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Draft Physical Chemistry, Fate, and Transport Assessment for Diethylhexyl Phthalate (DEHP)

Technical Support Document for the Draft Risk Evaluation
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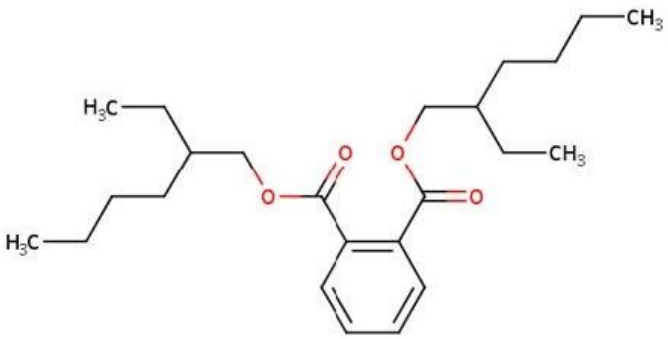

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ABBREVIATIONS AND ACRONYMS

A/O	Anaerobic/oxic
AS	Activated sludge
BAF	Bioaccumulation factor
BBP	Butyl Benzyl Phthalate
BCF	Bioconcentration factor
BMF	Biomagnification factor
BOD	Biological oxygen demand
BSAF	Biota-sediment accumulation factor
CASRN	Chemical Abstracts Service Registry Number
CDR	Chemical Data Reporting
CFR	Code of Federal Regulations
CTD	Characteristic travel distance
DBP	Dibutyl phthalate

114	DCHP	Dicyclohexyl phthalate
115	DEHP	Di-ethylhexyl phthalate
116	DEP	Diethyl phthalate
117	DIBP	Di-isobutyl phthalate
118	DINP	Di-isononyl phthalate
119	DMP	Dimethyl phthalate
120	DMR	Discharge Monitoring Reports
121	DMSO	Dimethylsulfoxide
122	DPE	Diphthalate ester
123	DRE	Destruction and removal efficiency
124	dw	Dry weight
125	EC50	Effect concentration at which 50 percent of test organisms exhibit an effect
126	ECHA	European Chemicals Agency
127	ECJRC	European Commission, Joint Research Centre
128	EPI	Estimation Programs Interface
129	FR	Federal register
130	HCl	Hydrochloric acid
131	HPLC	High performance liquid chromatography
132	HLC	Henry's Law constant
133	HOAc	Acetic acid
134	JNU	Jawaharlal Nehru University
135	Km	Maximum specific uptake rate (Monod kinetics)
136	LC50	Lethal concentration at which 50 percent of test organisms die
137	LOD	Limit of detection
138	Log K_{AW}	Logarithmic air:water partition coefficient
139	Log K_{OA}	Logarithmic octanol:air partition coefficient
140	Log K_{OC}	Logarithmic organic carbon:water partition coefficient
141	Log K_{OW}	Logarithmic octanol:water partition coefficient
142	Log K_{SW}	Logarithmic soil:water partition coefficient
143	LOQ	Limit of quantification
144	LRTP	Long-range transport potential
145	MDL	Method detection limit
146	NaOAc	Sodium acetate
147	NaOH	Sodium hydroxide
148	ND	Non-detect/not detected
149	NITE	National Institute of Technology and Evaluation
150	OC	Organic carbon
151	OCSPP	Office of Chemical Safety and Pollution Prevention
152	OECD	Organisation for Economic Co-operation and Development
153	OPPT	Office of Pollution Prevention and Toxics
154	·OH	Hydroxyl radical
155	PAE	Phthalate acid ester
156	POTW	Publicly owned treatment works
157	PVB	Polyvinyl butyral
158	PVC	polyvinyl chloride
159	QSPR	Quantitative structure-property relationship
160	SCAS	semi-continuous activated sludge system
161	SPM	Suspended particulate matter
162	SRC	Syracuse Research Corporation

$t_{1/2}$	Half-life
TCLP	Toxicity Characteristic Leaching Procedure
TMF	Trophic magnification factor
TOC	Total organic carbon
TRI	Toxics Release Inventory
TSCA	Toxic Substances Control Act
UV	Ultraviolet
ww	Wet weight
WWTP	Wastewater treatment plant

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Docket

Supporting information can be found in the public docket, Docket ID EPA-HQ-OPPT-2018-0433.

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Summary

The U.S. Environmental Protection Agency (EPA or the Agency) gathered and evaluated physical and chemical property data and information according to the process described in the Draft Protocol for Systematic Review in TSCA Risk Evaluations (U.S. EPA, 2021a). During the evaluation of di(2-ethylhexyl) phthalate (DEHP), EPA considered both measured and estimated physical and chemical property data/information summarized in Table 2-1, as applicable. *Draft Risk Evaluation for Di(2-ethylhexyl) phthalate (DEHP) – Systematic Review Supplemental File: Data Quality Evaluation and Data Extraction Information for Physical and Chemical Properties* (U.S. EPA, 2024a).

DEHP is liquid with a mild aromatic odor used as a plasticizer in the production of plastics, adhesives, rubber, and resins (NLM, 2015a). DEHP is a medium-chained branched phthalate ester with the chemical equation $C_{24}H_{38}O_4$ and a molar mass of 390.56 g/mol (NLM, 2015a). It is liquid at standard environmental temperatures and conditions and is insoluble in water with a water solubility of 0.003 mg/L in water (Elsevier, 2021). DEHP has a melting point of −55 °C, boiling point of 384 °C, and Henry's Law constant of 9.87×10^{-6} atm·m^3/mol at 25 °C (Cousins and Mackay, 2000).

1 INTRODUCTION

DEHP is a member of the phthalate class of chemicals and is mainly used as a plasticizer of polyvinyl chloride (PVC) and other polymers. DEHP is typically formed via the esterification of phthalic anhydride and 2-ethylhexanol. To be able to understand and predict the behaviors and effects of DEHP in the environment, its physical and chemical properties, and environmental fate and transport parameters are examined in the remainder of the technical support document.

DEHP is produced by the esterification of phthalic anhydride with 2-ethylhexanol. Typical technical grade DEHP is at least 99.0 to 99.6 percent pure (by ester content), with 0.1 percent maximum moisture content and 0.007 to 0.01 percent acidity (as acetic acid or phthalic acid) (NTP, 2021). Purity of DEHP from commercial manufacture is greater than 99 percent, with the remaining fraction comprised of isophthalic acid, terephthalic acid, and maleic acid as impurities (CPSC, 2010). The following sections discuss the selection of the physical and chemical properties of DEHP.

2 PHYSICAL AND CHEMICAL PROPERTY ASSESSMENT OF DEHP

2.1 Evidence Integration for Physical and Chemical Properties

Due to the relative availability of data, only studies with an overall data quality ranking of high were selected for use in determining the representative physical and chemical properties of DEHP for the purposes of the risk evaluation. Compared to other phthalate esters undergoing risk evaluations under TSCA, DEHP is a relatively data rich chemical, and studies with an overall data quality ranking of high were chosen to represent the best available data.

2.2 Final Selected Physical and Chemical Property Values for DEHP

Table 2-1. Final Selected Physical and Chemical Property Values for DEHP

Property	Selected Value	Reference	Overall Quality Determination
Molecular formula	C_{24} H_{38} O_4		
Molecular weight	390.56 g/mol		
Physical form	Liquid	Rumble (2018b)	High
Melting point	−55 °C	Rumble (2018b)	High
Boiling point	384 °C	Rumble (2018b)	High
Density	0.981 g/cm^3	Rumble (2018b)	High
Vapor pressure	1.42E-07 mmHg	NLM (2015a)	High
Water solubility	0.003 mg/L	EC/HC (2017) NTP (2000b) Elsevier (2021)	High
Octanol:water partition coefficient (log K_{OW})	7.60	NLM (2015a)	High
Octanol:air partition coefficient (log K_{OA})	10.76 (EPI Suite™)	U.S. EPA (2017)	High
Henry's Law constant	9.87E-06 atm·m^3/mol at 25 °C	Cousins and Mackay (2000)	High
Flash point	206 °C	O'Neil (2013a)	High
Autoflammability	390 °C	NIOSH (1988)	High
Viscosity	57.94 cP	Mylona et al. (2013)	High

2.3 Endpoint Assessments

2.3.1 Autoflammability

The EPA extracted and evaluated four sources containing DEHP flammability information. The selected source was determined to be of high quality with a reported DEHP flammability of 390 °C (NIOSH, 1988). Due to the limited number of high-quality data available, the EPA selected an autoflammability value of 390 °C as the representative value for the available flammability information (NIOSH, 1988). An autoflammability value was not selected in the Final Scope for the Risk Evaluation of DEHP (U.S.

EPA, 2021b).

2.3.2 Melting Point

The EPA extracted and evaluated 24 sources containing DEHP melting point information. Fifteen of the sources were identified and evaluated as overall high-quality data sources. The overall high-quality sources reported DEHP melting points ranging from –58 to –46 °C (NIOSH, 2019; U.S. EPA, 2019; DOE, 2016; NLM, 2015a; ECHA, 2012; OEHHA, 2011; NIOSH, 2007; Mitsunobu and Takahashi, 2006; EFSA, 2005; Park and Sheehan, 2000; NTP, 1992). U.S. EPA selected a melting point value of –55 °C (Rumble, 2018b) as a representative value of the available information obtained from the overall high-quality data sources. In addition, the selected value is consistent with the value selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b).

2.3.3 Boiling Point

The EPA extracted and evaluated 29 data sources containing DEHP boiling point information. Fifteen of the sources were identified and evaluated as overall high-quality data sources. The overall high-quality sources reported DEHP boiling points ranging from 230 to 384 °C (NIOSH, 2019; U.S. EPA, 2019; Rumble, 2018a; DOE, 2016; NLM, 2015a; ECHA, 2012; OEHHA, 2011; Rossol et al., 2009; NIOSH, 2007; EFSA, 2005; Park and Sheehan, 2000; NTP, 1992). EPA selected a boiling point value of 384 °C (Rumble, 2018b) as a representative value under normal environmental conditions within the available information obtained from the overall high-quality data sources, as these studies were conducted in a manner which would accurately measure boiling point under normal environmental temperatures and pressures. In addition, the selected value is consistent with the value selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b).

2.3.4 Density

The EPA extracted and evaluated 21 data sources containing DEHP density information. Ten of the sources were identified and evaluated as overall high-quality data sources. The overall high-quality sources reported DEHP density values ranging from 0.97 to 0.986 g/cm^3 (NCBI, 2020b; ECHA, 2016; NLM, 2015b; O'Neil, 2013b; NTP, 2003; ExxonMobil, 2001; De Lorenzi et al., 1998). EPA selected a density of 0.981 g/cm^3 (Rumble, 2018b) for the density of DEHP within the available information obtained from the overall high-quality data sources. In addition, the selected value is consistent with the value selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b).

2.3.5 Vapor Pressure

The EPA extracted and evaluated 28 data sources containing DEHP vapor pressure information. Eighteen of the sources were identified and evaluated as overall high-quality data sources. The overall high-quality sources reported DEHP vapor density values ranging from 1.42×10^{-7} to less than 0.01 mmHg (Elsevier, 2021; NIOSH, 2019; U.S. EPA, 2019; Rumble, 2018a; DOE, 2016; NLM, 2015a; O'Neil, 2013a; ECHA, 2012; OEHHA, 2011; Lu, 2009; NIOSH, 2007; Mitsunobu and Takahashi, 2006; Price, 2001; NTP, 2000a; NIOSH, 1988; Howard et al., 1985). EPA selected a vapor pressure value of 1.42×10^{-7} mmHg (NLM, 2015a) as a representative value of the available information obtained from the overall high-quality data sources under normal environmental conditions. In addition, the selected value is consistent with the value selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b).

2.3.6 Vapor Density

The EPA extracted and evaluated two data sources containing DEHP vapor pressure information. Two of the sources were identified and evaluated as overall high-quality data sources. The overall high-

quality sources reported DEHP vapor density value of 16 in two high-quality studies (NLM, 2015a; NIOSH, 1988). U.S. EPA selected a vapor density value of 16 (NLM, 2015a) as a representative value of the available information obtained from the overall high-quality data sources. In addition, the selected value is consistent with the value selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b).

2.3.7 Water Solubility

The EPA extracted and evaluated 44 data sources containing DEHP water solubility information. Twenty-one of the sources were identified and evaluated as overall high-quality data sources. The overall high-quality data sources identified water solubility values for DEHP ranging from 0.00006 mg/L at 12 °C to 0.4 mg/L at 25 °C (Mitsunobu and Takahashi, 2006; Boese, 1984). The large range of values available in the literature is likely due to the tendency of phthalate esters to form colloidal suspensions in water, leading to erroneously high measurements of DEHPs aqueous solubility via methods such as slow-stir, or shake flask water solubility tests. The EPA selected a representative non-colloidal water solubility of 0.003 mg/L for DEHP (Elsevier, 2021) for use in the risk assessment. This value was chosen to represent the range of non-colloidal water solubilities extracted from numerous data sources and is also the most commonly cited representative value for the non-colloidal water solubility of DEHP in all of the extracted primary and secondary data sources. This water solubility was chosen to better represent the distribution of DEHP in the environment and aqueous media.

2.3.8 Log Octanol/Water Partitioning Coefficient

The EPA extracted and evaluated 13 data sources containing DEHP octanol-water partitioning coefficient information from 30 studies. Eight of the sources were identified and evaluated as overall high-quality data sources. The overall high-quality sources reported DEHP log K_{OW} ranging from 6.69 to 8.66 (Elsevier, 2021; U.S. EPA, 2019; EC/HC, 2017; NLM, 2015a; ECHA, 2012; NTP, 2000b; Verbruggen et al., 1999; Mueller and Klein, 1992). EPA selected a measured log K_{OW} value of 7.60 (NLM, 2015a) for use in the risk evaluation, as it was the only measured value cited in the above studies. The selected value is consistent with the value selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b).

2.3.9 Log Octanol/Air Partitioning Coefficient

No data are available in the current literature pertaining to the octanol-air partitioning coefficient of DEHP. With no available data, EPA estimated a representative octanol/air partitioning coefficient of 10.76 via EPI Suite™ for use as the representative log K_{OA} value for DEHP (U.S. EPA, 2017).

2.3.10 Henry's Law Constant

The Henry's Law constant (HLC) selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b) was a value calculated in EPI Suite™ from the vapor pressure and water solubility of DEHP and was 2.08×10^{-5} atm·m^3/mole at 25 °C (U.S. EPA, 2012a). One overall high-quality data source was identified during the systematic review process. This measured value was chosen to best represent the HLC over the modeled values presented in the scoping document. The EPA selected a HLC value of 9.87×10^{-6} atm·m^3/mol at 25 °C (Cousins and Mackay, 2000) for this risk evaluation. DEHP is considered a semi-volatile organic compound (SVOC).

2.3.11 Flashpoint

The EPA extracted and evaluated five data sources containing DEHP flashpoint information. Three of the sources were identified and evaluated as overall high-quality data sources. The overall high-quality sources reported DEHP flash points ranging from 206 to 218 °C (Elsevier, 2021; O'Neil, 2013a; NIOSH, 2007; Bonnevie and Wenning, 1995; NIOSH, 1988). EPA selected a flashpoint value of 206 °C (O'Neil,

2013a) as a representative value of the available information obtained from the overall high-quality data sources under normal environmental conditions. The selected value is consistent with the value selected in the Final Scope for the Risk Evaluation of DEHP (U.S. EPA, 2021b).

2.3.12 Viscosity

The EPA extracted and evaluated two data sources containing DEHP viscosity information. The sources identified and evaluated received an overall high-quality data ranking. The selected value for the viscosity of DEHP is 57.94 cP at 25 °C (U.S. EPA, 2021b; Mylona et al., 2013).

2.4 Strengths, Limitations, Assumptions, and Key Sources of Uncertainty for the Physical and Chemical Property Assessment

Due to the water solubility of DEHP and its tendency to form colloidal suspensions in water, certain physical and chemical properties may be difficult to measure experimentally (water solubility, octanol/water partitioning coefficient, organic carbon partitioning coefficients) with traditional guideline tests. The representative physical and chemical values were selected based on professional judgement and the overall data quality ranking of the associated references. In some instances where no data were available, or there was a wide range of data that generally, but did not consistently agree with one another, models such as EPI Suite™ were used to estimate the value for the endpoint (octanol-water partitioning coefficient and organic carbon-water partitioning coefficient) and cross checked with reported data from systematic review.

3 APPROACH AND METHODOLOGY FOR FATE AND TRANSPORT ASSESSMENT

DEHP – Environmental Fate and Transport:
Key Points

EPA evaluated the reasonably available information to characterize the environmental fate and transport of DEHP, the key points are summarized below.

Given the consistent results from numerous high-quality studies, there is robust evidence that DEHP:

- is expected to have environmental biodegradation half-life in aquatic aerobic environments on the order of days to weeks (Section 0);
- is not expected to appreciably hydrolyze under environmental conditions (Section 4.2);
- is expected to degrade rapidly via direct and indirect photolysis (Section 4.3);
- is not expected to be subject to long range transport;
- is expected to show strong affinity and sorption potential for organic carbon in sediment and soil (Sections 6.2.2 and 6.3.1);
- will be removed at rates greater than 85 percent in conventional wastewater treatment systems (Section 7.2);
- will show strong affinity for adsorption to particulate matter and will not likely exist in gaseous phase when released to air (Sections 5.1 and 6.1); and
- is likely to be found, and accumulate, in indoor dust (Section 6.1.1).

As a result of limited studies identified, there is moderate confidence that DEHP:

- is expected to be removed in conventional drinking water treatment systems both in the treatment process, and via reduction by chlorination and chlorination byproducts in post treatment storage and drinking water conveyance (Section 7.3); and
- is not expected to be bioaccumulative in fish in the water column or benthic organisms exposed to sediment with elevated concentrations of DEHP (Section 8).

Reasonably available environmental fate and transport data—including biotic and abiotic biodegradation rates, removal during wastewater treatment, volatilization from lakes and rivers, and organic carbon-water partition coefficient (log K_{OC})—are the parameters used for the fate and transport assessment of the current draft risk evaluation. Information on the full extracted data set is available in the supplemental file *Draft Risk Evaluation for Di-ethylhexyl Phthalate (1,2-Benzenedicarboxylic acid, 1,2-bis(2-ethylhexyl) ester) (DEHP) – Systematic Review of Data Quality Evaluation and Data Extraction Information for Environmental Fate and Transport* (U.S. EPA, 2024b). Supportive fate estimates were based on modeling results from EPI Suite™ (U.S. EPA, 2012a), a predictive tool for physical and chemical properties and environmental fate estimation. Information regarding the model inputs is available in Section 3.1.

These were updated with additional information identified through the systematic review process after publication of the *Final Scope for the Risk Evaluation for Di-ethylhexyl Phthalate (1,2-Benzenedicarboxylic acid, 1,2-bis(2-ethylhexyl) ester) (DEHP) CASRN: 117-81-7* (U.S. EPA, 2021b).

3.1 EPI Suite™ Model Inputs and Settings

The approach described by Mackay (1996) using the Level III Fugacity model in EPI Suite™ (LEV3EPI™) was used for this Tier II analysis. LEV3EPI™ is described as a steady-state, non-equilibrium model that uses a chemical's physical and chemical properties and degradation rates to predict partitioning of the chemical between environmental compartments and its persistence in a model environment (U.S. EPA, 2012a). Environmental release information is useful for fugacity modeling because the emission rates will refine the fugacity model to more accurately predict a real-time percent mass distribution for each environmental medium. Environmental degradation half-lives were taken from high- and medium-quality studies that were identified through systematic review to reduce levels of uncertainties. The results of the Level III Fugacity modeling are presented and discussed in Section 5.2.

The following inputs parameters were used for the Level III Fugacity model in EPI Suite™:

- Melting point = –55 °C
- Vapor pressure = 1.42×10^{-7} mmHg
- Water solubility = 0.003 mg/L
- Log K_{OW} = 7.60
- SMILES: O=C(OCC(CCCC)CC)c(c(ccc1)C(=O)OCC(CCCC)CC)c1

4 TRANSFORMATION PROCESSES

Biodegradation pathways for the phthalates consist of primary biodegradation from phthalate diesters to phthalate monoesters, then to phthalic acid, and ultimately biodegradation of phthalic acid to form carbon dioxide (CO_2) and/or methane (CH_4) {Huang, 2012, 1597688}. The monoester phthalates are also expected to undergo biodegradation more rapidly than the diester form. The transformation products and degradants will not be considered in this fate and transport assessment as they are not expected to be as persistent as DEHP in environmental media. Both biotic and abiotic routes of degradation for DEHP are described in the following sections below.

4.1 Biodegradation

DEHP can be considered readily biodegradable under most aquatic and terrestrial environmental conditions. To determine the biodegradation potential of DEHP, EPA evaluated 38 data sources with overall quality determinations of high or medium containing biodegradation information in water, soil, and sediments under aerobic and anaerobic conditions (Table 4-1).

4.1.1 Biodegradation in Water

The aerobic primary biodegradation of DEHP in water has reported to be greater than 90 percent over 2 to 5 days in activated sludge (EC/HC, 2015a), 68.1 to 73.5 percent over 7 days in river water (Hashizume et al., 2002), 70 to 78 percent over 28 days in activated sludge (Monsanto, 1976), and greater than 99 percent over 28 days in acclimated activated sludge (SRC, 1983). Reported half-lives range from less than 5 days in activated sludge to less than 7 days in river water (Fujita et al., 2005). An additional study found no biodegredation over 20 days when using a microbial inoculum from a petrochemical waste treatment plant (Union Carbide, 1974). It was also found that biodegradation of DEHP in water using an activated sludge inoculum required gradual acclimation, with the unacclimated inoculum degrading 0 percent and the fully acclimated inoculum degrading 93 to 95 percent over 28 days (Tabak et al., 1981).

EPA identified seven studies that evaluated the ready biodegradability of DEHP in water using OECD guideline methods. Five of those studies reported that it passed the 10-day ready biodegradability test with losses of 55 to 86.16 percent over 28 to 29 days (NCBI, 2020a; EC/HC, 2015a; Scholz et al., 1997). Two studies using OECD guideline methods found that it did not pass the 10-day ready biodegradability test, reporting loses of 4 to 5 percent (EC/HC, 2015a) and 58.7 percent (Stasinakis et al., 2008) over 28 days. Additional non-OECD guideline die-away tests found that approximately 62 percent of DEHP was biodegraded over 5 weeks using river water (Saeger and Tucker, 1976) and calculated a half-life of 0.46 days using an acclimated activated sludge inoculum (SRC, 1984). A non-OECD guideline study also found that filtration of river water prior to a die-away test decreased biodegredation from 11 to 78 percent to 4 to 28 percent over 32 to 34 days (Wylie et al., 1982). The authors hypothesized that the presence of suspended solids in the unfiltered samples helped to facilitate biodegradation.

The ultimate biodegradation rate of DEHP in aerobic water has been reported to be 85.5 percent over 28 days using an inoculum of soil, activated sludge, and raw wastewater (SRC, 1983); 34.9 to 71.2 percent over 40 days using an inoculum of activated sludge (Subba-Rao et al., 1982); 66 percent over 96 hours using an activated sludge inoculum (Thomas et al., 1986); 54 percent over 33 days using an unreported inoculum (Union Carbide, 1974); and 73.81 to 86.16 percent over 27 days using an activated sludge inoculum (Saeger and Tucker, 1976). The ultimate biodegradation half-life of DEHP has been reported

to be greater than 14 days with loses of 30 to 70 percent over 14 days when using an activated sludge inoculum at a mixed liquor suspended solids concentration of approximately 100 mg/L and 15 to 35 percent over 14 days when using a river water inoculum with a suspended solids concentration of approximately 25 mg/L (Fujita et al., 2005).

While biodegradation rates will depend on environmental conditions, such pre-conditioning of microorganisms to the presence of DEHP (Tabak et al., 1981; Price et al., 1974; Union Carbide, 1974), the data suggest that the half-life of DEHP in aerobic waters will be on the order of days to weeks.

4.1.2 Biodegradation in Sediments

In aerobic sediments, rates of biodegradation of DEHP have been reported to be 5.9 to 19.79 percent over 28 days in a microcosm study using sediment from a lake in Missouri (Johnson et al., 1984). Half-lives in aerobic sediments have been reported to be 347 days in a microcosm study using sediment from a marine environment in Canada (Kickham et al., 2012), 7.3 to 27.5 days in a microcosm study using sediment from a river in Taiwan (Yuan et al., 2002), and approximately 14 days in a microcosm study using sediment from a river in Japan (Yuwatini et al., 2006). Reported biodegradation rates of DEHP in anaerobic sediments showed a high amount of variability, with rates of 0 percent over 365 days (Painter and Jones, 1990), 13 percent over 30 days (Kao et al., 2005), and up to 9.86 percent in 28 days (Johnson et al., 1984). Reported half-lives in anaerobic sediments show a similar level or variability with values ranging from 22.8 days (Yuan et al., 2002) to 279.5 days (Lertsirisopon et al., 2006). Overall, the data suggest that the half-life of DEHP in both aerobic and anaerobic sediments will be on the order of months to years.

4.1.3 Biodegradation in Soils

In aerobic soils, the half-life of DEHP has been reported to be 8.7 days in soil from an agricultural field (Yuan et al., 2011), 54 to 170 days in a silty sand soil (Rüdel et al., 1993), 20 to 31 days in silty loam soil (Rüdel et al., 1993), and 73 days in soil from an agricultural field (Lindequist Madsen et al., 1999). Additionally, there have been reported degradation rates of 98.9 percent over 49 days (Carrara et al., 2011), 10 percent over 10 days (Cartwright et al., 2000), 8.5 to 21.8 percent over 60 days (Gejlsbjerg et al., 2001), 55.5 to 90.47 percent over 112 days (He et al., 2018), 8.2 percent in 7 days (Schmitzer et al., 1988), 7 to 43 percent over 35 days (Zhu et al., 2018), and 31 to 38 percent over 42 days (Zhu et al., 2019). Temperature was shown to be an important factor, with reported half-lives of 223, 187, and 73 days in experiments conducted at 5, 10, and 20 °C, respectively (Lindequist Madsen et al., 1999).

Biodegredation rates in soils amended with biosolids were similar to those reported for unamended soils, with reported rates of 84.1 percent in a freshly amended soil over 146 days (Fairbanks, 1984), 89 percent in a preconditioned soil over 146 days (Fairbanks, 1984), 5.8 to 18.0 percent over 60 days in an amended soil (Gejlsbjerg et al., 2001), 95 to 96 percent in an amended soil in a 1-year field study (Petersen et al., 2003), approximately 40 percent over 84 days in an amended soil (Roslev et al., 1998). One study reported half-lives ranging from 5.8 to 9.9 days for a soil amended with biosolids at soil:biosolids ratios ranging from 0:1 to 1:1 (Yuan et al., 2011). The half-life for the unamended soil was 8.7 days and the shortest half-life was 5.8 days at a soild:biosolids ratio of 1:0.2. An additional study reported a half-life of 64 days when sampling from the top 20 cm of an amended agricultural soil (Tran et al., 2015).

Under anaerobic conditions, biodegredation rates in soils have been reported to be 34 percent over 30 days (Shanker et al., 1985) and 35 to 38 percent over 42 days (Zhu et al., 2019). Temperature was again shown to be an important factor impacting biodegradation, with rates of 25, 30, and 50 percent at 5, 10, and 20 °C, respectively, over 125 days in anaerobic soils amended with biosolids (Vavilin, 2007).

Overall, the data suggest that the half-life of DEHP in both aerobic and anerobic soils will be on the order of weeks to months.

Table 4-1. Summary of DEHP's Biodegradation Data

Environmental Conditions	Degradation Value	Half-life (days)	Reference	Overall Quality Determination
Aerobic primary biodegradation in water	81.5%/24 hours, 91%/48 hours, >91%/2–5 days	N.D.	EC/HC (2015a)	Medium
	N.D.	<5 days with activated sludge inoculum, <7 days in river water with no inoculum	Fujita et al. (2005)	High
	68.1–73.5%/7 days	N.D.	Hashizume et al. (2002)	Medium
	50%/24 hours (river die away method), 70–78%/28 days (semi-continuous activate sludge method)	N.D.	Monsanto (1976)	Medium
	N.D.	60–70 hours in groundwater impacted by DEHP; no biodegredation in waters not impacted by DEHP	NCBI (2020a)	Medium
	>99%/28 days	N.D.	SRC (1983)	High
	70–78%/24 hours (semi-continuous activated sludge method)	N.D.	Saeger and Tucker (1976)	High
Aerobic ready biodegradation in water	82%/29 days	N.D.	EC/HC (2015b)	Medium
	63%/28 days	N.D.		

Environmental Conditions	Degradation Value	Half-life (days)	Reference	Overall Quality Determination
	60–70%/28 days	N.D.		
	4–5%/28 days	N.D.		
	69%/28 days	N.D.	NCBI (2020a)	High
	58.7%/28 days	6.9 days	Stasinakis et al. (2008)	High
	81-84%/29 days	N.D.	Scholz et al. (1997)	High
Aerobic ultimate biodegradation in water	85.5%/28 days	N.D.	SRC (1983)	High
	30–70%/14 days with activated sludge inoculum, 14–35%/days in river and pond water	N.D.	Fujita et al. (2005)	High
	73.81–86.16%/27 days based on CO_2 evolution	N.D.	Saeger and Tucker (1976)	High
Aerobic biodegradation in sediment	5.9%/28 days, 9.98–19.79%/28 days (primary degradation)	N.D.	Johnson et al. (1984)	High
	13.79%/28 days (ultimate)	N.D.	Johnson et al. (1984)	High
	N.D.	347 days (ready)	Kickham et al. (2012)	High
	N.D.	7.3–27.5 days	Yuan et al. (2002)	High
	N.D.	Approximately 14 days	Yuwatini et al. (2006)	Medium
Anaerobic biodegradation in sediment	N.D.	27.5 days	Chang et al. (2005a)	High
	9.86%/28 days (ultimate)	N.D.	Johnson et al. (1984)	High
	13%/30 days	N.D.	Kao et al. (2005)	High
	N.D.	207.5–279.5 days	Lertsirisopon et al. (2006)	High
	0%/365 days in	N.D.	Painter and Jones (1990)	Medium

Environmental Conditions	Degradation Value	Half-life (days)	Reference	Overall Quality Determination
	freshwater sediment, 18%/365 days in salt marsh sediment			
	N.D.	22.8–39.1 days	Yuan et al. (2002)	High
Aerobic biodegradation in soil	98.8%/49 days	N.D.	Carrara et al. (2011)	High
	10%/10 days	N.D.	Cartwright et al. (2000)	High
	8.5–21.8%/60 days	N.D.	Gejlsbjerg et al. (2001)	High
	55.5–90.47%/112 days	N.D.	He et al. (2018)	High
	8.2%/7 days	N.D.	Schmitzer et al. (1988)	Medium
	7–43%/35 days	N.D.	Zhu et al. (2018)	High
	31–38%/42 days	N.D.	Zhu et al. (2019)	High
Anaerobic biodegradation in soil	N.D.	8.7 days	Yuan et al. (2011)	High
	N.D.	54–170 days in a silty sand, 20–31 days in a silty loam	Rüdel et al. (1993)	High
	N.D.	73 days	Lindequist Madsen et al. (1999)	High

4.2 Hydrolysis

The HYDROWIN™ module in EPI Suite™ was used to estimate the hydrolysis half-lives of DEHP. The estimated half-lives of DEHP were 195 days at pH 8 and 25 °C, and 5.36 years at pH 7 and 25 °C (U.S. EPA, 2017), indicating that hydrolysis is a possible degradation pathway of DEHP under more caustic conditions.

When compared to other degradation pathways, hydrolysis is not expected to be a significant degradation pathway under standard environmental conditions. However, higher temperatures, variations from standard environmental pH, and chemical catalysts present in the deeper anoxic zones of landfills may favor the degradation of DEHP via hydrolysis (Huang et al., 2013). This is discussed further in Section 6.3.3.

4.3 Photolysis

DEHP contains chromophores that absorb light at greater than 290 nm wavelength (NCBI, 2020b), and will undergo direct photodegradation in air. Gaseous CO_2 is the main product and 2-ethyl-1-hexene, 2-ethylhexanol, and phthalic acid are the major byproducts. Modeled indirect photodegradation half-lives indicated a slightly more rapid degradation rate, calculating a half-life of 5.58 hours using an estimated

rate constant of 2.39×10^{-11} cm^3/molecule-second at 25 °C, assuming a 12-hour day with 21.96×10^{-12} ·OH/cm^3 (U.S. EPA, 2017). Both of these rates indicate that DEHP degrades rapidly when released to the atmosphere and is likely not subject to long range transport in the atmosphere. In addition, Yu (2019) concluded that DEHP was readily photodegraded via direct exposure to direct sunlight in a simulated natural water and had a median half-life of approximately 4 hours when starting with an aqueous concentration of 50 µg/mL DEHP. This study also concluded that the presence of other natural reactive species (Fe^{3+}, NO_3^-, Cl^-) increased the indirect photodegradation rates of DEHP under simulated sunlight (Yu et al., 2019).

5 PARTITIONING

DEHP – Partitioning Analysis:
Key Points

EPA considered all reasonably available information identified by the systematic review process under TSCA to characterize the chemistry and fate and transport of DEHP. The following bullets summarize the key points of this partitioning analysis:

- When primarily released to water, approximately 46 to 62 percent of DEHP will partition to sediment, with the remaining fraction remaining in the water compartment.
- When released to air, approximately 85 percent of DEHP will partition to soil, with the remaining 15 percent distributed to the air, water, and sediment compartments.
- When primarily released to soil, DEHP will remain in soil completely.
- When released equally to air, water, and soil, DEHP will predominantly partition to the soil compartment (57–60%), with the remaining fractions partitioning to water (16–21%) or sediment (18–26%).

5.1 Tier I Analysis

DEHP is a member of the phthalate class of chemicals and is mainly used as a plasticizer of PVC and other polymers. To be able to understand and predict the behaviors and effects of DEHP in the environment, a Tier I analysis will determine whether an environmental compartment (*e.g.*, air, water, etc.) will accumulate DEHP at concentrations that may lead to environmental exposure (*i.e.*, major compartment) or are unlikely to result in risk (*i.e.*, minor compartment). The first step in identifying the major and minor compartments for DEHP is to consider partitioning values (Table 5-1) which indicate the potential for a substance to favor one compartment over another. DEHP does not naturally occur in the environment; however, DEHP has been detected in water, soil, and sediment in environmental monitoring studies indicating its ability to exist in those media (NLM, 2015a; ECJRC, 2008).

Table 5-1. Partitioning Values for DEHP

Parameter	Value(s)	Log Value(s)[a]	Reference	Predominant Phase
Octanol:water (K_{OW})	3.98E07	7.60	(NLM, 2015a)	Organic Carbon
Organic carbon:water (K_{OC})	8.71E04–5.25E05	4.94–5.72	(NCBI, 2020a)	Organic Carbon
	2.57E05, 3.02E05, 8.91E05	5.41, 5.48, 5.95	(Williams et al., 1995)	
	5.62E03–1.91E04	3.75–4.28	(He et al., 2019)	
Octanol:air (K_{OA})	5.69E10	10.755 (estimated)[b]	KOAWIN™ (U.S. EPA, 2017), (user input)[c]	Organic Carbon
Air:water (K_{AW})	1.82E–03	–2.74 (estimated)	(Lu, 2009)	Water

	1.58E–03	–2.80 (estimated)	(Cousins and Mackay, 2000)	

[a] Measured unless otherwise noted
[b] Information was estimated using EPI Suite™ (U.S. EPA, 2017)
[c] EPI Suite physical property inputs: MP = –55ºC, BP = 384ºC, VP = 1.42×10^{-7} mm Hg, WS = 0.003 mg/L, Log K_{OW} = 7.60, HLC = 9.87E-06 atm·m^3/mole, SMILES: O=C(OCC(CCCC)CC)c(c(ccc1)C(=O)OCC(CCCC)CC)c1

5.1.1 Soil, Sediment, and Biosolids

Based on the partitioning values shown in Table 5-1, DEHP will favor organic carbon over water or air. Because organic carbon is present in soil, biosolids, and sediment, they all are considered major compartments for DEHP. This is consistent with monitoring data from the Mersey Estuary in the United Kingdom, where high concentrations of DEHP were detected in sediment samples (1.220 µg/g and 1.199 µg/g at Speke and Runcorn, respectively) compared to water samples (0.125–0.693 ng/L and 279.78–637.96 ng/L in the dissolved and particulate phase, respectively) (Preston and Al-Omran, 1989).

5.1.2 Air

DEHP is a liquid at environmental temperatures with a melting point of –55 °C (NLM, 2015a) and a vapor pressure of 1.42×10^{-7} mm Hg at 25 °C (NLM, 2015a). The octanol-air coefficient (K_{OA}) indicates that DEHP will favor the organic carbon present in airborne particles. Based on its physical and chemical properties and short half-life in the atmosphere ($t_{1/2}$ = 5.85 hours (U.S. EPA, 2017)), DEHP is assumed not to be persistent in the air. The AEROWIN™ module in EPI Suite™ estimates that a large fraction of DEHP may be sorbed to airborne particulates and these particulates may be resistant to atmospheric oxidation. DEHP has been detected in both in ambient and indoor air as well as in settled house dust (NLM, 2024; Kubwabo et al., 2013; Wang et al., 2013; ECJRC, 2008).

5.1.3 Water

The air-water partitioning coefficient (K_{AW}) indicates that DEHP will favor water over air. With a water solubility of 0.001 to 0.003 mg/L at 25 °C, DEHP is considered to be insoluble in water (Elsevier, 2021). DEHP in water will partition to suspended organic material present in the water column based on DEHP's low water solubility and partition coefficients indicating its strong preference for organic matter. In addition, total seawater concentrations of DEHP measured in False Creek, British Columbia ranged from 170 to 444 ng/L; the dissolved fraction concentrations ranged from 77 to 200 ng/L and the suspended sediment fraction concentration ranged from 7,350 to 136,000 ng/g dry weight (dw) (Mackintosh et al., 2006). Although DEHP has low water solubility, surface water will be considered as a major compartment for DEHP since DEHP was quantified in the ng/L range.

5.2 Tier II Analysis

A Tier II analysis involves reviewing environmental release information for DEHP to determine if a specific media evaluation is needed. DEHP is used mainly as a plasticizer in polyvinyl chloride (PVC) products (ECJRC, 2008). DEHP may be released to the environment during production, distribution, processing in PVC and non-PVC polymers, use of products such as paints and sealants, disposal or recycling, wastewater treatment, and disposal of solid and liquid waste. Environmental release data for DEHP were not available from the Discharge Monitoring Reports (DMRs); however, the Toxics Release Inventory (TRI) reported the total on-site releases for 2022 to be 7.2 thousand pounds with 6.9 thousand

pounds released to air, 24 pounds released to water, and 263 pounds released to land. According to production data from the Chemical Data Reporting (CDR) 2020 reporting period, between 10,000,000 and 50,000,000 pounds of DEHP were produced annually from 2016 to 2019 for use in commercial products, chemical substances or mixtures sold to consumers, or at industrial sites. Because DEHP is not chemically bound to the polymer matrix, it can migrate from the surface of polymer products (EC/HC, 2015a; ECJRC, 2008). Therefore, DEHP can be released to the environment from polymer-based products during their use and disposal. Additionally, DEHP may be released to the environment from discharge of wastewater, and liquid and solid wastes. After undergoing wastewater treatment processes, the discharge of wastewater or liquid wastes results in effluent discharge to water and land application of biosolids.

Tier I analysis identified air as minor compartment where DEHP is not expected to result in environmental exposure. The short lifetime of DEHP in the atmosphere reduces the potential for free DEHP to undergo long range atmospheric transport. However, DEHP sorbed to particulates may be resistant to atmospheric oxidation. In addition, DEHP bound to particulates in air and particle deposition can be a significant pathway for DEHP to be transported to other environmental compartments. Particle-bound DEHP is subject to wet and dry deposition and can subsequently enter soil and surface water media.

The Level III Fugacity Model in EPI Suite™ (U.S. EPA, 2017) can be used to study and predict DEHP's behavior in and between different environmental compartments. The LEV3EPI™ module uses inputs on an organic chemical's physical and chemical characteristics and degradation rates to predict partitioning and transport of chemicals between environmental compartments, as well as the persistence of a chemical in a model environment (Figure 5-1). Four emission rates scenarios were used as inputs into the Level III Fugacity Model: equal releases of DEHP to each compartment and 100 percent release to each compartment, separately. Each iteration of the fugacity model was run assuming ready biodegradability of DEHP. The fugacity results using half-lives consistent with ready biodegradability (5, 10, and 45 days in water, soil, and sediment, respectively) are shown in Figure 5-1. A half-life in air of 5.85 hours was used (U.S. EPA, 2017), as well as a user-entered K_{OC} value of 262,000 (which corresponds to a log K_{OC} value of 5.418).

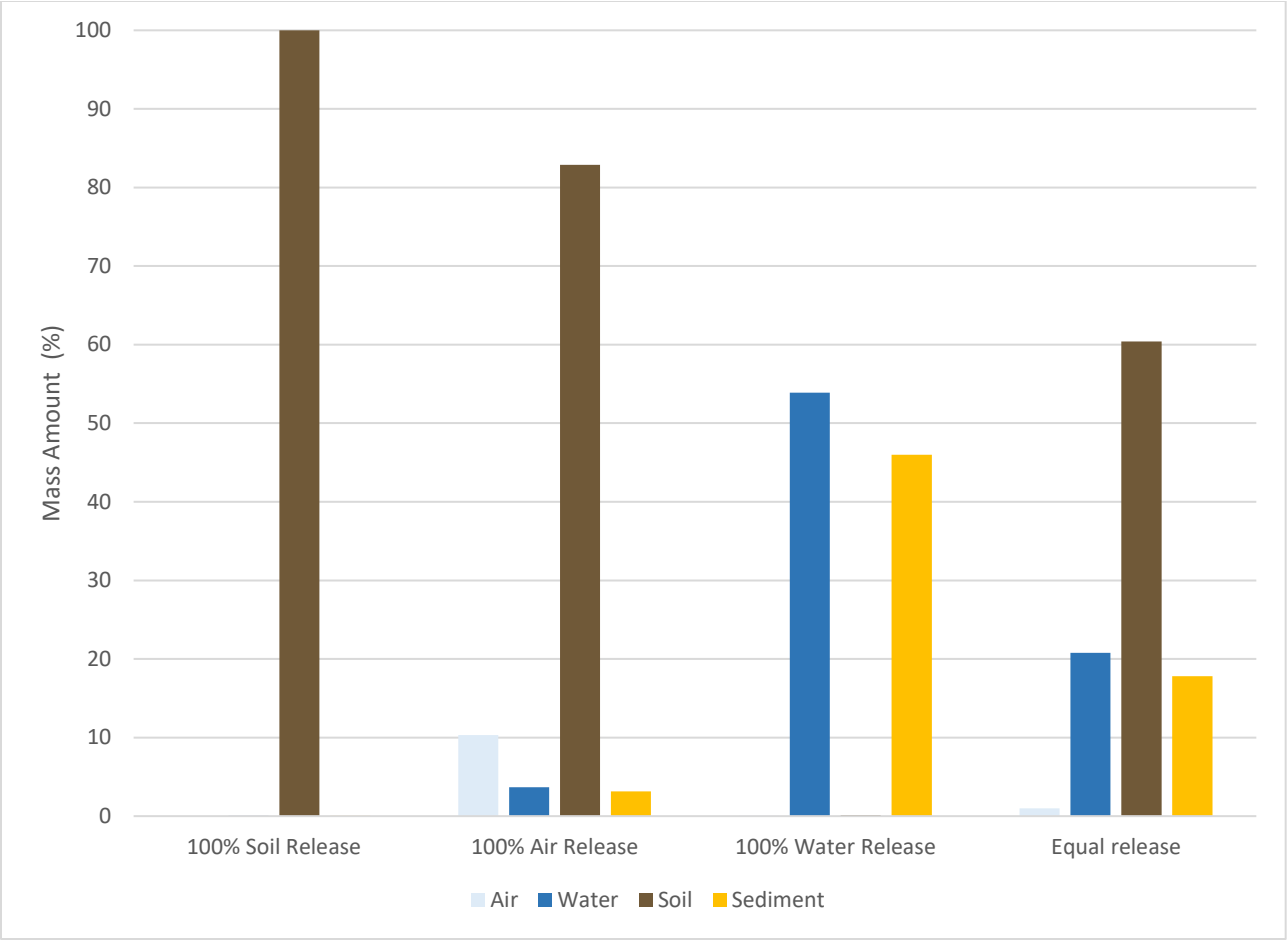

Figure 5-1. EPI Suite™ Level III Fugacity Modeling Graphical Result for DEHP Assuming Ready Biodegradability

The model predicts that DEHP will remain exclusively in soil when released primarily to soil. When released primarily to air, the model predicted that approximately 85 percent of DEHP will partition to soil, with the final 15 percent remaining in air or partitioning to the water and sediment compartments. When primarily released to water, the model predicts that DEHP will remain in the water compartment (54%) or partition into the sediment compartment. Under an equal release scenario, DEHP is expected to predominantly partition into the soil compartment at approximately 57 to 60 percent, with the remaining fractions partitioning to water (21%) or sediment (18%).

6 MEDIA ASSESSMENTS

DEHP has been reported to be present in the atmosphere, aquatic environments, and terrestrial environments. Once in the air, DEHP will primarily partition to organic matter present in airborne particles (see Section 6.1) and is expected to have a short half-life in the atmosphere. Similarly, DEHP is likely to partition to house dust and airborne particles in indoor air and is expected to have a longer half-life as compared to ambient (outdoor) air. DEHP present in surface water is expected to partition readily to aquatic sediments due its organic carbon-water partitioning coefficient, as measured in several EPA standard sediment samples from large river basins in the central United States (Williams et al., 1995). DEHP is expected to have an aerobic biodegradation half-life between 14 and 28 days. In terrestrial environments, DEHP may be present in soils and groundwater but is likely to be immobile in both media types. In soils, DEHP is expected to be deposited via air deposition and land application of biosolids, and is expected to have a half-life on the order of days to weeks. In addition, evidence suggests that DEHP is not bioaccumulative and has a low biomagnification potential in terrestrial organisms. In groundwater, DEHP is expected to be released via wastewater effluent and landfill leachates and to have a half-life of 14 to 56 days; therefore, it not likely to be persistent in most groundwater/subsurface environments.

6.1 Air and Atmosphere

DEHP is a liquid at environmental temperatures with a melting point of –55 °C (Rumble, 2018b) and a vapor pressure of 1.42×10^{-7} mmHg at 25 °C (NLM, 2015a). Based on its physical and chemical properties and short half-life in the atmosphere ($t_{1/2}$ = 5.85 hours (U.S. EPA, 2017)), DEHP was assumed to not be persistent in the air. The AEROWIN™ module in EPI Suite™ estimates that a large fraction of DEHP will be sorbed to airborne particles and these particulates may be resistant to atmospheric oxidation. Studies have detected DEHP in settled house dust, indoor air samples, and indoor particulate phase air samples in Canada and the United States (Preece et al., 2021; Kubwabo et al., 2013).

6.1.1 Indoor Air and Dust

In general, phthalate esters are ubiquitous in the atmosphere and indoor air. Their worldwide presence in air has been documented in the gas phase, suspended particles, and dust (Net et al., 2015). Most of the studies reported DEHP to be the predominant phthalate ester in the environment. Limited studies have reported the presence of particle-bound DEHP in indoor and outdoor settings (Gupta and Gadi, 2018; Hasegawa, 2003; Helmig et al., 1990). When indoors, DEHP is expected to partition to organic carbon present on indoor airborne particles. DEHP is expected to be more persistent in indoor air than in ambient (outdoor) air due to the lack of natural chemical removal processes, such as solar photochemical degradation.

The available information suggests that the concentration of DEHP in indoor dust is greater than in outdoor dust. The concentration on dust particles is also correlated to the presence of phthalate-containing articles in the environment, and the proximity to facilities producing phthalates. Kubwabo (2013) monitored the presence of 17 phthalate compounds in vacuum dust samples collected in 126 urban single-family homes in Canada. This study reported that DEHP was detected in all the collected dust samples, accounting for 88 percent of the median total concentration of phthalates in dust (Kubwabo et al., 2013). Wang (2013) evaluated the presence of phthalates in dust samples collected from indoor and outdoor settings in two major Chinese cities. This study reported the total phthalates concentration of the collected indoor dust samples were 3.4 to 5.9 times higher than those collected outdoors. The aggregate concentration of DEHP, DINP, and DIDP in indoor dust samples accounted for 91 to 94 percent of the total phthalate concentration. Additionally, Wang (2013) revealed that the

aggregate concentration of phthalates was higher in the commercial and industrial areas with heavy production of textiles, costumes, and toys. Abb (2009) evaluated the presence of phthalates in indoor dust samples collected from 30 households in Germany with a 100 percent detection frequency. Dust samples containing a high percentage of plastic (>50%) contained greater aggregate concentrations of phthalates. The aggregate concentration of DEHP, DIDP, and DINP accounted for 87 percent of the total phthalate concentration in dust (Abb et al., 2009).

Similarly, recent U.S. studies monitoring the presence of phthalates in dust from households have revealed DEHP and DINP to be detected in 96 to 100 percent of the collected samples (Hammel et al., 2019; Dodson et al., 2017). Hammel (2019) and Dodson (2017) reported the presence of phthalate esters in indoor air and on dust samples collected in U.S. homes. Dodson (2017) evaluated the presence of phthalate esters in air samples of U.S. homes before and after occupancy, reporting an increased presence of DEHP after occupancy due to daily anthropogenic activities that might introduce phthalate-containing products into indoor settings. Increasing trends could be expected for DEHP with its increased uses in household construction materials or consumer products.

6.2 Aquatic Environments

6.2.1 Surface Water

DEHP is expected to enter surface waters via industrial and municipal wastewater treatment effluents, surface water runoff, and, to a lesser degree, atmospheric deposition. A survey of phthalates conducted in Washington in 2021 detected dissolved DEHP in lake and river surface waters in 10 out of 27 samples, with concentrations ranging from 0.558 to 3.38 µg/L and a median concentration of 0.948 µg/L (WA DOE, 2022). Additionally, dissolved DEHP was detected in 2 out of 13 samples with detectable concentrations ranging from 2.67 to 5.94 µg/L in raw drinking water samples from California surface waters (Loraine and Pettigrov, 2006). In U.S. marine waters, monitoring studies have detected dissolved DEHP at concentrations up to approximately 1,000 ng/L in the Puget Sound (Keil et al., 2011), 18,000 ng/L in Lake Pontchartrain in Louisiana (Liu et al., 2013), and 316 ng/L in the Mississippi River Delta and Gulf of Mexico (Giam et al., 1978).

The principal properties governing the fate and transport of DEHP in surface water are water solubility, organic carbon-water partitioning coefficient, and volatility. Due to its Henry's Law constant (9.87×10^{-6} atm·m^3/mol at 25 °C), volatilization is not expected to be a significant source of loss of DEHP from surface water. The Tier II partitioning analysis (see Section 5.2) estimates that 46 percent will partition to suspended and benthic sediments when released to surface water bodies.

DEHP has a water solubility of 0.003 mg/L but is likely to form a colloidal suspension and may be detected in surface water at higher concentrations (Elsevier, 2021). DEHP in water will partition to suspended organic material present in the water column based on its water solubility and partitioning coefficients to organic matter.

Biodegradation of DEHP in surface water is generally rapid and multiple studies have shown that it passes a 10-day ready biodegradability test when using OECD guideline test methods (NCBI, 2020a; EC/HC, 2015a; Scholz et al., 1997). Based the results of multiple OECD guideline studies showing the ready biodegradability of DEHP and the additional data discussed in Section 0, the biodegradation half-life of DEHP in surface water is expected to be on the order of days to weeks.

6.2.2 Sediments

Based on its water solubility (0.003 mg/L) and tendency to sorb readily to organic matter (log K_{OC} =

5.41–5.95), DEHP will partition to the organic matter present in sediment and suspended solids when released into the aquatic environment. The Level III Fugacity Model in EPI Suite™ (U.S. EPA, 2017) predicts that 46 percent of the DEHP present in water will partition to and remain in sediments when assuming that DEHP is readily biodegradable (see Section 5.2). The available information suggests that in sediments DEHP will have a half-life on the order of months to years depending on the specific environmental conditions (see Section 0).

Concentrations of DEHP in urban Californian tidal marsh sediments were reported to range from 235 to 32,000 ng/g. DEHP was also found in sediments from the San Francisco Estuary at concentrations ranging from 124 to 332 mg/kg (IARC, 2013). Concentrations of DEHP in sediments from the Mississippi River Delta and Gulf of Mexico were reported as ranging from less than 0.1 to 248 ng/g, with lower concentrations in the river delta (mean of 69 ng/g) than on the coast (mean of 6.6 ng/g) or in the open gulf (mean of 2.0 ng/g) (Giam et al., 1978).

6.3 Terrestrial Environments

6.3.1 Soil

DEHP is expected to be deposited to soil via two primary routes: (1) application of biosolids and sewage sludge in agricultural applications or sludge drying applications; and (2) atmospheric deposition. No TRI data have been reported showing the application of DEHP-containing biosolids or otherwise applied to agricultural lands.

With a Henry's Law constant value of 9.87×10^{-6} atm·m^3/mol at 25 °C, DEHP is not likely to volatilize from soils. DEHP shows an affinity for sorption to soil and its organic constituents (log K_{OW} = 7.60, log K_{OC} = 5.41–5.95). Given that these properties indicate the likelihood of strong sorption to organic carbon present in soil, DEHP is expected to have low mobility in soil. For that reason, DEHP is unlikely to leach from the uppermost layer of soil and reach groundwater due to its low water solubility (0.003 mg/L).

No studies reporting the concentration of DEHP in field surveys of agricultural land have been identified. However, several experimental studies have demonstrated the ability of DEHP to degrade in aerobic and anaerobic soils. DEHP does appear to have potential for biodegradation under aerobic conditions, such that would exist in shallow soils. The half-life of DEHP in aerobic soils varies widely depending on the soil characteristics and biological activity. Highly active, wet, aerated soils have reported a half-life as short as 8 days, while dry, inactive, non-optimal soils have an environmental half-life as long as 468 days, in-line with abiotic degradation pathways of DEHP (Zhu et al., 2019; He et al., 2018; Zhu et al., 2018; Carrara et al., 2011; Gejlsbjerg et al., 2001; Cartwright et al., 2000; Schmitzer et al., 1988).

Anaerobic biodegradation of DEHP is also possible with half-lives ranging based on the soil characteristics and biological activity. The half-life of DEHP in highly organic, moist anaerobic soils have been reported as long as 9 days, while less optimal anaerobic soils extend to 170 days (Yuan et al., 2011; Lindequist Madsen et al., 1999; Rüdel et al., 1993). There is limited information available related to the uptake and bioavailability of DEHP in land applied soils. DEHP's solubility and sorption coefficients suggest that bioaccumulation and biomagnification will not be of significant concern for exposed organisms. Bioaccumulation and biomagnification are discussed further in Section 8.

Hydrolysis is not expected to be a significant source of DEHP degradation in moist soils due to its long half-life (see Section 4.2). Direct photolysis of DEHP may be a significant pathway for abiotic

degradation in the uppermost layer of soil which may be exposed to sunlight with a rapid half-life of less than 6 hours (see Section 4.3). However, photolysis would not be a significant degradation pathway for DEHP in deeper layers of soil extending beyond the penetrating power of the sunlight.

6.3.2 Biosolids

Sludge is defined as the solid, semi-solid, or liquid residue generated by wastewater treatment processes. The term "biosolids" refers to treated sludge that meet the EPA pollutant and pathogen requirements for land application and surface disposal and can be beneficially recycled (40 CFR part 503) (U.S. EPA, 1993). DEHP is expected to sorb largely to biosolids in wastewater treatment because of its high potential for sorption to particulate and organic media (log K_{OW} = 7.6, log K_{OC} = 5.41–5.95) and limited water solubility (0.003 mg/L). Like other phthalates, DEHP is expected to partition to biosolids during wastewater treatment and subsequently removed by physical separation processes (*e.g.*, sedimentation, filtration, dewatering, sludge thickening). At least one study has reported significant partitioning to sediment and particulate phases of sludge in wastewater treatment (Painter and Jones, 1990).

No wastewater treatment plant (WWTP) surveys monitoring DEHP in wastewater sludge or final biosolids have been identified. Several laboratory studies have demonstrated the capacity of wastewater treatment facilities to remove DEHP from sludge via aerobic and anaerobic biodegradation with half-lives of approximately 5 to 6 days (aerobic) and 7 days (anaerobic) (Kotowska et al., 2018; Chang et al., 2005b; Fujita et al., 2005). DEHP has been shown to be degraded to below the limits of detection in as short as 10 days (Fujita et al., 2005). Aerobic degradation of DEHP in sludge may be hastened with the use of select microbial strains with an aerobic half-life as short as 2 days in an inoculated sludge (Kotowska et al., 2018). However, there were mixed reports of DEHP removal during anaerobic digestion has. A study showed no detectable anaerobic biodegradation of DEHP during solids treatment but instead demonstrated significant removal via particulate sorption (Painter and Jones, 1990).

Aerobic biodegradation of DEHP in sludge is a two-step process. The first step consists of DEHP conversion to 2-ethylhexanol and a monoester phthalate followed by an additional degradation of monoester phthalate to phthalic acid and 2-ethylhexanol (Kotowska et al., 2018). The degradation products of aerobic and anaerobic degradation of DEHP were not further evaluated in this assessment.

No facilities reported off-site land application of land disposal of DEHP containing biosolids between 2017 to 2022. However, several facilities reported the disposal of DEHP-containing biosolids in landfills, discussed further in Section 6.3.3.

When applied to land as biosolids, DEHP is expected to have low mobility due to its high affinity to organic matter and particulates, and limited water solubility. Similarly, DEHP is not expected to be readily bioavailable when present in biosolids or soils. Once incorporated, DEHP has the potential to degrade under aerobic conditions, such that would exist in shallow soils. As discussed in Section 6.3.1, the half-life of DEHP in aerobic soils varies widely depending on the soil characteristics and biological activity. Highly active, wet, aerated soils have reported a half-life as short as 8 days while dry, inactive, non-optimal soils have an environmental half-life as long as 468 days, in-line with abiotic degradation pathways of DEHP (Zhu et al., 2019; He et al., 2018; Zhu et al., 2018; Carrara et al., 2011; Gejlsbjerg et al., 2001; Cartwright et al., 2000; Schmitzer et al., 1988).

Anaerobic biodegradation of DEHP is also possible with half-lives ranging based on the soil characteristics and biological activity. The half-life of DEHP in highly organic, moist anaerobic soils have been reported as rapid as 9 days while less optimal anaerobic soils extend to 170 days (Yuan et al., 2011; Lindequist Madsen et al., 1999; Rüdel et al., 1993).There is limited information available related

to the uptake and bioavailability of DEHP in land applied soils; DEHPs solubility and sorption coefficients suggest that bioaccumulation and biomagnification will not be of significant concern for exposed organisms. Bioaccumulation and biomagnification are discussed further in Section 8.

6.3.3 Landfills

For the purpose of this assessment, landfills will be considered to be divided into two zones: (1) an "upper-landfill" zone, with normal environmental temperatures and pressures, where biotic processes are the predominant route of degradation for DEHP; (2) and a "lower-landfill" zone where elevated temperatures and pressures exist, and abiotic degradation is the predominant route of degradation are the predominant route of degradation for DEHP. In the upper-landfill zone where oxygen may still be present in the subsurface, conditions may still be favorable for aerobic biodegradation, however, photolysis and hydrolysis are not considered to be significant sources of degradation in this zone. In the lower-landfill zone, conditions are assumed to be anoxic, and temperatures present in this zone are likely to inhibit anaerobic biodegradation of DEHP. Temperatures in lower landfills may be as high as 70 °C; At temperatures at and above 60 °C, biotic processes are significantly inhibited, and are likely to be completely irrelevant at 70 °C (Huang et al., 2013).

DEHP is deposited into landfills from consumer products containing DEHP and as biosolids containing DEHP from wastewater treatment. According to TRI data, ten WWTPs have reported the disposal of DEHP containing sludge from 2017 to 2022 with a total of 160 kg of DEHP disposed of in landfills (26.6 kg/year on average). Ten TRI facilities have reported disposal of DEHP-containing waste to RCRA landfills at a rate of 6,705 kg from 2017 to 2022 (1,117 kg/year on average) and 403,776 pounds of waste to other landfills over the same time frame (67,296 kg/year on average). No studies were identified reporting the concentration or degradation of DEHP in landfills, landfill leachate, or in the regions surrounding such landfills.

DEHP's water solubility (0.003 mg/L) and high tendency to sorb to particulate and organic media (log K_{OW} = 7.60, log K_{OC} = 5.41–5.95) suggest that DEHP is unlikely to be present in landfill leachate. In the event that DEHP does leach from the landfill, it is likely that DEHP will sorb strongly to the surrounding soil and any clay liners, preventing percolation to deeper groundwater. Hydrolysis will likely not be a major degradation pathway for degradation of DEHP in leachate with an estimated hydrolysis half-life of 5.36 years at a pH of 7 and at 25 °C (U.S. EPA, 2017). Photolysis may be a significant abiotic degradation for the portion of waste that is directly exposed to sunlight with a half-life less than 6 hours. Photolysis would only be relevant in the shallow, uppermost layer of waste and would not impact degradation beyond the penetrating power of the sunlight. Photolysis would also not occur following the application of the daily cover, which, like deeper waste, would be shielded from sunlight.

DEHP may degrade biologically via aerobic degradation in the upper landfill where aerobic conditions dominate. While literature is limited, some studies suggest DEHP is capable of being aerobically degraded with an aerobic half-life ranging from 8 days in oxygenated, moist, active environments to as long as 468 days in sub-optimal aerobic conditions (Zhu et al., 2019; He et al., 2018; Zhu et al., 2018; Carrara et al., 2011; Gejlsbjerg et al., 2001; Cartwright et al., 2000; Schmitzer et al., 1988). DEHP may degrade at a similar rate in the anoxic lower landfill with a reported half-life of 9 days in warm, moist environments but may be as long as 170 days in less optimal conditions (Yuan et al., 2011; Lindequist Madsen et al., 1999; Rüdel et al., 1993). However, as previously noted above, biological degradation would be limited by high temperatures exceeding the habitable zone of bacteria (Huang et al., 2013). In the case of high-temperature biodegradation (<60 °C), DEHP would likely be persistent with very limited abiotic degradation and no biological degradation.

6.3.4 Groundwater

There are several likely sources of DEHP in groundwater, including wastewater effluents and landfill leachates, which are discussed in Sections 6.3.3 and 7.2. In environments where DEHP is found in surface water, it may enter groundwater through surface water/groundwater interactions, especially in aquifer-supplied bodies of water. Diffuse sources include stormwater runoff and runoff from biosolids applied to agricultural land.

Given the strong affinity of DEHP to adsorb to organic matter present in soils and sediments (log K_{OC} = 5.41) (Williams et al., 1995), DEHP is expected to have low mobility in soil and groundwater environments. Furthermore, due to the insoluble nature of DEHP (0.003 mg/L), high concentrations of DEHP in groundwater are unlikely. In instances where DEHP could reasonably be expected to be present in groundwater environments (*e.g.*, proximal to landfills or agricultural land with a history of land-applied biosolids), limited persistence is expected based on rates of biodegradation of DEHP in aerobic environments; therefore, DEHP is not likely to be persistent in groundwater/subsurface environments unless anoxic conditions exist.

7 PERSISTENCE POTENTIAL OF DEHP

DEHP is not expected to be persistent in the environment, as it is expected to degrade rapidly under most environmental conditions, with delayed biodegradation in low-oxygen media. In the atmosphere, DEHP is unlikely to remain for long periods of time as its expected to undergo photolytic degradation through reaction with atmospheric hydroxyl radicals, with an estimated half-life of 5.5 hours. DEHP is predicted to hydrolyze slowly at ambient temperatures, but it is not expected to persist in aquatic media as it undergoes rapid aerobic biodegradation (see Section 6.2.1). DEHP has the potential to remain for longer periods of time in soil and sediments, but due to the inherent hydrophobicity (log K_{OW} = 7.60) and sorption potential (log K_{OC} = 5.51) DEHP is not expected to be bioavailable for uptake. Using the Level III Fugacity model in EPI Suite™ (LEV3EPI™) (see Section 5), DEHP's overall environmental half-life was estimated to be on the order of days to weeks (U.S. EPA, 2017). Therefore, DEHP is not expected to be persistent in the atmosphere, aquatic or terrestrial environments.

7.1 Destruction and Removal Efficiency

Destruction and Removal Efficiency (DRE) is a percentage that represents the mass of a pollutant removed or destroyed in a thermal incinerator relative to the mass that entered the system. EPA requires that hazardous waste incineration systems destroy and remove at least 99.99 percent of each harmful chemical in the waste, including treated hazardous waste (46 FR 7684) (Federal Register, 1981).

Currently there is limited available information on the DRE of DEHP. However, the DEHP annual releases from a Danish waste incineration facility were estimated to be 9 percent to air and 91 percent to a municipal landfill (ECJRC, 2008). These results suggest that DEHP present during incineration processes will very likely be released to landfills and the remaining small fraction released to air. Berardi (2019) reported greater than 99 percent removal of phthalate esters during incineration of solids from the primary and secondary settling basins of a WWTP in Italy. Based on its inherent hydrophobicity and high sorption potential, DEHP released to landfills is expected to partition to organic matter present in the landfills. Similarly, DEHP released to air is expected to partition mostly to soil, with the final fraction remaining in air or partitioning to the water and sediments as described in Section 5. In addition, DEHP in sediments and soils is expected to be rapidly sorbed to organic matter in these compartments limiting DEHP uptake into biota (Kickham et al., 2012). Lastly, DEHP released to air is expected to react rapidly via indirect photochemical processes within hours (U.S. EPA, 2017).

7.2 Removal in Wastewater Treatment

Wastewater treatment is performed to remove contaminants from wastewater using physical, biological, and chemical processes. Municipal wastewater treatment facilities either treat the influent from combined sewers (sanitary sewage and stormwater runoff) or separate sanitary sewers (sewage treatment plant). Generally, municipal wastewater treatment facilities apply primary and secondary treatments. During the primary treatment, screens, grit chambers, and settling tanks are used to remove solids from wastewater. Secondary treatment processes can remove up to 90 percent of the organic matter in wastewater using biological treatment processes such as trickling filters or activated sludge. Sometimes an additional stage of treatment such as tertiary treatment is used to further clean water for additional protection using advanced treatment techniques (*e.g.*, ozonation, chlorination, disinfection).

Several high-quality studies were identified in the systematic review process related to the fate and transport of DEHP in wastewater treatment systems. EPA selected 15 high-quality sources reporting the removal of DEHP in wastewater treatment systems employing aerobic and anaerobic biological treatment processes (Table 7-1). DEHP has been reported to have an estimated half-life of 23 days in WWTPs, based on available DEHP half-lives in surface water (NCBI, 2020a). Multiple studies reported

WWTPs to been capable of achieving 94 to 97.3 percent removal of DEHP present in municipal wastewater (Berardi et al., 2019; Tran et al., 2014; Shao and Ma, 2009; Fauser et al., 2003; Marttinen et al., 2003). Berardi (2019) reported DEHP to strongly be sorbed to solids, negligible biodegradation, 8 percent removal during ozonation, and 96.7 percent overall removal of DEHP in a WWTP in Italy. However, additional studies with similar removal efficiencies of DEHP have reported biodegradation to partially remove DEHP from wastewater. Marttinen (2003) identified the main removal mechanism of DEHP from wastewater to be sorption to sludge and partial removal by biodegradation processes. The study reported an overall 97 percent removal efficiency of DEHP from wastewater and 14 percent removal due to biodegradation. Similarly, Tran (2014) reported 94 percent removal efficiency of DEHP by biodegradation (19.5%) and sorption to sludge (74.6%) in a WWTP in France. Shao (2009) reported 96.1 percent removal efficiency of DEHP by biological treatment processes (59%) and sorption to sludge (41%) in a WWTP in China. Fauser (2003) reported 97.3 percent overall removal of DEHP in WWTP based on measured influent and effluent concentrations of DEHP in Denmark. The model results of this study reported that biodegradation accounted for 70.1 percent of the overall DEHP removal. Salaudeen (2018) explored the occurrence of DEHP in three WWTPs in Nigeria. The study reported 67 to 83 percent removal of DEHP in two WWTPs employing screening, grit removal, sedimentation, activated sludge, secondary clarification, and chlorination. The same study reported 35 percent DEHP removal in a WWTP with a similar treatment train, though excluding the secondary clarification step. The study attributes most of the removal to adsorption to settling particles and sludge, apparent from the greater DEHP removal efficiency in the two WWTPs that employed secondary clarification. Additionally, the authors attribute partial removal to biodegradation (Salaudeen et al., 2018). Gao (2014) reported less than 40 percent DEHP removal in three full-scale WWTPs with hydraulic retention times of 6 to 9.5 hours. Similar to other phthalate esters, DEHP has been reported to be more persistent in anaerobic WWTP processes when compared to aerobic treatment processes (Armstrong et al., 2018; Balabanic et al., 2012). EPA investigated the removal efficiencies of priority pollutants within 50 wastewater treatment facilities in the U.S. The study reported a median DEHP removal of 64 percent in WWTPs employing activated sludge systems (U.S. EPA, 1982). DEHP removals of 61.7, 75, and 93 percent have been reported in WWTPs employing activated sludge systems in Canada, Hong Kong, and Denmark, respectively (Wu et al., 2017; Osachoff et al., 2014; Roslev et al., 2007). Roslev (2007) reported an estimated 81 percent biodegradation of DEHP in an activated sludge treatment process with a hydraulic retention time of one day. Like in conventional WWTPs, sorption to sludge has been reported as the main removal mechanism of DEHP removal from wastewater (68% sorbed to sludge) (Marttinen et al., 2003), to be partially removed by biodegradation (14–70%) (Tran et al., 2014; Fauser et al., 2003; Marttinen et al., 2003), and to be more persistent under anaerobic conditions (21.7–46.7% removal) (Benabdallah El-Hadj et al., 2006).

Overall, DEHP has a high log K_{OW}, remains in suspended solids, and is efficiently removed from wastewater via accumulation in sewage sludge (Tran et al., 2014). DEHP is expected to be partially removed during aerobic solids digestion processes (Armstrong et al., 2018) and biodegradation (Roslev et al., 2007), and ineffectively removed under anaerobic solids digestion conditions (Armstrong et al., 2018). Air stripping is not expected to be significant wastewater removal processes. Based on the reported median removal of DEHP in U.S. POTWs, greater than 64 percent of the DEHP present in wastewater is expected to be accumulated in sewage sludge and released with biosolids disposal or application, with the remaining fraction sorbed to suspended solids in the wastewater treatment effluent and discharged with surface water (U.S. EPA, 1982).

966 **Table 7-1. Summary of DEHP's WWTP Removal Data**

Endpoint	Value	Additional Information	Reference
Half-life	$t_{1/2}$ = 23 days	Half-life: 23 days in wastewater treatment plants based on reported DEHP half-life in water.	NCBI (2020a)
Removal in wastewater treatment	96.1% removal	Average removal in STP in China. Treatment processes included: grit removal, primary clarifier, A/O activated sludge, and secondary clarifier.	Shao and Ma (2009)
	94% removal	94% removal efficiency by degradation and decantation based on GC-MS analysis in Fontenay-les-Briis (Essonne-France) WWTP	Tran et al. (2014)
	97% removal	DEHP removal in STP in Finland. Overall removal efficiency in primary and secondary treatment was 97%; volatilization was negligible; 14% was biodegraded; 68% was sorbed to sludge; 3% was discharged with effluent; 29% was removed via activated sludge process, and 32% removed via anaerobic digestion (assuming volatilization and abiotic transformation were negligible).	Marttinen et al. (2003)
	96.7% removal	Overall average DEHP removal efficiency in WWTP in Italy, including ozonation: 96.7%; overall average PAE removal efficiency with ozonation: 97.3%; average PAE removal efficiency without ozonation: 89.3%; average % DEHP in influent: 80%; average % DEHP in effluent: 87%	Berardi et al. (2019)
	97.3% removal	Influent/effluent removal % (8-day mean): 97.3%. Inlet total (µg/L): 35.4 ± 10.6; outlet total (µg/L): 0.96 ± 0.94; modelled value based on measured concentrations in Denmark. DEHP removal = 70.1% (degradation) + 27.2% (sorption) = 97.3%	Fauser et al. (2003)
	80% removal (aerobic), 70% removal (anaerobic)	Pilot scale: 70% anaerobic, 80% aerobic, 95% ultrafiltration, 100% reverse osmosis, 95% membrane bioreactor (approx.)	Balabanic et al. (2012)
	20–39% removal	Approximate removal of DEHP in three full scale WWTP in China with hydraulic retention times of 6 (WWTP1), 8 (WWTP2), and 9.5 h (WWTP3). Removal efficiency WWTP1 ca. 30%; WWTP2 ca. 20%; WWTP3 ca. 39%; less than 40% of DEHP removed from the aqueous phase by three different treatment processes	Gao et al. (2014)
	67–83% and 35% removal	Removal efficiency: 67.99% (Adelaide), 83.94% (Alice), and 35.98% (Seymour); Adelaide and Alice treatment processes include: screening, grit removal, sedimentation, activated sludge, secondary clarifier, and chlorination. Seymour	Salaudeen et al. (2018)

Endpoint	Value	Additional Information	Reference
		plant had similar treatment processes except for a secondary clarifier. Majority of the removal attributed to adsorption to settling particles and sludge than biodegradation. Treatment plant in Nigeria.	
	Aerobic sludge digestion: 35–77.6% Anaerobic sludge digestion: NS to 80.7% increase in concentration	DEHP was monitored in the influent, effluent and final solids of six WWTPs in Maryland and Washington D.C. WWTPs #1-4 use anaerobic digestion for sludge treatment; WWTPs #5-6 use aerobic processes. The treatment processes varied, and results varied, with some DEHP concentrations increasing, decreasing, or having no significant change. The percent change in concentration at each stage of treatment was calculated from the previous treatment step: WWTP #1: NS (anaerobic digestion effluent), +130% (final solids); WWTP #2: NS (anaerobic digestion effluent), NS (final solids); WWTP #3: NS (thermal hydrolysis effluent), +80.7% (anaerobic digestion), NS (final solids); WWTP #4: +107% (anaerobic digestion Effluent), NS (final solids); WWTP #5: –35% (aerobic digestion Effluent), NS (final solids); WWTP #6: –77.6% (aerobic digestion Effluent), NS (final solids) NS = change in concentration not significant and, thus, not calculated. Ultra-high performance liquid chromatograph (UHPLC) analysis	Armstrong et al. (2018)
Removal in activated sludge	64% removal secondary with activated sludge	U.S. Median % removal: primary (P): 0; activated sludge (AS): 62; trickling filter (TF): 24; oxygen activated sludge (OAS): 64; rotating biological contactor (RBC): 86; aerated lagoon (AL): 23; activated sludge and trickling filter (AS/TF): 87/72; tertiary (T): 65; 10–90% removal of DEHP within the 50 POTWs, 54% of POTWs reported ≥50% DEHP removal.	U.S. EPA (1982)
	61.7% removal	Removal efficiency: 61.7%, measured initial concentration: 40,609 ng/L, measured effluent concentration: 15,565 ng/L; experimental lab scale conventional activated sludge reactors in Canada.	Osachoff et al. (2014)
	93% removal	Activated sludge wastewater treatment plant in Denmark: 93% DEHP removal from effluent, 81% estimated overall microbial degradation of DEHP of 81%.	Roslev et al. (2007)

Endpoint	Value	Additional Information	Reference
	75%	DEHP was monitored in the influent and effluent of four sewage treatment plants in Hong Kong. Removal efficiency: Primary sedimentation *ca.* –10%; chemical enhanced primary treatment: *ca.* 65%; activated sludge: *ca.* 75%; sand filtration: *ca.* –50%; chlorination disinfection: *ca.* –25%; UV disinfection: *ca.* –15%; reverse osmosis: *ca.* –99%	Wu et al. (2017)
Removal (WWTP Anaerobic Sewage)	31.7–46.7% removal at 55 °C, 21.7–37.8% removal at 35 °C	Anaerobic sludge digestion in Spain. Removal efficiency: 31.7–46.7% under thermophilic conditions (55 °C). Removal efficiency: 21.7–37.8% under mesophilic conditions (35 °C)	Benabdallah El-Hadj et al. (2006)

7.3 Removal in Drinking Water Treatment

Drinking water in the United States typically comes from surface water (*i.e.*, lakes, rivers, reservoirs) and groundwater. Source water is pumped to drinking water treatment plants where it undergoes a series of water treatment steps before being distributed to homes and communities. In the United States, public water systems often use conventional treatment processes that include coagulation, flocculation, sedimentation, filtration, and disinfection, as required by law.

Limited information is available on the removal of DEHP in drinking water treatment plants. Based on its water solubility and log K_{OW}, DEHP in water it is expected to partition mainly to suspended solids present in 45 percent of DEHP released to water partitioning to sediments (U.S. EPA, 2012a). Based on the available information on the DEHP removal efficiency of flocculants and filtering media, DEHP is likely to be removed during drinking water treatment by sorption to suspended organic matter. Data sources reported 58.7 percent reduction in drinking water DEHP concentration from a conventional drinking water treatment effluent in China using chlorine for disinfection prior to distribution (Kong et al., 2017; Yang et al., 2014). These findings suggest that conventional drinking water treatment systems may have the potential to partially remove DEHP present in drinking water sources via sorption to suspended organic matter and filtering media and the use of disinfection technologies.

8 BIOACCUMULATION POTENTIAL OF DEHP

The presence of DEHP in several marine aquatic species in North America suggest that the substance is bioavailable in aquatic environments (Mackintosh et al., 2004). However, DEHP's water solubility of 0.003 mg/L and log K_{OC} of 5.41 to 5.95 suggest that DEHP has limited bioavailability, and therefore low bioaccumulation and biomagnification potential. EPA selected 25 overall high-quality data sources and one overall medium-quality data source reporting the aquatic bioconcentration, aquatic bioaccumulation, aquatic trophic magnification, terrestrial biota-sediment accumulation, and terrestrial bioconcentration of DEHP (Table 8-1). The available data sources discussed below, suggest that DEHP has low bioaccumulation potential in aquatic and terrestrial organisms (Adeogun et al., 2015b; Adeogun et al., 2015a; ECJRC, 2003b; Wofford et al., 1981), and no apparent biomagnification across trophic levels in aquatic food webs (Burkhard et al., 2012; Mackintosh et al., 2004).

Several studies have investigated the aquatic bioconcentration of DEHP in several aquatic species. The available data suggest that DEHP is expected to have a low bioaccumulation potential in aquatic species. Adeogun (2015a) evaluated the presence of phthalate esters in two lakes in Nigeria. The study reported DEHP fish bioconcentration (BCF) values of 0.60 to 15.18, 0.09 to 3.47, 0.66 to 9.25, 0.07 to 0.60, and 0.05 to 0.89 for tilapia, catfish, rume, snakehead, and odoe, respectively. In a similar study, Adeogun (2015b) explored the presence of phthalate esters in two lagoons in Nigeria, reporting DEHP BCFs values of 0.17 to 0.94, 0.17 to 4.31, and 0.14 to 1.61 in tilapia, catfish, and shrimp, respectively. Hayton (1990) reported DEHP BCF values of 1.6 to 51.5 in rainbow trout samples obtained from the Spokane Hatchery in Washington. The authors reported DEHP accumulation potential to decrease with an increase in trout size (BCF = 1.6 (441 ± 58 g trout), 8.9 (61 ± 5.7 g trout), and 51.5 (2.9 ± 0.6 g trout)) that could be associated with the physiological and anatomical changes during trout development (size increase). Barrows (1980) evaluated the bioconcentration and elimination of water pollutants in bluegill sunfish populations from Connecticut and Nebraska. The study reported a DEHP BCF value of 114 and a tissue half-life of 3 days. Karara (1984) developed a DEHP pharmacokinetic model for sheepshead minnow, reporting a DEHP BCF value of 637 and a depuration half-life of 38 days at 20 °C, after a 96-hour exposure period. In a separate study, the authors reported an apparent increase in DEHP accumulation as the temperature increased. The BCF values were 45, 131, and 637 at 10, 16, and 23 °C, respectively (Karara and Hayton, 1989). Wofford (1981) reported BCF values of 10.7 and 13.5 in Sheepshead Minnow after a two-hour exposure period at initial DEHP concentrations of 100 and 500 parts per billion (ppb). The same study reported BCF values of 6.9 to 11.2 and 10.2 to 16.6 for oysters and shrimp, respectively. Streufert (1980) reported BCF values of 292 and 408 in midge larvae after a DEHP exposure of 2 and 7 days, respectively. The same study reported 70 percent decrease in larval DEHP concentration after a five-day depuration period. Brown (1982) reported BCF values of 166, 140, 261, and 268 in *Daphnia magna* exposed to 3.2, 10, 32 and 100 µg/L of DEHP, respectively.

The available data sources suggest that DEHP is expected to have low bioaccumulation and food web magnification potential in marine species. Lee (2019) reported DEHP bioaccumulation factors (BAF) of 63.1, 316.2, and 1,258.93 L/kg dw for bluegill, bass, and carp/skygager, respectively. The same study reported biota-sediment accumulation factors (BSAFs) of 7.94×10^{-4} to 1.58×10^{-3} kg/kg dw for bluegill, bass, and carp/skygager. Hobson (1984) explored the toxicity of DEHP in shrimp during a 14-day dietary exposure resulting in DEHP whole-body residues of 0.249 to 18.25 parts per million (ppm). From the study, an average BAF of 0.00283 was calculated as DEHP whole-body residue per DEHP concentration in diet. Teil (2012) reported BSAF values of 1.3 ± 0.7 (49 g perch), 1.0 ± 2.7 (153 g roach), and 0.5 ± 0.7 (299 g chub) in fish samples collected from the Orge River in France. Adeogun (2015a) reported BSAF values of 0.02 to 0.8 in fish samples (tilapia, catfish, rume, snakehead, and odoe) collected from two lakes in Nigeria containing DEHP sediment concentrations of 0.95 to 1.2 mg/kg. Huang (2008) reported BSAF values of 13.8 to 40.9 (mullet), 2.4 to 28.5 (tilapia), 0.1

(seabream), and 0.9 (chub) in fish samples collected from Taiwanese rivers containing a mean sediment concentration of DEHP in of 4.1 mg/kg. Overall, the findings suggest low bioaccumulation potential in aquatic environments, but higher accumulation are expected to be seen in smaller organisms and those exposed to higher DEHP concentration in sediments. Additionally, the reported trophic magnification factors (TMF) of 0.34 and 0.4 indicate trophic dilution of DEHP from lower to higher trophic levels within the food-web (Burkhard et al., 2012; Mackintosh et al., 2004).

There is limited information on the bioconcentration and bioaccumulation of DEHP in terrestrial environments. Based on DEHP's log K_{OC} range of 5.41 to 5.95 (Williams et al., 1995) and water solubility (0.003 mg/L) (EC/HC, 2017), DEHP is expected to have low bioavailability in soils. This is supported by the reported low BCF value of 0.2 in earthworms (*Eisenia foetida*) (ECJRC, 2003b) and low BAF values of 0.073 to 0.244 and 0.97 to 1.1 in earthworms and moorfrog eggs (Hu et al., 2005; Larson and Thuren, 1987). Therefore, DEHP is expected to have low bioaccumulation and biomagnification potential in terrestrial organisms.

Sablayrolles (2013) evaluated the uptake of DEHP by tomato plants from soils amended with biosolids. The study reported BCF values of 0.006 to 0.07, 0 to 1.67, and 0 to 0.28 in tomato plant roots, leaves, and fruits, respectively. Cai (2008) evaluated the uptake of phthalic acid esters in radishes cultivated on a soil system with sewage sludge application. The study reported BCF values of 0.08 and 0.40 in the radish root and shoot, respectively. Li (2018) evaluated the uptake of phthalate esters on crops irrigated with treated sewage effluent in China. The study reported BCF values of 1.18 to 1.63 for wheat and 1.16 to 2.21 for maize, and a DEHP soil concentration of 0.64 to 1.06 mg/kg. Ma (2012) evaluated the use of alfalfa for the removal of phthatic esters from contaminated soils. The study reported BCF values of 65 to 100 in alfalfa crops growing in soil that had DEHP concentrations ranging from 0.15 to 0.25 mg/kg. The available information suggests that terrestrial plants have the potential to uptake DEHP from soil, but that DEHP is not likely to bioaccumulate (BCF <1,000) (U.S. EPA, 2012b).

Table 8-1. Summary of DEHP's Bioaccumulation Information

Endpoint	Value	Details	Reference
Aquatic			
Bioconcentration factor (BCF)	Tilapia: 0.60–15.18 Catfish: 0.09–3.47 Rume: 0.66–9.25 Snakehead: 0.07–0.60 Odoe: 0.05–0.89	Fish from Asejire Lake: muscle = 0.45 (*C. nigrodigitatus*), 0.66 (*M. rume*), 0.60 (*T. zilli*); gill = 0.57 (*C. nigrodigitatus*), 1.25 (*M. rume*), 6.66 (*T. zilli*); liver = 3.47 (*C. nigrodigitatus*), 1.05 (*M. rume*), 15.18 (*T. zilli*); kidney = 0.09 (*C. nigrodigitatus*), 9.25 (*M. rume*), 1.22 (*T. zilli*) Fish from Eleyele Lake: muscle = 0.05 (*H. odoe*), 0.60 (*P. obscura*), 0.48 (*T. zilli*); gill = 0.32 (*H. odoe*), 0.07 (*P. obscura*), 0.10 (*T. zilli*); liver = 0.48 (*H. odoe*), 0.20 (*P. obscura*), 0.24 (*T. zilli*); kidney = 0.89 (*H. odoe*), 0.50 (*P. obscura*), 1.62 (*T. zilli*)	Adeogun et al. (2015a)

Endpoint	Value	Details	Reference
	Tilapia: 0.17–0.94 Catfish: 0.17–4.31 Shrimp: 0.14 –1.61	Tilapia (*T. guineensis*) BCF: muscle = 0.46 (L) and 0.41 (E); gill = 0.21 (L) and 0.52 (E); liver =0.50 (L) and 0.17 (E); kidney = 0.94 (L) and 0.17 (E) Catfish (*C. nigrodigitatus*) BCF: muscle = 0.41 (L) and 1.06 (E); gill = 0.27 (L) and 0.66 (E); liver = 0.73 (L) and 0.17 (E); kidney = 4.31 (L) and 0.32 (E); shrimp (*M. vollenhovenii*); BCF = whole body = 1.61 (L) and 0.14 (E) L = Lagos and E = Epe	Adeogun et al. (2015b)
	Midge larvae: 292–408	Midge larvae (*Chironomus plumosus*) BCF after 2 days (wet weight): 292, BCF after 7 days (wet weight): 408 Elimination: 30% decrease after 1 day, 50% decrease after 3.4 days, 70% decrease after 5 days	Streufert et al. (1980)
	Bluegill sunfish (*L. macrochirus*): 114	$t_{1/2}$ = 3 days; following the apparent equilibrium or 28-day exposure period fish were transferred to pollutant free aquarium; sample days 1, 2, 4, and 7	Barrows et al. (1980)
	Daphnia magna: 140–268	BCF = 166, 140, 261, and 268 at test substance concentration of 3.2, 10, 32 and 100 µg/L, respectively	Brown and Thompson (1982)
	Rainbow trout (*S. gairdneri*): 1.6, 8.9, and 51.5	Use of fry or minnows to predict bioconcentration may not accurately reflect accumulation in larger fish. BCF = 1.6 (441±58 g trout), 8.9 (61±5.7 g trout), and 51.5 (2.9±0.6 g trout)	Hayton et al. (1990)
	Sheepshead minnow: 45–637	Model-predicted BCF of 45, 131, and 637 at 10, 16, and 23 °C, respectively, for sheepshead minnow (*Cyprinodon variegatus*)	Karara and Hayton (1989) Karara and Hayton (1984)
	Oyster: 6.9–11.2 Shrimp: 10.2– 16.6 Sheepshead minnow:10.7–13.5	American oyster: BCF = 11.2 ± 3.3 (100 ppb) and 6.9 ± 2.2 (500 ppb); brown shrimp: BCF = 10.2 ± 0.5 (100 ppb) and 16.6 ± 12.9 (500 ppb); sheepshead minnow: BCF = 10.7 (100 ppb) and 13.5 (500 ppb)	Wofford et al. (1981)

Endpoint	Value	Details	Reference
		Biodegradability index (ratio of metabolites to unmetabolized diester, average of exposures): 0.29 (oyster), 0.86 (shrimp), 13.67 (fish)	
Bioaccumulation factor (BAF)	Shrimp (*P. vannamei*): 0.00283 (Mean)	Bioaccumulation factor calculated as whole-body residue/analytical test substance concentration in diet. BAF = 0.00566, 0.00209, 0.00742, 0.000934, 0.000487, and 0.000363; mean BAF = 0.00283	Hobson et al. (1984)
	Bluegill: 63.1 Bass: 316.2 Carp: 1259 Skygager: 1259	Bluegill: 63.1 L/kg dw; bass: 316.2 L/kg dw; crucian carp and skygager: 1258.93 L/kg dw	Lee et al. (2019)
Biota-Sediment accumulation factor (BSAF)	Bluegill: 1.26E–03 Bass: 7.94E–04 Carp: 1.58E–03 Skygager: 1.58E–03	Bass: 7.94E–04 kg/kg dw; bluegill: 1.26E–03 kg/kg dw; crucian carp and skygager: 1.58E–03 kg/kg dw	Lee et al. (2019)
	Tilapia: 0.03–0.8 Catfish: 0.02–0.20 Rume: 0.06–0.53 Snakehead: 0.02–0.22 Odoe: 0.02–0.34	Fish From Asejire Lake: muscle = 0.02 (*C. nigrodigitatus*), 0.03 (*M. rume)*, 0.03 (*T. zilli*); gill = 0.03 (*C. nigrodigitatus*), 0.07 (*M. rume*), 0.38 (*T. zilli*); Liver = 0.20 (*C. nigrodigitatus*), 0.06 (*M. rume*), 0.88 (*T. zilli*); kidney = 0.05 (*C. nigrodigitatus*), 0.53 (*M. rume*), 0.07 (*T. zilli*); DEHP concentration in sediment = 1.2 mg/kg Fish From Eleyele Lake: Muscle = 0.02 (*H. odoe*), 0.22 (*P. obscura*), 0.18 (*T. zilli*); gill = 0.12 (*H. odoe*), 0.02 (*P. obscura*), 0.04 (*T. zilli*); liver = 0.18 (*H. odoe*), 0.07 (*P. obscura*), 0.09 (*T. zilli*); kidney = 0.34 (*H. odoe*), 0.19 (*P. obscura*), 0.62 (*T. zilli*); concentration of DEHP in sediment = 0.95 mg/kg	Adeogun et al. (2015a)
	Chironomus riparius larvae: 1.46 (mean)	BSAF based on the concentration in animal tissue dry weight (mg/kg)/concentration in sediment dry weight (mg/kg): Treatment 1: 160/100 = 1.6 Treatment 2: 1,400/1,000 = 1.4 Treatment 2: 14,000/10,000 = 1.4	Brown et al. (1996)

Endpoint	Value	Details	Reference
		Mean BSAF = 1.46 ≈ 1.5	
	Greenback mullet (*L. subviridis*): 13.8–40.9 Tilapia: 2.4–28.5 Seabream: 0.1 Chub: 0.9	Greenback mullet (*L. subviridis*): 13.8–40.9; Tilapia (*O. niloticus*): 2.4–28.5; Black seabream (*A. schlegeli*): 0.1; Pale chub (*Z. platypus*): 0.9; mean concentration of DEHP in sediment = 4.1 mg/kg	Huang et al. (2008)
	Fish: 0.5–1.3	Roach: 1.0 ± 2.7, Chub: 0.5 ± 0.7, and Perch: 1.3 ± 0.7	Teil et al. (2012)
Trophic magnification factor (TMF)	0.4	Moderate biotransformation rate with a reported half-life of 2.8 days. TMF determined from measured biomonitoring data in 171 reports. Reported TMF (<1.0) indicates trophic dilution, substantial biotransformation.	Burkhard et al. (2012)
	0.34	18 marine species, lower-upper 95% interval (0.18–0.64). Reported TMF (food-web magnification factor < 1.0) indicates trophic dilution, 66% loss of DEHP moving up one trophic level.	Mackintosh et al. (2004)
Terrestrial			
Bioconcentration factor (BCF)	Wheat: 1.18–1.63 Maize: 1.16–2.21	Winter wheat (*Triticum aestivum L.*): 1.42 and 1.55 (reclaimed water), 1.43 and 1.63 (mixed water), 1.18 and 1.30 (groundwater); DEHP Soil concentration of 1.01–2.39 mg/kg Summer maize (*Zea mays L.*): 1.16 (reclaimed water), 1.90 (mixed water), 2.21 (ground water); DEHP Soil concentration of 0.64-1.06 mg/kg	Li et al. (2018)
	Earthworm: 0.2	Earthworm (*Eisenia foetida*): 0.2 (dw), 0.034 (wet weight, converted from 0.15 conversion factor). Assuming a typical dry to wet weight conversion factor of 0.15 for earthworms and of 0.88 for soil, a BCF of 0.034 based on wet weights can be derived.	ECJRC (2003b)

Endpoint	Value	Details	Reference
	Radish: 0.08–0.40	Radish (*Raphanus sativus*): 0.40 (shoot), 0.08 (root); Control (100% soil), application rates of 10, 20, and 40 g/kg soil of sewage sludge (4.4 mg/kg DEHP), and application rate of 10 g/kg soil sludge compost (16 mg/kg DEHP)	Cai et al. (2008)
	Pondweed: 67.4–157.6 L/kg (plant concentration factor)	Pondweed Plant– uptake: 0.762/d, plant release: 0.572/d, microbial degradation in water: 0.082/d, plant degradation: 0.012/d	Chi and Gao (2015)
	Alfalfa: 65–100	BCF - approximation from bar graph (treatment condition) = 100 (A), 90 (AS-S), 100 (AS-A), 90 (AE-E), 100 (AE-A), 50 (AES-S), 65 (AES-E), 95 (AES-A) Phytoremediation of phthalates with alfalfa monoculture (A); alfalfa and *E. splendors* intercropping (AE); alfalfa and *S. plumbizincicola* intercropping (AS); and alfalfa, *E. splendors*, and *S. plumbizincicola* intercropping (AES); approximated DEHP soil concentration of 0.15–0.25 mg/kg.	Ma et al. (2012)
	Tomato plant: 0.006–0.07 (root) 0–1.67 (leaves) 0–0.28 (fruit)	Tomato plant (*Lycopersicon esculentum cv*): BCF data - Aquiculture - pure substances experiment BCF = root: 0.02, leaves: 0, fruits: 0; sludge filtrate experiment BCF = root: 0.006, leaves: 0.0007, fruits: 0.0003; soil culture - Biosolids A experiment BCF = root: 0.002, leaves: 0.03, fruits: 0.05; Biosolids B experiment BCF = root: 0.07, leaves: 1.67, fruits: 0.28; Biosolids C experiment BCF = root: 0.003, leaves: 0.16, fruits: 0.04	Sablayrolles et al. (2013)
	Lettuce:1.31–1.75 Strawberry:1.38–1.95 Carrot: 2.42–2.74	Lettuce leaf 1.31 ± 0.41; strawberry leaf 1.38 ± 0.19; carrot leaf 2.42 ± 0.46; lettuce root 1.75 ± 0.45; strawberry root 1.95 ± 0.41; carrot root 2.74 ± 0.19; 28-day exposure to DEHP nominal concentration of 500 µg/kg dry weight.	Sun et al. (2015)
Terrestrial biota-soil accumulation factor (BSAF)	Earthworms: 0.073–0.244	Earthworms (*E. fetida*) BSAF = 0.244 (soil 1); 0.073 (soil 2); organic matter: Soil 1 = 1.35%, Soil 2 = 4.53%; pH: Soil 1 = 7.58; Soil 2 = 8.28	Hu et al. (2005)

Endpoint	Value	Details	Reference
	Moorfrog: 0.97–1.1	Moorfrog (*Rana arvalis*) eggs: 0.97 (partitioning coefficient between sediment and tadpoles), 1.1 (partitioning coefficient based on uptake from water)	Larson and Thuren (1987)

9 OVERALL FATE AND TRANSPORT OF DEHP

The inherent physical and chemical properties of DEHP govern its environmental fate and transport. Based on DEHP's aqueous solubility, slight tendency to volatilize, and strong affinity for organic carbon, this chemical substance will preferentially partition to sediments, soils, and suspended solids in wastewater treatment processes. Soil, sediment, and sludge/biosolids are predicted to be the major compartments for DEHP as indicated by its physical and chemical and fate properties, and partitioning analysis. The designation of these major compartments is supported by monitoring studies that confirm the presence of DEHP. Surface water is expected to be a minor compartment despite it being the main receiving media for phthalates remaining in effluent discharged from wastewater treatment plants. In addition, phthalates in surface water will sorb strongly to suspended and benthic sediments. In areas where continuous releases of phthalates occur, higher levels of phthalates in surface water can be expected, trending downward distally from the point of releases. This concentration gradient also occurs for suspended and benthic sediments. Furthermore, biodegradation of DEHP is inhibited in anoxic environments (*i.e.*, sediments and landfills), and like other phthalates, it is expected to hydrolyze slowly and be very persistent in anaerobic environments.

If DEHP is released directly to the atmosphere, it is expected to adsorb to particulate matter. DEHP is not expected to undergo long-range transport facilitated by particulate matter due to the relatively rapid rates of both direct and indirect photolysis. Atmospheric concentrations of DEHP may be elevated proximal to sites of releases. However, off-gassing from landfills and volatilization from wastewater treatment processes are expected to be negligible sources of atmospheric DEHP due to its low vapor pressure and rapid photodegradation rates. Thus, DEHP is not expected to be a candidate chemical for long-range transport.

In indoor environments, DEHP released to air is expected to partition to airborne particles at concentrations three times higher than in vapor phase (ECJRC, 2003a) and is expected to have longer lifetime than in the atmosphere. The available information suggests that DEHP's indoor dust concentrations are correlated with the presence of phthalate-containing articles and the proximity to the facilities producing them (Kubwabo et al., 2013; Wang et al., 2013; Abb et al., 2009) as well as daily anthropogenic activities that might introduce DEHP-containing products indoors (Dodson et al., 2017).

In situations where aerobic conditions persist, DEHP is expected to degrade rapidly. In environments where anoxic conditions persist, such as sediments, landfills, and some soils, DEHP may be persistent since it is resistant to anaerobic biodegradation. In anaerobic environments, such as deep landfill zones, DEHP may be degraded by catalyzed hydrolysis.

10 WEIGHT OF THE SCIENTIFIC EVIDENCE CONCLUSIONS FOR FATE AND TRANSPORT

10.1 Strengths, Limitations, Assumptions, and Key Sources of Uncertainty for the Fate and Transport Assessment

Given the consistent results from numerous high-quality studies, there is a robust confidence that DEHP:

- is expected to undergo significant direct photolysis (Section 4.3);
- will partition to organic carbon and particulate matter in air (Sections 5 and 6.1);
- will biodegrade in aerobic surface water, soil, and wastewater treatment processes (Sections 0, 6.2.1, 6.3.2, and 7.2);
- does not biodegrade in anaerobic environments (Sections 0, 6.2, and 6.3);
- will be removed after undergoing wastewater treatment primarily via sorption to sludge at high fractions, with a small fraction being present in effluent (Section 7.2);
- is not bioaccumulative (Section 8);
- is not expected to biodegrade under anoxic conditions and may have high persistence in anaerobic soils and sediments (Sections 0, 6.2.2, and 6.3.2); and
- may show persistence in surface water and sediment proximal to continuous points of release (Sections 0, 6.2.2, and 6.3.2).

As a result of limited studies identified, there is a moderate confidence that DEHP:

- showed no significant degradation via hydrolysis under standard environmental conditions, but hydrolysis rate was seen to increase with increasing pH and temperature in deep-landfill environments (Section 6.3.3); and
- is expected to be removed in conventional drinking water treatment systems by standard treatment process, and via reduction by chlorination and chlorination byproducts in post-treatment storage and drinking water conveyance (Section 7.3).

The findings that were found to have a robust weight of evidence supporting them had one or more high-quality studies that were largely in agreement with each other. The findings that were said to have a moderate weight of evidence were based on a mix of high- and medium-quality studies that were largely in agreement, but varied in sample size and consistency of findings.

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