4 Occurrence, Fate, Transport, and Exposure Pathways

This chapter reviews the fate, transport, and occurrence of tire particles containing 6PPD and 6PPD-q in the environment. More research is needed on the fate, transport, occurrence, and persistence of 6PPD-q once released from tires and other rubber products to inform toxic reduction actions.

In the context of what is known regarding 6PPD and 6PPD-q occurrence, this section also discusses different pathways by which human or ecological receptors may be exposed to 6PPD and 6PPD-q.

Recent studies have investigated the occurrence of 6PPD and 6PPD-q in various environmental matrices across the globe. This section summarizes the current state of knowledge but is not intended to represent a comprehensive review of occurrence data. Additionally, reliability evaluation and comparison of analytical methods have not been performed for studies discussed in this document. The following index presents tables, organized by medium type, where summaries of peer-reviewed studies can be found.

Table	**Media Type**	**Available Publications**	**Link to PDF**	**Link to Executable File (Word Processor Format)**
4-1	Surface Water	12	PDF	W
4-2	Stormwater	9	PDF	W
4-3	Wastewater, water treatment plants, and tap water	8	PDF	W
4-4	Groundwater	1	PDF	W
4-5	Roadside soil	1	PDF	W
4-6	Sediment	3	PDF	W
4-7	Outdoor air	8	PDF	W
4-8	Road dust and roadside snow	7	PDF	W
4-9	Indoor and nonroad settled dust	6	PDF	W
4-10	Aquatic organisms and food	9	PDF	W

Note: PDF versions of each table are provided for the reader to view information in a visual format that is consistent across browsers and platforms. Executable files are provided to allow readers to sort information by the column of their choice, but may appear different visually depending on the software used to view this file. Instructions on how to sort information in a document formatted for a word processor format are widely available by internet search.

The studies listed in these tables are from peer-reviewed literature and do not capture the preliminary monitoring efforts by state, tribal, and local agencies. Some of these studies also measured a range of other PPDs and transformation products, which are not addressed in this document. Recent efforts have been made to summarize occurrence data in peer-reviewed literature (Mayer et al. 2024[ZTAVFS9G] Mayer, Paul, Kelly Moran, Ezra Miller, Susanne Brander, Stacey Harper, Manuel Garcia-Jaramillo, Victor Carrasco-Navarro, 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.Benis et al. 2023[XXB6GPKJ] Benis, Khaled Zoroufchi, Ali Behnami, Shahab Minaei, Markus Brinkmann, Kerry N. McPhedran, and Jafar Soltan. 2023. “Environmental Occurrence and Toxicity of 6PPD Quinone, an Emerging Tire Rubber–Derived Chemical: A Review.” Environmental Science & Technology Letters, September.

https://doi.org/10.1021/acs.estlett.3c00521.Chen et al. 2023[39YBXWMI] Chen, Xiaoli, Tao He, Xinlu Yang, Yijing Gan, Xian Qing, Jun Wang, and Yumei Huang. 2023. “Analysis, Environmental Occurrence, Fate and Potential Toxicity of Tire Wear Compounds 6PPD and 6PPD-Quinone.” Journal of Hazardous Materials 452 (June):131245.

https://doi.org/10.1016/j.jhazmat.2023.131245.Hua and Wang 2023[3FVXFWPE] Hua, Xin, and Dayong Wang. 2023. “Tire-Rubber Related Pollutant 6-PPD Quinone: A Review of Its Transformation, Environmental Distribution, Bioavailability, and Toxicity.” Journal of Hazardous Materials 459:132265. https://doi.org/10.1016/j.jhazmat.2023.132265.). Given the regional-specific conditions that impact the fate and transport of 6PPD-q (and TRWP and 6PPD), considerations should be made when interpreting these data. Further, the sampling and analytical methods used should be reviewed (for example, collecting and storing material, use of a commercially available standard) given the continued advancements made in quantifying this compound in environmental matrices (see also Section 5: Measuring, Mapping, and Modeling). The transport pathways and exposure risk to aquatic, terrestrial, and human systems is poorly understood (see Section 8.2).

Occurrence, Fate, and Transport

- Friction between the road and a tire during driving, braking, and turning leads to the generation and emission of TRWP.
- TRWP are carried beyond the road surface via stormwater or other pathways, such as air dispersion and deposition, and can enter aquatic or terrestrial systems.
- Fate and transport mechanisms that control occurrence vary among landscapes, geography, climate, and environmental conditions.
- The occurrence and persistence of 6PPD, 6PPD-q, TWP, and TRWP in the environment is poorly understood.
- More research is needed to standardize methods and fill in data gaps because initial studies have only scratched the surface.
- In addition, reused and recycled whole tires are a potential source of 6PPD and 6PPD-q, so more research is needed to understand the half-life of 6PPD in tires across varying environments (marine, freshwater, and terrestrial, etc.).

Understanding the mechanisms of toxic exposure, including the duration and mode of action, is needed to characterize the environmental risk (see also Section 2: Effects Characterization and Toxicity).

6PPD and 6PPD-q can be released to the environment from whole tires, TRWP, and reused/recycled/repurposed consumer products. For example, recycled tires can be used to modify asphalt, and 6PPD and 6PPD-q can be released from or sorbed to that material on the roadways (Lokesh et al. 2023[LBXMIT5W] Lokesh, Srinidhi, Siththarththan Arunthavabalan, Elie Hajj, Edgard Hitti, and Yu Yang. 2023. “Investigation of 6PPD-Quinone in Rubberized Asphalt Concrete Mixtures.” ACS Environmental Au, July. https://doi.org/10.1021/acsenvironau.3c00023.). Although whole-tire reuse and disposal has not been the main focus of the available occurrence data, it is important to note that more research is needed to investigate whole tires as a continued source of 6PPD and 6PPD-q. Whole tires are reused in many ways, such as marine reef structures, boat bumpers on docks, and landscaping materials. Regulation and guidance to provide proper storage, transport, and disposal of tires varies across states and should be evaluated to address 6PPD and 6PPD-q exposure concerns. The following subsections, which discuss environmental media, do not discuss whole-tire pollution, tire piles, or tires submerged or on land; these tires represent a source of 6PPD and 6PPD-q that is not well investigated or understood. See Section 1.2 for a brief discussion of tire life cycle and both Section 1.2 and Section 8.2 for discussion and summary of information needs and data gaps regarding sources of 6PPD and 6PPD-q.

TRWP are heterogeneous particles generated at the road surface by the friction of the tire on the road surface during driving. TRWP can be dispersed into the air or onto the roadway and includes wear particles from both the tire tread (i.e., TWP) and the road surface (i.e., road component) (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 road-wear component of TRWP have an impact on the characteristics and transport of the particles 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.). Elsewhere in this document TWP will be referred to as the tire fraction of the overall TRWP. See the Tire and Road-Wear Particle Background and Related Terms inset for more details.

An estimated 4.7 kg/year (equivalent to 10.3 pounds/year) per capita of TRWP is released to the environment 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 mass loading of 6PPD and 6PPD-q in the environment is expected to vary spatially given the differences in 6PPD-q and TRWP release rates, tire manufacturing, tire age, and vehicle attributes and operation (for example, weight, speed, and braking) (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.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.). Further, once released to roads and parking lots, the fate and transport of 6PPD-q and TRWP depends on many factors including tire particle characteristics (for example, size, shape, and density), road characteristics, regional weather, and environmental characteristics (Unice et al. 2019[TLVMH289] Unice, K.M., M.P. Weeber, M.M. Abramson, R.C.D. Reid, J.A.G. van Gils, A.A. Markus, A.D. Vethaak, and J.M. Panko. 2019. “Characterizing Export of Land-Based Microplastics to the Estuary — Part I: Application of Integrated Geospatial Microplastic Transport Models to Assess Tire and Road Wear Particles in the Seine Watershed.” Science of the Total Environment 646:1639–49. https://doi.org/10.1016/j.scitotenv.2018.07.368.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.). Road characteristics include traffic amount and type, vehicle type (for example, car, truck, electric vehicle), road surface, road size, road type (for example, local roads vs. highways), grade (steepness), and roadside slope and type (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.). Watershed characteristics and stormwater conveyance are expected to influence the transport of TRWP and 6PPD-q, including attributes such as roadside slope and conveyance (curb and gutter, grass ditch, paved ditch, presence/absence of stormwater drain and pipe, presence/absence of stormwater filtration or catchment), land use, seasonal traffic trends, seasonal weather patterns, regional stormwater and wastewater management practices, soil types, watershed size, and flood risk. Section 5.3.5.3 describes how these characteristics can be used in the USEPA Visualizing Ecosystem Land Management Assessments (VELMA) tool to identify potential hotspots of 6PPD-q contamination as a means of prioritizing locations to investigate and potentially mitigate impacts to the environment. Section 5: Measuring, Mapping, and Modeling provides additional discussion on how these factors can be measured, mapped, and used in models of TRWP, 6PPD, and 6PPD-q fate and transport.

Although TRWP containing 6PPD are mostly transported by surface water and stormwater, TRWP are also released and transported by atmospheric processes. In a road dust and sediment study (Klöckner et al. 2020[9B7NCVNZ] Klöckner, Philipp, Bettina Seiwert, Paul Eisentraut, Ulrike Braun, Thorsten Reemtsma, and Stephan Wagner. 2020. “Characterization of Tire and Road Wear Particles from Road Runoff Indicates Highly Dynamic Particle Properties.” Water Research 185 (October):116262. https://doi.org/10.1016/j.watres.2020.116262.), more coarse particles were found closer to the roadway, while smaller particles were more readily transported away from the road. As mentioned previously, TRWP are generally found more frequently and in higher quantities near roadways and in urban areas, particularly those with high-volume traffic patterns (Unice, Kreider, and Panko 2013[EU6MQU9K] Unice, K.M., Marisa L. Kreider, and Julie M. Panko. 2013. “Comparison of Tire and Road Wear Particle Concentrations in Sediment for Watersheds in France, Japan, and the United States by Quantitative Pyrolysis GC/MS Analysis.” Environmental Science & Technology 47 (15): 8138–47. https://doi.org/10.1021/es400871j.). Roadside vegetation and solid structures have been shown to mitigate the dispersion of airborne particles near roadways (Baldauf 2016[I5U5RA8E] Baldauf, Richard W. 2016. “Recommendations for Constructing Roadside Vegetation Barriers to Improve Near-Road Air Quality.” 321772. https://cfpub.epa.gov/si/si_public_record_report.cfm?Lab=NRMRL&dirEntryId=321772&simpleSearch=1&searchAll=Recommendations+for+constructing+roadside+vegetation+barriers+to+improve+near+road+air+quality.Greenwald, Sarnat, and Fuller 2024[ECNMWXRZ] Greenwald, Roby, Jeremy A. Sarnat, and Christina H. Fuller. 2024. “The Impact of Vegetative and Solid Roadway Barriers on Particulate Matter Concentration in Urban Settings.” PLOS ONE 19 (1): e0296885. https://doi.org/10.1371/journal.pone.0296885.) (see also Section 6.4: Air Particulate Migration). By volume, most TRWP are less than 100 µm (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.). TRWP have been observed in ambient air monitoring stations in the $PM_{2.5}$ fraction (Unice et al. 2019[TLVMH289] Unice, K.M., M.P. Weeber, M.M. Abramson, R.C.D. Reid, J.A.G. van Gils, A.A. Markus, A.D. Vethaak, and J.M. Panko. 2019. “Characterizing Export of Land-Based Microplastics to the Estuary — Part I: Application of Integrated Geospatial Microplastic Transport Models to Assess Tire and Road Wear Particles in the Seine Watershed.” Science of the Total Environment 646:1639–49. https://doi.org/10.1016/j.scitotenv.2018.07.368.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.Panko et al. 2019[H57M387X] Panko, Julie M., Kristen M. Hitchcock, Gary W. Fuller, and David Green. 2019. “Evaluation of Tire Wear Contribution to PM2.5 in Urban Environments.” Atmosphere 10 (2): 99. https://doi.org/10.3390/atmos10020099.Panko et al. 2013[UQNTNRM4] Panko, Julie M., Jennifer Chu, Marisa L. Kreider, and Ken M. Unice. 2013. “Measurement of Airborne Concentrations of Tire and Road Wear Particles in Urban and Rural Areas of France, Japan, and the United States.” Atmospheric Environment 72 (June):192–99. https://doi.org/10.1016/j.atmosenv.2013.01.040.). Because TRWP (or TWP) are categorized as microplastics, they are also discussed in Section 2.2.2.1 of the ITRC Microplastics Guidance Document (ITRC 2023[LLWEHVCX] ITRC. 2023. “Microplastics.” Washington, D.C.: Interstate Technology & Regulatory Council, MP Team. https://mp-1.itrcweb.org.).

Specific surface area is a key indicator of potential for release and/or transformation of chemicals contained in environmental particles like 6PPD in TRWP (Moran et al. 2023[9FSZ84KX] Moran, Kelly, Alicia Gilbreath, Miguel Mendez, Diana Lin, and Rebecca Sutton. 2023. “Tire Wear: Emissions Estimates and Market Insights to Inform Monitoring Design.” SFEI Technical Report SFEI Contribution #1049. Richmond, CA: San Francisco Estuary Institute.). For example, copper has been shown to leach from vehicle brake-pad wear particles at a high rate compared to some high-copper reference materials, likely because the wear-particle surface area is more than 150 times greater than the powdered reference materials (Hur, Yim, and Schlautman 2003[XN47T74F] Hur, Jin, Soobin Yim, and Mark A. Schlautman. 2003. “Copper Leaching from Brake Wear Debris in Standard Extraction Solutions. Electronic Supplementary Information (ESI) Available: Thermodynamic Equilibrium Speciation Results from the Geochemical Model MINTEQ. See Http://Www.Rsc.Org/Suppdata/Em/B3/B303820c/.” Journal of Environmental Monitoring 5 (5): 837. https://doi.org/10.1039/b303820c.). The greater the surface area, the greater the potential for formation of transformation products, including 6PPD-q, and for chemical release from the particle into the environment. Scanning electron micrographs (such as Figure 1-6) and focused ion beam images of TRWP reveal rough, irregular surfaces, which suggest that TRWP may have high surface areas (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.Milani et al. 2004[6N5I8G73] Milani, M., F.P. Pucillo, M. Ballerini, M. Camatini, M. Gualtieri, and S. Martino. 2004. “First Evidence of Tyre Debris Characterization at the Nanoscale by Focused Ion Beam.” Materials Characterization 52 (4–5): 283–88. https://doi.org/10.1016/j.matchar.2004.06.001.). Surface area typically has an inverse correlation with particle size (that is, smaller particles typically have greater total surface area per unit mass). The absence of TRWP surface-area data means that the portion of the particle size distribution (and associated transport pathway) with the greatest potential to release tire-related chemicals, including 6PPD and 6PPD-q, into the environment is unknown.

Modeling in the Seattle area found that the correlation between the presence of 6PPD-q in stormwater and vehicle miles traveled in the area's subwatersheds was slightly stronger than the correlation with subwatershed impervious area (Feist et al. 2017[4PSDP2BG] Feist, Blake E., Eric R. Buhle, David H. Baldwin, Julann A. Spromberg, Steven E. Damm, Jay W. Davis, and Nathaniel L. Scholz. 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.). If this correlation is observed in other locations, it would suggest that large tire particles, which deposit near roads, might release more chemicals into surface runoff than tire particles that are PM_{10} or smaller in diameter, which deposit throughout watersheds.

4.1 Water

4.1.1 Surface Water and Stormwater

Surface runoff (Table 4-1) and stormwater (Table 4-2) are presumed to be major transport pathways of TRWP, 6PPD, and 6PPD-q, which can then result in URMS (McIntyre et al. 2021[MVL2LKBM] McIntyre, Jenifer K., Jasmine Prat, James Cameron, Jillian Wetzel, Emma Mudrock, Katherine T. Peter, Zhenyu Tian, 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.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.McIntyre et al. 2018[G7QW7PSD] McIntyre, Jenifer, Jessica Lundin, James Cameron, Michelle Chow, Jay Davis, John Incardona, and Nathaniel Scholz. 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.Hiki et al. 2021[WZF69GXC] Hiki, Kyoshiro, Kenta Asahina, Kota Kato, Takahiro Yamagishi, Ryo Omagari, Yuichi Iwasaki, Haruna Watanabe, and Hiroshi Yamamoto. 2021. "Acute Toxicity of a Tire Rubber–Derived Chemical, 6PPD Quinone, to Freshwater Fish and Crustacean Species." Environmental Science & Technology Letters 8 (9): 779–84. https://doi.org/10.1021/acs.estlett.1c00453.Johannessen, Helm, and Metcalfe 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, Melissa Gonzalez, Jill Wetzel, Christopher Wu, Ximin Hu, et al. 2021. "A Ubiquitous Tire Rubber–Derived Chemical Induces Acute Mortality in Coho Salmon." Science 371 (6525): 185–89. https://doi.org/10.1126/science.abd6951.Seiwert et al. 2020[XRNTFZ69] Seiwert, Bettina, Philipp Klöckner, Stephan Wagner, and Thorsten Reemtsma. 2020. "Source-Related Smart Suspect Screening in the Aqueous Environment: Search for Tire-Derived Persistent and Mobile Trace Organic Contaminants in Surface Waters." Analytical and Bioanalytical Chemistry 412 (20): 4909–19. https://doi.org/10.1007/s00216-020-02653-1.French et al. 2022[3GCU2L57] French, B. F., D. H. Baldwin, J. Cameron, J. Prat, K. King, J. W. Davis, J. K. McIntyre, and N. L. Scholz. 2022. "Urban Roadway Runoff Is Lethal to Juvenile Coho, Steelhead, and Chinook Salmonids, But Not Congeneric Sockeye." Environmental Science & Technology Letters 9 (9): 733–38. https://doi.org/10.1021/acs.estlett.2c00467.Chow et al. 2019[7RMZ3UNQ] Chow, Michelle I., Jessica I. Lundin, Chelsea J. Mitchell, Jay W. Davis, Graham Young, Nathaniel L. Scholz, and Jenifer K. McIntyre. 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.Du et al. 2017[56E8Y27X] Du, Bowen, Jonathan M. Lofton, Katherine T. Peter, Alexander D. Gipe, C. Andrew James, Jenifer K. McIntyre, Nathaniel L. Scholz, Joel E. Baker, and Edward P. Kolodziej. 2017. "Development of Suspect and Non-Target Screening Methods for Detection of Organic Contaminants in Highway Runoff and Fish Tissue with High-Resolution Time-of-Flight Mass Spectrometry." Environmental Science: Processes & Impacts 19 (9): 1185–96. https://doi.org/10.1039/C7EM00243B.Scholz et al. 2011[S8ASEIXU] Scholz, Nathaniel L., Mark S. Myers, Sarah G. McCarthy, Jana S. Labenia, Jenifer K. McIntyre, Gina M. Ylitalo, Linda D. Rhodes, 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.Peter et al. 2020[5CPFCBQT] Peter, Katherine T., Fan Hou, Zhenyu Tian, Christopher Wu, Matt Goehring, Fengmao Liu, and Edward P. Kolodziej. 2020. "More than a First Flush: Urban Creek Storm Hydrographs

Demonstrate Broad Contaminant Pollutographs.” Environmental Science & Technology 54 (10): 6152–65.

https://doi.org/10.1021/acs.est.0c00872.Spromberg et al. 2016[GI97QYN4] Spromberg, Julann A., David H. Baldwin, Steven E. Damm, Jenifer K. McIntyre, Michael Huff, Catherine A. Sloan, Bernadita F. Anulacion, Jay W. Davis, and Nathaniel L. Scholz. 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.). Rain and snow melt (Table 4-8) pick up and transport dissolved and particulate contaminants from impervious surfaces and deliver them to natural waterbodies (Table 4-1), stormwater treatment structures (Table 4-2), or WWTP (Table 4-3) (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.Challis et al. 2021[T8TEWPCL] Challis, J. K., H. Popick, S. Prajapati, P. Harder, J. P. Giesy, K. McPhedran, and M. Brinkmann. 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.). Throughout the United States, MS4 are geographically more common, where stormwater is discharged to natural water bodies or stormwater treatment structures. In combined sewer systems, TRWP and associated chemicals are transported to WWTP under normal conditions but may be discharged to natural waterbodies under excessive runoff conditions as combined sewer overflow. In regard to the persistence of 6PPD-q, Foscari et al. (Foscari et al. 2024[JBUK7E3P] Foscari, Aurelio, Bettina Seiwert, Daniel Zahn, Matthias Schmidt, and Thorsten Reemtsma. 2024. “Leaching of Tire Particles and Simultaneous Biodegradation of Leachables.” Water Research 253 (April):121322. https://doi.org/10.1016/j.watres.2024.121322.) demonstrated in lab experiments the biodegradation of 6PPD-q and a corresponding concentration decrease when TRWP were not present, while 6PPD-q concentrations are relatively stable or may even increase when particles are present. The development of methods to accurately measure 6PPD and 6PPD-q in surface water (see Section 5.1.5: Sampling 6PPD-q in Water) will help address the fate, transport, and occurrence data gaps to inform management actions (see Section 8.2).

Occurrence in Water

- Surface runoff and stormwater are major mechanisms for transporting TRWP, 6PPD and 6PPD-q to receiving surface water.
- More studies are needed to understand how environmental, landscape, and stormwater characteristics effect the fate and transport of TRWP, 6PPD, and 6PPD-q.
- More studies are needed to understand what stormwater, wastewater and drinking water treatment technologies are most effective at preventing the transport of TRWP, 6PPD, and 6PPD-q.
- More studies are needed to understand if 6PPD or 6PPD-q are transported by surface water and groundwater.

6PPD and 6PPD-q can be released directly from tires and readily bind to particulates (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.); these particulates are transported by stormwater (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.). 6PPD and 6PPD-q can also be released from TRWP that are generated during driving, deposited along roadways, and transported by stormwater to waterbodies or treatment facilities. Detected environmental concentrations of 6PPD and 6PPD-q have been highest in urban runoff (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.Tian et al. 2021[X8BRFG3P] Tian, Zhenyu, Haoqi Zhao, Katherine T. Peter, Melissa Gonzalez, Jill Wetzel, Christopher Wu, Ximin Hu, et al. 2021. “A Ubiquitous Tire Rubber–Derived Chemical Induces Acute Mortality in Coho Salmon.” Science 371 (6525): 185–89.

https://doi.org/10.1126/science.abd6951.Cao et al. 2022[VBAMJHA7] Cao, Guodong, Wei Wang, Jing Zhang, Pengfei Wu, Xingchen Zhao, Zhu Yang, Di Hu, and Zongwei Cai. 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. 2023[JWRBWTKN] Zhang, Hai-Yan, Zheng Huang, Yue-Hong Liu, Li-Xin Hu, Liang-Ying He, You-Sheng Liu, Jian-Liang Zhao, and Guang-Guo Ying. 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.). Studies that measure and compare dissolved and suspended fractions of 6PPD and 6PPD-q in water are needed to understand the fate and transport of these contaminants' pathways from impervious surfaces to natural waterbodies.

Potential aquatic ecological receptors, which include freshwater and marine organisms (vertebrates, invertebrates, and plants), may be exposed to 6PPD-q and 6PPD through direct uptake of water through respiratory surfaces, ingestion, and absorption. The route of exposure may vary among species or life stage. People who engage in subsistence or recreational activities such as swimming, fishing, or boating may be exposed to 6PPD and 6PPD-q through incidental ingestion of and dermal contact with water contaminated by surface runoff. Human exposure to 6PPD and 6PPD-q during water-based activities is an emerging area of concern that also needs further study.

Waterbodies located near roadways and used as sources for drinking water may be vulnerable to environmental contamination with 6PPD and 6PPD-q. Surface water in streams and lakes that are drinking water sources may be affected by surface runoff and stormwater or, depending on the setting, effluent from WWTP. Two published studies report analyses of drinking water source samples connected to surface water, one in China and the other in the greater Toronto area in Canada (Table 4-3). As of May 2024, the ITRC Tire Anti-degradants team did not identify reports or studies for 6PPD and 6PPD-q detection in finished drinking water in the United States.

In China, H.-Y. Zhang et al. (Zhang et al. 2023[JWRBWTKN] Zhang, Hai-Yan, Zheng Huang, Yue-Hong Liu, Li-Xin Hu, Liang-Ying He, You-Sheng Liu, Jian-Liang Zhao, and Guang-Guo Ying. 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.) detected 6PPD in 30%–48% of filtered river source water samples and 6PPD-q in 100% of samples. Concentrations were in the low ng/L range, and 6PPD-q concentrations were higher than the parent chemical 6PPD. Within the drinking water treatment plant (DWTP), neither chemical was detected in samples drawn at each of six treatment stages. A Canadian study sampled for 6PPD-q in four WWTP and two DWTPs which use Lake Ontario as the source water (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-q was detected in WWTP influent and effluent but not in drinking water (pre- or post-treatment).

4.1.2 Groundwater

There is little information regarding the transport of 6PPD and 6PPD-q from surface water to groundwater (Table 4-4). Groundwater contamination by 6PPD and 6PPD-q, along with other PPD chemicals, was reported in a shallow aquifer in China (Zhang et al. 2023[D6T6D4JP] Zhang, Ruiling, Shizhen Zhao, Xin Liu, Lele Tian, Yangzhi Mo, Xin Yi, Shiyang Liu, Jiaqi Liu, Jun Li, and Gan Zhang. 2023. "Aquatic Environmental Fates and Risks of Benzotriazoles, Benzothiazoles, and p-Phenylenediamines in a Catchment Providing Water to a Megacity of China." Environmental Research 216 (January):114721. https://doi.org/10.1016/j.envres.2022.114721.). Samples from civil wells and household water directly connected to groundwater were analyzed as proxies for groundwater samples. The authors describe the hydrogeology of the aquifer as unconfined and highly permeable to the nearby river water. An important data gap in the United States is whether groundwater that serves as drinking water sources could be vulnerable to a similar contamination pathway. The transport potential will ultimately depend on the organic content and soil type present. More research is needed to evaluate the assumptions that 6PPD and 6PPD-q stay bound to particulates and do not readily move through soil (Cunningham and Schalk 2011[N2W34PYI] Cunningham, W.L., and C.W. Schalk. 2011. "Groundwater Technical Procedures of the U.S. Geological Survey: U.S. Geological Survey Techniques and Methods 1–A1." https://pubs.usgs.gov/tm/1a1/.).

4.1.3 Tap Water

One study that analyzed drinking water at the point of exposure (tap water) was identified during preparation of the current document (Table 4-3). In that study, 6PPD was detected in 25% of drinking water samples collected from 20 buildings in Singapore, while 6PPD-q was not detected (Marques dos Santos and Snyder 2023[GEI8HFLB] Marques dos Santos, Mauricius, and Shane Allen Snyder. 2023. "Occurrence of Polymer Additives 1,3-Diphenylguanidine (DPG), N-(1,3-Dimethylbutyl)-N′-Phenyl-1,4-Benzenediamine (6PPD), and Chlorinated Byproducts in Drinking Water: Contribution from Plumbing Polymer Materials." Environmental Science & Technology Letters, September. https://doi.org/10.1021/acs.estlett.3c00446.). The source of 6PPD in the drinking water samples was not identified but may be due to leaching of the chemical from plumbing components (for example, rubber gaskets, O-rings). The original sources of the drinking water sampled in the study were not identified as surface water, groundwater, or otherwise. More research is needed to understand potential exposures from drinking water broadly, including water at the point of use.

4.1.4 Wastewater and Biosolids

In some cities in the United States, stormwater is diverted to WWTP through combined sewer systems. Studies investigating 6PPD-q removal in WWTP have had mixed results (Table 4-3). Several studies showed a strong reduction or removal of 6PPD-q to nondetect levels in water (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, Li-Xin Hu, Liang-Ying He, You-Sheng Liu, Jian-Liang Zhao, and Guang-Guo Ying. 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.), and another study showed an increased mass of 6PPD-q in the effluent from the WWTP (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 follow up on this.

Biosolids are a necessary byproduct of our WWTP. WWTP may receive TRWP, 6PPD, and 6PPD-q from upstream sources, and as such they can end up in biosolids. Both 6PPD and 6PPD-q were detected in 100% of biosolid samples from WWTP in Hong Kong (Cao et al. 2023[D5FPK9YB] Cao, Guodong, Wei Wang, Jing Zhang, Pengfei Wu, Han Qiao, Huankai Li, Gefei Huang, Zhu Yang, and Zongwei Cai. 2023. "Occurrence and Fate of Substituted P-Phenylenediamine-Derived Quinones in Hong Kong Wastewater Treatment Plants." Environmental Science & Technology, October. https://doi.org/10.1021/acs.est.3c03758.), though more research is needed to characterize these occurrences in other localities. 6PPD-q has been detected in biosolids from a WWTP in Irvine, California (35.3±2.9 and 18.8±1.5 µg/kg, n=2) (Dennis, Braun, and Gan 2024[RNAS6357] Dennis, Nicole M., Audrey J. Braun, and Jay Gan. 2024. "A High-Throughput Analytical Method for Complex Contaminant Mixtures in Biosolids." Environmental Pollution 345:123517. https://doi.org/10.1016/j.envpol.2024.123517.).[6]

Table	Media Type	Link to PDF	Link to Executable File (Word Processor Format)
4-1	Surface Water		
4-2	Stormwater		
4-3	Wastewater, water treatment plants, and tap water		
4-4	Groundwater		

Note: PDF versions of each table are provided for the reader to view information in a visual format that is consistent across browsers and platforms. Executable files are provided to allow readers to sort information by the column of their choice, but may appear different visually depending on the software used to view this file. Instructions on how to sort information in a document formatted for a word processor format are widely available by internet search.

4.2 Soil

Modeled and measured physicochemical characteristics of 6PPD and 6PPD-q suggest that these compounds readily bind to soil and organics (Cao et al. 2022[VBAMJHA7] Cao, Guodong, Wei Wang, Jing Zhang, Pengfei Wu, Xingchen Zhao, Zhu Yang, Di Hu, and Zongwei Cai. 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.OSPAR Commission 2006[SVMKJM7X] OSPAR Commission. 2006. "Hazardous Substances Series 4-(Dimethylbutylamino)Diphenylamine (6PPD) 2005 (2006 Update)." Publication Number: 271/2006. https://www.ospar.org/documents?v=7029.); however, occurrence data are limited and more studies are needed (Table 4-5). Sampling protocols for measuring and understanding the occurrence and persistence of tire contaminants in soils along roadways are needed to address data gaps. Biodegradation of 6PPD and 6PPD-q in soil has been observed (Xu et al. 2023[4P2E4JLJ] Xu, Qiao, Gang Li, Li Fang, Qian Sun, Ruixia Han, Zhe Zhu, and Yong-Guan Zhu. 2023. "Enhanced Formation of 6PPD-Q during the Aging of Tire Wear Particles in Anaerobic Flooded Soils: The Role of Iron Reduction and Environmentally Persistent Free Radicals." Environmental Science & Technology, March. https://doi.org/10.1021/acs.est.2c08672.). Additional research is needed to understand other degradation pathways and overall stability in soil.

Exposure in terrestrial organisms (vertebrates, invertebrates, and plants) is poorly characterized, but it is possible that terrestrial receptors may be exposed via ingestion, inhalation, or absorption. The primary pathways through which humans may be exposed to 6PPD and 6PPD-q in soil are ingestion and dermal contact. Incidental ingestion can occur when people come into direct contact with contaminated soil and engage in hand-to-mouth behaviors.

An exposure assessment conducted by Cao et al. (Cao et al. 2022[VBAMJHA7] Cao, Guodong, Wei Wang, Jing Zhang, Pengfei Wu, Xingchen Zhao, Zhu Yang, Di Hu, and Zongwei Cai. 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.), using concentrations of total PPD compounds and their quinone transformation products in roadside soil, surface runoff, and air particles in Hong Kong, estimated that ingestion of roadside soil could be the primary contributor of human exposure to PPDs and PPDquinones, followed by dermal contact, and then inhalation of ambient air particulate. The relative importance of the exposure pathway reflected the lower concentrations of PPD chemicals and their transformation products in ambient air particulate as compared to concentrations in roadside soil and roadway runoff samples (Cao et al. 2022[VBAMJHA7] Cao, Guodong, Wei Wang, Jing Zhang, Pengfei Wu, Xingchen Zhao, Zhu Yang, Di Hu, and Zongwei Cai. 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.). It is unknown whether these exposure pathway trends are applicable to people in the United States. Additional research is needed to understand the potential human health impacts from soil exposure pathways.

Beneficial use of biosolids, or land application, returns nutrients to the soil in place of commercial fertilizers. In California, 6PPD-q was detected in biosolids from a WWTP (see Section 4.1.4: Wastewater and Biosolids). More research is needed to understand the fate, transport, and exposure risk of 6PPD-q in biosolids used for agriculture and landscaping.

Table	Media Type	Link to PDF	Link to Executable File (Word Processor Format)
4-5	Roadside soil	PDF	W

Note: The PDF version of this table is provided for the reader to view information in a visual format that is consistent across browsers and platforms. The executable file is provided to allow readers to sort information by the column of their choice, but may appear different visually depending on the software used to view this file. Instructions on how to sort information in a document formatted for a word processor format are widely available by internet search.

4.3 Sediment

Occurrence in Sediment

- Tire, road, and soil particles are transported by stormwater and surface water. The allocation between what stays suspended in water and what is deposited in the sediments is unknown.

- Standardized methods for measuring small TRWP in water and sediments are challenging. 6PPD q may provide a proxy for tire-derived microplastics that could represent a continued source of 6PPD and 6PPD q.
- More studies are needed to understand the fate and transport of TRWP in sediments including deposition, composition, biodegradation, and transformation processes.

In hydrology practices, sediment often refers to the benthic media at the bottoms of streams, rivers, estuaries, oceans, and lakes. In stormwater practices, the dirt and debris transported from impervious surfaces to stormwater catchments is referred to as sediment as well. In the San Francisco Bay Area alone, an estimated 0.3 to 2.4 million kg of TRWP wash off roads and parking lots into stormwater systems and enter San Francisco Bay via small tributaries annually (Moran et al. 2023[9FSZ84KX] Moran, Kelly, Alicia Gilbreath, Miguel Mendez, Diana Lin, and Rebecca Sutton. 2023. “Tire Wear: Emissions Estimates and Market Insights to Inform Monitoring Design.” SFEI Technical Report SFEI Contribution #1049. Richmond, CA: San Francisco Estuary Institute.). These estimates do not include contributions from San Francisco’s combined sewer system or from California’s Central Valley. Other urban areas likely have similar wash-off rates. As with soil, 6PPD and 6PPD-q will readily bind to sediment instead of the water phase; however, occurrence data are limited, and more studies are needed (Table 4-6). Studies conducted in the Jiaojiang River and the Pearl River Delta and Estuary in China found both 6PPD and 6PPD-q as the most dominant PPD and PPDquinones quantified in a large-scale survey of urban rivers, estuaries, coasts, and deep-sea sediments (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, acs.est.2c07652. https://doi.org/10.1021/acs.est.2c07652.). The concentration of 6PPD and 6PPD-q decreased with distance from the urban areas. The detection of 6PPD may suggest TRWP are a source and/or that the half-life of 6PPD varies between air and water, environmental conditions, and chemical phases (dissolved and suspended fractionation) (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, acs.est.2c07652. https://doi.org/10.1021/acs.est.2c07652.). More studies are needed to continue understanding the variability in partitioning and other physicochemical characteristics. Klöckner, Seiwert, Wagner, et al. (Klöckner et al. 2021[Y49MVKMM] Klöckner, Philipp, Bettina Seiwert, Stephan Wagner, and Thorsten Reemtsma. 2021. “Organic Markers of Tire and Road Wear Particles in Sediments and Soils: Transformation Products of Major Antiozonants as Promising Candidates.” Environmental Science & Technology 55 (17): 11723–32. https://doi.org/10.1021/acs.est.1c02723.) suggested using organic markers (specifically, the 6PPD transformation products N-formyl-6-PPD, hydroxylated N-1,3-dimethylbutyl-N-phenyl quinone diimine, and 6PPD-q) to measure TRWP. For 6PPD, a greater fraction of release was found in sediment compared to water following aging and biodegradation processes; however, more studies are needed to estimate leaching rates (Unice et al. 2015[NS59BGK2] Unice, K.M., Jennifer Bare, Marisa Kreider, and Julie Panko. 2015. “Experimental Methodology for Assessing the Environmental Fate of Organic Chemicals in Polymer Matrices Using Column Leaching Studies and OECD 308 Water/Sediment Systems: Application to Tire and Road Wear Particles.” Science of the Total Environment 533 (July):476–87. https://doi.org/10.1016/j.scitotenv.2015.06.053.Xu et al. 2023[4P2E4JLJ] Xu, Qiao, Gang Li, Li Fang, Qian Sun, Ruixia Han, Zhe Zhu, and Yong-Guan Zhu. 2023. “Enhanced Formation of 6PPD-Q during the Aging of Tire Wear Particles in Anaerobic Flooded Soils: The Role of Iron Reduction and Environmentally Persistent Free Radicals.” Environmental Science & Technology, March. https://doi.org/10.1021/acs.est.2c08672.). Anaerobic sediment conditions have been shown to produce more 6PPD-q (Xu et al. 2023[4P2E4JLJ] Xu, Qiao, Gang Li, Li Fang, Qian Sun, Ruixia Han, Zhe Zhu, and Yong-Guan Zhu. 2023. “Enhanced Formation of 6PPD-Q during the Aging of Tire Wear Particles in Anaerobic Flooded Soils: The Role of Iron Reduction and Environmentally Persistent Free Radicals.” Environmental Science & Technology, March. https://doi.org/10.1021/acs.est.2c08672.).

As with soil, the primary pathways through which humans may be exposed to 6PPD and 6PPD-q in sediment are also ingestion and dermal contact. Sediment disturbance due to human activities such as wading and swimming can resuspend sediment particles in the water column, making them available for dermal contact or incidental ingestion. Incidental ingestion can also occur when people come into direct contact with contaminated sediment and engage in hand-to-mouth behaviors. It is unknown whether skin absorption of the chemicals from these particles is possible. Additional research is needed to understand the potential human health impacts from sediment exposure pathways. Likewise, more research is needed to understand the ecological risks associated with TRWP, 6PPD, and 6PPD-q in sediments.

Table	Media Type	Link to PDF	Link to Executable File (Word Processor Format)
4-6	Sediment		

Note: The PDF version of this table is provided for the reader to view information in a visual format that is consistent across browsers and platforms. The executable file is provided to allow readers to sort information by the column of their choice, but may appear different visually depending on the software used to view this file. Instructions on how to sort information in a document formatted for a word processor format are widely available by internet search.

4.4 Air

Over time, as tires wear down, particles containing 6PPD and 6PPD-q are released into the environment (outdoor air), and present different potential exposure pathways. Additionally, these particles could infiltrate indoor environments, settling as dust on various surfaces. 6PPD and 6PPD-q have been detected in particulate matter in outdoor air; dusts collected from roads, tunnels, and paved parking; and settled indoor dusts. To date, much, but not all, of the data on 6PPD and 6PPD-q in air and dust were collected in China. This section reviews airborne TRWP and associated particle size, dust, 6PPD, and 6PPD-q.

TRWP, 6PPD, and 6PPD-q Occurrence in Air

- 6PPD and 6PPD-q have been observed in outdoor ambient air and fine particulate matter.
- 6PPD and 6PPD-q have been observed in dust along roads and highways, parking lots and garages, rubber playgrounds, recycling facilities, and homes.
- Tire dust has been observed in snow along roadways.
- More research is needed to understand the airborne exposure pathways for tire dust and related chemicals to humans and terrestrial and aquatic ecosystems.

In laboratory simulations of tire wear, TWPs are generated in multiple size fractions, including below 10 µm in diameter, with a large fraction of the total number of particles emitted below 0.1 µm, known as ultrafine particulate matter or $PM_{0.1}$ (Dahl et al. 2006[PTHCYGGU] Dahl, Andreas, Arash Gharibi, Erik Swietlicki, Anders Gudmundsson, Mats Bohgard, Anders Ljungman, Göran Blomqvist, and Mats Gustafsson. 2006. “Traffic-Generated Emissions of Ultrafine Particles from Pavement–Tire Interface.” Atmospheric Environment 40 (7): 1314–23. https://doi.org/10.1016/j.atmosenv.2005.10.029.Park, Kim, and Lee 2018[HIY3Z76P] Park, Inyong, Hongsuk Kim, and Seokhwan Lee. 2018. “Characteristics of Tire Wear Particles Generated in a Laboratory Simulation of Tire/Road Contact Conditions.” Journal of Aerosol Science 124 (October):30–40. https://doi.org/10.1016/j.jaerosci.2018.07.005.). $PM_{0.1}$ can readily be inhaled and can pass directly into the body. Particles, including TRWP, less than 10 µm in diameter are generally recognized to be respirable; the smaller they are, the deeper they can penetrate the lungs. The term “dust” can comprise different particle types and size fractions. We use the term here in the context of human health to indicate particles that are greater than 10 µm in diameter and therefore not respirable into the deep lung.