humphreys, and S.R. Townsend. "Results of a Preliminary Investigation on the Use of *Pinus radiata* Bark Against *Phytophthora cinnamomi* Rands." *Phyton* 34 (1976): 3-6.

Hardy, G.E. and K. Sivasithamparam. "Antagonism to Fungi and Actinomycetes Isolated From Composted Eucalyptus Bark to Phytophthora Drechsleri in a Steamed and Non-steamed Composted Eucalyptus Bark-amended Container Medium." *Soil Biology and Biochemistry* 27 (1995): 243-246.

Hoitink, H.A.J. "Composted Bark, A Lightweight Growth Medium With Fungicidal Properties." *Plant Disease* 64 (1980): 142-147.

Hoitink, H.A.J., M.J. Boehm, and Y. Hadar. "Mechanisms of Suppression of Soilborne Plant Pathogens in Compost-amended Substrates." In *Science and Engineering of Composting*, edited by H.A.J. Hoitink and H.M. Keener, 601-621. Worthington, OH: Renaissance Publications, 1993.

Hoitink, H.A.J. and P.C. Fahy. "Basis for the Control of Soilborne Plant Pathogens With Composts." *Annual Review of Phytopathology* 24 (1986): 93-114.

Hoitink, H.A.J., L.J. Herr, and A.F. Schmitthenner. "Survival of Some Plant Pathogens During Composting of Hardwood Tree Bark." *Phytopathology* 66 (1976b): 1369-1372.

Hoitink, H.A.J., Y. Inbar, and M.J. Boehm. "Status of Compost-amended Potting Mixes Naturally Suppressive to Soilborne Diseases of Floricultural Crops." *Plant Disease* 75 (1991a): 869-873.

Hoitink, H.A.J., Y. Inbar, and M.J. Boehm. "Compost Can Suppress Soil-borne Diseases in Container Media." *American Nurseryman* 178 (September 1991b): 91-94.

Hoitink, H.A.J. and G.A. Kuter. "Effects of Composts in Growth Media on Soilborne Plant Pathogens." In *The Role of Organic Matter in Modern Agriculture*, edited by Y. Chen and Y. Avnimelech, 289-306. Dordrecht, Netherlands: Martinus Nyhoff Publishers, 1986.

Hoitink, H.A.J. and H.A. Poole. "Composted Bark Mediums for Control of Soil-borne Plant Pathogens." *American Nurseryman* 144(5) (1976a): 15, 88-89.

Hoitink, H.A.J., A.F. Schmitthenner, and L.J. Herr. "Composted Bark for Control of Root Rot in Ornamentals." *Ohio Reporter* 60 (1975): 25-26.

Hoitink, H.A.J., D.M. VanDoren, Jr., and A.F. Schmitthenner. "Suppression of Phytophthora cinnamomi in a Composted Hardwood Bark Potting Medium." *Phytopathology* 67 (1977): 561-565.

Howarth, F.G. "Environmental Impacts of Classical Biological Control." *Annual Review of Entomology* 36 (1991): 485-509.

Hoy, M.A. "Biological Control of Arthropods: Genetic Engineering and Environmental Risks." *Biological Control* 2 (1992): 166-170.

Iannotti, D.A., M.E. Grebus, B.L. Toth, L.V. Madden, and H.A.J. Hoitink. "Oxygen Respirometry to Assess Stability and Maturity of Composted Municipal Solid Waste." *Journal of Environmental Quality* 23 (1994): 1177-1183.

Logsdon, G. "Using Compost for Plant Disease Control." *BioCycle* 34(10) (1993): 33-36.

Longworth, J.F. "Biological Control in New Zealand: Policy and Procedures." *New Zealand Entomologist* 10 (1987): 1-7.

Lopez-Real, J. and M. Foster. "Plant Pathogen Survival During the Composting of Agricultural Organic Wastes." In *Composting of Agricultural and Other Wastes*, by J.K.R. Gasser, 291-300. London: Elsevier Applied Science Publishers, 1985.

Malek, R.B. and J.B. Gartner. "Hardwood Bark as a Soil Amendment for Suppression of Plant Parasitic Nematodes on Container Grown Plants." *HortScience* 10 (1975): 33-35.

Mandelbaum, R. and Y. Hadar. "Effects of Available Carbon Source on Microbial Activity and Suppression of *Pythium aphanidermatum* in Compost and Peat Container Media." *Phytopathology* 80 (1990): 794-804.

Marull, J., J. Pinochet, and R. Rodriquez-Kabana. "Agricultural and Municipal Composts Residues for Control of Root-knot Nematodes in Tomato and Pepper." *Compost Science and Utilization* 5(1) (1997): 6-15.

Nelson, E.B. and C.M. Craft. "Suppression of Dollar Spot on Creeping Bentgrass and Annual Bluegrass Turf With Compost-amended Topdressings." *Plant Disease* 76 (1991): 954-958.

Pimentel, D. "Environmental Risks Associated With Biological Controls." *Ecological Bulletin* 31 (1980): 11-24.

Qasem, J.R. and H.A. Abu-Blan. "Antifungal Activity of Aqueous Extracts From Some Common Weed Species." *Annals of Applied Biology*. 127 (1995): 215-219.

Quarles, W. and J. Grossman. "Alternatives to Methyl Bromide in Nurseries -- Disease Suppressive Media." *The IPM Practicioner* 17(8) (1995): 1-13.

Roy, A.K. "Effect of Decaffeinated Tea Waste and Water Hyacinth Compost on the Control of Meloidogyne graminicola on Rice." *Indian Journal of Nematology* 6 (1976): 73-77.

Segall, L. "Marketing Compost as a Pest Control Product." *BioCycle* 36 (1995): 65-67.

Self, R.L. "Pine Bark in Potting Mixes, Grades and Age, Disease and Fertility Problems." *Proceedings of The International Plant Propogators' Society* 28 (1978): 363-368.

Tavoularis, K., A. Papadaki, and V. Manios. "Effect of Volatile Substances Released From Olive Tree Leave Compost on the Vegetative Growth of Rhizoctonia solani and Fusarium oxysporum F. sp. lycopersici." *Acta Horticulturae* 382 (1995): 183-186.

Yohalem, D.S., R.F. Harris, and J.H. Andrews. "Aqueous Extracts of Spent Mushroom Substrate for Foliar Disease Control." *Compost Science and Utilization* 2(4) (1994): 67-74.

Chapter 6

Compost-Enhanced Phytoremediation of Contaminated Soil

Phytoremediation is a developing technology in which higher plants and microorganisms associated with plant roots are the active agents for uptake and/or degradation of toxic inorganic and organic compounds in soil and water. This method successfully intercepts nitrate and prevents its transfer from groundwater to surface water. It also is used in a number of applications with organics-contaminated water (Table 9). As indicated in Chapter 4, plants also reduce the erosional transport of contaminated soil when compared to unvegetated material. Given this, phytoremediation provides a straightforward approach to both the degradation and containment of contaminated soil and water, as shown in Figure 40. In this case, contaminated water is stripped of contaminants as it flows past the plant roots, as a result of waste uptake by the plants. Depending on the contaminant, degradation might occur in the rhizosphere (the soil adjacent to plant roots) or within the plant itself. If the compound is not degraded, it will likely volatilize. Regardless of the ultimate fate of the contaminant, once contact with the plant occurs, the water is no longer contaminated. This process might be suitable for soil remediation and/or inexpensive confinement of shallow contaminated water.

Phytoremediation of metal-contaminated soil relies on the ability of plants to accumulate metals at concentrations substantially above those found in the soil in which they grow (Kelly, 1995; Brown, 1994; Brown, 1995; Cunningham, 1995; Cornish, 1995). Since plant uptake requires that metals be in an environmentally mobile form (Schnoor, 1995), the use of compost is likely to be an impediment to successful phytoremediation, as compost immobilizes toxic metals (see Chapter 4 for examples).

Table 9

Phytoremediation of Contaminated Soil or Water[a]

Contaminated Material	Contaminants	Results
Water (hydroponic system in laboratory)	Nitrobenzene	Complete uptake from solution
Soil	Trinitrotoluene	Essentially complete treatment
Soil	Trichloroethylene	Enhanced mineralization
Contaminated soil	Pentachlorophenol and phenanthrene	Enhanced mineralization
Soil	Trinitrotoluene	Enhanced degradation

[a] Adapted from Schnoor, 1995.

Numerous reports indicate that plants can take up and degrade toxic organic compounds in soil, while other work indicates microorganisms in the rhizosphere are very competent degraders of soil-borne organics. Rhizosphere microorganisms are able to degrade the herbicide 2,4-dichlorophenoxyacetic acid (2,4-D) much more rapidly than those in root-free soil and convert a higher percentage of carbon in 2,4-D to carbon dioxide, as shown in Figure 41 (Shann, 1994). In contrast, enhanced mineralization of ^{14}C-labeled pyrene was not found in rhizosphere soil (Schwab, 1994 and Schwab, 1995). These apparently conflicting results are due to the relatively high mobility of 2,4-D in soil as compared to pyrene. As a result of rapid water uptake by plants, desorption of contaminants from soil may be the rate-limiting step for degradation (Schnoor, 1995). Based on the examples shown in Table 9, plants might decrease remediation time, as well as enhance the complete destruction of target compounds. Further work is required to define the characteristics of plants and soil systems before an understanding of the appropriateness of phytoremediation for particular situations can be attained.

Phytoremediation has very large economic advantages over mechanically intensive technologies because plants require little maintenance in comparison to machinery. The following are the major constraints of the method:

- Relatively slow remediation rates. The time until site closure can be years. This constraint means that phytoremediation cannot be the method of choice when rapid site closure is a necessity.

- Lack of information about the fate of compounds in planted soil. Losses of volatile ^{14}C from ^{14}C-labeled naphthalene are about 50 percent higher in planted soil than in unplanted soil (Watkins, 1994). Poor recovery is probably the result of inefficient capture of volatile organics and/or carbon dioxide and can be solved by the development of better test systems. Chapter 2 details the issue of whether partial degradation of xenobiotics, followed by conversion of metabolites into immobile forms, is a sufficient remedy for contamination. This same issue arises with phytoremediation, because immobilization of carbon from xenobiotics in conjugated forms is promoted in planted systems. The results, presented in Figure 42, indicate that studies of the fate of xenobiotic residues when they enter soil would be appropriate. Because of the complexity of plants, microorganisms, and soil systems and the uncertainties of chemical behavior in these systems, further research is necessary before this method can be employed on a large scale.

- Difficulties in establishing plants in toxic, contaminated matrices, and in compacted and barren materials that are not conducive to plant growth. This constraint can be overcome by the addition of compost. A small body of research indicates that compost can reduce toxicity of contaminated soil (probably through the adsorption of the toxic compounds to organic matter in the compost). Figure 43 compares the growth of herbicide-sensitive weed species when grown in contaminated material from an agrichemical retail site. In the absence of compost, little weed growth occurs, but addition of compost detoxifies the soil and good weed growth occurs. In this case, plant growth also accelerated decontamination when compared with soil without compost addition, as shown in Table 10.

The amount of compost needed to achieve beneficial effects varies with the project goals. For example, 20 percent w/w compost is sufficient to maximize plant growth in herbicide-contaminated soil (Figure 44), but 40 percent compost is needed to accelerate herbicide degradation in the same soil (Figure 45). The decrease in remediation time for relatively degradable compounds like metolachlor strongly suggests that phytoremediation—if healthy and vigorous plants can be

established—has considerable potential for enhancing bioremediation activities, particularly in situations such as urban brownfields (Chapter 4), where cost and time are important components in choosing a remediation method.

Table 10

Effects of Mix Composition and Planting on Pesticide Degradation, Following 40 Days of Plant Growth[a]

Mixture	Treatment	Trifluralin	Metolachlor	Pendimethalin
		mg kg^{-1} soil		
Initial concentration	None	2.2 ± 0.9	3.0 ± 0.2	11.8 ± 5.1
100% contamination	Planted	0.80 ± 0.82 (0.27)[(b)]	3.4 ± 5.0 (0.25)	1.6 ± 0.4 (0.02)
100% contamination	Not planted	0.48 ± 0.77 (0.77)	0.99 ± 1.4 (0.25)	1.8 ± 0.4 (0.02)
50:50 soil	Planted	nd[(c)]	nd	0.5 ± 0.6 (0.01)
50:50 soil	Not planted	0.52 ± 0.53 (0.07)	0.18 ± 0.16 (<0.001)	1.0 ± 0.2 (0.02)
50:50 compost	Planted	0.36 ± 0.33 (0.02)	nd	1.5 ± 0.6 (0.02)
50:50 compost	Not planted	0.44 ± 0.69 (0.08)	2.8 ± 3.4 (0.29)	2.6 ± 3.4 (0.12)

[a] Values are means ± standard deviations of duplicate extractions of four replications per treatment.
[b] Values in parentheses indicate the probability that the values are less than experiences from dilution alone (based on a one-tailed t-test for means of unequal variance).
[c] nd = not detected.

Source: Liu, 1995

Figure 40

Potential Fates of Xenobiotics in Planted Soils

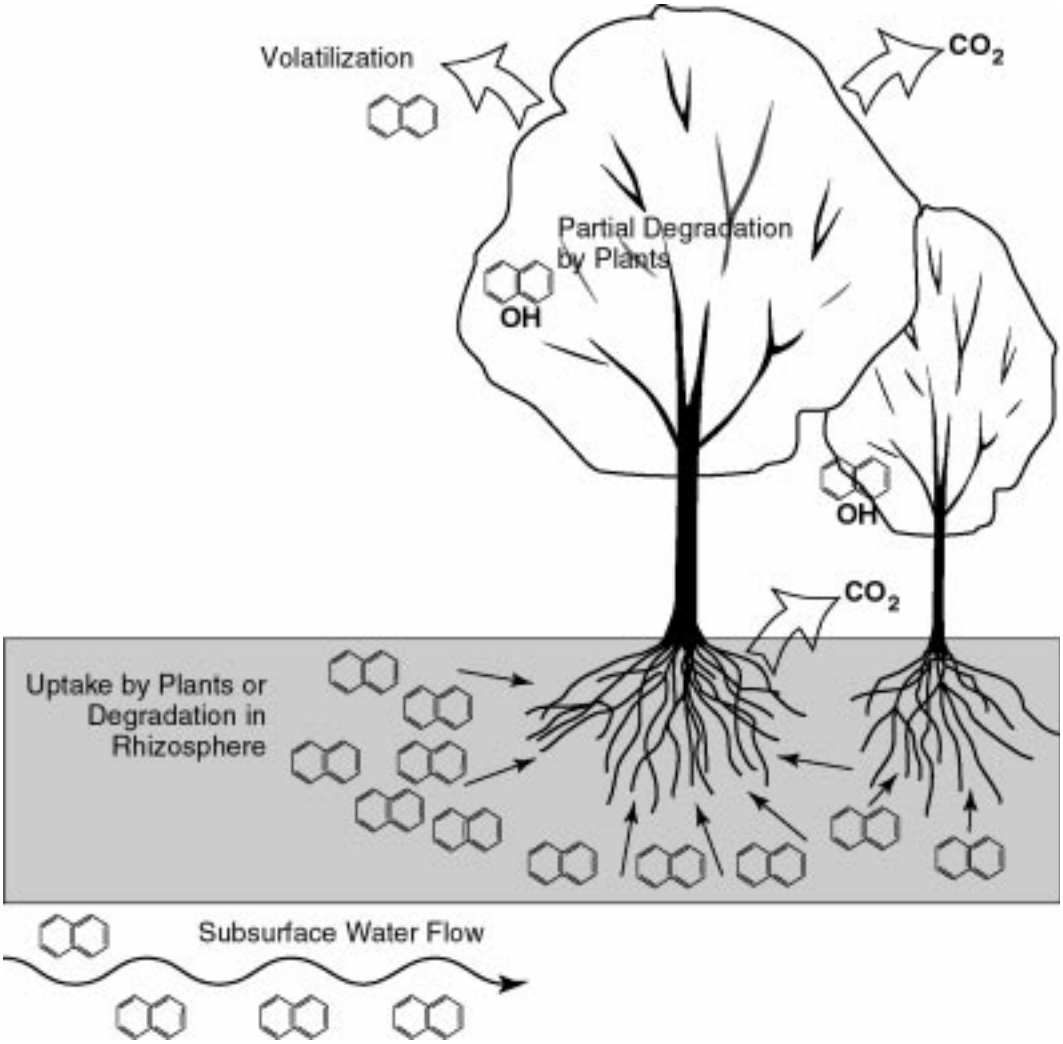
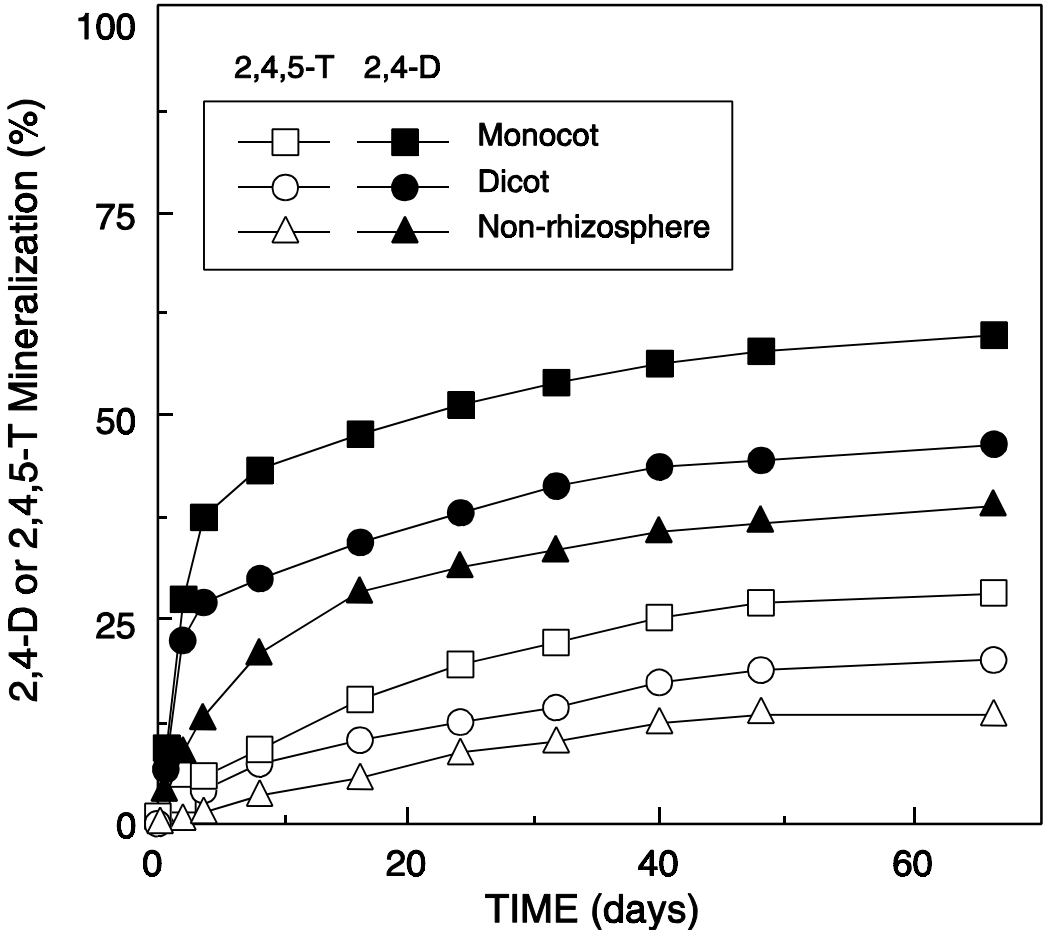


Figure 41

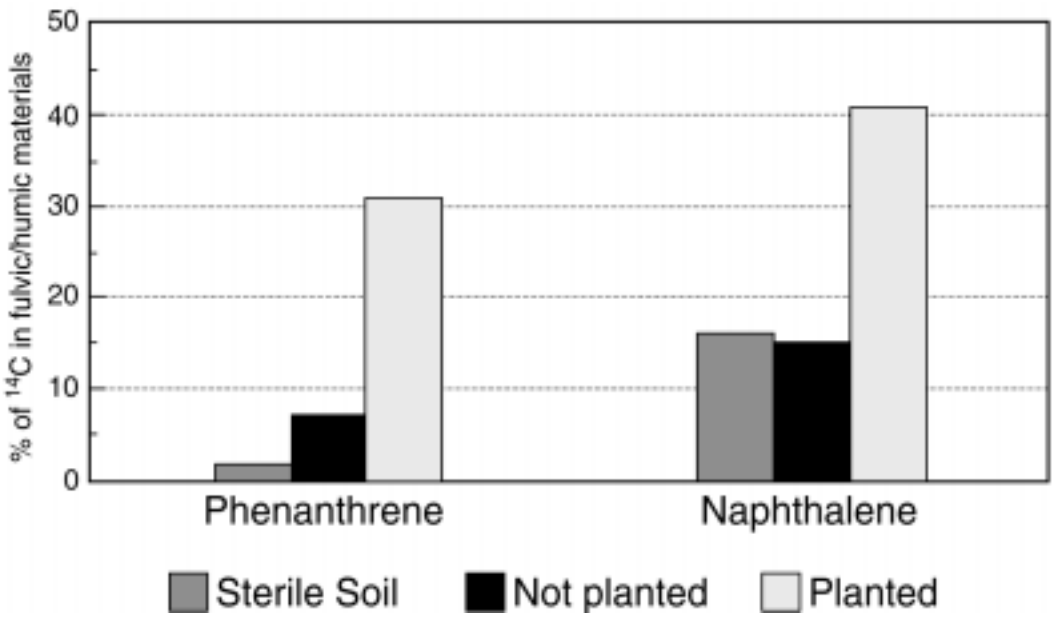
Enhanced Degradation Rates and Mineralization Percentage in Rhizosphere Versus Non-rhizosphere Soil



Source: Shann, 1994

Figure 42

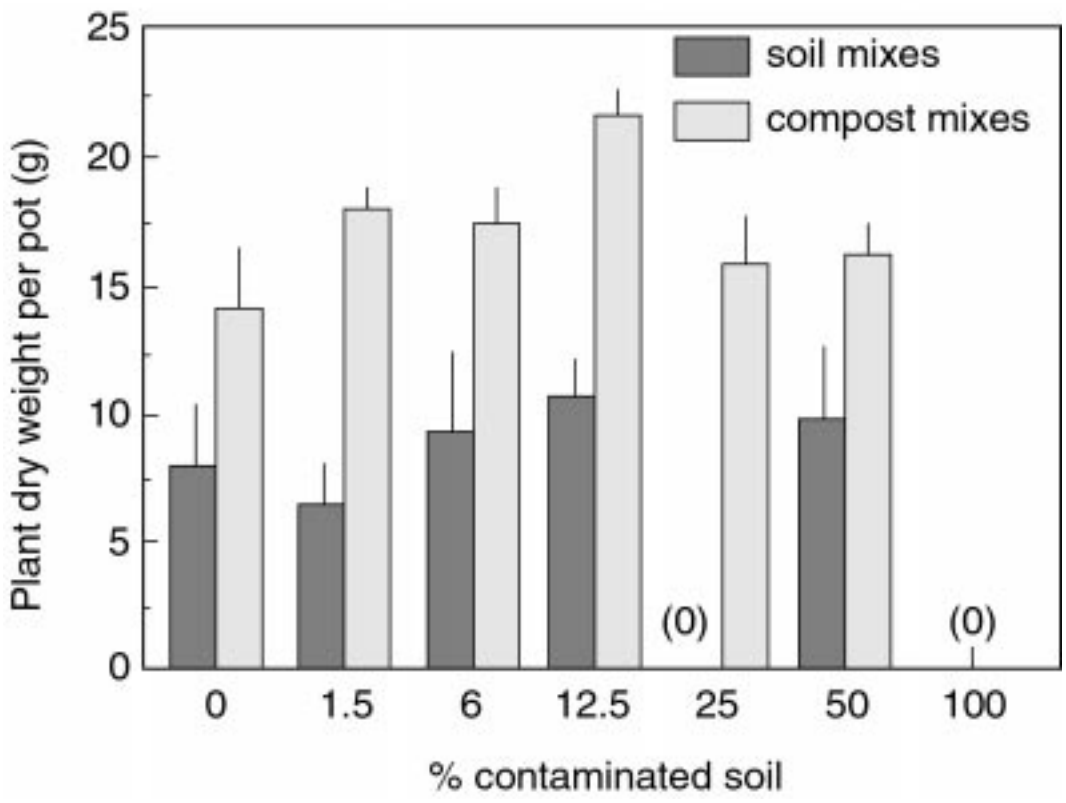
Influence of Plants on Immobilization of ^{14}C From Aromatic Compounds in Soil



Source: Walton, 1994 (Table 1)

Figure 43

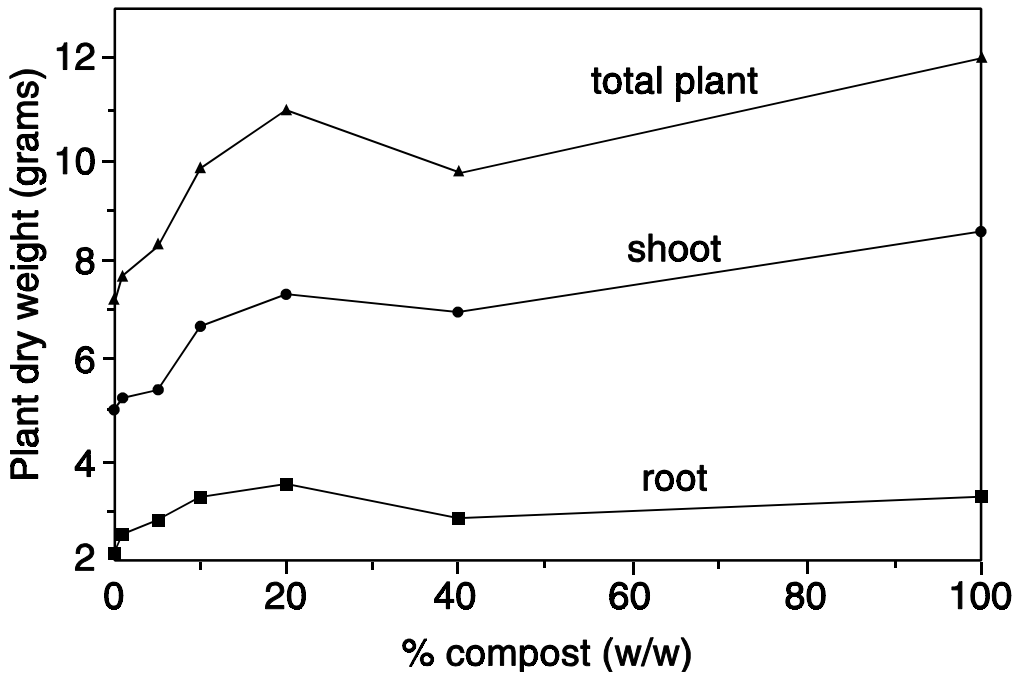
Reduction of Phytotoxicity in Herbicide-Contaminated Soil by Compost



Source: Cole, 1994

Figure 44

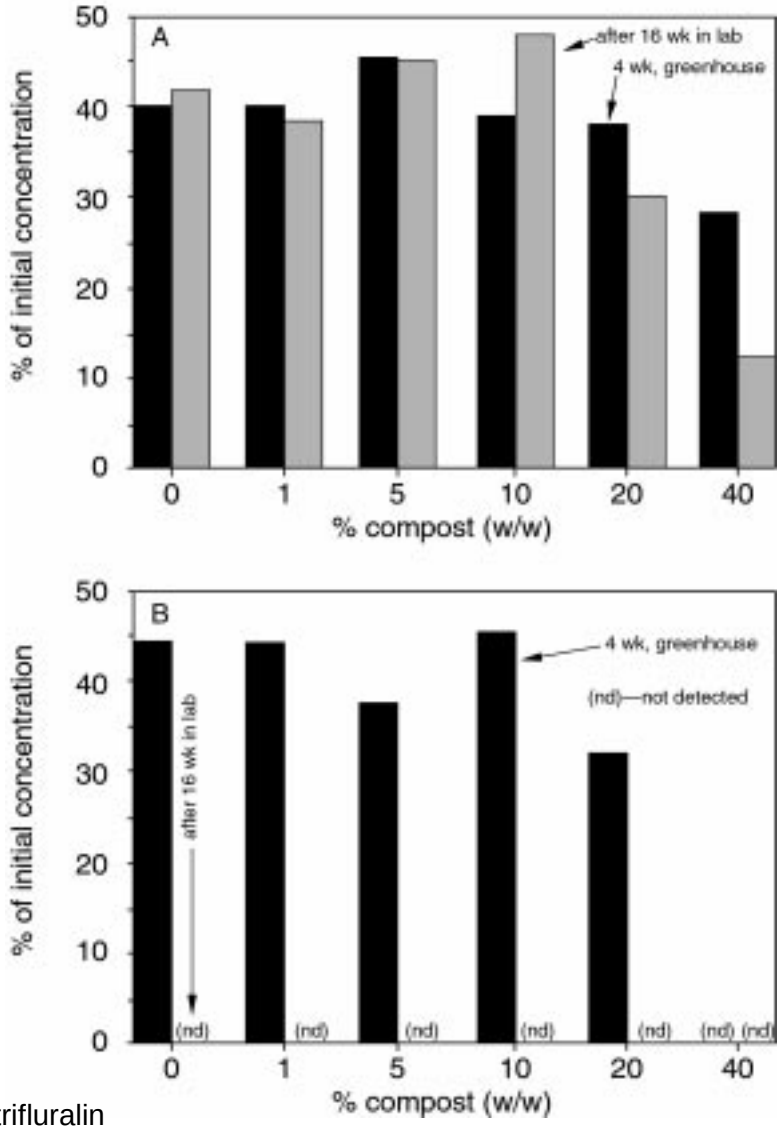
Effect of Amount of Compost Added on Plant Growth in Contaminated Soil



Source: Liu, 1996

Figure 45

Effect of Amount of Compost Added on Rates of Pesticide Degradation in Contaminated Soil



A=Degradation of trifluralin
B=Degradation of metolachlor

Source: Liu, 1996

References

Brown, S.L., R.L. Chaney, J.S. Angle, and A.J.M. Baker. "Phytoremediation Potential of *Thlaspi caerulescens* and Bladder Campion for Zinc- and Cadmium-contaminated Soil." *Journal of Environmental Quality* 23 (1994): 1151-1157.

Brown, S.L., R.L. Chaney, J.S. Angle, and A.J.M. Baker. "Zinc and Cadmium Uptake by Hyperaccumulator *Thlaspi caerulescens* and Metal Tolerant *Silene vulgaris* Grown on Sludge-amended Soils." *Environmental Science and Technology* 29 (1995): 1581-1585.

Cornish, J.E., W.C. Goldberg, R.S. Levine, and J.R. Benemann. "Phytoremediation of Soils Contaminated With Toxic Elements and Radionuclides." In *Bioremediation of Inorganics*, edited by R.E. Hinchee, J.L. Means, and D.R. Burris, 55-63. Columbus, OH: Battalle Press, 1995.

Cunningham, S.D., W.R. Berti, and J.W. Haung. "Remediation of Contaminated Soil and Sludges by Green Plants." In *Bioremediation of Inorganics*, edited by R.E. Hinchee, J.L. Means, and D.R. Burris, 33-54. Columbus, OH: Battalle Press, 1995.

Kelly, R.J. and T.F. Guerin. "Feasibility of Using Hyperaccumulating Plants to Bioremediate Metal-contaminated Soil." In *Bioremediation of Inorganics*, edited by R.E. Hinchee, J.L. Means, and D.R. Burris, 25-32. Columbus, OH: Battalle Press, 1995.

Liu, X. and M.A. Cole. "Minimum Effective Compost Addition for Remediation of Pesticide Contaminated Soil." In *The Science of Composting*, edited by M. de Bertoldi, P. Sequi, B. Lemmes, and T. Papi, 903-912. London: Blackie Academic and Professional, 1996.

Schnoor, J.L., L.A. Licht, S.C. MiCutcheon, N.L. Wolf, and L.H. Carriera. "Phytoremediation of Organic and Nutrient Contaminants." *Environmental Science and Technology* 29 (1995): 318A-323A.

Schwab, A.P. and M.K. Banks. "Biologically Mediated Dissipation of Polyaromatic Hydrocarbons in the Root Zone." In *Bioremediation Through Rhizosphere Technology*, edited by T.A. Anderson and J.R. Coats, 132-141. Washington, DC: American Chemical Society, 1994.

Schwab, A.P., M.K. Banks, and M. Arunachalam. "Biodegradation of Polycyclic Aromatic Hydrocarbons in Rhizosphere Soil." In *Bioremediation of Recalcitrant Organics*, edited by R.E. Hinchee, D.B. Anderson, and R.E. Hoeppel, 23-29. Columbus, OH: Battelle Press, 1995.

Walton, B.T., A.M. Hoylman, M.M. Perez, T.A. Anderson, T.R. Johnson, E.A. Guthrie, and R.F. Christman. "Rhizosphere Microbial Communities as a Plant Defense Against Toxic Substances in Soil." In *Bioremediation Through Rhizosphere Technology*, edited by T.A. Anderson and J.R. Coats, 82-92. Washington, DC: American Chemical Society, 1994.

Watkins, J.W., D.L. Sorensen, and R.C. Sims. "Volatilization and Mineralization of Naphthalene in Soil-grass Microcosms." In *Bioremediation Through Rhizosphere Technology*, edited by T.A. Anderson and J.R. Coats, 123-131. Washington, DC: American Chemical Society, 1994.

Chapter 7

Development of Special-Purpose (Customized) Composts

The majority of the research described in this report was conducted with little discrimination among composts, other than their ready availability. Where different types or ages of compost were compared, substantial differences were found in the ability of the compost to accelerate degradation of organic compounds (Chapter 2) and in disease-suppressive ability (Chapter 5). Compost maturity is certainly a factor in revegetation studies, since numerous researchers have reported that immature composts are phytotoxic. The relatively high success rate for various projects, in spite of the apparently random selection of compost, strongly suggests that particular activities of compost can be enhanced, thereby increasing the effectiveness of the compost. Composts of this type are referred to as "tailor-made" or "designer" composts. The term "special-purpose compost" is used in this chapter to describe composts that are specially treated during production to enhance specific attributes, produced from particular feedstocks to increase activity, to which specific microorganisms have been added, and to which constituents other than organic feedstocks have been added.

In addition to relatively random selection of compost for their research, most researchers conducted their studies with unamended compost. Substantial literature indicates minerals play a major role in controlling the environmental fate and availability of both organic and inorganic components (Hassett, 1989; Ziekle, 1989; Scow, 1993; Dixon, 1977). Little of this work, however, has been applied to improving compost. This chapter describes several cases where the performance of compost was significantly enhanced by special treatment.

The special treatment of feedstock has the potential to improve compost's metal removal capabilities (Chang, 1995). A recent study conducted with sewage sludge serves as a precedent for potential improvement of metal-binding activity of biosolids compost. In the study, various additions were made to a sewage sludge culture. Copper-binding—but not cadmium-binding—activity varied substantially among the initial cultures (Figure 46). In addition, particular treatments significantly increased the absorption capacity of the cultures for particular metals. It is likely that the same type of process could be used to develop biosolids compost for the types of applications described in Chapter 4.

The metal-binding capacity of composts can be improved by the addition of inorganic materials. For example, the addition of soluble iron and/or phosphate salts to compost increases lead immobilization as a result of forming complex lead-iron-phosphate minerals. Similarly, research by several investigators indicates that some clay minerals interact with lead to form lead-containing minerals in which the bioavailability of the lead is remarkably low (Ryan, no date). Addition of such clays may enhance the ability of compost to decrease lead availability. This suggestion raises the issue of whether immobilization of metals is a sufficient endpoint for remediation (see Chapter 4). Nevertheless, decreased lead availability provides an illustration of the potential for improving the desirable characteristics of compost.

One promising technique in bioremediation is the establishment of desirable microorganisms in soil by adding them as an inoculant (Brown, 1993). This process is referred to as "bioaugmentation." One of the common problems with bioaugmentation is the difficulty in establishing exogenous microorganisms in the contaminated soil (Alexander, 1994; Van Veen, 1997). The addition of microorganisms in compost often results in a 2- to 15-fold increase in bacterial and fungal populations for at least 6 weeks after adding the compost to contaminated soil (Cole, 1996). It appears from these results that the compost protects organisms from predation and other problems that ordinarily result in their loss when added to soil. If this statement is true, then production of composts containing particularly good degraders of pollutants could be a viable approach to microbial introductions into soil.

Disease-suppressive organisms isolated from compost can be added to compost at high populations (Hoitink, 1990). The resulting compost has better disease-suppressing activity than uninoculated compost (Hoitink, 1993). In addition, compost with more consistent disease suppression can be produced by isolating antagonistic organisms from compost, propagating them in the laboratory, and adding them back to raw materials prior to composting (Nakasaki, 1996). Both of these examples support the suggestion that compost used for bioremediation can be improved in the same manner.

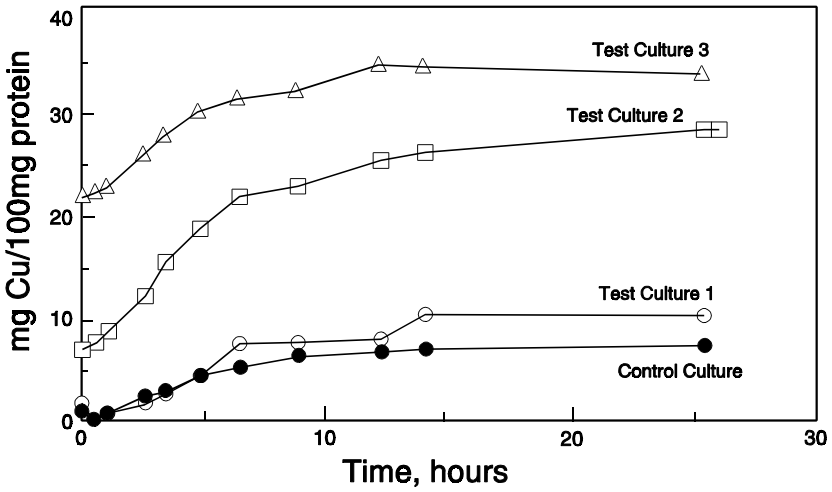
Several studies in Chapter 3 demonstrate that compost biofilter performance improves substantially after an extended exposure time to contaminated air. This behavior is strongly suggestive of selection for a highly competent population of degrading organisms in the compost. The poor performance of the filters initially might be attributed to the lack of appropriate organisms in sufficient numbers in the starting material. If this interpretation is

correct, then isolation of appropriate microorganisms from effective biofilters and introduction into ineffective biofilters may be a rapid method for improving filter performance.

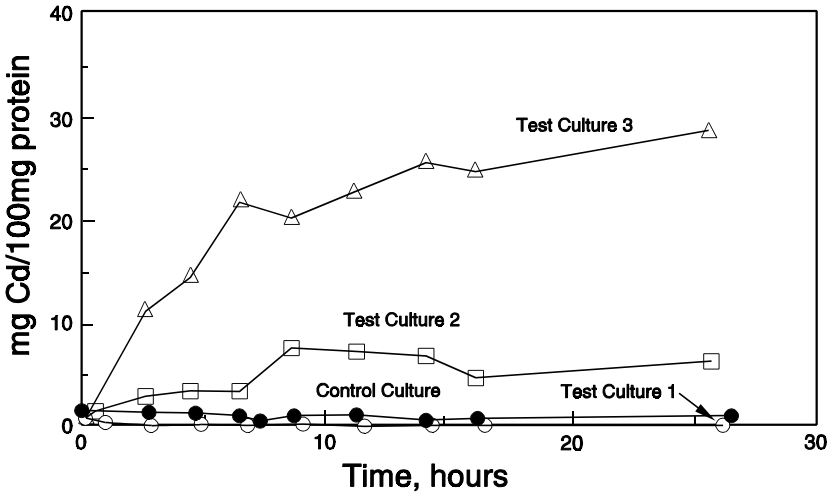
Several references in Chapter 1 demonstrate that microbial populations are large and that their biodiversity is high during the composting process and in mature compost. Since the environmental conditions during composting are radically different from those experienced by organisms in most natural environments, it is possible that compost-derived organisms might have abilities not found in the microbial populations of soil and water. For this reason, further studies on microbial ecology of compost are likely to have beneficial effects, not only for the composting industry but also for uses of compost-based materials.

Figure 46

Enhancement of Metal-Binding Capacity of Sewage Sludge Cultures by Nutrient Amendment and Prior Exposure to Subtoxic Concentrations of Copper and Cadmium



Effect of culture acclimation and stimulation of copper uptake efficiencies.



Effect of culture acclimation and stimulation of cadmium uptake efficiencies.

There is substantial diversity among organisms in terms of their ability to accumulate metals. Given the diversity of organisms in different composts and the wide range of composition among composts produced from different raw materials (see Chapter 1), it is likely that substantial variations in metal-binding ability will be found among different composted materials.

Source: Chang, 1995

References

Alexander, M. *Biodegradation and Bioremediation*, 226-247. San Diego: Academic Press, 1994.

Brown, R.A., W. Mahaffey, and R.D. Norris. "In Situ Bioremediation: The State of the Practice." In *In Situ Bioremediation: When Does It Work?*, 121-135. Washington, DC: National Academy Press, 1993.

Chang, D., K. Fukushi, and S. Ghosh. "Stimulation of Activated Sludge Cultures for Enhanced Heavy Metal Removal." *Water Environment Research* 67 (1995): 822-827.

Cole, M.A., X. Liu, and L. Zhang. "Plant and Microbial Establishment in Pesticide-Contaminated Soils Amended With Compost." In *Bioremediation Through Rhizosphere Technology*, edited by T.A. Anderson and J.R. Coats, 210-222. Washington, DC: American Chemical Society, 1994.

Dixon, J.B. and S.B. Weed. *Minerals in Soil Environments*. Madison, WI: Soil Science Society of America, Inc., 1977.

Hassett, J.J. and W.L. Banwart. "The Sorption of Nonpolar Organics by Soils and Sediments." In *Reactions and Movement of Organic Chemicals in Soils*, edited by B.L. Sawhney and K. Brown, 31-44. Madison, WI: Soil Science Society of America, Inc., 1989.

Hoitink, H.A.J. "Production of Disease Suppressive Compost and Container Media, and Microorganism Culture for Use Therein." U.S. Patent 4,960,348. February 13, 1990.

Hoitink, H.A.J., M.J. Boehm, and Y. Hadar. "Mechanisms of Suppression of Soilborne Plant Pathogens in Compost-amended Substrates." In *Science and Engineering of Composting*, edited by H.A.J. Hoitink and H.M. Keener, 601-621. Worthington, OH: Renaissance Publications, 1993.

Nakasaki, K., M. Kubo, and H. Kubota. "Production of Functional Compost Which Can Suppress Phytopathogenic Fungi of Lawn Grass by Inoculating Bacillus subtilis Into Grass Clippings." In *The Science of Composting*, edited by M. de Bertoldi, P. Bert, and P. Tiziano, 87-95. London: Blackie Academic and Professional, 1996.

Ryan, J.A. and P. Zhang. "Soil Lead Remediation: Is Removal the Only Option?" Unpublished manuscript distributed on the Internet. No date.

Scow, K.M. "Effect of Sorption-desorption and Diffusion Processes on the Kinetics of Biodegradation of Organic Chemicals in Soil." In *Sorption and Degradation of Pesticides and Organic Chemicals in Soil*, 73-114. Madison, WI: Soil Science Society of America, Inc., 1993.

van Veen, J.A., L.S. van Overbeek, and J.D. van Elsas. "Fate and Activity of Microorganisms Introduced Into Soil." *Microbiology and Molecular Biology Reviews* 61 (1997): 121-135.

Ziekle, R.C., T.J. Pinnavaia, and M.M. Mortland. "Absorption and Reactions of Selected Organic Molecules on Clay Mineral Surfaces." In *Reactions and Movement of Organic Chemicals in Soils*, edited by B.L. Sawhney and K. Brown. Madison, WI: Soil Science Society of America, Inc., 1989.

Chapter 8

Bibliography

Introduction

Anonymous. *Compost Facility Operating Guide*. Alexandria, VA: The Composting Council, 1994.

BioCycle Staff (eds.). *Composting Source Separated Organics*. Emmaus, PA: The JG Press, Inc., 1994.

Chang, Y. and H.J. Hudson. "The Fungi of Wheat Straw Compost. I. Ecological Studies." *Transactions of the British Mycological Society* 50 (1967): 649-666.

Cole, M.A., L. Zhang, and X. Liu. "Remediation of Pesticide Contaminated Soil by Planting and Compost Addition." *Compost Science and Utilization* 3 (1995): 20-30.

Dalzell, H.W., A.J. Biddlestone, K.R. Gray, and K. Thurairajan. *Soil Management: Compost Production and Use in Tropical and Subtropical Environments.* FAO Soils Bulletin 56. Rome: Food and Agriculture Organization of the United Nations, 1987.

Eastwood, D.J. "The Fungus Flora of Composts." *Transactions of the British Mycological Society* 35 (1952): 215-220.

Fálcon, M.A., E. Corominas, M.L. Pérez, and F. Perestelo. "Aerobic Bacterial Populations and Environmental Factors Involved in the Composting of Agricultural and Forest Wastes of the Canary Islands." *Biological Wastes* 20 (1987): 89-99.

Finstein, M.S., F.C. Miller, and P.F. Strom. "Monitoring and Evaluating Composting Process Performance." *Journal of the Water Pollution Control Federation* 58 (1986): 272-278.

Finstein, M.S., F.C. Miller, and P.F. Strom. "Waste Treatment Composting as a Controlled System." In *Biotechnology, Volume 8*, edited by W. Schonborn, 363-398. Weinheim, Federal Republic of Germany: VCH Verlagsgesellschaft, 1986.

Finstein, M.S., F.C. Miller, P.F. Strom, S.T. MacGregor, and K.M. Psarianos. "Composting Ecosystem Management for Waste Treatment." *Bio/Technology* 1 (1983): 347-353.

Finstein, M.S., and M.L. Morris. "Microbiology of Municipal Soil Waste Composting." *Advances in Applied Microbiology* 19 (1975): 113-151.

Garland, G.A., T.A. Grist, and R.E. Green. "The Compost Story: From Soil Enrichment to Pollution Remediation." *BioCycle* 36 (October 1995): 53-56.

Gasser, J.K.R. *Composting of Agricultural and Other Wastes*. London: Elsevier Applied Science Publishers, 1985.

Godden, B., M. Penninckx, A. Piérard, and R. Lannoye. "Evolution of Enzyme Activities and Microbial Populations During Composting of Cattle Manure." *European Journal of Applied Microbiology and Biotechnology* 17 (1983): 306-310.

Haug, R.T. *The Practical Handbook of Compost Engineering*. Boca Raton, FL: Lewis Publishers, 1993.

Hogan, J.A., F.C. Miller, and M.S. Finstein. "Physical Modeling of the Composting Ecosystem." *Applied and Environmental Microbiology* 55 (1989): 1082-1092.

Hoitink, H.A.J. and H.M. Keener. *Science and Engineering of Composting*. Worthington, OH: Renaissance Publications, 1993.

Jeris, J.S. and W.R. Regan. "Controlling Environmental Parameters for Optimum Composting. II. Moisture, Free Air Space and Recycle." *Compost Science* 14(2) (1973): 8-15.

McKinley, V.L. and J. R.Vestal. "Biokinetic Analyses of Adaptation and Succession: Microbial Activity in Composting Municipal Sewage Sludge." *Applied and Environmental Microbiology* 47 (1984): 933-941.

Nakasaki, K., M. Sasaki, M. Shoda, and H. Kubota. "Change in Microbial Numbers During Thermophilic Composting of Sewage Sludge With Reference to CO_2 Evolution Rate." *Applied and Environmental Microbiology* 49 (1985): 37-41.

Nakasaki, K., M. Sasaki, M. Shoda, and H. Kubota. "Characteristics of Mesophilic Bacteria Isolated During Thermophilic Composting of Sewage Sludge." *Applied and Environmental Microbiology* 49 (1985): 42-45.

Poincelot, R.P. *The Biochemistry and Methodology of Composting*. Connecticut Agricultural Experiment Station Bulletin 127. New Haven, CT: Connecticut Agricultural Experiment Station, 1972.

Rynk, R. (ed.). *On-Farm Composting Handbook*. Ithaca, NY: Northest Regional Agricultural Engineering Service, Cooperative Extension, 1992.

Strom, P.F. "Effect of Temperature on Bacterial Species Diversity in Thermophilic Solid Waste Composting." *Applied and Environmental Microbiology* 50 (1985): 899-905.

Strom, P.F. "Identification of Thermophilic Bacteria in Solid Waste Composting." *Applied and Environmental Microbiology* 50 (1985): 906-913.

Struwe, S. and A. Kjøller. "Changes in Population Structure During Decomposition." In *Microbial Communities in Soil*, edited by V. Jensen, A. Kjøller, and L.H. Sørensen, 149-162. London: Elsevier Applied Science Publishers, 1986.

Tosin, M.F. and C. Bastioli. "Effect of the Composting Substrate on Biodegradation of Solid Materials Under Controlled Composting Conditions." *Journal of Environmental Polymer Degradation* 4 (1996): 55-63.

U.S. EPA. *Composting: Yard and Municipal Solid Waste*. Washington, DC, no date.

Vestjens, T. "Tunnel Composting Technology." *Mushroom Journal* 531 (1994): 14-15.

Waksman, S.A. and T.C. Cordon. "Thermophilic Decomposition of Plant Residues in Composts by Pure and Mixed Cultures of Microorganisms." *Soil Science* 47 (1939): 217-225.

Waksman, S.A., T.C. Cordon, and N. Hulpoi. "Influence of Temperature Upon the Microbiological Population and Decomposition Processes in Composts of Stable Manure." *Soil Science* 47 (1939): 83-113.

Waksman, S.A., W.W. Umbreit, and T.C. Cordon. "Thermophilic Actinomycetes and Fungi in Soils and in Composts." *Soil Science* 47 (1939): 37-61.

Webley, D.M. "The Microbiology of Composting. I. The Behaviour of the Aerobic Mesophilic Bacteria Flora of Composts and Its Relation to Other Changes Taking Place During Composting." *Proceedings of the Society of Applied Bacteriology* 2 (1947): 83-99.

Remediation of Soils Contaminated With Toxic Organic Compounds

Anonymous. "Hazardous Waste Composting." *The Hazardous Waste Consultant* (June/July 1992): 1.12-1.13.

Arndt, W., E. Schindlbeck, H. Parlar, and F. Korte. "Behavior of Organophosphorus Insecticides in Garbage and Waste Composting." *Chemosphere* 10 (1981): 1035-1040.

Buswell, J.A. "Potential of Spent Mushroom Substrate for Bioremediation Purposes." *Compost Science and Utilization* 2 (1994): 31-36.

Cole, M.A., X. Liu, and L. Zhang. "Plant and Microbial Establishment in Pesticide-contaminated Soils Amended With Compost." In *Bioremediation through Rhizosphere Technology,* edited by T.A. Anderson and J.R. Coats, 210-222. Washington, DC: American Chemical Society, 1994.

Cole, M.A., X. Liu, and L. Zhang. "Effect of Compost Addition on Pesticide Degradation in Planted Soils." In *Bioremediation of Recalcitrant Organics*, edited by R.E. Hinchee, D.B. Anderson, and R.E. Hoeppel, 183-190. Columbus, OH: Battelle Press, 1995.

Cole, M.A., L. Zhang, and X. Liu. "Remediation of Pesticide Contaminated Soil by Planting and Compost Addition." *Compost Science and Utilization* 3 (1995): 20-30.

Cook, B.D., P.B. Bloom, and T.R. Halbach. "A Method for Determining the Ultimate Fate of Synthetic Chemicals During Composting." *Compost Science and Utilization* 2 (1994): 42-50.

Crawford, S.L., G.E. Johnson, and F.E. Goetz. "The Potential for Bioremediation of Soils Containing PAHs by Composting." *Compost Science and Utilization* 1 (1993): 41-47.

de Bertoldi, M., P. Bert, and P. Tiziano. *The Science of Composting*. London: Blackie Academic and Professional, 1996.

Diaz, L.F., G.M. Savage, and C.G. Golueke. "Stabilization of Hazardous Wastes Through Biotreatment." In *The Science of Composting*, by M. de Bertoldi, P. Bert, and P. Tiziano, 849-862. London: Blackie Academic and Professional, 1996.

Fantoni, A., P. Muraro, C. Picco, and G. Zorzi. "Biodegradation of Thiram in Composting Process." In *The Science of Composting*, by M. de Bertoldi, P. Bert, and P. Tiziano, 1152-1156. London: Blackie Academic and Professional, 1996.

Fogarty, A.M. and O.H. Tuovinen. "Microbiological Degradation of Pesticides in Yard Waste Composting." *Microbiological Reviews* 55 (1991): 225-233.

Fyock, O.L., S.B. Nordrum, S. Fogel, and M. Findley. "Pilot Scale Composting of Petroleum Production Sludges." In *Third Annual Symposium on Environmental Protection in the Energy Industry: Treatment and Disposal of Petroleum Sludges*, edited by K.L. Sublette and T.M. Harris. Tulsa, OK: University of Tulsa, 1991.

Hogan, J.A. "Composting for Soil Remediation." In *Biological Treatment of Hazardous Wastes*, by G.A. Lewandowski and L.J. DeFilippi. New York, NY: John Wiley and Sons, Inc., 1998.

Kabrick, R.M. and J.R. Coover. "Composting as BDAT for Solvent (F Wastes) Contaminated Soils." In *Environmental Engineering: Proceedings of the 1989 Speciality Conference*, edited by J.F. Malina. New York, NY: American Society of Civil Engineers, 1989.

Kamnikar, B. "Bioremediation of Contaminated Soil." *Pollution Engineering* 24 (November 1, 1992): 50-52.

Lemmon, C.R. and H.M. Pylypiw, Jr. "Degradation of Diazinon, Chlorpyrifos, Isofenphos, and Pendimethalin in Grass and Compost." *Bulletin of Environmental Contamination and Toxicology* 48 (1992): 409-415.

Martens, R. "Concentrations and Microbial Mineralization of Four to Six Ring Polycyclic Aromatic Hydrocarbons in Composted Municipal Waste." *Chemosphere* 11 (No date): 761-770.

McNabb, D.H., R.L. Johnson, and I. Guo. "Aggregation of Oil- and Brine-contaminated Soil to Enhance Bioremediation." In *Hydrocarbon Bioremediation*, by R.E. Hinchee, B.C. Alleman, R.E. Hoeppel, and R.N. Miller, 296-302. Boca Raton, FL: Lewis Publishers, 1994.

Michel Jr., F.C., D. Graeber, L.J. Forney, and C.A. Reddy. "Fate of Lawn Care Pesticides During the Composting of Yard Trimmings." In *The Science of Composting*, by M. de Bertoldi, P. Bert, and P. Tiziano, 1230-1231. London: Blackie Academic and Professional, 1996.

Nishio, M. and S. Kusano. "Fluctuation Patterns of Microbial Numbers in Soil Applied With Compost." *Soil Science and Plant Nutrition* 26 (1980): 581-593.

Okeke, B.C., J.E. Smith, A. Paterson, and I.A. Watson-Craik. "Aerobic Metabolism of Pentachlorophenol by Spent Sawdust Culture of 'Shiitake' Mushroom." *Biotechnology Letters* 15 (1993): 1077-1080.

Racke, K.D. and C.R. Fink. "Fate of Organic Contaminants During Sewage Sludge Composting." *Bulletin of Environmental Contamination and Toxicology* 42 (1989): 526-533.

Rao, N., H.E. Grethlein, and C.A. Reddy. "Mineralization of Atrazine During Composting With Untreated and Pretreated Lignocellulosic Substrates." *Compost Science and Utilization* 3 (1995): 38-46.

Regan, Sr., R.W. "Use of SMS as a Compost Matrix to Degrade Pesticide Residuals." *Compost Science and Utilization* 2 (1994): 56-62.

Rhodes, S.H. and P.C. Peck. "Composting for Remediation of Soil Contaminated With Pharmaceutical Residues." In *Bioremediation of Recalcitrant Organics*, by R.E. Hinchee, R.E. Hoeppel, and D.B. Anderson, 341-348. Boca Raton, FL: Lewis Publishers, 1995.

Savage, G.M., L.F. Diaz, and C.G. Golueke. "Disposing of Hazardous Wastes by Composting." *BioCycle* 26(1) (1985): 31-34.

Sikora, L.J., D.D. Kaufman, M.A. Ramirez, and G.B. Wilson. "Degradation of Pentachlorophenol and Pentachloronitrobenzene in a Laboratory Composting System." In *Land Disposal of Hazardous Waste: Proceedings of the 8th Annual Research Symposium*, edited by D.W. Shultz, 372-382. Washington, DC: U.S. EPA, 1982.

Snell, J.R. *Rate of Biodegradation of Toxic Organic Compounds While in Contact With Organics Which Are Actively Composting*. PB84-193150. Washington, DC: National Technical Information Service, 1982.

Tan, E., C.H. Ho, W.H. Griest, and R.L. Tyndall. "Mutagenicity of Trinitrotoluene and Its Metabolites Formed During Composting." *Journal of Environmental Toxicology and Environmental Health* 36 (1992): 165-175.

Valo, R. and M. Salkinoja-Salonen. "Bioreclamation of Chlorophenol-contaminated Soil by Composting." *Applied Microbiology and Biotechnology* 25 (1986): 68-75.

Vogtmann, H., P.V. Fragstein, and P. Draeger. "The Degradation of Agrochemicals During Composting." *Proceedings of the Second International Symposium on Peat in Agriculture and Horticulture*. Bet Dagan: Hebrew University of Jerusalem, 1983.

Weston, R.F., Inc. *Windrow Composting Demonstration for Explosives-Contaminated Soils at the Umatilla Depot Activity Hermiston, Oregon*. Report CETHA-TS-CR-93043, 1993.

Williams, R.T., P.S. Ziegenfuss, and P.J. Marks. *Field Demonstration—Composting of Explosives-Contaminated Sediments at the Louisiana Army Ammunition Plant (LAAP): Final Report*. West Chester, PA: Roy F. Weston, Inc., 1988.

Williams, R.T., P.S. Ziegenfuss, and W.E. Sisk. "Composting of Explosives and Propellant Contaminated Soils Under Thermophilic and Mesophilic Conditions." *Journal of Industrial Microbiology* 9 (1992): 137-144.

Yare, B.S. "A Comparison of Soil-phase and Slurry-phase Bioremediation of PNA-containing Soils." In *On-Site Bioreclamation*, edited by R.E. Hinchee and R.F. Olfenbuttel, 173-187. Boston: Butterworth-Heinemann, 1991.

Compost-Based Biofilters for Treatment of Contaminated Air and Wastewater Streams

Bohn, H.L. "Compost Scrubbers of Malodorous Air Streams." *Compost Science* 17 (Winter 1976): 15-17.

Eitzer, B.D. "Volatile Chemical Emissions at Composting Facilities Are Significantly Below Workplace Guidelines." *Frontiers of Plant Science* 47 (Fall 1994): 2-3.

Everwijn, T.S., F.R. Hoffman, H. Ramhit, C.E. Schultz, and J.W.A. Verwaart. *Bodemreinigingstechnieken*, 68. Amsterdam: Uitgeverij Boom, 1992.

Fischer, K. "Environmental Impact of Composting Plants." In *The Science of Composting*, edited by M. de Bertoldi, P. Bert, and P. Tiziano, 81-86. London: Blackie Academic and Professional, 1996.

Hwang, Y., T. Matsuo, K. Hanaki, and N. Suzuki. "Removal of Odorous Compounds in Wastewater by Using Activated Carbon, Ozonation, and Aerated Biofilter." *Water Research* 28 (1994): 2309-2319.

Pinnette, J.R., M.D. Giggey, G.E. Hendry, and C.M. Richardson. "Moisture Balance of an Open Biofilter." *Compost Science and Utilization* 1(2) (1993): 8-22.

Pomeroy, R.D. "Biological Treatment of Odorous Air." *Journal of the Water Pollution Control Federation* 54 (1982): 1541-1545.

Prokop, W.H. and H.L. Bohn. "Soil Bed System for Control of Rendering Plant Odors." *Journal of the Air Pollution Control Association* 35 (1985): 1332-1338.

Selby, M.A. "Soil Filters at Treatment Plant." *BioCycle* 27 (July 1986): 33.

Stewart, W.C. "Biofiltration for the Capture and On-site Destruction of VOC's in Aerosol Can Puncturing and Recycling Operations." Unpublished manuscript, no date.

Stewart, W.C. and R.R. Thom. "Test Results and Economics of Using an Innovative, High-rate, Vapor-phase Biofilter in Industrial Applications." Unpublished manuscript, no date.

Van der Hoek, K.W. and J. Oosthoek. "Composting: Odour Emission and Odour Control by Biofiltration." In *Composting of Agricultural and Other Wastes*, edited by J.K.R. Gasser, 271-281. London: Elsevier Applied Science Publishers, 1985.

Van Langenhove, H., E. Wuyts, and N. Schamp. "Elimination of Hydrogen Sulfide From Odorous Air by a Wood Bark Biofilter." *Water Research* 20 (1986):1471-1476.

Vembu, K. and C.S. Walker. "Biofiltration Holds VOCs, Odors at Bay." *Environmental Protection* (February 1995): 27-30, 58.

Walker, J.M. "Control of Composting Odors." In *Science and Engineering of Composting*, edited by H.A.J. Hoitink and H.M. Keener, 185-241. Worthington, OH: Renaissance Publications, 1993.

Williams, T.O. and F.C. Miller. "Biofilters and Facility Operations." *BioCycle* 33 (November 1992): 75-79.

Potential for Reclamation of Mine Spoils and Brownfields With Compost

Allievi, L., A. Marchesini, C. Salardi, V. Piano, and A. Ferrari. "Plant Quality and Soil Residual Fertility Six Years After a Compost Treatment." *Bioresource Technology* 43 (1993): 85-89.

Autio, W.R., D.W. Greene, D.R. Cooley, and J.R. Schupp. "Improving the Growth of Newly Planted Apple Trees." *HortScience* 26 (1991): 840-843.

Baker, A.J.M. and R.R. Brooks. "Terrestrial Higher Plants Which Hyperaccumulate Metallic Elements—A Review of Their Distribution, Ecology, and Phytochemistry." *Biorecovery* 1 (1989): 81-126.

Bastian, R.K. "Overview on Sludge Utilization." In *The Forest Alternative (for treatment and utilization of municipal and industrial wastes)*, edited by D.W. Cole, C.L. Henry, and W.L. Nutter, 7-25. Seattle, WA: University of Washington Press, 1986.

Berry, C.R. "Reclamation of Severely Devastated Sites With Dried Sewage Sludge in the Southeast." In *The Forest Alternative (for treatment and utilization of municipal and industrial wastes)*, edited by D.W. Cole, C.L. Henry, and W.L. Nutter, 497-514. Seattle, WA: University of Washington Press, 1986.

Boyd, V. "Pint-sized Plants Pack a Punch in Fight Against Heavy Metals." *Environmental Protection* (May 1996): 38-39.

Chaney, R.L. "Plant Uptake of Inorganic Waste Constituents." In *Land Treatment of Hazardous Wastes*, by J.F. Parr, P.B. Marsh, and J.M. Kla, 50-76. Park Ridge, NJ: Noyes Data Corporation, 1983.

Davey, C.B. "Sawdust Composts: Their Preparation and Effect on Plant Growth." *Soil Science Society of America Proceedings* 17 (1953): 59-60.

Haynes, J. "Applying Compost and Mulches to Control Erosion." *BioCycle* 38 (May 1997): 55-57.

Long, C. "The OG Complete Guide to Compost." *Organic Gardening* 44 (April 1997): 56-60.

MacConnell, G.S., C.G. Wells, and L. J. Metz. "Influence of Municipal Sludge on Forest Soil Mesofauna." In *The Forest Alternative (for treatment and utilization of municipal and industrial wastes)*, edited by D.W. Cole, C.L. Henry, and W.L. Nutter, 177-187. Seattle, WA: University of Washington Press, 1986.

Pietz, R.I., C.R. Carlson, Jr., J.R. Peterson, D.R. Zenz, and C. Lue-Hing. "Application of Sewage Sludge and Other Amendments to Coal Refuse Material. I. Effects on Chemical Composition." *Journal of Environmental Quality* 18 (1989): 164-169.

Sabey, B.R., R.L. Pendleton, and B.L. Webb. "Effect of Municipal Sewage Sludge Application on Growth of Two Reclamation Shrub Species in Copper Mine Spoils." *Journal of Environmental Quality* 19 (1990): 580-586.

Suppression of Plant Diseases and Pests by Compost

Achimu, P. and E. Schlösser. "Control of Plasmopara viticola With Compost Filtrates." *Mededelingen (Rijksuniversiteit te Gent. Fakulteit van de Landbouwkundige en Toegepaste Biologische Wetenschappen)* 52/2a (1991): 171-178.

Akhtar, M. and M.M. Alam. "Utilization of Waste Materials in Nematode Control: A Review." *Bioresource Technology* 45 (1993): 1-7.

Brinton, W.F., A. Trankner, and M. Droffner. "Investigations Into Liquid Compost Extracts." *BioCycle* 37 (1996): 68-70.

Campbell, R. "Microbial Interactions Leading to Biocontrol of Root Diseases—Reality or Myth?" *Aspects of Applied Biology* 22 (1989): 165-172.

Conner, D.E., J.P. Blake, and J.O. Donald. "Microbiological Safety of Composted Poultry Farm Mortalities." *American Society of Agricultural Engineers Paper No. 91-4053*, 1991.

Cook, R.J. "Making Greater Use of Introduced Microorganisms for Biological Control of Plant Pathogens." *Annual Review of Phytopathology* 31 (1993): 53-80.

Cronin, M.J., D.S. Yohalem, R.F. Harris, and J.H. Andrews. "Putative Mechanism and Dynamics of Inhibition of the Apple Scab Pathogen Venturia inaequalis by Compost Extracts." *Soil Biology and Biochemistry* 28 (1996): 1241-1249.

Doyle, J.M. "Soil Amendments and Biological Control." *Golf Course Management* (March 1991): 90-96.

Gilbert, R.G. and G.E. Griebel. "The Influence of Volatile Substances From Alfalfa on Verticillium dahliae in Soil." *Phytopathology* 59 (1969): 1400-1403.

Hoitink, H.A.J. and P.C. Fahy. "Basis for the Control of Soilborne Plant Pathogens With Composts." *Annual Review of Phytopathology* 24 (1986): 93-114.

Hoitink, H.A.J. and G.A. Kuter. "Effects of Composts in Growth Media on Soilborne Plant Pathogens." In *The Role of Organic Matter in Modern Agriculture*, edited by Y. Chen and Y. Avnimelech, 289-306. Dordrecht, The Netherlands: Martinus Nijhoff Publishers, 1986.

Hoy, M.A. "Use of Parasites and Predators in the Biological Control of Arthropod Pests: Emerging Technologies and Challenges." In *Entomology Serving Society: Emerging Technologies and Challenges*, edited by S.B. Vinson and R.L. Metcalf, 272-297. Lanham, MD: Entomological Society of America, 1991.

Kwok, O.C.H., P.C. Fahy, H.A.J. Hoitink, and G.A. Kuter. "Interactions Between Bacteria and *Trichoderma hamatum* in Suppression of Rhizoctonia Damping-off in Bark Compost Media." *Phytopathology* 77 (1987): 1206-1212.

Mandelbaum, R. and Y. Hadar. "Methods for Determining Pythium Suppression in Container Media." *Compost Science and Utilization* 5(2) (1997):15-22.

Mankau, R. "Biocontrol: Fungi as Nematode Control Agents." *Journal of Nematology* 12 (1980): 244-252.

Muller, R. and P.S. Gooch. "Organic Amendments in Nematode Control. An Examination of the Literature." *Nematropica* 12 (1982): 319-326.

Nelson, E.B. "The Biological Control of Turfgrass Diseases." *Golf Course Management* (April 1992): 78-90.

Nelson, E.B. "Biological Controls." *TurfGrass Trends* (January 1994): 1-9.

Poswal, M.A.T. and A.D. Akpa. "Current Trends in the Use of Traditional and Organic Methods for the Control of Crop Pests and Diseases in Nigeria." *Tropical Pest Management* 37 (1991): 329-333.

Owens, L.D., R.G Gilbert, G.E. Griebel, and J.D. Menzies. "Identification of Plant Volatiles That Stimulate Microbial Respiration and Growth in Soil." *Phytopathology* 59 (1969): 1468-1472.

Ringer, C.E., P.D. Millner, L.M. Teerlinck, and B.W. Lyman. "Suppression of Seedling Damping-off Disease in Potting Mix Containing Animal Manure Compost." *Compost Science and Utilization* 5(2) (1997): 6-14.

Rodriguez-Kábana, R. "Organic and Inorganic Nitrogen Amendments to Soil as Nematode Suppressants." *Journal of Nematology* 18 (1986): 129-135.

Rodriguez-Kábana, R., G. Morgan-Jones, and I. Chet. "Biological Control of Nematodes: Soil Amendments and Microbial Antagonists." *Plant and Soil* 100 (1987): 237-247.

Serra-Wittling, C., S. Houot, and C. Alabouvette. "Increased Soil Suppressiveness to Fusarium Wilt of Flax After Addition of Municipal Solid Waste Compost." *Soil Biology and Biochemistry* 28 (1996): 1207-1214.

Still, S.M., M.A. Dirr, and J.B. Gartner. "Phytotoxic Effects of Several Bark Extracts on Mung Bean and Cucumber Growth." *Journal of the American Society of Horticultural Science* 101 (1976): 34-37.

Tuitert, G. and G.J. Bollen. "The Effect of Composted Vegetable, Fruit and Garden Waste on the Incidence of Soilborne Plant Diseases." In *The Science of Composting*, edited by M. de Bertoldi, P. Bert, and P. Tiziano, 1365-1369. London: Blackie Academic and Professional, 1996.

Weller, D.M. "Biological Control of Soilborne Plant Pathogens in the Rhizosphere With Bacteria." *Annual Review of Phytopathology* 26 (1988): 379-407.

Weltzien, H.C. "Biocontrol of Foliar Fungal Diseases With Compost Extracts." In *Microbial Ecology of Leaves*, edited by J.H. Andrews and S.S. Hirano, 430-450. New York: Springer-Verlag, 1991.

Wilkinson, J.F. "Applying Compost to the Golf Course." *Golf Course Management* (March 1994): 80-88.

Yohalem, D.S., R. Voland, E.V. Nordheim, R.F. Harris, and J.H. Andrews. "Sample Size Requirements to Evaluate Spore Germination Inhibition by Compost Extracts." *Soil Biology and Biochemistry* 28 (1996): 519-525.

Compost-Enriched Phytoremediation of Contaminated Soil

Cole, M.A., L. Zhang, and X. Liu. "Remediation of Pesticide Contaminated Soil by Planting and Compost Addition." *Compost Science and Utilization* 3(4) (1985): 20-30.

Pera, A., G. Vallini, I. Sireno, M.L. Bianchin, and M. de Bertoldi. "Effect of Organic Matter on Rhizosphere Microorganisms and Root Development of Sorghum Plants in Two Different Soils." *Plant and Soil* 74 (1983): 3-18.

Schnoor, J.L., L.A. Licht, S.C. McCutcheon, N.L. Wolfe, and L.H. Carriera. "Phytoremediation of Organic and Nutrient Contaminants." *Environmental Science and Technology* 29 (1995): 318A-323A.

U.S. DOE. "Phytoremediation Research Needs." DOE/EM-0224. Washington, DC. U.S. Department of Energy, 1994.