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The assimilation of organic hazardous wastes by municipal solid waste landfills

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SUMMARY

Co-disposal of 12 compounds representing major organic classes (aromatic hydrocarbons, halogenated hydrocarbons, pesticides, phenols, and phthalate esters) with shredded municipal solid waste was tested using a laboratory-scale column and pilot-scale lysimeter to characterize transport and transformation phenomena including sorption, volatilization and bioassimilation. Leachate and gases emitted from the lysimeters were examined for identifiable products of biotransformation. The results of this investigation provided a mechanistic evaluation of the attenuating and assimilative capacity of municipal solid waste landfills for specific organic compounds. Physical/chemical organic compound characteristics were related to refuse characteristics and composition to predict compound fate. Such knowledge is useful in developing landfill management and operational strategies consistent with the need for control of pollutant releases.

INTRODUCTION

Landfilling of solid waste has long been the method of choice for disposal of municipal solid waste. Because of the extremely heterogeneous nature of solid waste (including 0.1–5% by weight household hazardous wastes; [28]), a variety of organic compounds are found in landfilled refuse. The fate and behavior of a specific organic compound is directed by numerous transport and transformation pathways active within a landfill, including advection (as moisture percolates through the landfill), sorption on the solid waste surface, biodegradation, and volatilization and transport by gaseous degradation end-products. In particular, because of the extended reaction times available, there is opportunity for microbial acclimation to the more recalcitrant compounds, enhancing the likelihood for biotransformation under the prevailing anaerobic conditions.

At present there are approx. 9244 operating municipal solid waste landfills in the United States [32]. Although landfill dependency is diminishing, landfills will continue to play an important role in municipal solid waste disposal long into the future. Solid waste placed in these landfills is a heterogeneous mixture of paper products, food

wastes, vegetative matter, textiles, plastics, leather, rubber, glass, metals, and ash originating from industrial, residential, agricultural, and commercial sources. The composition of solid waste is variable, being a function of climate, season, population, demographics, and geographical location.

Within a landfill, a complex sequence of physically, chemically, and biologically mediated events occurs. As a consequence of these processes, refuse is degraded or transformed. Stabilization of municipal refuse proceeds through several discrete phases beginning with placement of waste followed by an increase in moisture content, depletion of available oxygen as a consequence of microbial activity, a shift to anaerobic microbial activity accompanied by an increase in gas production rates, and eventual maturation of the landfill.

The organic content of refuse is approx. 75–80% (dry weight) including proteins, lipids, carbohydrates (cellulose and hemicellulose), and lignins. Approximately two-thirds of this material is biodegradable, one-third recalcitrant. The biodegradable portion can be further divided into a readily biodegradable fraction (food and yard wastes), and moderately biodegradable fraction (paper, textiles, and wood) [36].

As water percolates through the landfill, contaminants are leached from the solid waste. The characteristics of the leachate produced are highly variable depending on the composition of the solid waste, rate of water application, refuse moisture content, and landfill design, opera-

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tion, and age. Initially, leachate may contain, at extremely high concentrations, organic and inorganic constituents such as volatile fatty acids, carbohydrates, alcohols, ammonia, and heavy metals and other priority pollutants. With time, concentrations of leachate constituents typically decline as a result of washout and/or biological activity.

Organic contaminants of leachate are primarily soluble components or decomposition products of biodegradable fractions of municipal refuse. However, in a review of risks associated with landfill leachate, Brown and Donnelly [7] reported that hazardous organic compounds were found in leachate from all 58 landfills investigated regardless of the type of waste accepted. The origin of these chemicals is thought to be hazardous waste from small-quantity generators, hazardous waste illegally dumped, hazardous household waste such as paints, solvents, oils, cleaning compounds, pesticides, and degreasing compounds, as well as plasticizers and pharmaceutical materials routinely placed in landfills.

Contamination of groundwater by organic pollutants contained in leachates has led to several investigations of leachate composition. Organic compounds typically found at highest concentration in leachates were volatile fatty acids produced during the decomposition of lipids (two- to 12-carbon fatty acids), proteins (aromatic acids), and carbohydrates [1,30]. Aromatic hydrocarbons, including benzene, various xylenes, and toluene, were often found at lower concentrations [14,30]. These compounds were considered to be constituents of gasoline and fuel oils. Sawney and Kozloski [29] reported that the presence of the more soluble, less volatile aromatic components of gasoline suggested that the more volatile components were being gas-stripped from the landfill.

Non-volatile classes of compounds such as phenolic compounds (primarily cresols but also hydroxyphenyl acetate derivatives) may be degradative byproducts of lignin. A small complex fraction found in several leachates contained nicotine, caffeine, and phthalate plasticizers [1].

Alkyl phosphates; nitrogen-containing compounds such as benzonitrile, methylbenzonitrile, aniline, tetramethylthiourea, cyanobenzoic acid, cinnoline, benzothiazole, and *N*-propylmethylbenzamide; chlorinated aromatic and aliphatic compounds; and pesticides were frequently encountered as a result of co-disposal of municipal and industrial wastes [26,30]. Reinhard et al. [26] observed that only mobile, relatively hydrophilic compounds were encountered in leachate-contaminated groundwaters, suggesting that more hydrophobic compounds were attenuated within the landfill or soil.

The dominant organic class in leachate shifts as the

age of the landfill increases due to the ongoing microbial and physical/chemical processes within the landfill. An investigation of leachates obtained from landfills operated from 1 to 20 years found that the relative abundance of high-molecular mass humic-like substances decreased with age, while intermediate-sized fulvic materials showed significantly smaller decreases [10]. The relative abundance of organic compounds present in these leachates was observed to decrease with time in the following order: free volatile fatty acids, low-molecular mass aldehydes and amino acids, carbohydrates, peptides, humic acids, phenolic compounds, and fulvic acids.

In summary, the fate of an organic compound within a landfill, appears to be related to the age and activity of the landfill as well as to the characteristics of the compound including aqueous solubility, volatility, hydrophobicity, and biodegradability. Potential environmental contamination by hazardous organic components emitted by municipal landfills necessitates appropriate management of landfill gases and leachates, requiring characterization of expected pathways for these contaminants. Presented herein are results of laboratory and pilot-scale investigations into the behavior of organic hazardous compounds co-disposed with municipal solid waste. Specifically, 12 test compounds were selected to represent a broad range of organic classes including volatile organic compounds, polar non-volatile compounds, and non-polar non-volatile compounds.

MATERIALS AND METHODS

The physical and chemical properties of test organic compounds are provided in Table 1. Test organic compounds included two halogenated aliphatic compounds, dibromomethane (DBM) and trichloroethene (TCE); three chlorinated benzene compounds, 1,4-dichlorobenzene (DCB), 1,2,4-trichlorobenzene (TCB), and hexachlorobenzene (HCB); two phenolic compounds, 2-nitrophenol (NP) and 2,4-dichlorophenol (DCP); a nitroaromatic compound, nitrobenzene (NB); two pesticides, γ -hexachlorocyclohexane or lindane (LIN) and 1,2,3,4,10,10 α -hexachloro 6,7-epoxy-1,4,4 α ,5,6,8,8 α -octahydro-1,2-endo, exo-5,8-dimethanonaphthalene or dieldrin (DIE); a polynuclear aromatic hydrocarbon, naphthalene (NAP); and a phthalate ester, bis(2-ethylhexyl)phthalate (BEHP)*.

Fresh municipal refuse was obtained from the Dekalb

Registry numbers: Dibromomethane, 74-95-3; trichloroethene, 79-01-6; 1,4-dichlorobenzene, 106-46-7; 1,2,4-trichlorobenzene, 120-82-1; 2-nitrophenol, 88-75-5; 2,4-dichlorophenol, 120-83-2; gamma-hexachlorocyclohexane, 58-89-9; nitrobenzene, 98-95-3; naphthalene, 91-20-3; Dieldrin, 60-57-1; bis(2-ethylhexyl)phthalate, 117-81-7; hexachlorobenzene, 118-74-1.

TABLE 1

Physical and chemical properties of test organic compounds^a

| Compound | Molecular mass | Aqueous solubility (mg/l) | Vapor pressure at 100 °C (kPa) | Log octanol/water partition coefficient | Henry's law constant ^b (unitless) |
|---|----------------|---------------------------|--------------------------------|---|--|
| Trichloroethene (TCE) | 131.4 | 1 100 (20 °C) | 150 | 2.29 | 0.37 |
| Dibromomethane (DBM) | 173.9 | 11 700 (15 °C) | 101 | 1.45 | 0.038 |
| 1,4-Dichlorobenzene (DCB) | 147.0 | 49 (22 °C) | 8.1 | 3.38 | 0.117 |
| Nitrobenzene (NB) | 123.1 | 1 900 (20 °C) | 3.3 | 1.85 | 0.00046 |
| 2-Nitrophenol (NP) | 139.1 | 2 100 (20 °C) | 2.54 | 1.76 | 0.0032 |
| Naphthalene (NAP) | 128.2 | 26.2 (20 °C) | 2.5 | 3.37 | 0.015 |
| 2,4-Dichlorophenol (DCP) | 163.0 | 4 500 (20 °C) | 1.9 | 2.75 | 0.0017 |
| 1,2,4-Trichlorobenzene (TCB) | 181.5 | 19 (22 °C) | 3.3 | 4.04 | 0.216 |
| Lindane (LIN) | 290.9 | 17 (24 °C) | 0.17 | 3.72 | 0.0 |
| Dieldrin (DIE) | 381.0 | 0.1 | 2.39×10^{-5} (25 °C) | – | 0.0 |
| <i>bis</i> (2-ethylhexyl)Phthalate (BEHP) | 391.0 | 0.285 (24 °C) | 0.0002 | 5.2 | 0.0 |
| Hexachlorobenzene (HCB) | 284.8 | 0.11 (24 °C) | 133 (114.4 °C) | 5.61 | 0.0 |

^a From Callahan et al. [9] and Verschuere [33].^b Henry's law constant is the ratio between gas phase concentration and liquid phase concentration.

County Sanitation Department after shredding at the Buford Highway Pulverization Plant in Atlanta, GA. The refuse is characterized in Table 2.

The 3.0-m deep pilot-scale lysimeter was constructed of 0.9-m diameter steel sections. Approximately 380 kg (wet weight) of shredded municipal refuse were placed in the column to a depth of 1.9 m. Organic test compounds were placed 30 cm above the bottom of the column. Loading for each compound except DIE was approx. 2.2 mg compound/g dry refuse. DIE was loaded at approx. 0.5 mg/g. A second column, operated in parallel and containing municipal refuse but no test compounds, served as a control.

After loading and sealing the column, water addition began in order to bring the column to field capacity. Once leachate production was initiated, the column received regular water additions totalling 1637 l over a 1500-day period. Leachate was sampled every 3 weeks for analysis

TABLE 2

Characterization of refuse

| | |
|---------------------------------|------|
| Refuse density, g/ml | 0.69 |
| Ash, percent dry weight | 31.3 |
| Lipids, percent dry weight | 4.6 |
| Elemental analysis ^a | |
| Nitrogen, percent dry weight | 2.2 |
| Carbon, percent dry weight | 58.7 |
| Hydrogen, percent dry weight | 8.6 |

^a Ash-free basis

of test compounds. Gas produced during biodegradation of refuse was vented through a metering device and sampled and analysed monthly.

A laboratory-scale column was also employed to evaluate the fate of test compounds under conditions which minimized biodegradation, thus permitting independent evaluation of physical/chemical transport phenomena. A Kimax[®] glass drain pipe (7.6-cm inside diameter) was used for column construction and packed with 358 g (wet weight) of refuse to a depth of 30 cm. Refuse was dried at 103 °C, ground to approx. 3 mm in diameter, and autoclaved at 120 °C at 103 kPa for 1 min to minimize biological activity.

Pore volume was approx. 850 ml. Glass reducers (7.6 cm to 2.5 cm) fitted with Teflon[®] plugs were used as end caps. End caps were clamped to the glass pipe and sealed with gas-tight Teflon[®] gaskets. Refuse was packed between perforated Teflon end plates to distribute flow. Teflon collars were placed at one-third depths to prevent short-circuiting down the column walls. The bottom cap was filled with glass wool. Teflon[®] tubing and fittings permitted water addition and drainage and gas headspace sampling. The column was placed in a dark, constant temperature room at 20 °C.

Pre-weighted samples of test compounds (at loadings equivalent to those of the pilot-scale column) were placed on the top of the refuse layer without solvent. Solid test compounds were ground to a powder prior to placement. After the test compounds had been inserted, a layer of glass beads was added for flow distribution, the column

was sealed and purged with dry nitrogen gas to displace oxygen. Some loss of volatile compounds occurred during this procedure.

Deaerated organic-free water (160 ml) was added to the column each day for 120 days. Water was introduced in a single application and allowed to percolate in an unsaturated mode down the column and to collect in the bottom end fittings to be drained on the following day. Feed water was organic-free water buffered with a 0.01 N acetate solution. Feed water chemical oxygen demand (COD) averaged 490 mg/l (range 339 to 560 mg/l). Leachate was analysed three times per week for test compounds, headspace gas was analysed weekly.

At the completion of column leaching operations, the columns were disassembled and the contents removed and sectioned. Each section was thoroughly mixed, and a representative sample of approx. 10 g was placed in a cellulose thimble in a Soxhlet extractor and extracted with methylene chloride for 24 h. The extract was concentrated to approx. 1 ml and analysed for test organic compounds in a Hewlett Packard gas chromatograph, Model 5830A equipped with a flame ionization detector (FID).

Methyl chloride extraction and concentration of leachate samples followed procedures provided in EPA Test Methods 624/625 [31]. Test organic compounds in pilot-scale column leachates were analysed using a Hewlett Packard Gas Chromatograph (GC) Model 5711A interfaced with a Finnigan Model 4023 Mass Spectrometer and Data System. For laboratory-scale column non-volatile leachate constituents, a Hewlett

Packard GC, Model 5830A and FID was used. For laboratory-scale volatile leachate compounds and pilot and laboratory-scale gas analysis, a Perkin-Elmer Sigma 1 Analyzer GC equipped with an FID was used.

RESULTS AND DISCUSSION

Disposition of test organic compounds is summarized in Table 3 for laboratory and pilot-scale columns.

Test compound volatilization

Only compounds with Henry's Law Constants greater than 0.04 (DBM, TCE, DCB, and TCB) were observed in laboratory-scale column headspaces. In addition to these compounds, NAP and NP were detected on occasion at trace levels in pilot-scale test column gases. Volatilization and gas stripping for both laboratory and pilot-scale columns proved to be minor pathways for test compounds. With the exception of TCE in the laboratory-scale column, less than 1% of compound mass was transported from the columns via the gas phase. Approximately 20% of TCE was volatilized from the laboratory-scale column. Vinyl chloride, a known TCE degradation product [4], was consistently detected in pilot-scale test column gas during the study. TCE biodegradation may account for differences in TCE volatilization observed between laboratory and pilot-scale columns.

Test compound leaching

Only soluble, less hydrophobic test compounds were eluted from the laboratory and pilot-scale columns during

TABLE 3

The fate of test organic compounds in laboratory and pilot-scale columns

| Compound | Volatilized (%) | | Leached (%) | | Retained (%) | | Transformed (%) Pilot ^a |
|----------------------------|-----------------|-------|-------------|-------|--------------|-------|---------------------------------------|
| | Laboratory | Pilot | Laboratory | Pilot | Laboratory | Pilot | |
| Dibromomethane | 0.6 | <0.1 | 99.4 | 27.4 | ND | ND | 72.6 |
| Trichloroethene | 17.2 | 0.1 | 82.8 | 14.6 | ND | ND | 85.4 |
| Nitrobenzene | ND ^b | ND | 99.9 | <0.1 | 0.1 | ND | 99.8 |
| 2,4-Dichlorophenol | ND | ND | 31.3 | 11.7 | 68.7 | 5.3 | 83.0 |
| 1,4-Dichlorobenzene | 0.8 | <0.1 | 2.2 | 2.5 | 97.0 | 54.0 | 43.5 |
| Naphthalene | ND | <0.1 | ND | 1.3 | 100.0 | 59.5 | 39.2 |
| 1,2,4-Trichlorobenzene | ND | <0.1 | ND | 0.1 | 100.0 | 57.9 | 42.0 |
| 2-Nitrophenol | ND | <0.1 | 99.9 | <0.1 | 0.1 | ND | 99.9 |
| Lindane | ND | ND | ND | ND | 100.0 | 81.2 | 18.8 |
| Hexachlorobenzene | ND | ND | ND | ND | 100.0 | 97.7 | 3.3 |
| bis(2-ethylhexyl)Phthalate | ND | ND | ND | ND | 100.0 | ND | 100.0 |
| Dieldrin | ND | ND | ND | ND | 100.0 | ND | 100.0 |

^a It is assumed that mass not leached, retained, or volatilized was transformed.

^b Not detected.

the duration of the study, including DBM, TCE, NB, NP, and DCP. The typical behavior of these mobile compounds for the laboratory-scale column is shown in Fig. 1. Because of apparent biodegradation, these compounds were detected in the pilot-scale column at much lower concentrations (less than 10 mg/l). The compounds were eluted from laboratory and pilot-scale columns in the same order and appeared in the leachate at about the same time relative to pore volume additions. With the exception of DCP, leaching from the laboratory-scale column was the primary fate pathway for these compounds.

Leachate concentration for TCE, DBM, NP, and NB was observed to rapidly decline following appearance in pilot-scale columns, coinciding with the onset of reducing conditions, as indicated by negative ORP. Probable transformation products were detected shortly after reduction in the concentration of DBM and TCE occurred. Bromide, a probable daughter product of DBM [34], was found in pilot-scale column leachate but was absent in control column leachates. As mentioned previously, vinyl chloride, a recognized daughter product of anaerobic transformation of TCE, was found in test column gases (but again, absent from the control column). It should be pointed out that biotransformation of TCE yielded a more mobile and toxic byproduct.

Mineralization of nitroaromatics, NP and NB, requiring aromatic ring cleavage, is reported to be strongly inhibited under reducing conditions [22]. Because of the nitro-group, the aromatic ring has a low electron density and is resistant to electrophilic attack. The reduction of the aryl nitro-group to the amine group, however, has been widely observed for a variety of compounds [21,22]. While leachates were not examined specifically for potential NP or NB transformation products, it is likely that the

disappearance of these mobile compounds soon after reducing conditions were established was a result of the reduction of the aryl nitro-group. The resulting aryl amine has been reported to rapidly react with carbonyl and quinone moieties commonly found in humic substances [25], and may have been retained in the landfill in that form.

The degradation of chlorophenols through reductive removal of aryl halogens followed by mineralization of the aromatic moiety mediated by microorganisms contained in sewage sludges, pond sediments, and methanogenic aquifers has been observed by several investigators [6,13,16,18,20,24]. Mono-halogenated phenolic compounds have been detected on occasion in the pilot-scale test column, suggesting that dehalogenation of DCP has been occurring.

Sorption of test compounds

Mobile test compounds were eluted from the columns in the approximate order of increasing affinity for the refuse. Affinity can be quantified using linear solid-liquid partition coefficients experimentally derived from sorption isotherms for the test compounds on refuse [27]. These coefficients were found to be positively correlated with the octanol-water partition coefficient for each compound, a measure of compound hydrophobicity (correlation coefficient of 0.97 for a log-log relationship). Using the experimental partition coefficients (provided in Table 4), the expected retardation relative to water velocity for each compound can be predicted using Equation 1.

$$\text{Retardation factor} = 1 + \rho K_p / \Theta_w \quad (1)$$

where: K_p , linear solid-liquid partition coefficient, ml/g; ρ , bulk density, g/ml; and Θ_w , water content (fraction).

Table 4 compares experimental and predicted retardation factors for mobile compounds in the laboratory-scale

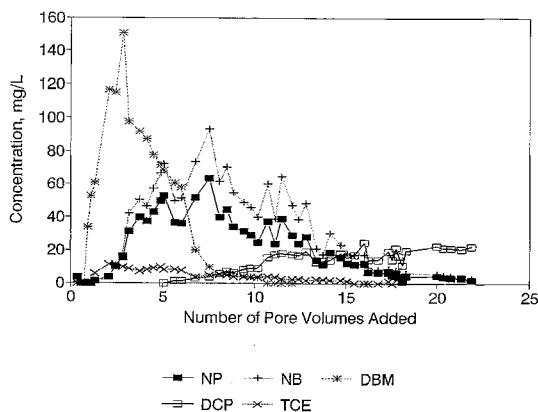


Fig. 1. Concentration of mobile test organic compounds 2-nitrophenol (NP), nitrobenzene (NB), dibromomethane (DBM), 2,4-dichlorophenol (DCP), and trichloroethene (TCE) in pilot-scale column leachate.

TABLE 4

Retardation factors for test organic compounds leached from laboratory-scale columns

| Compound | Partition coefficient K_p , ml/g | Retardation factors | |
|-----------------|---------------------------------------|-------------------------|-----------------------|
| | | Calculated ^a | Measured ^b |
| Dibromomethane | 7.24 | 4.8 | 3.2 |
| Nitrobenzene | 17.4 | 10.0 | 8.1 |
| 2-Nitrophenol | 29.5 | 16.3 | 7.7 |
| Trichloroethene | 36.3 | 19.0 | 6.0 |

^a From equation 1.

^b Number of pore volumes added when mass centroid of transport curve was reached.

column. Predicted and experimental values are within a factor of two for all compounds except TCE. The predicted retardation factor does not account for gas phase transport, and therefore, underestimates TCE mobility. In addition, TCE volatility, and subsequent transport in the gas phase, promotes dispersion of TCE, resulting in a broader transport curve as seen in Fig. 1.

At the completion of column testing, the contents of the column were examined for retained test compounds. The more mobile, hydrophilic compounds were not detected in pilot-scale column refuse extractions, providing supporting evidence of biotransformation. Sectioning of laboratory-scale columns was sufficient to reveal chromatographic effects of leaching on the compounds retained, shown in Fig. 2. As would be expected from their hydrophobic nature (high octanol-water partition coefficients), DIE, HCB, and BEHP were still highly concentrated at the top of the columns. LIN, TCB, and NAP exhibited slight movement down the columns, DCB was distributed throughout the column, and DCP had moved far enough down the column to appear in the leachate.

With the exception of DCP, these hydrophobic compounds were not detected at significant concentration in pilot-scale column leachate during the 4 years of operation. Approximately 50% of DCB, TCB, and NAP was recovered from the refuse at the completion of leaching. Nearly 100% of HCB and 80% of LIN was recovered while BEHP and DIE were not detected in refuse extractions.

The solid phase demonstrated strong affinity for extremely hydrophobic compounds (log octanol-water partition coefficients greater than three). As a result, the opportunity for biotransformation and ultimate mineralization by acclimated microbial agents was enhanced. While analysis of biodegradation products of these hydro-

phobic compounds was not conducted, anaerobic biodegradation pathways are known to exist for BEHP [17], LIN [2,8,12,15] and DIE [21] and DCP [20]. TCB and DCB, however, have been found to resist degradation under anaerobic conditions [5], as has NAP [3,23]. Degradation of HCB under anaerobic conditions has been reported by Fathepure [11].

SUMMARY AND CONCLUSIONS

The co-disposal of 12 compounds representing major organic compound classes with shredded municipal solid waste was investigated. Transport and transformation phenomena including sorption, volatilization, and bio-assimilation were investigated. The results demonstrated the capacity of a municipal solid waste landfill to attenuate and/or assimilate a variety of organic compounds.

Volatilization for test compounds proved to be a minor transport pathway. Mobile, more hydrophilic compounds, including dibromomethane, trichloroethene, 2-nitrophenol, and nitrobenzene, were assimilated in the pilot-scale column, apparently via biotransformation. In the case of dibromomethane and trichloroethene, the detection of daughter products confirmed this pathway. More hydrophobic compounds, including 2,4-dichlorobenzene, 1,2,4-trichlorobenzene, naphthalene, lindane, dieldrin, *bis*(2-ethylhexyl)phthalate, and hexachlorobenzene, were retained within the columns associated with the solid phase. Such retention and consequential delayed migration enhances the in situ attenuating and assimilative capacity of a landfill and affords greater opportunity for more complete biological and chemical degradation of otherwise recalcitrant constituents. Transformation of DCB, TCB, NAP, LIN, BEHP, and DIE may have occurred during pilot-scale lysimeter testing.

Although many organic compounds may be attenuated and subjected to in situ assimilation, it may be inappropriate to place other materials in municipal landfills, such as extremely volatile organic compounds or compounds which may be transformed into more mobile and toxic daughter products. To avoid the ultimate escape of organic pollutants into the environment, a landfill must be operated to optimize the biological stabilization process, to minimize excessive leachate generation, and to isolate the landfill from the groundwater by proper site selection, site preparation, leachate and gas management, liner use, and post-closure procedures which may include the ultimate removal of accumulated leachate. Leachate recycle should be considered in this strategy because of its ability to retain mobile compounds and distribute nutrients until biodegradation is efficiently established.

In conclusion, the results of this investigation provided important insight regarding the fate and behavior of

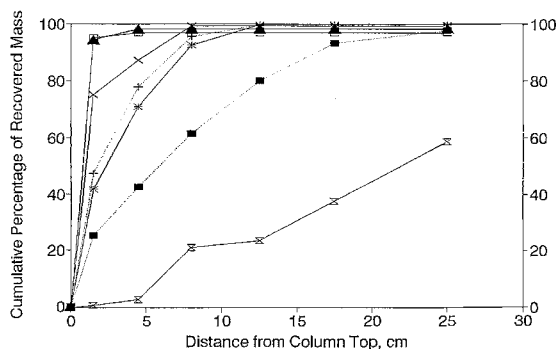


Fig. 2. Refuse concentration profiles of test organic compounds: 2,4-dichlorophenol (DCP), 1,4-dichlorobenzene (DCB), 1,2,4-trichlorobenzene (TCB), naphthalene (NAP), lindane (LIN), hexachlorobenzene (HCB), *bis*(2-ethylhexyl)phthalate (BEHP), and dieldrin (DIE) placed in laboratory-scale column.

organic compounds disposed in municipal solid waste landfills. Such knowledge is useful in developing landfill management and operational strategies consistent with the need for control of pollutant releases and for protection against adverse health and environmental impacts.

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