1 Introduction

This section introduces the concerns arising from the 2020 discovery of 6PPD-q. It summarizes the discovery of 6PPD-q and its toxic effects, the identification of vehicle tires as the source of 6PPD-q and reasons for the continued use of 6PPD, transport and exposure pathways, the impacts to both fish and human populations, detection of 6PPD-q in the environment, and solutions and approaches for mitigation, This section also provides an overview of topics for which information is lacking and a summary of how decision-makers might address 6PPD-q and use this document as a resource.

1.1 Summary: What Is 6PPD-q and What Is the Concern?

1.1.1 Overview

For decades, adult coho salmon (*Oncorhynchus kisutch*) in the Pacific Northwest have been dying en masse in urbanized areas when storms coincide with their migration upstream to spawn. Because of the correlation with rain events and a series of insightful investigations, the mortality seemed linked to contamination in stormwater runoff from roads (McIntyre et al. 2018 [G7QW7PSD] McIntyre, Jenifer, Jessica Lundin, James Cameron, et al. 2018. “Interspecies Variation in the Susceptibility of Adult Pacific Salmon to Toxic Urban Stormwater Runoff.” Environmental Pollution 238: 196–203. https://doi.org/https://doi.org/10.1016/j.envpol.2018.03.012. Chow et al. 2019 [7RMZ3UNQ] Chow, Michelle I., Jessica I. Lundin, Chelsea J. Mitchell, et al. 2019. “An Urban Stormwater Runoff Mortality Syndrome in Juvenile Coho Salmon.” Aquatic Toxicology 214 (September): 105231. https://doi.org/10.1016/j.aquatox.2019.105231. Spromberg et al. 2016 [GI97QYN4] Spromberg, Julann A., David H. Baldwin, Steven E. Damm, et al. 2016. “Coho Salmon Spawner Mortality in Western US Urban Watersheds: Bioinfiltration Prevents Lethal Storm Water Impacts.” Journal of Applied Ecology 53 (2): 398–407. https://doi.org/https://doi.org/10.1111/1365-2664.12534.). Researchers named the phenomenon urban runoff mortality syndrome (URMS) (McIntyre et al. 2021 [MVL2LKBM] McIntyre, Jenifer K., Jasmine Prat, James Cameron, et al. 2021. “Treading Water: Tire Wear Particle Leachate Recreates an Urban Runoff Mortality Syndrome in Coho but Not Chum Salmon.” Environmental Science & Technology 55 (17): 11767–74. https://doi.org/10.1021/acs.est.1c03569.; Huang et al. 2021 [EZEWIV8E] Huang, Wei, Yumeng Shi, Jialing Huang, et al. 2021. “Occurrence of Substituted p-Phenylenediamine Antioxidants in Dusts.” Environmental Science & Technology Letters 8 (5): 381–85. https://doi.org/10.1021/acs.estlett.1c00148. Jin et al. 2023 [P9WXQJUR] Jin, Ruihe, Yan Wu, Qun He, et al. 2023. “Ubiquity of Amino Accelerators and Antioxidants in Road Dust from Multiple Land Types: Targeted and Nontargeted Analysis.” Environmental Science & Technology 57 (28): 10361–72. https://doi.org/10.1021/acs.est.3c01448.). According to the Washington State Department of Ecology (WA Ecology), “…for over 20 years, scientists faced a mystery: coho salmon (also known as silver salmon) returning to urban streams and rivers in the Puget Sound region were dying before they could lay their eggs. The culprit was unknown, but it seemed linked to toxic chemicals running off our roads and highways” (Flores 2023 [KYFH4S96] Flores, Mugdha. 2023. “Saving Washington’s Salmon from Toxic Tire Dust.” January. https://ecology.wa.gov/blog/january-2023/saving-washington-s-salmon-from-toxic-tire-dust.). In some cases, 90% mortality of returning coho salmon was observed (Huang et al. 2021 [EZEWIV8E] Huang, Wei, Yumeng Shi, Jialing Huang, et al. 2021. “Occurrence of Substituted p-Phenylenediamine Antioxidants in Dusts.” Environmental Science & Technology Letters 8 (5): 381–85. https://doi.org/10.1021/acs.estlett.1c00148. Jin et al. 2023 [P9WXQJUR] Jin, Ruihe, Yan Wu, Qun He, et al. 2023. “Ubiquity of Amino Accelerators and Antioxidants in Road Dust from Multiple Land Types: Targeted and Nontargeted Analysis.” Environmental Science & Technology 57 (28): 10361–72. https://doi.org/10.1021/acs.est.3c01448.).

In 2020, Z. Tian et al. (2021) identified a transformation product of 6PPD (Figure 1-1), 6PPD-q (Figure 1-2), as a causative toxicant of URMS observed in coho salmon in Washington State. 6PPD supports the durability and safety of tires and is used as the primary anti-degradant that prevents the breakdown of rubber resulting from reactions with atmospheric ozone (Rossomme et al. 2023 [AXGUT6MJ] Rossomme, Elliot, William M. Hart-Cooper, William J. Orts, Colleen M. McMahan, and Martin Head-Gordon. 2023. “Computational Studies of Rubber Ozonation Explain the Effectiveness of 6PPD as an Antidegradant and the Mechanism of Its Quinone Formation.” Environmental Science & Technology, March 24, acs.est.2c08717. https://doi.org/10.1021/acs.est.2c08717.; Tian et al. 2022 [BICQHLBC] Tian, Zhenyu, Melissa Gonzalez, Craig A. Rideout, et al. 2022. “6PPD-Quinone: Revised Toxicity Assessment and Quantification with a Commercial Standard.” Environmental Science & Technology Letters, ahead of print, January 11. https://doi.org/10.1021/acs.estlett.1c00910.), oxygen (Santoso et al. 2007 [GZL3D5KN] Santoso, M., U. Giese, and R. H. Schuster. 2007. Investigations on Initial Stage of Aging of Tire Rubbers by

Chemiluminescence Spectroscopy. 80: 762–76.

https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/5714930.), and free radicals (Scott 1985 [6SJ7VVGU] Scott, Gerald. 1985. “A Review of Recent Developments in the Mechanisms of Antifatigue Agents.” Rubber Chemistry and Technology 58 (2): 269–83. https://doi.org/10.5254/1.3536065.). 6PPD is used in every tire on the road (USTMA 2024 [372BNAEP] USTMA. 2024. USTMA Consortium Preliminary (Stage 1) Alternatives Analysis Report for CA DTSC. https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf.), creating the possibility of widespread contamination by 6PPD and 6PPD-q in every area impacted by roads.

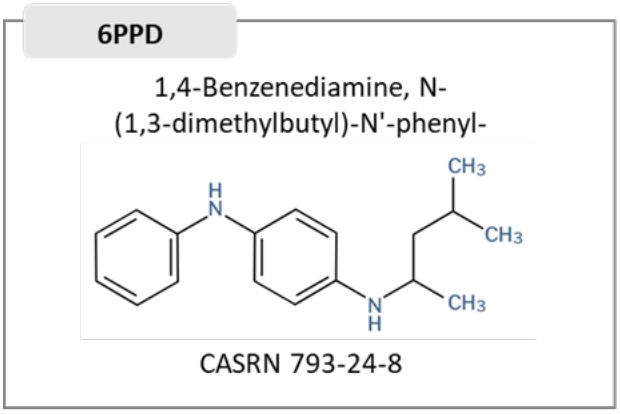


Figure 1-1 Chemical structure of 6PPD

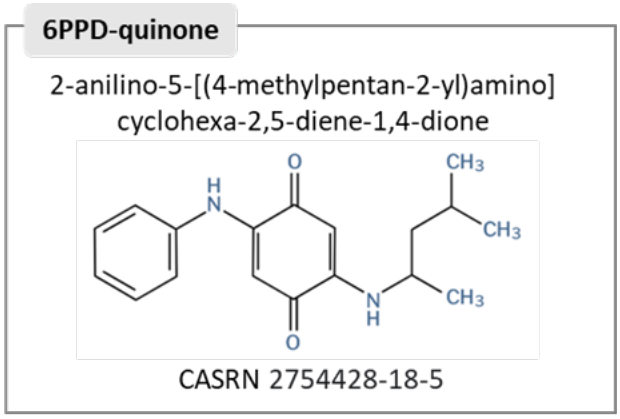


Figure 1-2 Chemical structure of 6PPD-quinone

For more on the discovery of 6PPD-q and how this approach could be used to identify contaminants causing toxic effects, please see the ITRC case study from the Contaminants of Emerging Concern Team.

The identification of 6PPD-q has also generated concerns about the toxicity of the parent 6PPD compound itself. Throughout this document, we will highlight information about each chemical as appropriate (see also Section 3: Chemical Properties. Evaluating both these chemicals is important for estimating and evaluating toxicity and hazard, for understanding environmental fate and transport, and for developing solutions to mitigate the harm caused by 6PPD-q (ITRC 2022 [NBCYMAJE] ITRC. 2022. “PFAS Technical and Regulatory Guidance Document and Fact Sheets.” Washington D.C.: Interstate Technology & Regulatory Council, PFAS Team. https://pfas-1.itrcweb.org/.).

In addition to coho (also known as silver) salmon, 6PPD-q has been found to be lethal to brook trout *(Salvelinus fontinalis)* (Brinkmann et al. 2022 [QN6HYEV7] Brinkmann, Markus, David Montgomery, Summer Selinger, et al. 2022. “Acute Toxicity of the Tire Rubber–Derived Chemical 6PPD-Quinone to Four Fishes of Commercial, Cultural, and Ecological Importance.” Environmental Science & Technology Letters, March 2, acs.estlett.2c00050. https://doi.org/10.1021/acs.estlett.2c00050.); lake trout *(Salvelinus namaycush)* (Roberts et al. 2024 [FMG8VP7Y] Roberts, Catherine, Junyi Lin, Evan Kohlman, et al. 2024. “Acute and Sub-Chronic Toxicity of 6PPD-Quinone to Early-Life Stage Lake Trout (Salvelinus namaycush).” Preprint, bioRxiv, April 3. https://doi.org/10.1101/2024.03.26.586843.); coastal cutthroat trout *(Oncorhynchus clarkii clarkii)* (Shankar et al. 2024 [FBNQNIWI] Shankar, Prarthana, Ellie M. Dalsky, Joanne E. Salzer, et al. 2024. “Evaluation of Lethal and Sublethal Effects of 6PPD-Q on Coastal Cutthroat Trout (Oncorhynchus Clarkii Clarkii).” U.S. Geological Survey. Csv,xml. https://doi.org/10.5066/P16SMKIJ.); rainbow trout *(Oncorhynchus mykiss)* (Nair et al. 2023 [9V5ES4MI] Nair, Pranav, Jianxian Sun, Linna Xie, et al. 2023. “In Process: Synthesis and Toxicity Evaluation of Tire Rubber–Derived Quinones.” Preprint. Chemistry, June 20. https://doi.org/10.26434/chemrxiv-2023-pmxvc. Brinkmann et al. 2022 [QN6HYEV7] Brinkmann, Markus, David Montgomery, Summer Selinger, et al. 2022. “Acute Toxicity of the Tire Rubber–Derived Chemical 6PPD-Quinone to Four Fishes of Commercial, Cultural, and Ecological Importance.” Environmental Science & Technology Letters, March 2, acs.estlett.2c00050. https://doi.org/10.1021/acs.estlett.2c00050.; (Huang et al. 2021 [EZEWIV8E] Huang, Wei, Yumeng Shi, Jialing Huang, et al. 2021. “Occurrence of Substituted p-Phenylenediamine Antioxidants in Dusts.” Environmental Science & Technology Letters 8 (5): 381–85. https://doi.org/10.1021/acs.estlett.1c00148. Jin et al. 2023 [P9WXQJUR] Jin, Ruihe, Yan Wu, Qun He, et al. 2023. “Ubiquity of Amino Accelerators and Antioxidants in Road Dust from Multiple Land Types: Targeted and Nontargeted Analysis.” Environmental Science & Technology 57 (28): 10361–72. https://doi.org/10.1021/acs.est.3c01448.); and white-spotted char *(Salvelinus leucomaenis)*, an Asiatic species (Hiki and Yamamoto 2022 [VQE4EZWI] Hiki, Kyoshiro, and Hiroshi Yamamoto. 2022. “The Tire-Derived Chemical 6PPD-Quinone Is Lethally Toxic to the White-Spotted Char Salvelinus

leucomaenis pluvius but Not to Two Other Salmonid Species." Environmental Science & Technology Letters 9 (12): 1050–55. https://doi.org/10.1021/acs.estlett.2c00683.). Steelhead, the ocean-going (or anadromous) form of rainbow trout, have not been specifically tested for toxicity effects when exposed to 6PPD-q, but French et al. (2022) observed mortality in steelhead *(O. mykiss)* treated with roadway runoff. Some acute mortality from 6PPD-q exposure is seen in juvenile Chinook salmon or king salmon *(Oncorhynchus tshawytscha)* (Lo et al. 2023 [LA4CEWYX] Lo, Bonnie P., Vicki L. Marlatt, Xiangjun Liao, et al. 2023. "Acute Toxicity of 6PPD-Quinone to Early Life Stage Juvenile Chinook (Oncorhynchus tshawytscha) and Coho (Oncorhynchus kisutch) Salmon." Environmental Toxicology and Chemistry 42 (4): 815–22. https://doi.org/10.1002/etc.5568.); however, results are mixed (Montgomery et al. 2023 [X3FANIWH] Montgomery, David, Xiaowen Ji, Jenna Cantin, et al. 2023. "Not Yet Peer Reviewed: Toxicokinetic Characterization of the Inter-Species Differences in 6PPD-Quinone Toxicity Across Seven Fish Species: Metabolite Identification and Semi-Quantification." Preprint, bioRxiv, August 20. https://doi.org/10.1101/2023.08.18.553920. Greer et al. 2023 [P6RF5UFR] Greer, Justin B., Ellie M. Dalsky, Rachael F. Lane, and John D. Hansen. 2023. "Establishing an In Vitro Model to Assess the Toxicity of 6PPD-Quinone and Other Tire Wear Transformation Products." Environmental Science & Technology Letters, ahead of print, May 2. https://doi.org/10.1021/acs.estlett.3c00196.), and effects have not been observed at environmentally relevant concentrations (see Section 4: Occurrence, Fate, Transport, and Exposure Pathways). Table 1-1 summarizes acute toxicities for some salmonids.[1] Additional details on toxicity research is available in Section 2: Effects Characterization and Toxicity of this document.

Table 1-1. Acute toxicity of 6PPD-quinone to various salmonids

Species	LC_{50} (µg/L)	Test duration (hours)	Toxicity key
Coho salmon (*Oncorhynchus kisutch*)	0.04 (Lo et al. 2023) 0.08 (Greer et al. 2023a) 0.095 (Z. Tian et al. 2022)	24	Higher
Brook trout (*Salvelinus fontinalis*)	0.2 [fry], 0.5 [fingerlings] (Philibert et al. 2024) 0.59 (Brinkmann et al. 2022)	24	
Lake trout (*Salvelinus namaycush*)	0.51 (Roberts et al. 2024)	24	
White-spotted char (*Salvelinus leucomaenis pluvius*)	0.51 (Hiki and Yamamoto 2022b)	24	
Rainbow trout/steelhead (*Oncorhynchus mykiss*)	0.64 (Nair et al. 2023) 1.0 (Brinkmann et al. 2022) 2.26 (Di et al. 2022)	96	
Chinook salmon (*Oncorhynchus tshawytscha*)	67.3 (Lo et al. 2023), 82.1 (Greer et al. 2023a)	24	
Sockeye salmon (*Oncorhynchus nerka*)	Not acutely toxic at 50 (Greer et al. 2023a)	24	
Atlantic salmon (*Salmo salar*)	Not acutely toxic at 12.2 (Foldvik et al. 2022)	48	
Brown trout (*Salmo trutta*)	Not acutely toxic at 12.2 (Foldvik et al. 2022)	48	
Arctic char (*Salvelinus alpinus*)	Not acutely toxic at 12.7 (Brinkmann et al. 2022)	24	
Westslope cutthroat trout (*Oncorhynchus clarkii lewisi*)	Not acutely toxic at 10 (Montgomery et al. 2023a)	24	
Pink salmon (*Oncorhynchus gorbuscha*)	Not acutely toxic at 12.8 (Foldvik et al. 2024)	48	Lower

Notes: µg/L=micrograms per liter. Selected salmonid species in the table are listed from very high to low across a toxicity gradient based on the LC_{50} value, with the following ratings: coho=very high; brook trout, lake trout, and white-spotted char=high; rainbow trout / steelhead=medium high; Chinook salmon, sockeye salmon, Atlantic salmon, brown trout, Arctic char, Western cutthroat trout, and pink salmon=low. For the sake of brevity, tolerant salmonids not native to North America were excluded from this table. For reference, 6PPD-q has been measured as high as 2.85 µg/L in surface water (Johannessen et al. 2022 [E9K7U5U3] Johannessen, Cassandra, Paul Helm, Brent Lashuk, Viviane Yargeau, and Chris D. Metcalfe. 2022. “The Tire Wear Compounds 6PPD-Quinone and 1,3-Diphenylguanidine in an Urban Watershed.” Archives of Environmental Contamination and Toxicology 82 (2): 171–79. https://doi.org/10.1007/s00244-021-00878-4.). For a complete list, please see Table 2-1 and Table 2-2. The LC_{50} for coastal cutthroat trout (*Oncorhynchus clarkii clarkii*) has not yet been

released, but quality-assured data showing significant toxicity was released by Shankar et al. (Shankar et al. 2024 [FBNQNIWI] Shankar, Prarthana, Ellie M. Dalsky, Joanne E. Salzer, et al. 2024. “Evaluation of Lethal and Sublethal Effects of 6PPD-Q on Coastal Cutthroat Trout (Oncorhynchus Clarkii Clarkii).” U.S. Geological Survey. Csv,xml. https://doi.org/10.5066/P16SMKIJ.).

Habitats for known sensitive fish species (for example, *O. kisutch*, *O. mykiss, O. clarkii clarkii*, S. fontinalis, and S. namaycush*) are geographically dispersed across the United States. The composite map (Figure 1-3) shows native habitats for four of the fish species in blue, and non-native (i.e., introduced) habitats are shown as rust colored. It is important to note that while this map represents the nationwide distribution of sensitive fish species, the amount of chemical in the local waterway will determine whether there are effects on fishes in these habitats. See Section 5: Measuring, Mapping, and Modeling for more information.

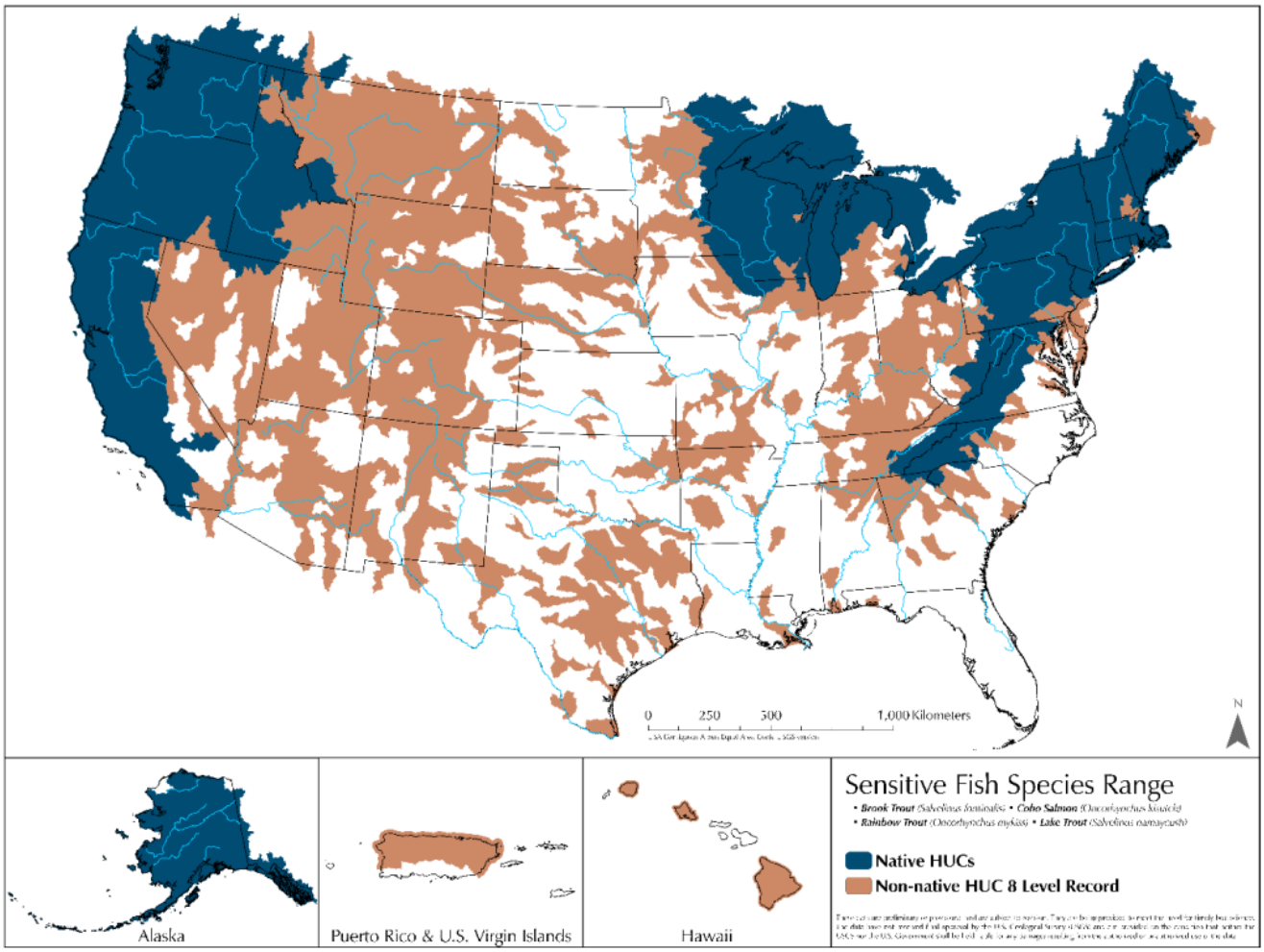


Figure 1-3. Aggregated range for 6PPD-q sensitive fish species: coho salmon (*Oncorhynchus kisutch*), rainbow trout/steelhead *(Oncorhynchus mykiss)*, brook trout *(Salvelinus fontinalis*) and lake trout *(Salvelinus namaycush)*. When native and non-native habitat overlap for the different species, the native habitat is indicated. Habitats are organized by hydrologic unit code (HUC), which indicates nested watersheds that are categorized by the U.S. Geological Survey (USGS). *Coastal cutthroat trout *(Oncorhynchus clarkii clarkii)* range was not specifically included in this map because the data indicating their sensitivity to 6PPD-q became available late in the production of this document (Shankar et al. 2024 [FBNQNIWI] Shankar, Prarthana, Ellie M. Dalsky, Joanne E. Salzer, et al. 2024. “Evaluation of Lethal and Sublethal Effects of 6PPD-Q on Coastal Cutthroat Trout (Oncorhynchus Clarkii Clarkii).” U.S. Geological Survey. Csv,xml. https://doi.org/10.5066/P16SMKIJ.). Their native range largely occurs within the native ranges of coho and rainbow trout/steelhead.

1.1.2 Short History of 6PPD in Tires

6PPD is the most widely used anti-degradant in tires (Gradient 2024 [LHN7K744] Gradient. 2024. Preliminary (Stage 1) Alternatives Analysis Report: Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N’-Phenyl-p-Phenylenediamine (6PPD).

https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf.). It belongs to the chemical class *para*-phenylenediamines (PPDs), which are broadly used as antioxidants or antiozonants in rubber and other products (Gradient 2024 [LHN7K744] Gradient. 2024. Preliminary (Stage 1) Alternatives Analysis Report: Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N'-Phenyl-p-Phenylenediamine (6PPD). https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf.). 6PPD is an efficient anti-degradant, reacting with oxygen and ozone to limit weathering and degradative oxidation of tire rubber (Figure 1-4) (Rossomme et al. 2023 [AXGUT6MJ] Rossomme, Elliot, William M. Hart-Cooper, William J. Orts, Colleen M. McMahan, and Martin Head-Gordon. 2023. "Computational Studies of Rubber Ozonation Explain the Effectiveness of 6PPD as an Antidegradant and the Mechanism of Its Quinone Formation." Environmental Science & Technology, March 24, acs.est.2c08717. https://doi.org/10.1021/acs.est.2c08717.; (Hu et al. 2022 [ZYXPMXFA] Hu, Ximin, Haoqi Nina Zhao, Zhenyu Tian, Katherine T. Peter, Michael C. Dodd, and Edward P. Kolodziej. 2022. "Transformation Product Formation upon Heterogeneous Ozonation of the Tire Rubber Antioxidant 6PPD (N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine)." Environmental Science & Technology Letters, ahead of print, April 12. https://doi.org/10.1021/acs.estlett.2c00187.); Santoso et al. 2007 [GZL3D5KN] Santoso, M., U. Giese, and R. H. Schuster. 2007. Investigations on Initial Stage of Aging of Tire Rubbers by Chemiluminescence Spectroscopy. 80: 762–76. https://hero.epa.gov/hero/index.cfm/reference/details/reference_id/5714930.). The addition of 6PPD prevents hardening of rubber compounds in the tire, including treads, and thus improves tire wear life and contributes to consistent traction over the lifetime of the tire (Pulford 1983 [RFZN73MA] Pulford, C. 1983. Antioxidant Effects during Blade Abrasion of Natural Rubber. 28: 709–13.).

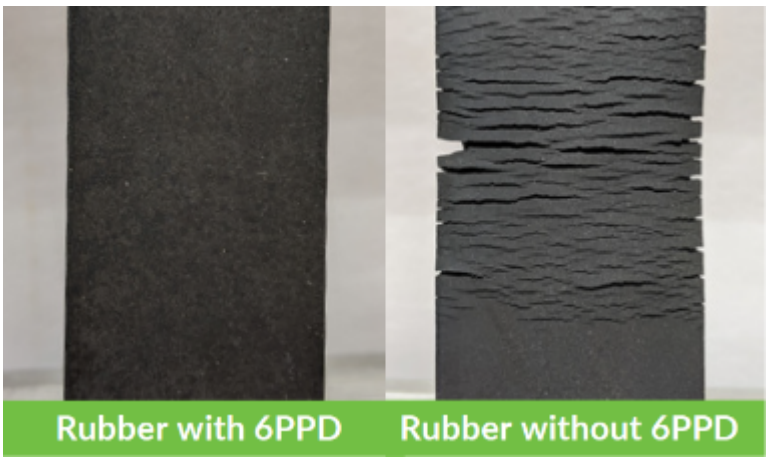


Figure 1-4 Aged rubber with and without 6PPD.
SOURCE: U.S. Tire Manufacturers Association, used with permission.

In addition to providing direct protection to the exterior of the tire against oxygen and ozone, 6PPD also protects internal components of the tire from heat and free radicals that can degrade the tire throughout its life (Kuczkowski 1990 [GJD3TURD] Kuczkowski, J. A. 1990. "Effects of Ozone on Tires and the Control of These Effects." In Ozone Risk Communication and Management, Gilbert, C. E., Beck, B. D., Calabrese, E. J. (eds.). Taylor & Francis. Huntink, N.M. and Datta, R.N. 2003 [RTIIEIBC] Huntink, N.M., and Datta, R.N. 2003. "A Novel Slow Release Antidegradant for the Rubber Industry—Part 1: Migration Behavior of Newly Developed Anti-Ozonant Compared to Conventional Antidegradants." Kautschuk Gummi Kunststoffe 56 (6): 310–15. Chasar and Layer 2010 [HM7KYWSL] Chasar, DW, and R. W. Layer. 2010. "Basic Rubber Compounding." In The Vanderbilt Rubber Handbook, 14th ed. M.F. Sheridan (Ed.). R.T. Vanderbilt Company.). Due to this protective effect against rubber degradation, 6PPD is currently critical to tire durability and ultimately to motor vehicle safety (Gradient 2024 [LHN7K744] Gradient. 2024. Preliminary (Stage 1) Alternatives Analysis Report: Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N'-Phenyl-p-Phenylenediamine (6PPD). https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf.). Over time, the amount of 6PPD in the tire decreases as it reacts with ozone and oxygen, triggering aging. The weathered tire eventually starts to crack, harden, and lose strength. 6PPD is consumed as it reacts, and 6PPD-q is one of the transformation products (Figure 1-5).

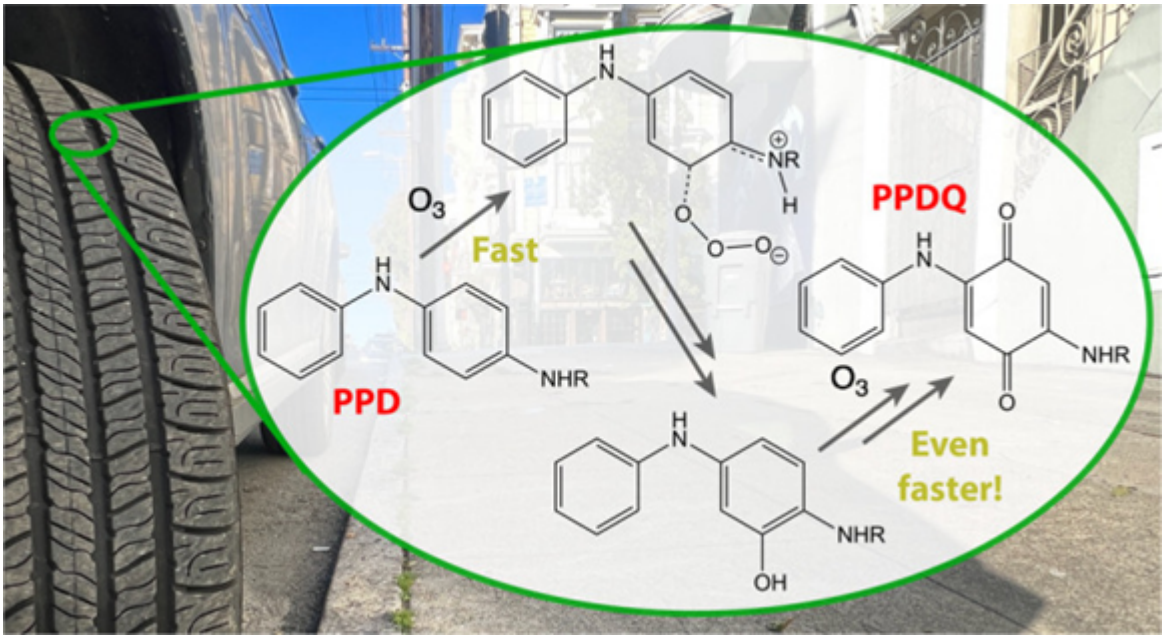


Figure 1-5: 6PPD is consumed when it reacts with ozone. In this figure, 6PPD is represented as PPD and 6PPD-q is represented as PPDQ. PPD reacts with ozone, forming short-lived intermediates (unlabeled), and ultimately yields PPDquinone. Other reactions between ozone and 6PPD also occur (Hu et al. 2023 [BFCN5BLS] Hu, Ximin, Haoqi (Nina) Zhao, Zhenyu Tian, Katherine T. Peter, Michael C. Dodd, and Edward P. Kolodziej. 2023. "Chemical Characteristics, Leaching, and Stability of the Ubiquitous Tire Rubber–Derived Toxicant 6PPD-Quinone." Environmental Science: Processes & Impacts 25 (5): 901–11. https://doi.org/10.1039/D3EM00047H.).
SOURCE: Rossomme et al. (2023), used with permission CC-BY 4.0.

Prior to the development of the PPD family of antiozonants, there was often "rapid deterioration and loss of physical properties which caused failures in rubber goods" (Kuczkowski 1989 [IDS6JDJZ] Kuczkowski, J. A. 1989. "The Inhibition of Oxidative and Ozonic Processes in Elastomers." In Oxidation Inhibition in Organic Materials, J. Pospisil and P.P Klemchuk (eds.). Taylor & Francis. https://books.google.com/books?id=HEOnh9bgu0IC.). The effect of ozone on the degradation of tire-rubber compounds was not fully understood until the 1930s. At that time, a typical tire lasted only 10,000 miles or roughly two years. In the 1930s, waxes were identified as a static ozone protector for rubber compounds, but wax did not work for products that required dynamic applications, where the rubber stretches and flexes when in use, like a tire. Failure of tires and other rubber parts on military vehicles, which were stored from World War II and placed into service for the Korean War, led the U.S. government to sponsor research to study ways to prevent the cracking and degrading of rubber compounds.

This research was published in the Rock Island Arsenal Technical Report (Ofner 1967 [R8ATIUAM] Ofner, Robert. 1967. Information Sources on Rubber for Engineers and Designers. U.S. Army Weapons Command. Rock Island Arsenal: Research and Engineering Division. https://apps.dtic.mil/sti/tr/pdf/AD0660315.pdf.), which identified a broad class of chemically modified PPDs as the most effective antiozonants for rubber compounds (Gilbert et al. 1990 [DL5MC2ZL] Gilbert, C. E., B. D. Beck, and E. J. Calabrese. 1990. Ozone Risk Communication and Management. Taylor & Francis.).

Following the Rock Island Arsenal Technical Report, the first PPD antiozonants developed were active against ozone but they were not as effective as 6PPD because they protected rubber compounds for only approximately 1.5 years. Phenyl-p-phenylenediamine (IPPD) and diaryl-p-phenylene diamine (DAPD) were among the first PPDs to be developed and were the first to be used in rubber compounds, in the mid-1960s. DAPD reacts minimally with ozone. IPPD reacts too fast with ozone, leading to premature depletion. The speed of the reaction with ozone is a critical consideration when assessing the utility of the antiozonants. The final PPDs to become commercialized were 6PPD, 7PPD, and 8PPD (Kuczkowski 1989 [IDS6JDJZ] Kuczkowski, J. A. 1989. "The Inhibition of Oxidative and Ozonic Processes in Elastomers." In Oxidation Inhibition in Organic Materials, J. Pospisil and P.P Klemchuk (eds.). Taylor & Francis. https://books.google.com/books?id=HEOnh9bgu0IC.).

Some tire manufacturers began using 6PPD in tire manufacturing in the mid-1960s and early 1970s. In 1964, a British patent (Monsanto Company 1965 [I3PYYL4M] Monsanto Company. 1965. Preservation of Diene Rubbers (Great Britain Patent No. 1035262A). Patent 1035262A, issued 1965.) was published regarding the manufacturing of the 6PPD molecule, and in 1968

a new factory was built, which increased the supply of 6PPD to the U.S. tire industry. By 1975, 6PPD accounted for 60% of the antiozonants used in tires (USEPA 1975 [9GIVZ872] USEPA. 1975. Environmental Aspects of Chemical Use in Rubber Processing Operations. EPA-560/1-75-002; Office of Toxic Substances. https://nepis.epa.gov/Exe/ZyPDF.cgi/2000IUPB.PDF?Dockey=2000IUPB.PDF.). To this day, 6PPD is used in all tires and is the primary anti-degradant used, although 6PPD may be blended with other anti-degradants (USTMA 2024 [372BNAEP] USTMA. 2024. USTMA Consortium Preliminary (Stage 1) Alternatives Analysis Report for CA DTSC. https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf.).

1.2 Transport Pathways: How Do 6PPD and 6PPD-q Get into the Environment?

1.2.1 Overview

As tires roll over a road surface, friction between the road and the tire generates tiny fragments of rubber, called TRWP. These particles contain both the intentionally added 6PPD and its transformation product, 6PPD-q. 6PPD-q is one of several transformation products formed by the reaction of 6PPD and ozone (Seiwert et al. 2022 [QDRRVWMW] Seiwert, Bettina, Maolida Nihemaiti, Mareva Troussier, Steffen Weyrauch, and Thorsten Reemtsma. 2022. “Abiotic Oxidative Transformation of 6-PPD and 6-PPD Quinone from Tires and Occurrence of Their Products in Snow from Urban Roads and in Municipal Wastewater.” Water Research 212: 118122. https://doi.org/10.1016/j.watres.2022.118122.). TRWP, 6PPD, and 6PPD-q may be present in many places impacted by tire use. More information is available in Section 4: Occurrence, Fate, Transport, and Exposure Pathways of this document. The callout box Tire and Road-Wear Particle Background and Related Terms presents a definition for TRWP and how this term relates to tire-wear particles (TWP) and other types of tire particles.

Tire and Road-Wear Particle Background and Related Terms

Tire and road-wear particles (TRWP) act as vectors for transport of 6PPD and 6PPD-q and, after settled in the environment, TRWP may act as a source of these and other chemicals. Thus, the fate and transport of 6PPD and 6PPD-q are inextricably linked with the fate and transport of TRWP. At times, this document discusses TRWP when information is not available on the fate and transport of 6PPD and 6PPD-q specifically.

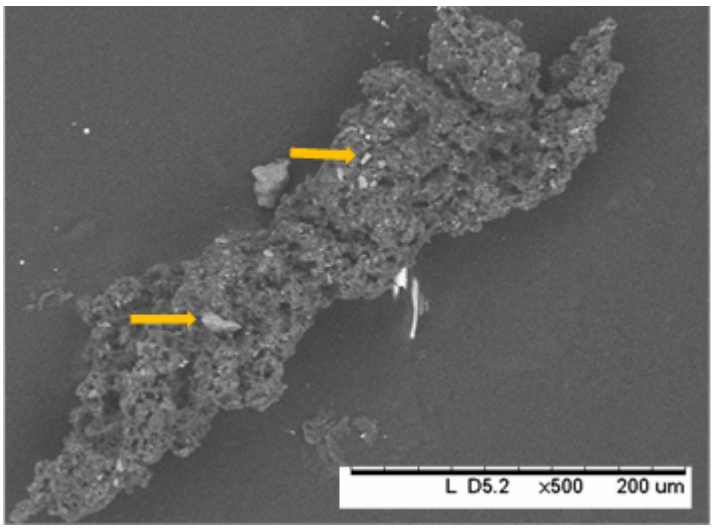


Figure 1-6. Scanning electron micrograph of TRWP collected from a storm drain. Yellow arrows indicate the inclusion of debris, from the road or brakes. The large surface area of the TRWP facilitates leaching of 6PPD and 6PPD-q.

Source: K. Paterson of the San Francisco Estuary Institute (Used with permission)

TRWP form from friction between a tire and the road surface during driving, braking, and turning. As the name TRWP implies, they have two separate components—tire-wear particles (TWP) and the road component (see Figure 1-6). TWP are made of tire rubber, which contains natural and synthetic polymers, chemical additives (such as 6PPD), and chemical transformation products (such as 6PPD-q). The large surface area of TWP facilitates leaching of 6PPD, 6PPD-q, and other chemicals to the

environment. TWP are one of the most prevalent types of microplastics found in urban stormwater runoff (Mayer et al. 2024 [ZTAVFS9G] Mayer, Paul, Kelly Moran, Ezra Miller, et al. 2024. “Where the Rubber Meets the Road: Emerging Environmental Impacts of Tire Wear Particles and Their Chemical Cocktails.” Science of The Total Environment 927 (June): 171153. https://doi.org/10.1016/j.scitotenv.2024.171153. Ziajahromi et al. 2023 [YZAD6ZJV] Ziajahromi, Shima, Hsuan-Cheng Lu, Darren Drapper, Andy Hornbuckle, and Frederic D. L. Leusch. 2023. “Microplastics and Tire Wear Particles in Urban Stormwater: Abundance, Characteristics, and Potential Mitigation Strategies.” Environmental Science & Technology 57 (34): 12829–37. https://doi.org/10.1021/acs.est.3c03949.). Models predict that more than 1.52 million metric tonnes of TWP (equivalent to approximately 10.3 pounds per person) are emitted annually in the United States (Kole et al. 2017 [NZZMY6WC] Kole, Pieter Jan, Ansje J. Löhr, Frank G. A. J. Van Belleghem, and Ad M. J. Ragas. 2017. “Wear and Tear of Tyres: A Stealthy Source of Microplastics in the Environment.” International Journal of Environmental Research and Public Health 14 (10): 1265. https://doi.org/10.3390/ijerph14101265.]).

The road-wear component of TRWP contains road fragments and other car-related contaminants, such as those generated from brake wear (Ha et al. 2023 [PYHTRF8Y] Ha, Jin U., Seok H. Bae, Yu J. Choi, et al. 2023. “Control of Tire Wear Particulate Matter through Tire Tread Prescription.” Polymers 15 (13): 2795. https://doi.org/10.3390/polym15132795.). These road-wear components impact the physical characteristics (for example, mass, surface area, density) of TRWP, which therefore impacts TRWP fate and transport in the environment (Kreider et al. 2010 [QCJY4JI9] Kreider, Marisa L., Julie M. Panko, Britt L. McAtee, Leonard I. Sweet, and Brent L. Finley. 2010. “Physical and Chemical Characterization of Tire-Related Particles: Comparison of Particles Generated Using Different Methodologies.” Science of the Total Environment 408 (3): 652–59. https://doi.org/10.1016/j.scitotenv.2009.10.016. Baensch-Baltruschat et al. 2020 [SG7DEPVC] Baensch-Baltruschat, Beate, Birgit Kocher, Friederike Stock, and Georg Reifferscheid. 2020. “Tyre and Road Wear Particles (TRWP)—A Review of Generation, Properties, Emissions, Human Health Risk, Ecotoxicity, and Fate in the Environment.” Science of the Total Environment 733 (September): 137823. https://doi.org/10.1016/j.scitotenv.2020.137823.).

The source materials used in studies of 6PPD, 6PPD-q, and other tire-related chemicals includes both TRWP and lab-generated tire particles. Some lab-generated tire particles are prepared using techniques that do not simulate road conditions, such as sanding or cryo-milling. Other lab-generated tire particles are prepared using techniques that simulate tire and road wear, such as rolling drums covered in asphalt over the tire’s tread. For simplicity, this document includes all types of lab-generated tire particles within our definition of TWP because these particles were not generated from friction between a tire and an actual road surface.

A third source of tire particles is the shredding and grinding of scrap tires for other uses, such as crumb rubber infill on artificial turf fields, rubber-modified asphalt, and other products including those listed in Table 1-3. In this document, studies of the fate and transport of these products and/or their components are identified by product type/use and not included in our definition of TWP.

The terminology surrounding tire particles is evolving, which leads to inconsistency in the published literature. To get around this challenge, some researchers have proposed using the umbrella term microrubber to include all microplastics that predominantly contain synthetic and natural rubber polymers (Halle et al. 2020 [47UILE7G] Halle, Louise L., Annemette Palmqvist, Kristoffer Kampmann, and Farhan R. Khan. 2020. “Ecotoxicology of Micronized Tire Rubber: Past, Present and Future Considerations.” Science of The Total Environment 706 (March): 135694. https://doi.org/10.1016/j.scitotenv.2019.135694. Tamis et al. 2021 [MPU4FIFJ] Tamis, Jacqueline E., Albert A. Koelmans, Rianne Dröge, et al. 2021. “Environmental Risks of Car Tire Microplastic Particles and Other Road Runoff Pollutants.” Microplastics and Nanoplastics 1 (1): 10. https://doi.org/10.1186/s43591-021-00008-w.). To date, the term microrubber has not been universally embraced.

The consensus of this ITRC team was to use TRWP for particles generated from vehicular travel on roads; use TWP for lab-generated tire particles and the tire component of TRWP; and identify non-vehicular sources of tire particles by the intended use.

As shown in Figure 1-7, TRWP containing 6PPD and 6PPD-q migrate to waterways through various transport pathways including atmospheric deposition, direct runoff from roads, and conveyance from stormwater drains. TRWP have also been

detected in stormwater and surface waters on multiple continents (McIntyre et al. 2021 [MVL2LKBM] McIntyre, Jenifer K., Jasmine Prat, James Cameron, et al. 2021. “Treading Water: Tire Wear Particle Leachate Recreates an Urban Runoff Mortality Syndrome in Coho but Not Chum Salmon.” Environmental Science & Technology 55 (17): 11767–74.

https://doi.org/10.1021/acs.est.1c03569. Rauert et al. 2022 [LAH96NFL] Rauert, Cassandra, Suzanne Vardy, Benjamin Daniell, Nathan Charlton, and Kevin V. Thomas. 2022. “Tyre Additive Chemicals, Tyre Road Wear Particles and High Production Polymers in Surface Water at 5 Urban Centres in Queensland, Australia.” Science of The Total Environment 852: 158468.

https://doi.org/10.1016/j.scitotenv.2022.158468. Challis et al. 2021 [T8TEWPCL] Challis, J. K., H. Popick, S. Prajapati, et al. 2021. “Occurrences of Tire Rubber–Derived Contaminants in Cold-Climate Urban Runoff.” Environmental Science & Technology

Letters 8 (11): 961–67. https://doi.org/10.1021/acs.estlett.1c00682. Maurer et al. 2023 [TJQR62IC] Maurer, Loïc, Eric Carmona, Oliver Machate, Tobias Schulze, Martin Krauss, and Werner Brack. 2023. “Contamination Pattern and Risk Assessment of Polar Compounds in Snow Melt: An Integrative Proxy of Road Runoffs.” Environmental Science & Technology 57 (10):

4143–52. https://doi.org/10.1021/acs.est.2c05784. Cao et al. 2022 [VBAMJHA7] Cao, Guodong, Wei Wang, Jing Zhang, et al. 2022. “New Evidence of Rubber-Derived Quinones in Water, Air, and Soil.” Environmental Science & Technology 56 (7): 4142–50.

https://doi.org/10.1021/acs.est.1c07376. Johannessen and Metcalfe 2022 [6AEMVTD8] Johannessen, Cassandra, and Chris D. Metcalfe. 2022. “The Occurrence of Tire Wear Compounds and Their Transformation Products in Municipal Wastewater and Drinking Water Treatment Plants.” Environmental Monitoring and Assessment 194 (10): 731. https://doi.org/10.1007/s10661-022-10450-9.). 6PPD and 6PPD-q have been found in the following contexts:

- Airborne particulates (Johannessen et al. 2022 [RYBDCBV4] Johannessen, Cassandra, Amandeep Saini, Xianming Zhang, and Tom Harner. 2022. “Air Monitoring of Tire-Derived Chemicals in Global Megacities Using Passive Samplers.” Environmental Pollution 314 (December): 120206. https://doi.org/10.1016/j.envpol.2022.120206. Cao et al. 2022 [VBAMJHA7] Cao, Guodong, Wei Wang, Jing Zhang, et al. 2022. “New Evidence of Rubber-Derived Quinones in Water, Air, and Soil.” Environmental Science & Technology 56 (7): 4142–50.

  https://doi.org/10.1021/acs.est.1c07376.; Zhang et al. 2022 [G77DTKD6] Zhang, Yanhao, Caihong Xu, Wenfen Zhang, et al. 2022. “p-Phenylenediamine Antioxidants in PM2.5: The Underestimated Urban Air Pollutants.” Environmental Science & Technology 56 (11): 6914–21. https://doi.org/https://doi.org/10.1021/acs.est.1c04500.; Ji et al. 2022 [QJ23CAKR] Ji, Jiawen, Jinze Huang, Niannian Cao, et al. 2022. “Multiview Behavior and Neurotransmitter Analysis of Zebrafish Dyskinesia Induced by 6PPD and Its Metabolites.” Science of The Total Environment 838: 156013. https://doi.org/10.1016/j.scitotenv.2022.156013.)
- Sediment (Zhu et al. 2024 [3FETIQAB] Zhu, Jianqiang, Ruyue Guo, Fangfang Ren, Shengtao Jiang, and Hangbiao Jin. 2024. “Occurrence and Partitioning of p-Phenylenediamine Antioxidants and Their Quinone Derivatives in Water and Sediment.” Science of the Total Environment 914 (March): 170046.

  https://doi.org/10.1016/j.scitotenv.2024.170046. Zeng et al. 2023 [TK5YR8WJ] Zeng, Lixi, Yi Li, Yuxin Sun, Liang-Ying Liu, Mingjie Shen, and Bibai Du. 2023. “Widespread Occurrence and Transport of p-Phenylenediamines and Their Quinones in Sediments across Urban Rivers, Estuaries, Coasts, and Deep-Sea Regions.” Environmental Science & Technology, January 31, acs.est.2c07652. https://doi.org/10.1021/acs.est.2c07652.)
- Soil (Cao et al. 2023 [D5FPK9YB] Cao, Guodong, Wei Wang, Jing Zhang, et al. 2023. “Occurrence and Fate of Substituted P-Phenylenediamine-Derived Quinones in Hong Kong Wastewater Treatment Plants.” Environmental Science & Technology, ahead of print, October 5. https://doi.org/10.1021/acs.est.3c03758.)
- Biosolids (Cao et al. 2023 [D5FPK9YB] Cao, Guodong, Wei Wang, Jing Zhang, et al. 2023. “Occurrence and Fate of Substituted P-Phenylenediamine-Derived Quinones in Hong Kong Wastewater Treatment Plants.” Environmental Science & Technology, ahead of print, October 5. https://doi.org/10.1021/acs.est.3c03758.)
- Rubber products other than tires (Sherman et al. 2024 [NGSQ8TR4] Sherman, Anya, Thibault Masset, Lukas Wimmer, et al. 2024. “The Invisible Footprint of Climbing Shoes: High Exposure to Rubber Additives in Indoor Facilities.” Preprint. https://chemrxiv.org/engage/api-gateway/chemrxiv/assets/orp/resource/item/65b74ca0e9ebbb4db9311694/original/the-invisible-footprint-of-climbing-shoes-high-exposure-to-rubber-additives-in-indoor-facilities.pdf. Zhao et al. 2023 [NMVDB224] Zhao, Haoqi Nina, Ximin Hu, Melissa Gonzalez, et al. 2023. “Screening P-Phenylenediamine Antioxidants, Their Transformation Products, and Industrial Chemical Additives in Crumb Rubber and Elastomeric Consumer Products.” Environmental Science & Technology, ahead of print, February 9.

https://doi.org/10.1021/acs.est.2c07014.)

- Indoor dust (Zhang et al. 2024 [ZQPREK6H] Zhang, Zhuxia, Xijin Xu, Ziyi Qian, et al. 2024. “Association between 6PPD-Quinone Exposure and BMI, Influenza, and Diarrhea in Children.” Environmental Research 247: 118201.

  https://doi.org/10.1016/j.envres.2024.118201. Zhu et al. 2024 [WEPL88BC] Zhu, Jianqiang, Ruyue Guo, Shengtao Jiang, Pengfei Wu, and Hangbiao Jin. 2024. “Occurrence of p-Phenylenediamine Antioxidants (PPDs) and PPDs-Derived Quinones in Indoor Dust.” Science of the Total Environment 912: 169325.

  https://doi.org/10.1016/j.scitotenv.2023.169325. Huang et al. 2021 [EZEWIV8E] Huang, Wei, Yumeng Shi, Jialing Huang, et al. 2021. “Occurrence of Substituted p-Phenylenediamine Antioxidants in Dusts.” Environmental Science & Technology Letters 8 (5): 381–85. https://doi.org/10.1021/acs.estlett.1c00148.)
- Road dust (Huang et al. 2021 [EZEWIV8E] Huang, Wei, Yumeng Shi, Jialing Huang, et al. 2021. “Occurrence of Substituted p-Phenylenediamine Antioxidants in Dusts.” Environmental Science & Technology Letters 8 (5):

  381–85. https://doi.org/10.1021/acs.estlett.1c00148. Jin et al. 2023 [P9WXQJUR] Jin, Ruihe, Yan Wu, Qun He, et al. 2023. “Ubiquity of Amino Accelerators and Antioxidants in Road Dust from Multiple Land Types: Targeted and Nontargeted Analysis.” Environmental Science & Technology 57 (28): 10361–72. https://doi.org/10.1021/acs.est.3c01448.)

In humans 6PPD-q has been measured in urine (Du et al. 2022 [DWFYR89F] Du, Bibai, Bowen Liang, Yi Li, Mingjie Shen, Liang-Ying Liu, and Lixi Zeng. 2022. “First Report on the Occurrence of N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine (6PPD) and 6PPD-Quinone as Pervasive Pollutants in Human Urine from South China.” Environmental Science & Technology Letters,

ahead of print, November 21. World. https://doi.org/10.1021/acs.estlett.2c00821.), serum (Zhang et al. 2024 [BZQEGEXI] Zhang, Jing, Guodong Cao, Wei Wang, et al. 2024. “Stable Isotope-Assisted Mass Spectrometry Reveals in Vivo Distribution, Metabolism, and Excretion of Tire Rubber-Derived 6PPD-Quinone in Mice.” Science of the Total Environment 912 (February):

169291. https://doi.org/10.1016/j.scitotenv.2023.169291.), and CSF (Fang et al. 2024 [2L4QI2CG] Fang, Jiacheng, Xiaoxiao Wang, Guodong Cao, et al. 2024. “6PPD-Quinone Exposure Induces Neuronal Mitochondrial Dysfunction to Exacerbate Lewy Neurites Formation Induced by α-Synuclein Preformed Fibrils Seeding.” Journal of Hazardous Materials 465 (March): 133312. https://doi.org/10.1016/j.jhazmat.2023.133312.).

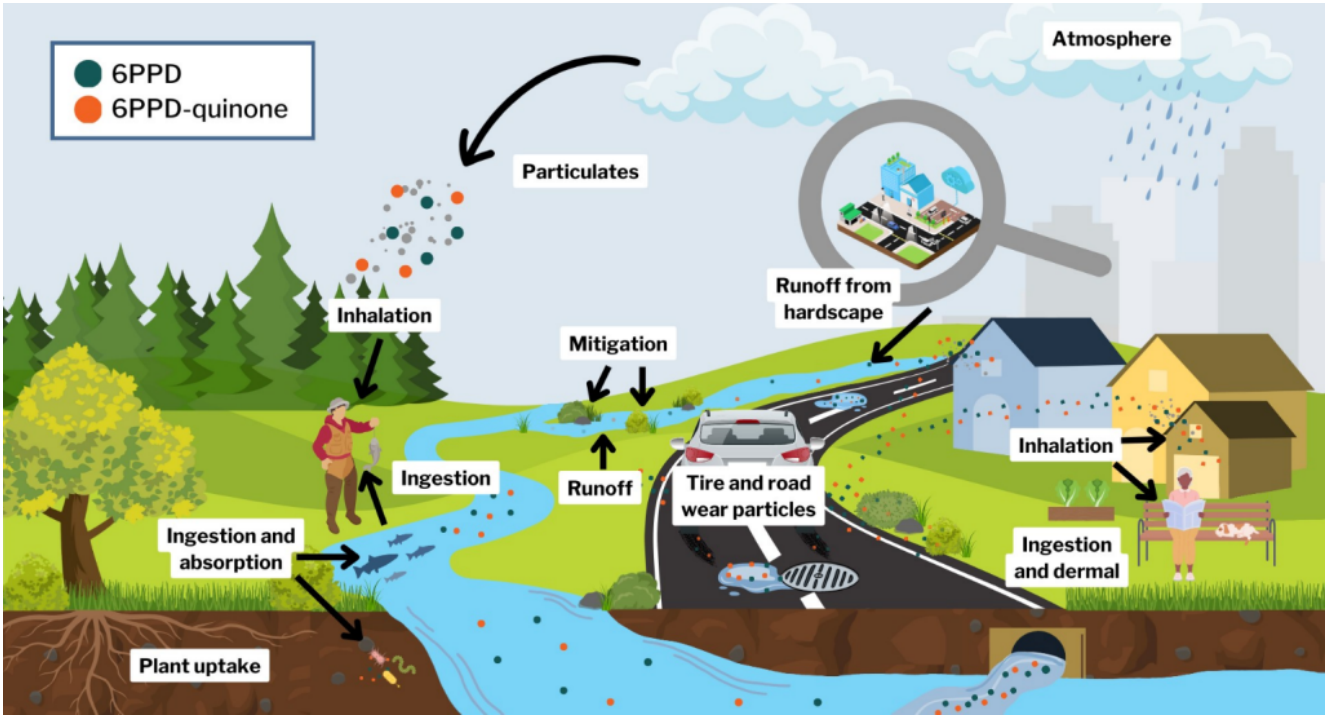


Figure 1-7. Conceptual transport and exposure model. 6PPD in tires is converted to 6PPD-q when exposed to ozone. 6PPD and 6PPD-q are contained in tire- and road-wear particles (TRWP) that can be transported in the air and can stay near the roadway and be transported to surface waters through stormwater drains and runoff. TRWP containing 6PPD and 6PPD-q in surface waters can be ingested and absorbed by fishes and other aquatic species and cause acute mortality. The aquatic exposure pathway is well established. Biomonitoring

studies indicate that people are exposed, but the primary pathways of exposure are the subject of ongoing research. Potential exposure routes to humans can include inhalation, dermal exposure, and ingestion via TRWP deposition on surfaces, soils, and plants (including foods) and uptake into plants. Exposed fish can be ingested by humans and other species. 6PPD and 6PPD-q contamination in the environment can potentially be mitigated by green stormwater infrastructure. Research is ongoing to further define 6PPD-q's environmental behaviors, exposures, and the potential development of adverse health outcomes.
Source: Washington State Department of Ecology.

1.2.2 How Does 6PPD-q Reach Waterways?

TRWPs are nearly ubiquitous in the urban environment (Wagner et al. 2018 [4UCJI65Q] Wagner, Stephan, Thorsten Hüffer, Philipp Klöckner, Maren Wehrhahn, Thilo Hofmann, and Thorsten Reemtsma. 2018. "Tire Wear Particles in the Aquatic Environment — A Review on Generation, Analysis, Occurrence, Fate and Effects." Water Research 139 (August): 83–100. https://doi.org/10.1016/j.watres.2018.03.051. Kole et al. 2017 [NZZMY6WC] Kole, Pieter Jan, Ansje J. Löhr, Frank G. A. J. Van Belleghem, and Ad M. J. Ragas. 2017. "Wear and Tear of Tyres: A Stealthy Source of Microplastics in the Environment." International Journal of Environmental Research and Public Health 14 (10): 1265. https://doi.org/10.3390/ijerph14101265.). see Figure 1-7). TRWPs may contain 6PPD-q when they are emitted from the tire (Zhao et al. 2023 [ENE6F3HC] Zhao, Haoqi Nina, Ximin Hu, Zhenyu Tian, et al. 2023. "Transformation Products of Tire Rubber Antioxidant 6PPD in Heterogeneous Gas-Phase Ozonation: Identification and Environmental Occurrence." Environmental Science & Technology 57 (14): 5621–32. https://doi.org/10.1021/acs.est.2c08690. Lattimer et al. 1983 [3WW4X5AB] Lattimer, R. P., E. R. Hooser, R. W. Layer, and C. K. Rhee. 1983. "Mechanisms of Ozonation of N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine." Rubber Chemistry and Technology 56 (2): 431–39. https://doi.org/10.5254/1.3538136.). After TRWPs are in the environment, the 6PPD they contain may continue to act as a source for the generation of 6PPD-q. TRWPs are shed along roadways and parking areas and transported via air and surface water. Stormwater is a major route of transport from the road to waterbodies where, if present, aquatic species can be exposed to 6PPD-q (Tian et al. 2022 [BICQHLBC] Tian, Zhenyu, Melissa Gonzalez, Craig A. Rideout, et al. 2022. "6PPD-Quinone: Revised Toxicity Assessment and Quantification with a Commercial Standard." Environmental Science & Technology Letters, ahead of print, January 11. https://doi.org/10.1021/acs.estlett.1c00910. Tian et al. 2021 [X8BRFG3P] Tian, Zhenyu, Haoqi Zhao, Katherine T. Peter, et al. 2021. "A Ubiquitous Tire Rubber–Derived Chemical Induces Acute Mortality in Coho Salmon." Report. Science 371 (6525): 185–89. https://doi.org/10.1126/science.abd6951.). Coarse TRWP are likely to be deposited onto surfaces near roadways, while finer TRWP can be transported and dispersed in air (Baensch-Baltruschat et al. 2020 [SG7DEPVC] Baensch-Baltruschat, Beate, Birgit Kocher, Friederike Stock, and Georg Reifferscheid. 2020. "Tyre and Road Wear Particles (TRWP)—A Review of Generation, Properties, Emissions, Human Health Risk, Ecotoxicity, and Fate in the Environment." Science of the Total Environment 733 (September): 137823. https://doi.org/10.1016/j.scitotenv.2020.137823.). TRWP transport may result in direct 6PPD-q deposition into surface waters or onto streambanks and impervious surfaces where it can be mobilized by stormwater runoff (Johannessen et al. 2022 [YXQSYBCM] Johannessen, Cassandra, John Liggio, Xianming Zhang, Amandeep Saini, and Tom Harner. 2022. "Composition and Transformation Chemistry of Tire-Wear Derived Organic Chemicals and Implications for Air Pollution." Atmospheric Pollution Research 13 (9): 101533. https://doi.org/10.1016/j.apr.2022.101533. Johannessen et al. 2022 [E9K7U5U3] Johannessen, Cassandra, Paul Helm, Brent Lashuk, Viviane Yargeau, and Chris D. Metcalfe. 2022. "The Tire Wear Compounds 6PPD-Quinone and 1,3-Diphenylguanidine in an Urban Watershed." Archives of Environmental Contamination and Toxicology 82 (2): 171–79. https://doi.org/10.1007/s00244-021-00878-4.).

Many urban stormwater systems are designed to control flooding, not capture and treat contaminants that are transported to and contained in the stormwater. In separate storm sewer systems, rainwater is transported to natural receiving waters through a network of ditches and pipes, usually without natural or engineered green spaces to remove deposited airborne particulates or water pollutants. Additionally, some areas with installed stormwater best management practices (BMPs) fail to contain stormwater discharge due to increased urbanization and storm events that are larger than the infrastructure was designed for (Levin et al. 2020 [28SGXBLF] Levin, Phillip S., Emily R. Howe, and James C. Robertson. 2020. "Impacts of Stormwater on Coastal Ecosystems: The Need to Match the Scales of Management Objectives and Solutions." Philosophical Transactions of the Royal Society B: Biological Sciences 375 (1814): 20190460. https://doi.org/10.1098/rstb.2019.0460.), leading to direct conveyance of 6PPD and 6PPD-q to vulnerable aquatic ecosystems. In general, combined sewer systems limit the discharge of 6PPD-q into surface water by sending stormwater to wastewater treatment plants (WWTP) (Seiwert et al. 2022 [QDRRVWMW] Seiwert, Bettina, Maolida Nihemaiti, Mareva Troussier, Steffen Weyrauch, and Thorsten Reemtsma. 2022.

“Abiotic Oxidative Transformation of 6-PPD and 6-PPD Quinone from Tires and Occurrence of Their Products in Snow from Urban Roads and in Municipal Wastewater.” Water Research 212: 118122. https://doi.org/10.1016/j.watres.2022.118122.

Maurer et al. 2023 [TJQR62IC] Maurer, Loïc, Eric Carmona, Oliver Machate, Tobias Schulze, Martin Krauss, and Werner Brack. 2023. “Contamination Pattern and Risk Assessment of Polar Compounds in Snow Melt: An Integrative Proxy of Road Runoffs.”

Environmental Science & Technology 57 (10): 4143–52. https://doi.org/10.1021/acs.est.2c05784. Zhang et al. 2023 [JWRBWTKN] Zhang, Hai-Yan, Zheng Huang, Yue-Hong Liu, et al. 2023. “Occurrence and Risks of 23 Tire Additives and Their Transformation Products in an Urban Water System.” Environment International 171 (January): 107715. https://doi.org/10.1016/j.envint.2022.107715.). A Canadian study found two WWTP that use the same type of reactors to

degrade waste had net discharge of 6PPD-q into surface waters (Johannessen and Metcalfe 2022 [6AEMVTD8] Johannessen, Cassandra, and Chris D. Metcalfe. 2022. “The Occurrence of Tire Wear Compounds and Their Transformation Products in Municipal Wastewater and Drinking Water Treatment Plants.” Environmental Monitoring and Assessment 194 (10): 731. https://doi.org/10.1007/s10661-022-10450-9.). More research is needed to understand the dynamics of 6PPD and 6PPD-q in different WWTP.

Additional investigation is needed to determine the environmental concentrations of both 6PPD and 6PPD-q in urban streams to understand potential impacts on sensitive species in regions throughout the United States (see Figure 1-3). The fate of 6PPD and 6PPD-q in the environment requires more research, including, for example, factors that influence the formation of 6PPD-q in tires and TRWPs. Additional uncertainties include the transport and deposition of 6PPD and 6PPD-q from TRWPs, leaching rates from TRWPs, and the persistence and bioaccumulation potential of both 6PPD and 6PPD-q.

Many states have programs to divert scrap tires from landfills. Scrap tires are repurposed and recycled into crumb rubber used on sports fields, rubber-modified asphalt, and tire-derived aggregate used in civil engineering projects. Research is ongoing to determine whether and to what extent these potential sources result in human or ecological exposures. Table 1-3 provides a summary of dispositions for waste tires, including beneficial uses and applications in which tires are used as ingredients or components and methods of discard, including disposal and burning.

Table 1-3. Examples of used tire disposition

Disposition	Description or Examples
Building Construction	Accessibility ramps, flooring, sealant, roofing, waterproof membranes, and other construction materials can be produced from used tires.
Synthetic Fields, Tracks, and Playgrounds	Athletic fields using synthetic turf may use crumb rubber as a cushioning infill. Track and field facilities may use crumb rubber recycled from old tires in or under new synthetic surfaces.
Road and Traffic Maintenance	Erosion control, weed abatement, seismic transition coverings, traffic control cones, wheel stops, and curb ramps are all practical applications for used tires.
Rubberized Asphalt Concrete / Rubber-Modified Asphalt (RAC/RMA)	RAC/RMA produces a durable surface by blending ground-up recycled tires with asphalt prior to mixing in conventional materials.
Tire-Derived Aggregate	Chipped tires are often repurposed in civil engineering for fill, drainage, and vibration mitigation in construction projects.
Retread	Worn commercial tires receive new treads.
Material Feedstock	Ground tires are used to feed industrial processes as rubber or fuel.
Miscellaneous Repurposing	Aquatic bumpers, art projects, Earthship homes, swings, shoe soles, etc.
Disposal and Open Dumping	Whole tires may be disposed of in landfills or, in some instances, dumped.
Other	Burning, export, etc.

Notes: RAC=rubberized asphalt concrete; RMA=rubber-modified asphalt

Section 4: Occurrence, Fate, Transport, and Exposure Pathways discusses other potential routes of exposure.

1.3 What and Who Are Affected?

1.3.1 Impacts on Fishes

Of the species studied to date, coho salmon have the highest sensitivity to 6PPD-q (Tian et al. 2022 [BICQHLBC] Tian, Zhenyu, Melissa Gonzalez, Craig A. Rideout, et al. 2022. "6PPD-Quinone: Revised Toxicity Assessment and Quantification with a Commercial Standard." Environmental Science & Technology Letters, ahead of print, January 11. https://doi.org/10.1021/acs.estlett.1c00910.). In observations of URMS, mortality ranged from 20%–90% (Scholz et al. 2011 [S8ASEIXU] Scholz, Nathaniel L., Mark S. Myers, Sarah G. McCarthy, et al. 2011. "Recurrent Die-Offs of Adult Coho Salmon Returning to Spawn in Puget Sound Lowland Urban Streams." PLOS ONE 6 (12): e28013. https://doi.org/10.1371/journal.pone.0028013. Spromberg and Scholz 2011 [CT5HUEEI] Spromberg, Julann A., and Nathaniel L. Scholz. 2011. "Estimating the Future Decline of Wild Coho Salmon Populations Resulting from Early Spawner Die-Offs in Urbanizing Watersheds of the Pacific Northwest, USA." Integrated Environmental Assessment and Management 7 (4): 648–56. https://doi.org/10.1002/ieam.219.). Modeling indicates that this level of mortality could result in localized extinction of coho within 8 to 115 years, depending on whether the URMS occurs at the low end (20%) or the high end (90%) of the observed range (Spromberg and Scholz 2011 [CT5HUEEI] Spromberg, Julann A., and Nathaniel L. Scholz. 2011. "Estimating the Future Decline of Wild Coho Salmon Populations Resulting from Early Spawner Die-Offs in Urbanizing Watersheds of the Pacific Northwest, USA." Integrated Environmental Assessment and Management 7 (4): 648–56. https://doi.org/10.1002/ieam.219.). Some populations of coho salmon are already listed under the Endangered Species Act (ESA), such as the lower Columbia River (threatened) and California Central Coast (endangered). The degree to which URMS has played a role in their decline is unknown (DTSC 2022 [2M3Z8Z4F] DTSC. 2022. Product-Chemical Profile for Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine (6PPD) from the California Department of Toxic Substances Control (DTSC). https://dtsc.ca.gov/wp-content/uploads/sites/31/2022/05/6PPD-in-Tires-Priority-Product-Profile_FINAL-VERSION_accessible.pdf .).

Regarding other species of salmonids, we did not identify any current information about observations of URMS in populations of brook trout or rainbow trout/steelhead.[2] Brook trout populations have been reported to be in decline in many locations within their range (Smith and Sklarew 2013 [EGWKDGVU] Smith, Albert K., and Dann Sklarew. 2013. "A Mid Atlantic Brook Trout (Salvelinus fontinalis) Stream Sustainability Statistic for Rating Non-Tidal Streams." Sustainability of Water Quality and Ecology 1–2 (December): 68–81. https://doi.org/10.1016/j.swaqe.2013.08.001. Eastern Brook Trout Venture 2024 [6I74E3G5] Eastern Brook Trout Venture. 2024. "Eastern Brook Trout Health Map (Trout Unlimited)." https://easternbrooktrout.org/science-data/ebtjv-maps/copy_of_EBTJV%20Map%206_09_11.jpg/image_view_fullscreen.). Smith and Sklarew (Smith and Sklarew 2013 [EGWKDGVU] Smith, Albert K., and Dann Sklarew. 2013. "A Mid Atlantic Brook Trout (Salvelinus fontinalis) Stream Sustainability Statistic for Rating Non-Tidal Streams." Sustainability of Water Quality and Ecology 1–2 (December): 68–81. https://doi.org/10.1016/j.swaqe.2013.08.001.) found several factors related to stream quality that correlate with the absence or reduction in brook trout numbers; one of those factors was the distance between a creek and nearby roads. This correlation may not be directly related to 6PPD-q. Instead, as can be the case with many aquatic ecosystems, such declines could be a result of multiple stressors, including other water quality issues associated with impervious surfaces. Additional research would be needed to determine whether 6PPD-q poses a direct risk to brook trout populations. Rainbow trout are present or have been introduced throughout the United States. Native West Coast populations of rainbow trout and steelhead, the oceangoing form of rainbow trout, are in decline and include threatened and endangered populations (NOAA Fisheries 2023 [97J7UAAD] NOAA Fisheries. 2023. "Steelhead Trout | NOAA Fisheries." NOAA, February 9. https://www.fisheries.noaa.gov/species/steelhead-trout.). Current species assessments, many of which were developed before the identification of 6PPD-q, point to myriad impacts driving the decline, including habitat loss and degradation, dams, urbanization, stormwater, water diversion, temperature increases, agriculture, and timber harvesting. For example, the California Department of Fish and Wildlife developed an assessment for rainbow trout / steelhead. (California Department of Fish and Wildlife [UQBR2QNX] California Department of Fish and Wildlife. n.d. Biogeographic Information and Observation System (BIOS). V. v5.99.22. Accessed April 9, 2019. https://apps.wildlife.ca.gov/bios/.).

1.3.2 Potential Ecological System Impacts

As keystone species, salmon contribute to wider ecosystem integrity (Hyatt, K.D. and Godbout, L. 2000 [5GZ6MNL3] Hyatt, K.D.,

and Godbout, L. 2000. “A Review of Salmon as Keystone Species and Their Utility as Critical Indicators of Regional Biodiversity and Ecosystem Integrity.” L. M. Darling, Editor. Proceedings of a Conference on the Biology and Management of Species and Habitats at Risk, Kamloops, B.C., 15–19 Feb., 1999 (Victoria, B.C.) Two: 520. https://www.env.gov.bc.ca/wld/documents/fr02hyatt2.pdf.). Coho salmon and oceangoing steelhead support ecosystem health (including riverine and marine) by providing a food source for other species and contributing to nutrient cycling (Field and Reynolds 2012 [MSBZH2UY] Field, R. D., and J. D. Reynolds. 2012. “Ecological Links between Salmon, Large Carnivore Predation, and Scavenging Birds.” Journal of Avian Biology 44: 9–16. Holtgrieve and Schindler 2011 [52CBYUQ3] Holtgrieve, G. W., and D. E. Schindler. 2011. “Marine-Derived Nutrients, Bioturbation, and Ecosystem Metabolism: Reconsidering the Role of Salmon in Streams.” Ecological Society of America 92: 375–85.). Their migration from the ocean to their natal streams, where they spawn and ultimately die, provides marine nutrients to terrestrial environments (Naiman et al. 2002 [7UB96QLR] Naiman, Bilby, Schindler, and Helfield. 2002. “Pacific Salmon, Nutrients, and the Dynamics of Freshwater and Riparian Ecosystems.” Ecosystems 5: 399–417.). Additionally, Washington State’s Puget Sound Southern Resident orca whales—federally listed as an endangered species—rely on salmon as a primary food source (NOAA Fisheries 2022 [P3KT2TMB] NOAA Fisheries. 2022. “In the Spotlight: Southern Resident Killer Whale.” January 4. https://www.fisheries.noaa.gov/species/killer-whale/spotlight.). Additional research is needed to assess how acute mortality in coho salmon and potential sublethal and/or chronic effects of 6PPD-q may impact population and ecosystem-level outcomes (see Section 8: Information Gaps and Research Needs).

1.3.3 Tribal Nations

Indigenous communities have serious concerns about the loss of coho salmon and potentially other aquatic species due to exposure to 6PPD-q from stormwater runoff into fish-bearing watersheds. Testimony from Natural Resources Director of the Nisqually Tribe David Troutt to the U.S. House of Representatives Committee on Natural Resources on 6PPD-q introduces some of the deep concerns raised by some tribal nations:

The tribes of the Salish Sea consider the salmon to be their brothers—family members to be honored, protected, treasured, and a gift from the creator. Salmon have been the primary source of protein for the tribes for 10,000 years. The location and movement of their villages were directly connected to the returns of salmon and steelhead. Their mythology and traditions are inextricably linked to salmon. Salmon is the central figure in Nisqually culture and traditions.

Salmon and fishing for salmon on the Nisqually River is the life blood of the Nisqually people. (Troutt 2021 [Q4K9HZHT] Testimony of David Troutt: Hearing before the House Committee on Natural Resources, Subcommittee on Oversight and Investigations, U.S. House of Representatives (2021) (testimony of David Troutt). https://democrats-naturalresources.house.gov/imo/media/doc/2021_07_15_Written%20Testimony_David%20Troutt.pdf.)

In the Pacific Northwest in particular, salmon play a significant role in the cultural practices, food sovereignty, community health, traditional knowledge, way of life, and identity as Salmon People for various tribal nations (Columbia River Inter-Tribal Fish Commission, 2021). These tribal nations’ right to fish is an inherent right, and for tribal nations along the West Coast (NOAA Fisheries 2023 [2SAX845N] NOAA Fisheries. 2023. “Sovereign Relations on the West Coast | NOAA Fisheries.” NOAA, October 24. https://www.fisheries.noaa.gov/west-coast/partners/sovereign-relations-west-coast.) the right has been affirmed through treaty rights and reaffirmed through court case decisions. For example, the Boldt Decision (also known as United States v. Washington, 1974) established that the tribes are entitled to 50% of the fishing catch in their usual and accustomed fishing grounds within Washington State. Additionally, the decision requires that the tribes and Washington State comanage fisheries (University of Washington Gallagher Law Library, 2023). Because of this comanagement status, the tribes are important decision-makers in Washington State. More than 50 additional court filings under U.S. v. Washington between 1974 and 2021 have expanded on the Boldt Decision and have continued to reaffirm tribal treaty rights. The Boldt Decision created a precedent that has impacted Indigenous and Aboriginal rights to fish and use natural resources nationally and internationally. The decision has been cited in court cases involving the Chippewa Tribe in Minnesota (Tribal Treaties Database, 2024), tribes in Michigan and Wisconsin, the Māori people in New Zealand (New Zealand Ministry for Culture and Heritage, 2023), First Nations in Canada (Harris 2008 [5X7TJCHU] Harris, Douglas C. 2008. “The Boldt Decision in Canada: Aboriginal Treaty Rights to Fish on the Pacific, in Alexandra Harmon, Ed.” In The Power of Promises: Rethinking Indian Treaties In the Pacific Northwest. University of Washington Press. https://commons.allard.ubc.ca/cgi/viewcontent.cgi?referer=&httpsredir=1&article=1179&context=fac_pubs.), and other Indigenous peoples (Ziontz [ZW5F8CK3] Ziontz, Jacob. n.d. “Far-Reaching Rights: An Era of Innovation in Treaty Law in

Washington State That Impacted the Rights of Aboriginal Peoples Worldwide." Accessed July 15, 2024. https://www.historylink.org/File/10085.).

Although many tribes share a common interest in protecting salmon populations, each tribal nation has its own interests. The impact of 6PPD-q on salmon mortality is a compounding factor that complicates tribally led salmon recovery efforts like reintroduction, hatchery management, and habitat restoration. Additionally, a variety of factors negatively impact the resilience of salmon populations and poses challenges to tribal fisheries management. The following information captures some, but not all, of these interests and concerns as identified by tribal nations. Human-made blockages of waterways (for example, dams and culverts) create physical barriers for salmon passage, impeding their ability to spawn and complete their life cycle in natal streams. Habitat degradation and climate change reduce the availability of habitats that can support living salmon. Climate change increases water temperatures, reduces the availability of cold-water refuges and estuary habitats, and lowers the water level of many streams by reducing precipitation and snow melt (NOAA Fisheries 2023 [BVP2RCVL] NOAA Fisheries. 2023. "Ecosystem Interactions and Pacific Salmon | NOAA Fisheries." NOAA, August 31. https://www.fisheries.noaa.gov/west-coast/sustainable-fisheries/ecosystem-interactions-and-pacific-salmon.); alternatively, climate change can lead to increased streamflow from extreme weather events like heavy rain events, which can change salmon habitat (Mantua et al. 2010 [ZHLUKQ2D] Mantua, Nathan, Ingrid Tohver, and Alan Hamlet. 2010. "Climate Change Impacts on Streamflow Extremes and Summertime Stream Temperature and Their Possible Consequences for Freshwater Salmon Habitat in Washington State." Climatic Change 102 (1–2): 187–223. https://doi.org/10.1007/s10584-010-9845-2.; Snover et al. 2019 [UN9SA5AK] Snover, A. K., C. L. Raymond, H. A. Roop, and H. Morgan. 2019. No Time to Waste. The Intergovernmental Panel on Climate Change's Special Report on Global Warming of 1.5°C and Implications for Washington State. Briefing Paper Prepared by the Climate Impacts Group, University of Washington, Seattle. https://cig.uw.edu/wp-content/uploads/sites/2/2019/02/NoTimeToWaste_CIG_Feb2019.pdf.). Tribal resource managers face many challenges; therefore, to have a tangible impact on salmon populations they often address salmon recovery from a holistic point of view.

As David Troutt's testimony indicated, coho salmon and other sensitive trout species are an important element of the cultural practice and diet of many tribal nations in the Pacific Northwest. Thus, for the tribal nations of this region, the decline of the coho salmon population from 6PPD-q may diminish the availability of a healthy protein source and a culturally appropriate food and negatively affect the cultural traditions associated with harvesting and preparing the food (DTSC 2022 [2M3Z8Z4F] DTSC. 2022. Product-Chemical Profile for Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine (6PPD) from the California Department of Toxic Substances Control (DTSC). https://dtsc.ca.gov/wp-content/uploads/sites/31/2022/05/6PPD-in-Tires-Priority-Product-Profile_FINAL-VERSION_accessible.pdf .). Another concern expressed by some tribal members (DTSC 2021 [TIUY9CXL] DTSC. 2021. DTSC Tribal Consultations and Meetings: Summary of Input on Motor Vehicle Tires Containing 6PPD. https://dtsc.ca.gov/wp-content/uploads/sites/31/2021/12/Summary-of-Tribal-Input-SCP-6PPD.pdf.) is the concern that 6PPD-q may pass through the food web (DTSC 2022 [2M3Z8Z4F] DTSC. 2022. Product-Chemical Profile for Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine (6PPD) from the California Department of Toxic Substances Control (DTSC). https://dtsc.ca.gov/wp-content/uploads/sites/31/2022/05/6PPD-in-Tires-Priority-Product-Profile_FINAL-VERSION_accessible.pdf ., DTSC 2021 [TIUY9CXL] DTSC. 2021. DTSC Tribal Consultations and Meetings: Summary of Input on Motor Vehicle Tires Containing 6PPD. https://dtsc.ca.gov/wp-content/uploads/sites/31/2021/12/Summary-of-Tribal-Input-SCP-6PPD.pdf.). Many tribal nations harvest salmon as the fish come back to freshwater to spawn. That migration can be triggered by storms; the flow of water helps the salmon surmount physical stream barriers, such as sand bars, but stormwater may contain 6PPD and 6PPD-q (Tian et al. 2022 [BICQHLBC] Tian, Zhenyu, Melissa Gonzalez, Craig A. Rideout, et al. 2022. "6PPD-Quinone: Revised Toxicity Assessment and Quantification with a Commercial Standard." Environmental Science & Technology Letters, ahead of print, January 11. https://doi.org/10.1021/acs.estlett.1c00910. Challis et al. 2021 [T8TEWPCL] Challis, J. K., H. Popick, S. Prajapati, et al. 2021. "Occurrences of Tire Rubber–Derived Contaminants in Cold-Climate Urban Runoff." Environmental Science & Technology Letters 8 (11): 961–67. https://doi.org/10.1021/acs.estlett.1c00682. Johannessen et al. 2021 [U9BWIDJ5] Johannessen, Cassandra, Paul Helm, and Chris D. Metcalfe. 2021. "Detection of Selected Tire Wear Compounds in Urban Receiving Waters." Environmental Pollution 287 (October): 117659. https://doi.org/10.1016/j.envpol.2021.117659. Tian et al. 2021 [X8BRFG3P] Tian, Zhenyu, Haoqi Zhao, Katherine T. Peter, et al. 2021. "A Ubiquitous Tire Rubber–Derived Chemical Induces Acute Mortality in Coho Salmon." Report. Science 371 (6525): 185–89. https://doi.org/10.1126/science.abd6951.). Thus, in

addition to the potential toxicity to the fish themselves, the people who harvest and eat the salmon may be exposed to these chemicals. The human health impacts of exposure to 6PPD-q are still unstudied. That same concern about 6PPD-q passing though the food web exists for the animals that hunt or scavenge salmon or the carcasses. The toxicokinetics of 6PPD-q in exposed fish and their carcasses has yet to be characterized, so whether this represents a route of exposure remains a data gap, and the toxicological impacts on these species are largely unstudied.

Some tribal members have also cited concerns about plant uptake of 6PPD-q, which could impact the safety of traditionally harvested plants. There is also a larger concern stemming from the fact that salmon are a keystone species; reductions in their populations have implications not just for population health, but for ecosystem resilience.

Given these many concerns, Earthjustice submitted a petition on behalf of the Yurok Tribe, the Port Gamble S'Klallam Tribe, and the Puyallup Tribe of Indians to the USEPA in 2023 to establish regulations prohibiting the manufacturing, processing, use, and distribution of 6PPD under Section 21 of the Toxic Substances Control Act (TSCA) (Earthjustice 2023 [PB6HUXGY] Earthjustice. 2023. "U.S. Fishing Groups Sue Tire Manufacturers Over 6PPD Impacts on Salmon, Steelhead." Earthjustice. https://earthjustice.org/press/2023/u-s-fishing-groups-sue-tire-manufacturers-over-6ppd-impacts-on-salmon-steelhead.). This petition was supported by the Affiliated Tribes of Northwest Indians and the states of Connecticut, Oregon, Rhode Island, Vermont, and Washington (EPA-HQ-OPPT 2023).

Many tribal nations have called for the federal and state governments to evaluate this dilemma through a holistic lens, which may include assessing the structures and institutions that caused the problem in the first place. This includes, but is not limited to, transportation infrastructure and pursuing solutions that address these underlying challenges.

1.3.4 Potential Economic and Community Health Concerns

If exposure to 6PPD-q is shown to cause population declines in sensitive species (DTSC 2022 [2M3Z8Z4F] DTSC. 2022. Product-Chemical Profile for Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine (6PPD) from the California Department of Toxic Substances Control (DTSC). https://dtsc.ca.gov/wp-content/uploads/sites/31/2022/05/6PPD-in-Tires-Priority-Product-Profile_FINAL-VERSION_accessible.pdf . Feist et al. 2017 [4PSDP2BG] Feist, Blake E., Eric R. Buhle, David H. Baldwin, et al. 2017. "Roads to Ruin: Conservation Threats to a Sentinel Species across an Urban Gradient." Ecological Applications 27 (8): 2382–96. https://doi.org/https://doi.org/10.1002/eap.1615.), those declines can have an impact on the economic well-being of communities that rely on the species for subsistence, commercial, recreational, and tourism-based fish-related activities. The known sensitive species, coho salmon, brook trout, lake trout, and rainbow trout, provide significant economic value because of their importance for commercial fishers and recreational anglers (USGS 2023 [BHT5YTKH] USGS. 2023. "Brook Trout (Salvelinus fontinalis) — Species Profile. United States Geological Survey (USGS)." USGS Nonindigenous Aquatic Species Database. https://nas.er.usgs.gov/queries/factsheet.aspx?SpeciesID=939. USFWS 2000 [W2Z72ERF] USFWS. 2000. "Rainbow Trout (Oncorhynchus mykiss) | U.S. Fish & Wildlife Service." July 10. https://www.fws.gov/species/rainbow-trout-oncorhynchus-mykiss.). Impacts to the populations of these species from 6PPD-q exposures may raise concerns for state fish and wildlife agencies throughout the country.

Impacts to human health from environmental exposures to 6PPD and/or 6PPD-q have yet to be documented. If 6PPD-q or low levels of 6PPD are discovered to have adverse human health impacts, there may be environmental justice concerns for communities near roadways (Health Effects Institute Panel on the Health Effects of Long-Term Exposure to Traffic-Related Air Pollution. 2022 [P6LUHI38] Health Effects Institute Panel on the Health Effects of Long-Term Exposure to Traffic-Related Air Pollution. 2022. Systematic Review and Meta-Analysis of Selected Health Effects of Long-Term Exposure to Traffic-Related Air Pollution. Special Report 23. Health Effects Institute. https://www.healtheffects.org/system/files/hei-special-report-23_6.pdf.). 6PPD-q has been found in roadway dust and airborne particulate (Johannessen et al. 2022 [RYBDCBV4] Johannessen, Cassandra, Amandeep Saini, Xianming Zhang, and Tom Harner. 2022. "Air Monitoring of Tire-Derived Chemicals in Global Megacities Using Passive Samplers." Environmental Pollution 314 (December): 120206. https://doi.org/10.1016/j.envpol.2022.120206. Cao et al. 2023 [D5FPK9YB] Cao, Guodong, Wei Wang, Jing Zhang, et al. 2023. "Occurrence and Fate of Substituted P-Phenylenediamine-Derived Quinones in Hong Kong Wastewater Treatment Plants." Environmental Science & Technology, ahead of print, October 5. https://doi.org/10.1021/acs.est.3c03758.), and communities living near roadways are predominantly persons of color and lower income (Rowangould 2013 [9KKD6N4U] Rowangould, G. M. 2013. "A Census of the US Near-Roadway Population: Public

Health and Environmental Justice Considerations." Transportation Research, Part D: Transport and Environment 2013 (25): 59–67. https://doi.org/10.1016/j.trd.2013.08.003.; Boogaard et al. 2022 [JTM8JHCV] Boogaard, H., A. P. Patton, R. W. Atkinson, et al. 2022. "Long-Term Exposure to Traffic-Related Air Pollution and Selected Health Outcomes: A Systematic Review and Meta-Analysis." Environment International 164: 107262. https://doi.org/10.1016/j.envint.2022.107262.). Differential exposures to 6PPD-q may occur in vulnerable populations and overburdened communities. For more information see Section 2: Effects Characterization and Toxicity, Section 4: Occurrence, Fate, Transport, and Exposure Pathways, and Section 8: Information Gaps and Research Needs of this document.

1.4 How Do We Identify and Measure 6PPD-q?

Some private labs developed methods to detect and quantitate 6PPD-q in aqueous matrices (see for example Hunt et al. 2021 [FI465BMH] Hunt, Kathy, Ralph Hindle, and Tarun Anumol. 2021. Quantitation of Toxic Tire Degradant 6PPD-Quinone in Surface Water. Application Note: Environmental. Agilent Technologies, Inc.; Neilson 2021 [HWAFMKHN] Neilson, Leighanne. 2021. "SGS AXYS Measures the Major Antiozonant Degradation Product 6-PPD Quinone and 6-PPD." SGS AXYS, December 14. https://www.sgsaxys.com/2021/12/14/new-sgs-axys-is-pleased-to-measure-the-major-antiozonant-degradation-product-6-ppd-quinone-and-its-parent-compound-6-ppd-at-sub-ng-l-reporting-limits/.), and some commercial labs provide 6PPD-q testing. USEPA released a draft analytical method for detection of 6PPD-q in aqueous matrices, predominantly stormwater and surface water (USEPA 2023 [7AAJEWWG] USEPA. 2023. Draft Method 1634: Determination of 6PPD-Quinone in Aqueous Matrices Using Liquid Chromatography with Tandem Mass Spectrometry (LC/MS/MS). EPA 821-D-24-001. Office of Water (4303T), Office of Science and Technology. https://www.epa.gov/system/files/documents/2024-01/draft-method-1634-for-web-posting-1-23-24_508.pdf.), using liquid chromatography (LC) with tandem mass spectrometry (LC-MS/MS). Washington State Department of Ecology (Washington State Department of Ecology 2023 [HJQ3HEWU] Washington State Department of Ecology. 2023. "Standard Operating Procedure (SOP): Extraction and Analysis of 6PPD-Quinone (Mel730136, Version 1.2)." June 3.) also has a procedure for measuring 6PPD-q ("Standard Operating Procedure (SOP): Extraction and Analysis of 6PPD-quinone"). These methods are especially important because they allow us to quantitatively characterize the nature and extent of 6PPD-q contamination in the environment and are fundamental to establishing long-term monitoring programs as well. Vetted water sampling protocols are equally important because 6PPD-q levels tend to peak during and shortly after storms, making monitoring a challenge. Section 5: Measuring, Mapping, and Modeling 6PPD and 6PPD-q discusses best practices.

Another approach to finding 6PPD-q is field research—specifically salmonid biological monitoring for URMS or pre-spawn morality—which has been used to identify salmon-bearing streams where stormwater pollution might be a driver for water quality and aquatic life impacts (Halama et al. 2024 [5UMEQW95] Halama, Jonathan, Robert B. McKane, Bradley L. Barnhart, et al. 2024. "Watershed Analysis of Urban Stormwater Contaminant 6PPD-Quinone Hotspots and Stream Concentrations Using a Process-Based Ecohydrological Model." Frontiers in Environmental Science 12 (March). https://doi.org/10.3389/fenvs.2024.1364673.). One example of this type of research has been Longfellow Creek in Seattle, which has been studied by agencies and community scientists since at least 2002. Watershed analyses of storm sewer systems, hydrology, and salmon habitat can help identify 6PPD-q hotspots and set the stage for spatial analysis of solution prioritization (Washington State Department of Ecology 2022 [K2CG7KTE] Washington State Department of Ecology. 2022. 6PPD in Road Runoff Assessment and Mitigation Strategies. Nos. 22-03–020. Environmental Assessment and Water Quality Programs. https://apps.ecology.wa.gov/publications/documents/2203020.pdf.).

1.5 After We Find It, How Can We Mitigate It? What Else Can We Do?

Implementation and expansion of stormwater control measures (SCM) may reduce exposure to 6PPD-q and other pollutants in aquatic habitats. Research efforts are seeking to enhance and improve upon these SCMs, such as optimizing for the removal of 6PPD-q and other contaminants from stormwater runoff before it enters receiving water bodies. Mitigation and stormwater management will be key to reducing the potential impacts in the near term. Bioretention filtration has been shown to be effective at preventing coho mortality (McIntyre et al. 2023 [F7NAIVJ4] McIntyre, Jenifer, Julann Spromberg, James Cameron, John P. Incardona, Jay W. Davis, and Nathaniel L. Scholz. 2023. "Bioretention Filtration Prevents Acute Mortality and Reduces Chronic Toxicity for Early Life Stage Coho Salmon (Oncorhynchus kisutch) Episodically Exposed to Urban Stormwater Runoff." Science of the Total Environment 902 (December): 165759. https://doi.org/10.1016/j.scitotenv.2023.165759. Spromberg et al. 2016 [GI97QYN4] Spromberg, Julann A., David H. Baldwin,

Steven E. Damm, et al. 2016. “Coho Salmon Spawner Mortality in Western US Urban Watersheds: Bioinfiltration Prevents Lethal Storm Water Impacts.” Journal of Applied Ecology 53 (2): 398–407. https://doi.org/https://doi.org/10.1111/1365-2664.12534.). Reductions in other stormwater pollutants, such as metals, are also seen when this SCM is applied (McIntyre et al. 2021 [MVL2LKBM] McIntyre, Jenifer K., Jasmine Prat, James Cameron, et al. 2021. “Treading Water: Tire Wear Particle Leachate Recreates an Urban Runoff Mortality Syndrome in Coho but Not Chum Salmon.” Environmental Science & Technology 55 (17): 11767–74. https://doi.org/10.1021/acs.est.1c03569.). SCM can be expensive to implement and maintain; thus, there is a need to ensure that implementation is focused on the areas of highest risk, to the extent possible. Mitigation strategies should also consider the potential for airborne transport and exposures when designing BMPs for 6PPD-q. Solutions to 6PPD-q will likely include a mixture of approaches such as source control, alternatives to 6PPD in tires, and SCMs. Consideration of alternatives to 6PPD are already underway (Gradient 2024 [LHN7K744] Gradient. 2024. Preliminary (Stage 1) Alternatives Analysis Report: Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N’-Phenyl-p-Phenylenediamine (6PPD). https://www.ustires.org/sites/default/files/2024-03/USTMA%20Consortium%206PPD%20AA%20Preliminary%20Report_3-25-24.pdf.; DTSC 2022 [2M3Z8Z4F] DTSC. 2022. Product-Chemical Profile for Motor Vehicle Tires Containing N-(1,3-Dimethylbutyl)-N′-Phenyl-p-Phenylenediamine (6PPD) from the California Department of Toxic Substances Control (DTSC). https://dtsc.ca.gov/wp-content/uploads/sites/31/2022/05/6PPD-in-Tires-Priority-Product-Profile_FINAL-VERSION_accessible.pdf. Washington State Department of Ecology 2023 [M64YC38F] Washington State Department of Ecology. 2023. 6PPD Alternatives Assessment Hazard Criteria. Nos. 23-04–036. https://apps.ecology.wa.gov/publications/documents/2304036.pdf. Washington State Department of Ecology 2021 [2UEJGNJ2] Washington State Department of Ecology. 2021. “Technical Memo: Assessment of Potential Hazards of 6PPD and Alternatives.” November 29. https://www.ezview.wa.gov/Portals/_1962/Documents/6ppd/6PPD%20Alternatives%20Technical%20Memo.pdf.). See Section 6: Mitigation Measures and Solutions for more information.

1.6 What We Don’t Know: Knowledge and Research Gaps

6PPD and 6PPD-q are contaminants of emerging concern (CEC), and many data gaps and questions about them remain. These questions, while important, do not obviate the need for action based on available information to date regarding the impact of 6PPD and 6PPD-q. For a detailed list with explanation, see Section 8: Information Gaps and Research Needs.

1.7 Governance

Ongoing research is investigating the full scope of rubber products containing 6PPD, the ubiquitousness of tires, and TRWPs that may contain 6PPD and 6PPD-q. Meanwhile, the issue is already being considered on the legal and governance fronts. We include some examples here for greater awareness and note how different statutes are being and may be used to address the 6PPD/6PPD-q challenge.

Stormwater laws and permits (authorized through the Clean Water Act [CWA], including the National Pollutant Discharge Elimination System [NPDES]) permits,) may be tools to mitigate 6PPD and 6PPDq pollution. How stormwater permits are changed, used, or developed to address 6PPDq is generally yet to be determined; two draft permits developed within Washington State include permit changes that are intended to address 6PPDq: the Washington State municipal separate storm sewer systems (MS4) stormwater general permits (Washington State Department of Ecology 2023 [TX3IER4R] Washington State Department of Ecology. 2023. “Municipal Stormwater Permit Reissuance—Washington State Department of Ecology.” https://ecology.wa.gov/regulations-permits/permits-certifications/stormwater-general-permits/municipal-stormwater-general-permits/municipal-stormwater-permit-reissuance.) and the USEPA’s stormwater individual permit for Joint Base Lewis-McChord (USEPA 2017 [W3Z5GUCI] USEPA, Region 10. 2017. “NPDES Stormwater Permit for Joint Base Lewis-McChord MS4 in Washington.” Reports and Assessments. September 29. https://www.epa.gov/npdes-permits/npdes-stormwater-permit-joint-base-lewis-mcchord-ms4-washington.). In August 2024, Washington State adopted a quantitative freshwater acute water quality standard for 6PPD-q under the authority of the CWA (see Section 7.8.2: Other Relevant CWA Programs).

Beyond stormwater management, several other statutes may play a role in controlling, mitigating, or eliminating 6PPD and 6PPD-q, depending on the fate and transport and/or exposure pathway. Relevant statutes may include the following:

- Toxic Substances Control Act (TSCA, see Section 7.2)

- Comprehensive Environmental Response, Compensation, and Liability Act (CERCLA), also known as Superfund (see Section 7.3)
- Resource Conversation and Recovery Act (RCRA, see Section 7.4)
- Endangered Species Act (ESA, see Section 7.5)
- Magnuson-Stevens Fishery Conservation and Management Act (MSA, see Section 7.6)
- Safe Drinking Water Act (SDWA, see Section 7.7)

For example, the USEPA granted a citizens petition under the TSCA and "plans to take action to address the risk to the environment presented by 6PPD, and the degradant 6PPD-q through an advance notice of proposed rulemaking under TSCA section 6," (USEPA 2023 [EUYBKVIF] USEPA. 2023. "EPA Grants Tribal Petition to Protect Salmon from Lethal Chemical." News Release. November 2. https://www.epa.gov/newsreleases/epa-grants-tribal-petition-protect-salmon-lethal-chemical.). USEPA's 6PPD-q website includes information on available resources and agency actions to address 6PPD-q. In addition, the states of California and Washington have already initiated some regulatory actions on alternatives and more. For more information see Section 6.2.1 and Section 7: Policies, Regulations, and Laws.

In November 2023, two fishing groups, the Institute for Fisheries Resources and the Pacific Coast Federation of Fishermen's Associations, filed a lawsuit against 13 U.S.-based tire manufacturers under Section 9 of the ESA (Earthjustice 2023 [PB6HUXGY] Earthjustice. 2023. "U.S. Fishing Groups Sue Tire Manufacturers Over 6PPD Impacts on Salmon, Steelhead." Earthjustice. https://earthjustice.org/press/2023/u-s-fishing-groups-sue-tire-manufacturers-over-6ppd-impacts-on-salmon-steelhead.). In June 2022, notice letters of intent to sue under the CWA were sent to five municipalities in the Puget Sound (Seattle, Mukilteo, Normandy Park, Burien, and SeaTac) by the organization Puget Soundkeeper, though no complaints have been filed in court at this time (Puget Soundkeeper 2022 [4FJMQ2WI] Puget Soundkeeper. 2022. "Puget Sound Municipalities Fail to Address 6PPD-Quinone, Putting Salmon at Risk." Puget Soundkeeper Alliance, June 16. https://pugetsoundkeeper.org/2022/06/16/6ppd-mukilteo-burien-seatac-normandy-park-seattle/.).

Environmental regulations may often regulate a specific media (stormwater, groundwater, solid waste, air, etc.), but they are not mutually exclusive—hence the challenge in regulating something like TRWP containing 6PPD and 6PPD-q. For multiple routes of exposure, including for example via aerial deposition, a multi-regulatory approach may need to be taken to significantly impact the issue. For more information see Section 7: Policies, Regulations, and Laws.

1.8 Steps for Addressing 6PPD-q

Table 1-4 provides the basic steps for an environmental decision-maker to follow when assessing 6PPD and 6PPD-q. It also explains how they can use this guidance document in their decision-making.

Table 1-4: Checklist for decision-makers and environmental managers—Do you have this problem, and what are the first steps?

Problem	Resources
Do I have sources of 6PPD?	See this Introduction, Section 4: Occurrence, Fate, Transport and Exposure Pathways, and Section 5: Measuring, Mapping, and Modeling
Do I have potential ecological or human receptors? Do I have concentrations of 6PPD-q in my aquatic environment that can impact sensitive species?	See Section 2: Effects Characterization and Toxicity and Section 5: Measuring, Mapping, and Modeling
Do I have ways (exposure pathways) for 6PPD/6PPD-q to reach potentially sensitive species at concentrations that may cause adverse effects? Examples: stormwater inventory, discharges, confluence of sources (for example, roadways) to aquatic habitats, tire-derived assets (for example, artificial turf fields), etc.	See Section 4: Occurrence, Fate, Transport, and Exposure Pathways
Do I have tools to interrupt exposure pathways and manage sources?	See Section 6: Mitigation Measures and Solutions and Section 7: Policies, Regulations, and Laws

What are the information gaps for 6PPD and 6PPD-q?	See Section 8: Information Gaps and Research Needs

6PPD and 6PPD-q pose many challenges that are often associated with CEC, including addressing critical effects observed in the environment when many knowledge gaps exist. For more information on a framework for addressing CEC in general, see the ITRC document on CEC.